Re-Addressing The Role Of Knitted Textile Design Knowledge: Auxetic Textiles From A Practice-Led, Designer-Maker Perspective

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ABSTRACT

This study reacts to the segregation of knowledge and practice surrounding weft-knitted textiles, their design and applications. This study challenges current disciplinary practices that divide knit into scientific, design and art areas by describing a designer-maker methodology, which is used to produce auxetic, weft-knitted textiles. By using a designer-maker's practice-led perspective to create functional fabrics, it seeks to challenge the perception that technical and functional research in textiles is or should be the domain of scientific methodologies and engineering practice.

This study does not apply external methodologies to the research design, but extracts its methods and values from an existing knit design practice, built from experiential knowledge, that becomes the basis for the methodology. Qualitative and quantitative measures of success are both vital to the methodology used in this study and both subjective and objective perspectives are embraced.

The practical work uses designer-maker practice to lead the development of 30 auxetic fabric samples. These fabrics are appraised using a variety of methods including personal reflection, numerical measurement and feedback from focus groups of other practitioners. The information developed on auxetic materials is presented in various ways such as using percentages, diagrams, photographs and videos to encourage dissemination and knowledge transfer between different disciplinary groups. Auxetic effect is conveyed in photographic, diagrammatic, video, graphical, percentage and Poisson's ratio data to increase understanding to wide audiences and to satisfy traditional, scientific auxetic researchers as well as a new area of design-based practitioners.

This study presents the case that there is a valuable, transferrable knowledge in knit design practice that represents existing methodologies used by knit practitioners as well as providing a new methodology for consideration by science and engineering practitioners. This is demonstrated through the production of auxetic, knitted fabrics using a design approach that incorporates qualitative, quantitative, practical, aesthetic, functional and theoretical skills.

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Videos of auxetic fabric samples available at: https://vimeo.com/album/2903363 using the password MGlazzardthesis

The video files can be organised alphabetically and are named as Samples 1-30, 3D-prints 1-4. Videos of three additional samples are included that receive mention in focus groups or other sample discussion.

LIST OF SAMPLES

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Sample 1a (Liu et al. reproduction + elastomeric)

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AUTHOR'S DECLARATION & PUBLICATIONS

I declare that the information in this thesis is original work by the author (Martha Glazzard). Third-party material is credited where included and permissions are obtained. Work already published by the author relating to this thesis features in the following publications:

- GLAZZARD, M. and BREEDON, P., 2014. Weft-knitted auxetic textile design. *Physica Status Solidi (b),* 251 (2), 267-272.
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- GLAZZARD, M. and BREEDON, P., 2012. Designing a Knit Methodology for Technical Textiles. *In: Smart Design: First International Conference Proceedings, 22-24 November 2011*. Springer, pp. 103-108.

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- ALDERSON, A. and ALDERSON, K.L., 2007. Auxetic materials. Proceedings of the Institution of Mechanical Engineers, Part G, Journal of Aerospace Engineering, 221 (4), 565-575.
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Chapter 1: Introduction

1. INTRODUCTION

In the subject of knit[1], there are many different disciplines, practices and perspectives at work. Work in knitted textiles spans design, engineering, science, art, craft and fashion. This thesis addresses the similarities and differences of those approaches and challenges the ingrained segregation that comes from disciplinary-focused practice.

The fields of knit, design, auxetic materials and knowledge transfer are all practised in this thesis. Existing perceptions of and conventions in these fields are questioned and analysed. This study uses the approach of a knit designer to document and analyse her motives and actions in the creation of weft-knitted auxetic textiles. The methods of producing these textiles and sharing the information about them are major focuses for this work.

1.1. Research question

1.1.1. Aim

- To reassess the value of knit design methodology to areas of design, engineering and making, via demonstrating trans-disciplinary knowledge through designing and making auxetic textiles using inherent, practice-led knit skills and understanding.

1.1.2. Objectives

- To identify generic knit and knit design approaches within research methodology using a practice-led approach and incorporating the views of others.
- To explicate tacit knowledge using multidisciplinary practice and the designing of functionality.
- To create auxetic textiles using the perspective of a knitted textile designer, thereby demonstrating interdisciplinary knowledge transfer and contributing to the auxetic research field.
- To use parallel methods of practice-led design and reflection alongside development of fabrics with auxetic functionality to demonstrate mixed methodology.
- To use pragmatic textile skills in order to illustrate an integrated design process between functionality and traditional aesthetic[2] design considerations.
- To present this information in a style suitable for practitioners of different backgrounds through considered verbal and visual use and feedback through showcasing.
- To inform methods of design practice for knit with regard to function-focused knitted materials.

1.2. Background and overview

The background of my own practice includes education in knitwear design & knitted textile design and the making of knitted objects through that knowledge. It also includes experience of working as a knitting machine technician, facilitating problem solving for students of knitwear and knitted textiles

[1] 'Knit' in this study refers to weft-knit unless otherwise stated.
[2] 'Aesthetic' in this study refers primarily to visual aesthetics, but may refer to all sensory perceptions.

(as well as other subjects) towards a variety of outcomes. During my time as a technician, I began working on research projects that required fitting a knitted textile method into a broader range of projects both collaboratively and individually. The combination of these experiences has given me an in-depth and complex view on knit, not only as a design tool, but also as a fundamental knowledge tool. The study described in this thesis came about after being dissatisfied with the existing literature on knit that appeared to bear no resemblance to the practice I know. Literature describing knitted textile, knit design or knitted technical textile projects would describe practical information that I understood, but from a perspective that I felt was not representative of my practice. This dissatisfaction led to a desire to promote the epistemological aspects of knit above disciplinary connotations. Though research was available on the technical and artistic applications of knitting, there was no exploration of the motives, thought processes and experiential knowledge that the knitters I have met seemed to share. The technical information and scientific research was presented in an inflexible manner and the artistic sides of knitting presented on a case-by-case basis describing various projects. Neither of these approaches captured what I considered to be the essence of methodologies, approaches or fundamental knowledge sets in knit. After deciding to embark on a PhD in knit it soon became apparent to me that I had no satisfactory research base to draw on; no methodological framework that represented the practice I knew. This realisation led to the need to first define an area through a reflective methodology built on personal experience, to find empathetic audiences for support and to manifest the thinking, doing and making into a traditional, written format.

Therefore, this thesis offers an overview (in **Chapter 2**) of the context of knit in practical and methodological terms, focusing on those areas which I consider to be under-represented in academic literature – namely the design, making and thought processes involved. Practical, generic and technical knitting information is described as well as methodological stances in current literature. The context review aims to give an overview of the current perceptions of knit as a subject, how it is practised, categorised, divided and, importantly, the generic processes at the heart of any knit practice. This thesis argues that design knowledge is important, applicable and often maligned in existing knit literature. In order to demonstrate the strength of the fundamental knowledge that is integral to knit design, this thesis applies it to a technical area not known for its design outcomes – the area of auxetic materials (materials that expand, when stretched in a transverse direction to the stretch). This applies skills and knowledge (including: making experience, technical knowledge, visual appraisal, reflection and aesthetic considerations) towards a function-focused outcome. The area of auxetic materials was chosen because it has geometric, structural and physical aspects, which could be easily incorporated into knit design. A paper by Liu et al. (2010) showed an early indication that weft-knitted textiles could be used to produce auxetic materials, but this paper used scientific, engineering methodology to achieve this. I then decided to create auxetic weft-knitted textiles using my own experiential, design-based knowledge. This process is discussed in terms of a practice-led, designer-maker (Howell, 2013) perspective in **Chapter 3**, which gives a detailed description of the factors that shape the design of this study. Methods used for knitting, testing, analysis, recording and disseminating used in this study are described.

The practical development takes place in four stages, described in **Chapters 4-7** (Stages 1-4). This thesis describes 30 fabrics that display auxetic behaviour. These are based around 7 stitch structures and use alterations of pattern, scale, yarn and placement to change both the aesthetic qualities and the auxetic behaviour.

During each stage, both the methodology and the fabrics are assessed using both formal and informal testing methods. Personal reflection is used throughout and there is discussion of the knitting work undertaken, assessment of and reflection on samples and discussion of changes to fabrics or to the research design. Each stage ends with a focus group, made up of design practitioners, discussing the practical work. This provides alternative assessment by collecting responses from other practitioners in order to validate the openly subjective methods for assessment and development of the practical work. The role of testing in this thesis challenges conventions in scientific writing and incorporates a mixture of the qualitative and subjective alongside quantitative measuring of auxetic behaviour. As well as measuring the auxetic behaviour, fabric samples are assessed for their aesthetic qualities and against the success of the knitting (i.e. whether the quality is acceptable, the handle is good, the fabric has flaws, etc.[3]). Some fabrics are tested for auxetic behaviour with preliminary measuring equipment (tape measures), some with a testing frame (which are then photographed and measured using image-analysis software), and some auxetic behaviour is measured subjectively using sight from photographs and videos. This approach covers both qualitative and quantitative methods, which are both important to my practice of knit design.

To conclude the practical development of this thesis, the fabrics are used for two smaller projects to demonstrate knowledge transferability (discussed in **Chapter 8**). In the first project fabrics are given to a small group of Master's students for them to develop design applications and in the second I translate some of the fabrics into 3D-printed structures using interpretations of each fabric's structural geometry. Conference participation and research papers are discussed for their contribution to the transfer of knowledge and to test and validate the practical and theoretical contributions of this study through dissemination.

Chapter 9 assesses the work from this thesis against the aim and objectives, as well as discussing possibilities for future work. It collates the main points of contribution to knowledge and brings together the theoretical conclusions from the practical development stages.

1.2.1. Publications related to this thesis

- GLAZZARD, M. and BREEDON, P., 2014. Weft-knitted auxetic textile design. *Physica Status Solidi (b),* 251 (2), 267-272.

[3] In addition to the discussion of the 30 auxetic fabrics in the main thesis body, further information on the fabrics as well as other, developmental fabrics can be found in the appendices and accompanying videos.

- GLAZZARD, M. and BREEDON, P., 2013. Exploring 3D-Printed Structures Through Textile Design. *In: Research Through Design 2013 Conference Proceedings, Gateshead, UK, 3-5 September 2013*. Northumbria University, pp. 51-54.
- GLAZZARD, M., 2012. Reclaiming a Knitter's Perspective. *In: Defining Contributions 18 May 2012*. Nottingham Trent University, pp. 25-30.
- GLAZZARD, M. and BREEDON, P., 2012. Designing a Knit Methodology for Technical Textiles. *In: Smart Design: First International Conference Proceedings, 22-24 November 2011*. Springer, pp. 103-108.

1.3. What this research features…

At its core, this research communicates a designer-maker, practice-led methodology in knit to a wider audience that is based in the pragmatic, competent and skilful production of items, which are appraised aesthetically and functionally. The main discussion is focused on machine-knitted fabrics, but there are many elements that would be applicable to hand-knitted and manually-manipulated knitted fabrics (such as domestic and hand-operated knitting machine-produced fabrics). The discussion does not aim to consider the popularity and purpose of hand-knitting, but it concentrates chiefly and pragmatically on the structure created (and the reasoning behind it) rather than the specific process of its creation.

The question of whether this methodology is something that can be extended into producing artefacts of interest to practitioners from external fields that are rooted largely in the scientific or engineering disciplines is explored through practical experimentation with structures and materials. Two questions to be addressed are: what information is required to satisfy readers from different backgrounds and what areas must remain intact to satisfy the personal, explorative nature of a (or my own) knitted textile design practice?

To support this, a discussion is therefore necessary about the nature of a personal methodology and whether this is a viable and rigorous methodology. By collaborating with a wide-ranging group of contributors in the form of supervisors, advisors, participants and audiences, measures are taken to assess the methodology and results using critical reflection during each focus group and dissemination (discussed at the end of each practical stage and in the knowledge transfer chapter).

Ultimately, a functional textile is created and discussed through both quantitative and qualitative means. This satisfies the values inherent in my experience of knit design knowledge that relies on both data types to realise any kind of product.

This research aims to promote knowledge transfer between more ‘scientific’ or ‘artistic’ practitioners when considering textile production. It aims to facilitate knowledge transfer by presenting easily-understood information about methods in lay terms, using multiple versions and formats of information when necessary (including numerical, pictorial, diagrammatical, photographical etc.).

1.4. … and what it does not

It is not the aim of this study to create a piece of research that will methodologically fit into all of the areas from which it draws knowledge and inspiration. Its ambition is to stay true to a practice-led knit and designer-maker methodology, and from this to create transferrable and communicable knowledge, materials and processes. This thesis provides new ways of documenting existing practice in knit design, which could create or inform new practice in other areas such as the sciences. Where there are differences and challenges between the practice in this study and other, predominant methodologies, these will be described and reflected upon.

This study does not produce an inflexible and rigorous (Wood, 2000:48) study, but presents a personal methodology, validated by dissemination and knowledge transfer. This is done using an inclusive and adaptive approach, which allows participants, audiences and readers to draw their own conclusions.

This study does not aim to create widely-generalisable knowledge about auxetic materials, knitwear design, knitted textile design, textile design or knowledge transfer between practical disciplines. The study does not aim to produce large-scale, generalisable theory. It aims to demonstrate that a design approach is a valid methodology for creation of technical textiles, or textiles outside areas of traditional design involvement.

The elements of this study that take influence from fields outside textile design do so selectively and respectfully. There is no attempt to summarise large areas of knowledge and literature from other fields in any sections of this dissertation. Due to the cross-disciplinary nature of this research, it is necessary to use information from subjects outside knit design, but these are used to complement existing methodological practice, not to replace it. Similarly, external methodologies are not adopted to satisfy sections such as testing, instead, simple techniques are used that can be easily understood and executed without specialist training.

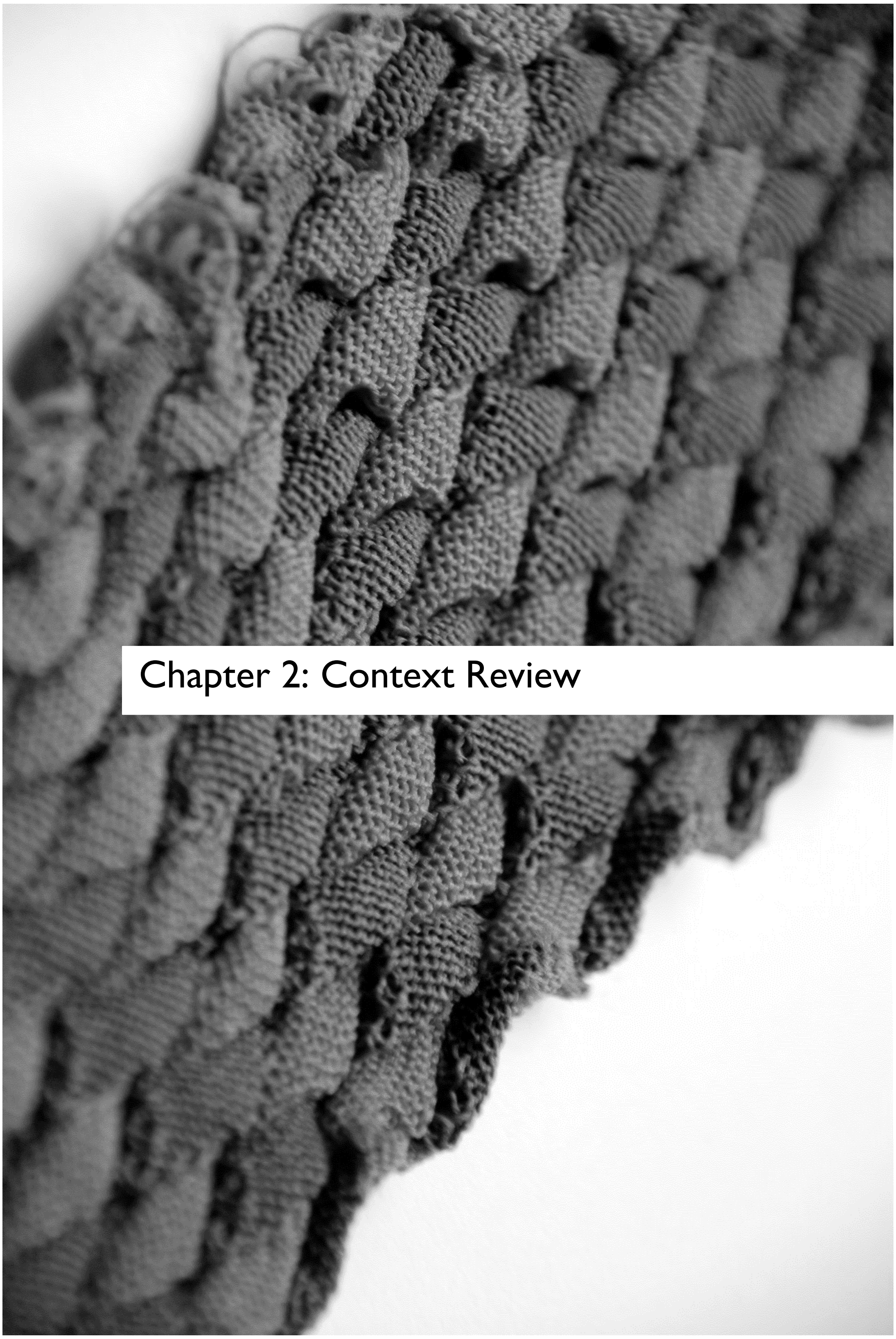
1.5. Format of this thesis

The content of this thesis represents the non-linear nature of the design process within. This non-linearity is celebrated rather than eradicated, and a certain level of the complexity of the design process must be present in the thesis to represent the process. Though events are listed chronologically, signposts[4] exist within the text to guide the reader to relevant information that may come earlier or later in the thesis, reflecting feedback loops in the design process. Because of the personal nature of the process undertaken, the writing style will change into first person narrative when discussing my practice explicitly. This distinguishes my identity as the author, the researcher and the practitioner; a person who embraces the subjective nature of this study (Hyland, 2002). For clarity, the bulk of text will be written in a passive, non-personal voice.

[4] The signposts can be found in the form of links between different sections of this thesis that have relevance to each other. These links are shown in bold type.

My knit design methodology values physical appraisal of fabrics, which is used in the formation of this thesis but, for readers who do not have access to the fabrics they are represented in this thesis by photographs, diagrams and stills from videos. Further representation of the fabrics can be seen in the accompanying videos available at: https://vimeo.com/album/2903363 using the password 'MGlazzardthesis'. Testing information, where used, is included both in the text and in tables, and there is detailed information about the fabric development and testing results available in the appendices attached to this thesis.

Chapter 2: Context Review



2. CONTEXT REVIEW

2.1. Chapter outline

This chapter will cover historical and current literature pertaining to the knitted stitch and its uses, as well as broader, current application for textiles in design and innovation. This review is of context, not solely literature; some of the important practical knowledge comes from experience and practice, and is essential to provide context surrounding the practicalities of knitting. This practical knowledge is shown in a comprehensive guide to the knitted stitch structure, enough to provide the reader with sufficient knowledge to interpret the later, practice-led findings. Auxetic materials are introduced and discussed for their current areas of development and application.

Focus will begin on knitted textiles as a pragmatic practice and skill set in order to familiarise readers with knit processes salient to the practical work described in **Chapters 4-7**. Then discussion will widen out to place knit within the larger areas of textiles and then design. This will provide context for the design of this research project. An outline of the considerations within knit will move into discussions of how related subjects are working together across different disciplines. Finally, there will be a discussion of auxetic materials and their current development in research, both within and outside textile disciplines.

There will be discussion within this chapter of the approaches used in working with 'technical textiles', assessing those from different disciplinary backgrounds. This will cover a wide range of disciplines and allow for an overview of the motives and methods used in current knit innovation.

2.2.Knitted textiles definitions and understanding

2.2.1. Problems with defining knit as a field

It is my opinion that, in the generic (or possibly, ultimate) knit practitioner, there is something of the artist, designer, engineer, technologist, salesperson, computer programmer, technician, craftsperson and manufacturer. The designer-maker approach, as favoured in this thesis, sees the knit practitioner as having input and control over all aspects of the designing, making and dissemination processes. This is not well reflected in the literature on knitting and knit practices, as each piece of writing on the subject excludes at least some of these elements.

Knitting is a significant process in domestic, design and industrial fields. It has a long history in practice and in everyday life. Early examples of knitting using an eyed-needle date back to the 5th century AD (Spencer, 2001: 7) and knitting using two pins recorded in religious paintings of 1350. The invention of machine knitting is credited to Reverend William Lee in Nottinghamshire in 1589 (ibid.: 9), whose mechanised invention slowly evolved into the machines used today. During most of this long history, the concern of knitted textile production was largely to do with making clothing and products for human use on the body and in the home (for modesty or protection against the elements). The process of early knit production[5] is likely to be seen by modern standards as a 'craft' method, but this design and making

[5] Garments made by individuals or as part of cottage industries.

process provides the origin of all the methodologies now used in knit. The distinction between craft and industry and human and machine production[6] is relatively modern and is, for some, a matter of nuance.

Enforcement of disciplinary divisions between the functional and the artistic qualities of knit has been promoted through educational, research and commercial separations in practice and product. This has meant that even practitioners who use the same fundamental knowledge are likely to have difficulty in communicating their ideas and processes. This thesis argues that a design approach to knit practice offers significant contributions to technical and functional outcomes. This is a salient topic for discussion, because segregation inherent in education, research and publication systems surrounding knit practice can wrongly misrepresent design and obscure its contributions to technical and functional outcomes.

This chapter questions the division between the methodologies and the methodological languages of the different factions of knitted textile creation. It outlines a personal perspective on how design knowledge can be recorded and shared without having to exclude important qualitative information, while aiming to include readers from different design and non-design backgrounds.

2.2.2. Knit practices

Knit occupies a peculiar place among the different textile subjects. It can be seen as too industrial, too technical, too fashion to be 'textile' (when textile refers to the art & design subject). In his book 'Textile Design', Simon Clarke does not refer to knit at all, instead offering advice on print, weave and embroidery only (Clarke, 2011).

It is also sometimes too hobbyist or too textile-based to be considered 'fashion'. Nonetheless, knit is a mode of textile construction and makes up a large proportion of the textile and apparel industry (Francis & Sparkes, 2011: 77). The hobbyist nature of knit has seen connotations for many years with amateur practice (Turney, 2009: 11). Knit as a hobby remains popular because knitting is easy to produce at home on knitting needles. Knitting has had a renaissance of popularity in recent years (ibid.) in both craft and fashion circles, but the literature, especially academic texts, remains mixed on what kind of subject knit is, who practises it and the importance of this fabric and its production. The distinctions between hobby, industry, fashion and textile do not provide concrete agreement on how knit should be categorised. Claudia Eckert describes knit in such a way that it encompasses other, established definitions:

> *Knitwear design thus combines the scope of fashion design, which is concerned with the shape of garments, and textile design, which creates fabric with woven or printed patterns.*
>
> Eckert, 1999: 31

Many problems with defining knit as a 'field' stem from the number of different disciplinary fields knit can be found in, or that can be found within knit. Knit can be situated as a design subject, a science subject,

[6] For further information, see the output from TRIP symposium at Loughborough University, 2011 (Loughborough University, 2011).

an art form, a craft, an industry, a hobby, a fashion discipline and more. This leads to a number of pre-conceptions from both practitioners in knit and those from outside perspectives, as to what knitting is, what it is for, who does it and why. **Figure 2.1** shows a diagrammatic representation of some of the practices involved in the wide spectrum of what can be related to or considered a knit practice. Inspired by the representation of jewellers' practices by Untracht (1982: 11-12) this image, like Untracht's, aims to represent the complexity of relationships between practices and to show some of the divides present. It does not aim to further impose any of these boundaries or to create a hierarchy of practices or roles within the field. The couture designer and the researcher are at the centre of the diagram to show their driving influence over the other sectors. The research and development and the couture role both have freedom to diversify the product range in their own outcomes and those of others. Both roles exert influence over a number of related roles.

What the diagram in **Figure 2.1** highlights is that certain elements, such as the heritage of knitting and the modes of production, are ubiquitous and necessary in each area. Heritage, for example, may be the push of an industry, such as a traditional factory, or it may influence the knowledge of designers, engineers, technicians, programmers, manufacturers, etc. The relationships between considerations and outcomes are widely complex and changeable with time.

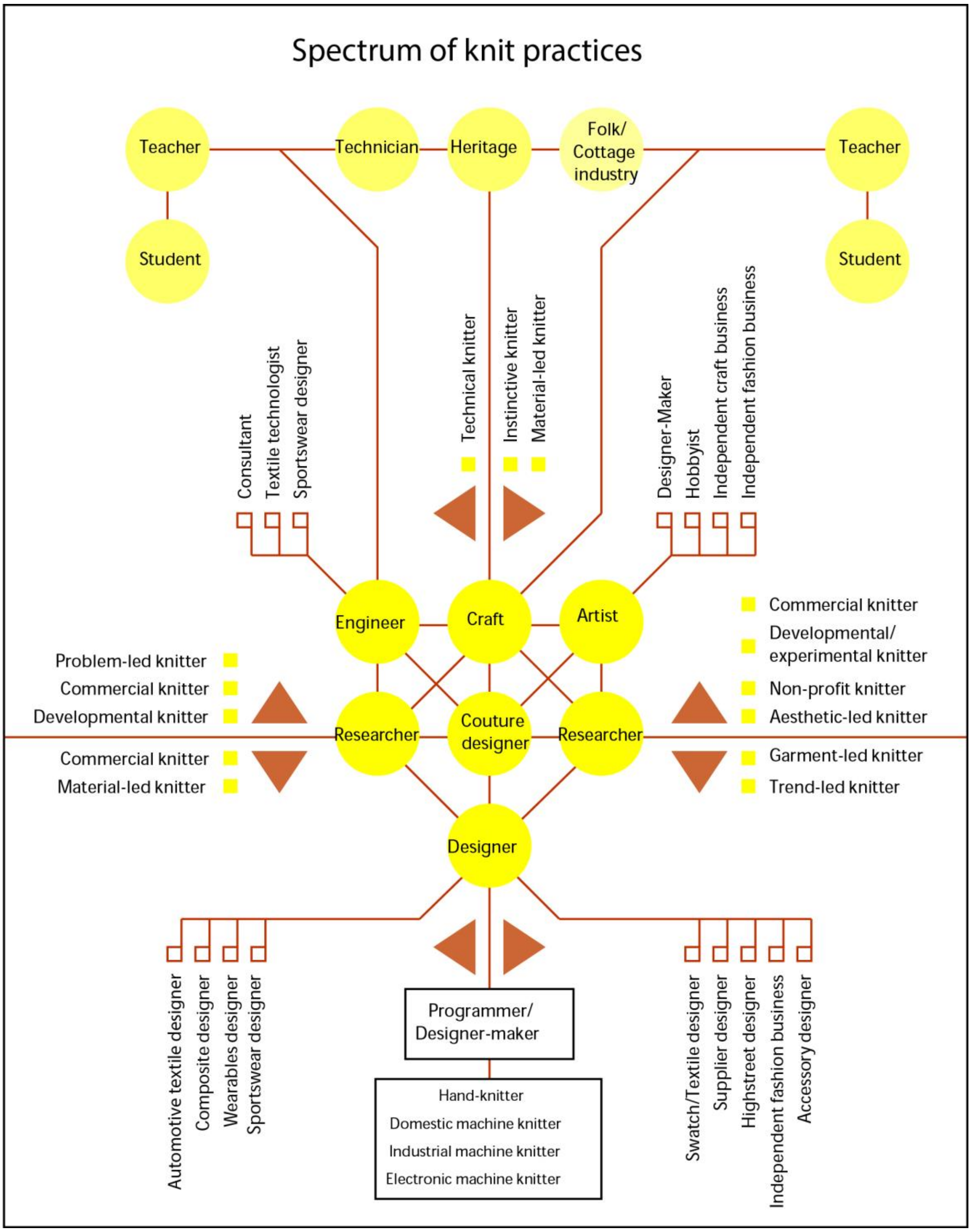


Figure 2.1 Diagrammatic representation of different knit practices (inspired by Untracht, 1982: 12).

In the interest of trying to quell some of these problems, I shall, when possible, talk about 'knit', 'knitting' or 'knitted textiles' as a process – a specific type of structure without connotation for motive and usage. Specific terminology can be used to break 'knit' apart into various sub-disciplines. For example, knitted textile engineering; knitted textile design; knit as craft; knit as art; etc. can be used to try to make individual motives and practices clear. To begin, it is essential to define in pragmatic terms, what knitting is. An account follows in section **2.3.** describing the physical and practical qualities of knitted fabrics.

2.2.3. Knitted textile design practice and methodology

Due to knit design's variable place between textile design and fashion design, it is sometimes omitted entirely from writing by authors who deem it to be outside their subject, for example, Clarke does not consider knit among the topics for discussion in his book on 'Textile Design' (2011). Whereas in other literature about textile design (including Briggs-Goode & Townsend [2011]), knit is an important area for discussion. One problem with current literature is a lack of transparency in stating how the author's relationship to the materials will affect the knowledge transfer from author to reader. In a subject as wide as textile design and production, there is a large amount of room for individual subjectivity, and this should not necessarily be hidden, but accepted and declared.

Similarly to textile design, fashion design texts can be used to clarify the motives behind their design methodologies. Winifred Aldrich favours transparent and inclusive handling of information. She writes that information presented to a designer about fabric properties is often presented in such a way that a designer (or pattern-cutter) cannot use or understand (2007: 9). She offers a guide to learning methods to appraise and understand fabrics for their various properties, focusing on those that are essential for consideration in the making of garments or textile products. Aldrich champions an experiential, subjective approach, while supporting this with elements of a quantitative approach. Concepts such as fabric thickness and weight are easily quantifiable, but to learn about more elusive qualities like handle and drape is a task that requires practice and qualitative evaluation (ibid.: 26). It is Aldrich's belief that designers may never truly grasp the complexity of the materials they use, unless they are experienced in the physical properties to the point where their fabric knowledge becomes instinctive or tacit[7].

As part of a balanced textile practice, like Aldrich, I would argue that, though the motives for quantifying fabric analysis are valuable, the subjective, human process cannot be completely, simply or effectively replaced. Any development in quantifying the tacit knowledge of textile designers should incorporate the previous methods, not aim to replace them. This thesis uses both quantitative and qualitative appraisal methods in the manner of my own knit design practice. The methods used are not hierarchical, but co-dependent. An advanced and practical understanding of knitting for design and engineering outcomes (and in particular, machine knitting) requires attention to numerical data, measurement and technical record-keeping, but this may be in addition to subjective and tacit decisions or processes[8].

2.2.4. Knitwear practice and methodology

Though knit design methodology often lacks emphasis and clarity in literature, several authors have produced writings that cover various aspects of knit in detail. The following texts have provided useful context for the documentation of the various considerations giving rise to the documentation of the methodology in this thesis. Spencer (2001) and Brackenbury (1992), have both written observations of the skills, technology and considerations required to produce knitted fabrics, with an emphasis on

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[7] Tacit knowledge refers to that knowledge, which is known but cannot be expressed (Polanyi, 1966: 5) and is discussed further in section **2.6.7.**

[8] Freeform and artistic approaches to knitting may not require the same recording of data, as the maker may not wish or require results to be repeatable or reproducible.

how these are used within the apparel industry. Black (2002) and Tellier-Loumagne (2005) have focused on machine-knitted textile design possibilities, with emphases on structure and application. Other authors such as Newton (1998) have concentrated on hand-knitters and their various methods and design possibilities. Eckert (1997; 1999; Eckert & Demaid, 1997; Eckert & Stacey, 2003) has explored in detail how the knitwear designer works in an industrial environment. Francis and Sparkes (2011) have provided a recent overview into how the knitwear design process works with a broader consideration of the complexity of educational and industrial aspects.

In order to explain the variable, adaptable and intuitive skills of a knit designer, it is important to view the possibilities of how the process might vary from person to person or from project to project. The process of designing knitwear or knitted textiles can have several different starting points, depending on the project being undertaken. As outlined by Glazzard & Breedon (2011: 105), some examples of starting points for a knit project might be:

- the yarn (e.g. a project determined by a yarn manufacturer)
- a trend (i.e. a moveable direction impacting on or driven by culture, [Raymond, 2010: 14] such as a fashion or technology trend)
- a silhouette or garment type (e.g. the need for an extra garment type in a clothing collection)
- a stitch structure type (e.g. driven by trend information or swatch companies)
- colours, textures, patterns, details, seams, etc. (e.g. driven by trend information)
- designing to specifications of costs or markets (e.g. a market-led brief)
- draping/modelling on the stand (e.g. developmental, craft or bespoke methods rather than industrial)
- specific applications/problem driven (e.g. technical or garment applications)

These various starting points dictate different considerations within a design process, though each designer is not limited to one process. A skilled knitwear or knitted-textile designer will be experienced in many or all of these techniques and will know how to adapt and combine methods to suit each project. Consideration has been given to how the various starting points for a knit design project affect the methodological process in **Figure 3.36** in section **3.7.**

2.2.5. Glossary of terms used for knit practitioners/practices

The definitions offered below comprise my views on the meanings of the following terms. There is a distinct amount of crossover between the various practices described, so this glossary provides guidelines rather than rigorous definitions. Wherever possible, terms in this thesis should be considered for their plain-English usage, rather than for academic connotations they might have elsewhere.

Knit	The process of knitting or any fabric or structure produced.
Knitting	The process of knitting or any fabric or structure produced.
Knitted textiles	Any textile produced by knitting.
Practitioner	Any person who carries out practical work – research, design, programming, engineering, etc.

Knit practice	Work and processes conducted by any knit practitioner.
Knit design	This encompasses all areas of knit that have an interest in design. Also referred to as 'generic' knit design.
Knitwear design	The process of designing clothing and accessories using knit. A commercial or craft practice primarily.
Knitted textile design	The process of designing fabrics using knit. The outcome may be used in clothing or accessories. A commercial, craft or art practice.
Hand-knitting	Making knitted fabrics by hand (using hand-held knitting needles).
Machine-knitting	Making knitted fabrics using a knitting machine (hand or electronically operated).

2.3. Knitting process

The process of knitting can be most simply described as a method of textile construction involving 'forming a fabric by the intermeshing of loops of yarn' (McIntyre & Daniels, 1995: 180). Spencer describes the term *yarn* as 'an assembly, of substantial length and relatively small cross-section, of fibres or filaments, with or without twist' Spencer, 2001: 3). This definition *yarn* covers all types of natural and synthetic staple fibre assemblies and natural or synthetic filaments. Yarn will be used in this text to broadly describe the materials used for knitting. In terms of 'technology' or equipment, knitting uses ranges of processes from hand-used knitting needles through to state-of-the-art electronic machinery. Below, three main distinctions in knitting technology are discussed:

1. Hand-knitting needles (or pins) are used by hand to draw loops through the previous set of loops. This method holds wide possibility for variation in design of fabric and complex effects can be produced with relative ease, as the user can control all aspects using her or his hands. Designs can be altered on a stitch-by-stich basis during the making process. Hand-knitting is a slow process that varies with the speed of the individual.
2. Hand-operated knitting machines exist in various types (such as domestic, semi-industrial or industrial hand flat machines), with various capabilities (such as patterning settings for Fair Isle, lace, etc. with manual, mechanical or electronic selection). The fabric can be altered during the knitting process, but due to the machine process, this is mainly possible between courses (when the carriage is not over the needles). This process is quicker than hand-knitting, but with the inclusion of hand-manipulated embellishments, is still a time-intensive process.
3. Electronic/automated knitting machines also exist in various forms (for example, circular machines, V-bed machines, fully-fashioning machines, seamless knitting machines, etc.). Historically, these can be programmed manually, but more recent machines are built to be programmed using computer software. Once the programme is taken to the machine, there are few alterations that can be made in situ. Generally, if a design alteration is to be made, the programme will have to be changed and the fabric re-knitted. Speed varies depending on stitch structure and modern machines have variable speed controls. The main use of these machines is industrial, so ideally, they should run at, or close to, their top speeds for optimum production levels.

The processes explained above are reminiscent of the range of methodological categories employed in knit. The hand-knitting process could be likened to an artistic or craft approach that allows freedom of formation and development through qualitative decision, whereas the electronic machine-knitting process is reminiscent of an engineering methodology, which demands thorough planning and preparation before commencing trials and production. However, the relationships between technologies and approaches to knit are flexible, adaptive and any correlation tends to be by association rather than a rule. For quantitative purposes, scientific approaches value the regularity of stitch and the repeatability of electronic machine knitting, but a fashion designer or craftsperson may also value these qualities.

With this in mind, the fundamental knowledge important to a knit approach might be about the structural process of constructing a fabric, or it might be about the means of operating a particular technology/equipment in order to produce the fabric. Additionally to the method of making, the use of materials is essential to any knit practice; mostly these will be yarns. Yarns consist of fibres which can range from synthetic polymer monofilaments to natural animal fibres. A practitioner will have an idea of which yarn type they need to use depending on the desired use or aesthetic. The method of production may influence the choice of yarn (e.g. certain combinations of machinery and yarns are problematic or impossible with regard to yarn thickness, strength, elasticity, etc.).

So far, this chapter has ascertained that there are several key considerations that will be present in any knitting practice. These are:

- Knowledge of structures
- Mode of production
- Materials (yarn) and appropriate knowledge
- Understanding of end use (N.B. end use may be the production of fabric, as in swatch design)

Other knowledge needed by practitioners is particular to their practice. Examples of this knowledge include: whether practitioners test for success in fabrics and how they do so; whether and how they finish fabrics/garments/swatches/products; at what stage and if they consider aesthetic qualities; etc.

It is not the aim of this thesis to provide a full account of the history and development of hand knitting, through to machine knitting technology. For a more detailed account, please refer to '*Knitting Technology: a comprehensive handbook and practical guide*' by David Spencer (2001). For clarity and reference, a brief account of the process of knitting will follow in **section 2.3.2.** of this chapter. There will also be an account of several common stitch structures, which have potential for use in engineering and design purposes. Some of the structures feature prominently in technical knit literature and some feature prominently in knit design applications. This overview aims to demonstrate the possibility and flexibility available when designing knitted structures. A range of stitch structures has been chosen to represent a diverse selection of physical and aesthetic properties. Many of these structures can be adapted and combined to increase the possible variations.

2.3.1. Structures overview

The structures discussed in this section provide a brief overview of the possibilities for knitted stitch structures. The featured structures have been chosen to provide context for the range of knitting possible within knit projects and to specifically illustrate the processes and structures described in the practical stages of this thesis.

It is a matter for some debate as to which of the knitted structures are the most fundamental. This largely depends on the purpose for which they are being used. In order to understand the practical elements of this thesis (described in **Chapters 4-7**), it is useful to know the possibilities for knitted structures, their properties, advantages and limitations. Spencer (2001: 60-81) describes the 'four primary base weft-knitted structures' as plain, rib, interlock and purl. These are four of the most basic and common knitted forms. They are all uniform stitch patterns, which describe an all-over structure. Beginning with these four structures, what follows is an overview of some common knitted structures, as described, on non-specific knitting machinery, used for technical and garment applications. The following sections (**2.3.1.1. – 2.3.2.6.**) give an overview into structures chosen to represent the variation of structures within knit practices.

The key in **Figure 2.2** shows how stitches, empty needles and transfers are represented in the knitting diagrams in this section. The diagrams are presented as the view of a 'V-bed' knitting machine from above as in **Figure 2.3**. The two rows are representative of the front and back needle beds. In principle, the front and back needle beds are the same, and each is capable of the same tasks. The gauge of a knitting machine[9] refers to the number of needles per inch on the needle bed. For example, a 5 gauge machine has 5 needles per inch and a 10 gauge has 10 needles per inch. The needles used in a 10 gauge machine will be finer than those on a 5 gauge machine.

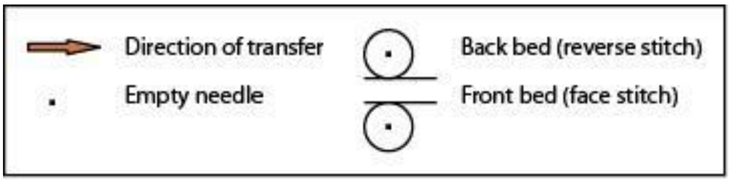
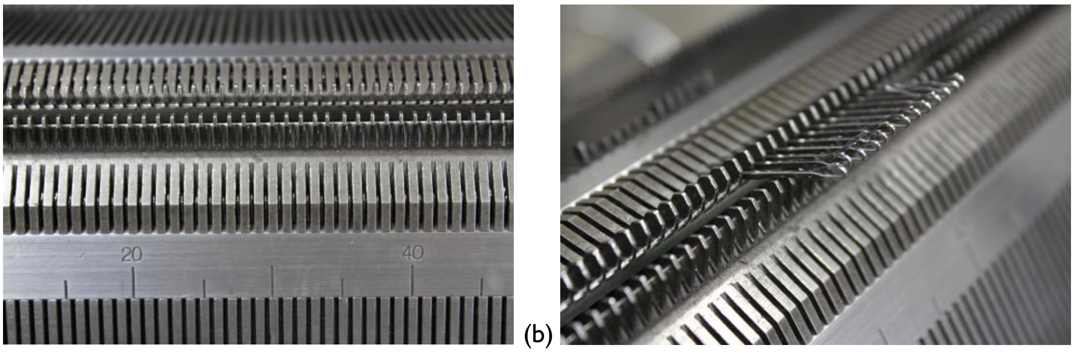


Figure 2.2 Key for machine knitting stitch diagrams below.

[9] This definition excludes a number of knitting machines types (not used in this study), which use different gauges (McIntyre & Daniels, 1995: 148-149).

(a) 

(b)

Figure 2.3 View of the needle beds on a V-bed knitting machine (image shows a Dubied). Image (a) shows the two beds opposite to each other, with the needles slightly staggered from one another. Image (b) shows the needles in each channel.

2.3.1.1. Plain knit

(Also known as: plain, single-bed knitting, single-jersey, stockinette, stocking stitch.)

A relatively light fabric knitted on a single bed of needles (**Figure 2.4a**). The technical face of the fabric shows the yarn in vertical wales (columns) of 'v' shapes, whereas the technical back shows the heads of the loops and the bases of the sinker loops as interlocked curves forming horizontal rows (Spencer 2001: 60-61) as shown in the photograph in **Figure 2.4** and the diagram in **Figure 2.5**. Because of its stitch structure, plain knit has a tendency to curl when taken off the machine or cut (Brackenbury, 1992: 25). On a rectangle of fabric, the top and bottom edges will curl around to the face of the fabric and the side edges (or selvedges) will curl towards the back. Plain knit is more extensible in the horizontal axis than in the vertical. Here the stretch is provided by the shape of the loops and their ability to extend and flatten when pulled across the width.

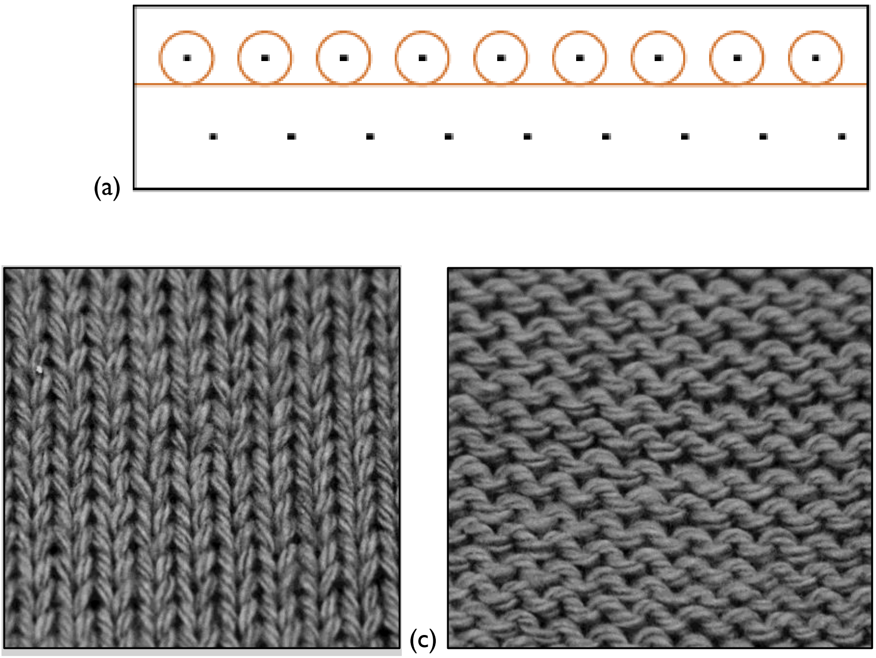
(a) 
(b) (c)

Figure 2.4 Plain knit fabric.

(a) diagram of plain knit fabric, photographs (b) technical front (c) technical back of plain knit fabric.

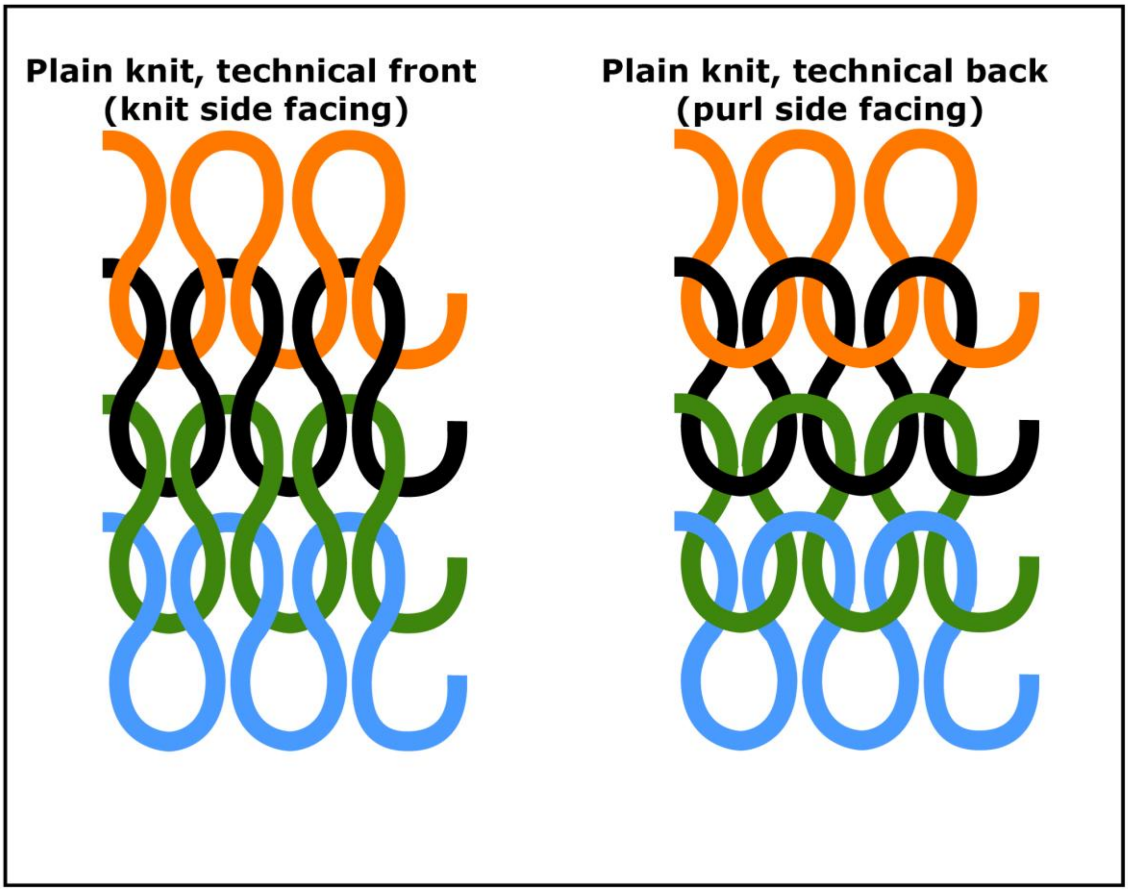
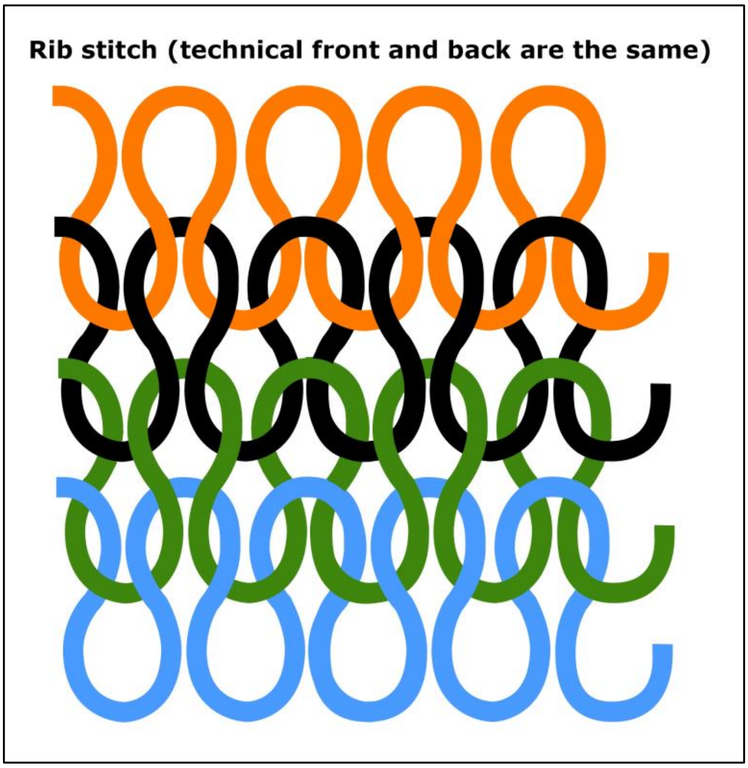


Figure 2.5 Diagram showing front and back of plain knitted fabric. Each row (or course) is shown in a different colour to show the relationship between the rows of loops.

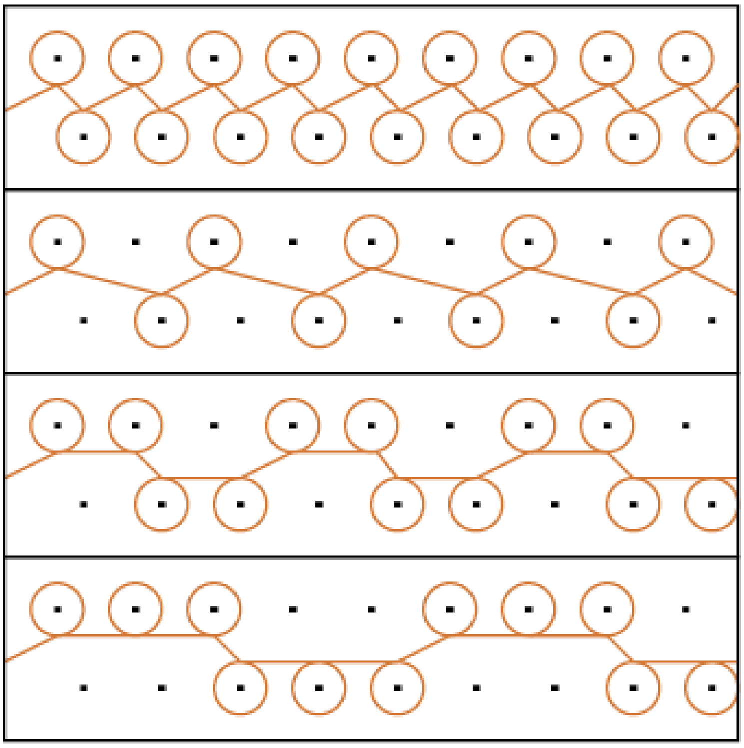
2.3.1.2. Rib

(Also known as: ribbing, double-jersey.)

Rib fabric is knitted on two beds of needles. The vertical linear structure comes from the interplay between the face loops and reverse loops. Common rib structures are full needle, 1x1, 2x2 and 3x3. In a 1x1 rib, the needle layout is one needle in action (knitting) and one needle out of action (not knitting) repeated across the bed. On the opposite needle bed, the pattern is repeated with the needle in action sitting opposite the needle out of action from the facing bed (as shown in **Figure 2.6b**).



(a)



(b)

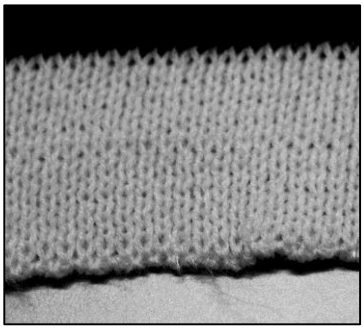
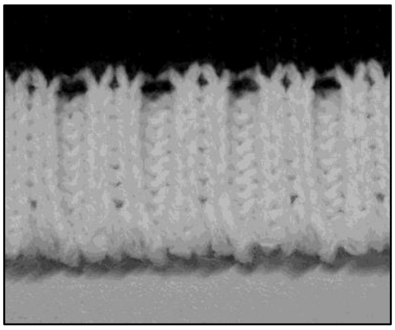
(c)  (d) 

Figure 2.6 Rib stitch structure.

Diagram of rib structure (a) diagram of yarn on knitting machine (b) From top to bottom– full needle rib; 1x1 rib; 2x2 rib; 3x3 rib. (c) 1x1 needle rib, (d) 2x1 needle rib.

By knitting with this needle formation, the face stitches form columns, between which the reverse of the stitch from the opposite bed can be seen. This produces a fabric, which has the same appearance on the front and back of the fabric. A rib fabric is a more dense and extensible fabric than a plain fabric. It also does not curl as plain fabric does because of the balance provided by alternating face and reverse stitches.

2.3.1.3. Interlock and half-gauge

Interlock is a half-gauged, double-bed fabric. By half-gauge it means that only every other needle is used in each course. This effectively changes the gauge of the knitting machine to half of the stated gauge (e.g. an 8 gauge machine in half-gauge would effectively be a 4 gauge machine – though the needle size may not be suitable for thicker yarns). In an interlock fabric, one course of rib is knitted, but only on half of the needles (as in a 1x1 rib). The next course is the same structure, but knitted on the alternate needles that were left empty in the previous course (**Figure 2.7**). As stated by Ray, 'loops made by one set of needles are locked by the loops made by the other set of needles' (2012: 49). A single-bed half-gauge fabric has a similar effect but on the empty needle in each course there is a float of yarn past the empty needle (**Figure 2.8**). In both of these structures, it takes two traverses of the knitting machine to make one course of fabric.

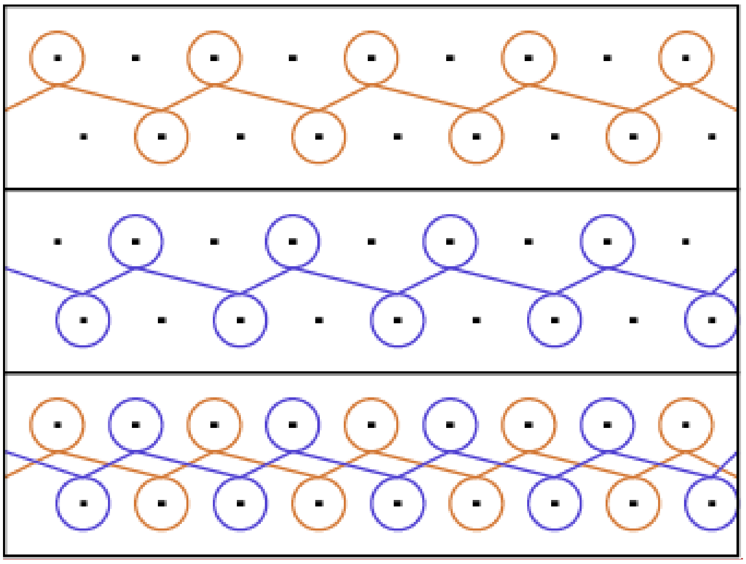
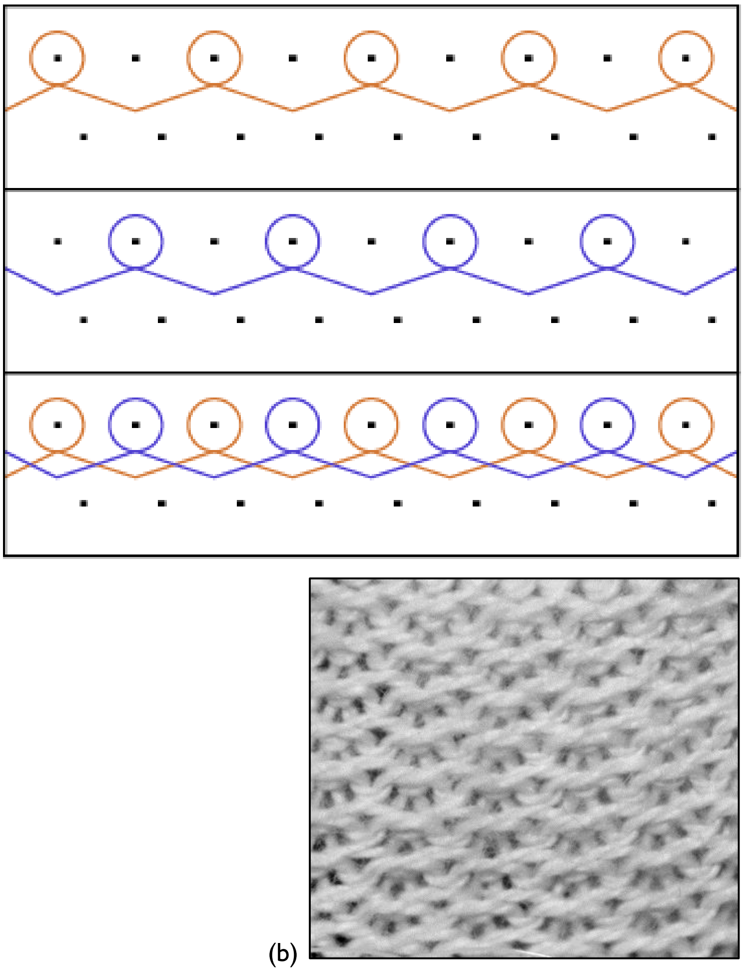


Figure 2.7 Interlock stitch structure.

From top to bottom – course 1; course 2; knitting as seen after both courses knitted.

(a)



(b)

Figure 2.8 Half-gauge stitch structure.

(a) Diagrammatic representation of half-gauge, from top to bottom – course 1; course 2; knitting as seen after both courses knitted. (b) Photograph of half-gauge – technical reverse showing.

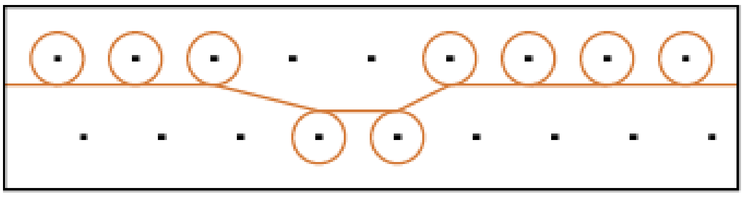
2.3.1.4. Purl

(Also known as: relief stitch, links-links, garter stitch.)

Purl structure, as described by Spencer (2001: 76-77), refers to any number of fabrics with 'one or more wales, which contain both face and reverse loops.' In its most simple form, purl structure may be described as a fabric where courses are knitted on alternating needle beds – forming a structure known as a 'purl rib'. A single course purl rib (known as garter stitch) shows mainly the reverse loops on both sides of the fabric, forming ridged rows. Purl ribs with multiple courses produce a similar effect to a rib - which, in contrast to rib structures have a high extension and recovery in the vertical axis. There are also several common, traditional, hand-knitting patterns, which are often used in machine-knitted garment production, for example: garter stitch, moss stitch and basket weave. **Figure 2.9** shows two different structures knitted on both needle beds. Because of the interplay between the stitches, a face stitch will protrude and reverse stitches recede when adjacent in the same course (along the horizontal axis). Likewise, reverse stitches will protrude and face stitches recede when adjacent in the same wale (along the vertical axis). This can cause a three-dimensional pattern effect that can be used for visual pattern production or to create texture. Some of these 'combinations of knit and purl can create surprising effects that are difficult to imagine from the charting alone' (Tellier-Loumagne 2005:130). The use of relief stitch forms an important basis for the practical stages in **Chapters 4-7**.

Purl fabrics do not have a 'wrong' side. Where the knit (face) stitches show on one side, they will show as purl (reverse) on the back and vice-versa. In industrial knitting, double-bed machines are used that have the ability to quickly and easily produce complex relief structures.

(a)



(b)

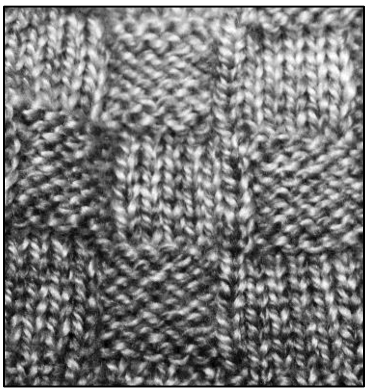


Figure 2.9 Relief purl stitch structure.

(a) Diagram of irregular purl pattern showing some needles in action on front and back beds.

(b) Photograph of 'basket weave' relief pattern on knitted fabric.

2.3.2. Common structures, properties and uses

This section provides a brief introduction to some common stitch structures as used in knit. It is the ability to combine these stitches and their inherent characteristics that make knitting a versatile and exciting technique that can be used for many outcomes, from dramatic effects in clothing to the integration of electronic technology into fabric structures. It is the knit practitioner's knowledge of the structures that dictates how successful the final outcome will be.

In this thesis, it is the stitch and fabric structure that is of the most importance, so, for brevity, discussion will be kept to structures rather than about yarn and machinery information. For further information on structures, their variations and possibilities, Tellier-Loumagne (2005) offers a comprehensive and diverse visual guide.

2.3.2.1. Tubular

(Also known as: circular knit, knitting in the round.)

Tubular knit is most likely to be plain single-bed knitting that is either knitted on alternating front and back beds of a V-bed machine so that a tube of fabric is achieved (**Figure 2.10**), or on a specific circular knitting machine (these dedicated machines may have double-bed capabilities to knit tubular rib; they may be able to incorporate tuck, hold, stripe or jacquard patterns). Tubular is a common fabric for cut and sew applications where large quantities of plain fabrics are required, e.g. t-shirts and leggings. The use of both beds or a large, specialised machine creates a large tube that can be cut open and cut into panels (Francis & Sparkes, 2012: 57-58). This fabric is also used in tubular form where seams are undesirable, e.g. in socks and underwear.

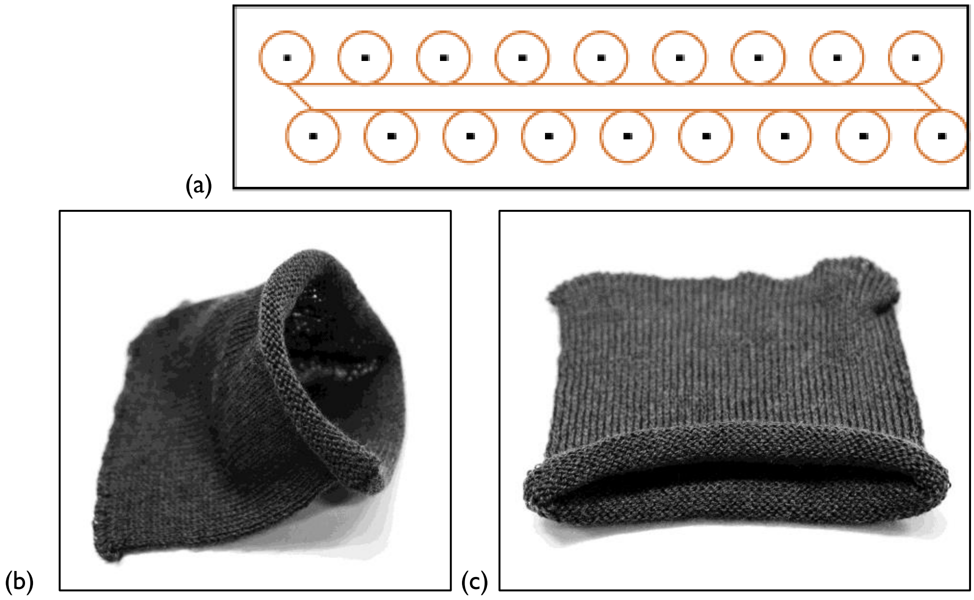


Figure 2.10 Tubular fabric structure.
(a) Diagram of tubular fabric knitted on a V-bed machine showing front and back bed knitting joined at the sides and (c) – Two views of a piece of tubular-knitted fabric.

2.3.2.2. Tuck

Tuck stitches are made when yarn is put onto the needle with the stitch from the previous course, but it not knitted (**Figure 2.11**). Stitches can be tucked for one or several courses subject to the machine or method used and depending on the design. Tucking can be used to create patterns, which in single-bed will show most of their interest in texture on the reverse side, and on double-bed (and face side of single-bed) will create grid patterns. Tucking can also be used to incorporate yarns into fabric that are not suitable for knitting (e.g. yarns that are too stiff, thick or brittle). This is because the tucked stitch is not subject to as much deformation as a full knitted loop. Tucking is the method used in spacer fabrics to incorporate monofilaments into the fabric **(Figure 2.12**). Tuck stitches usually make the fabric wider and shorter (because not every course knits a full stitch. In fabric such as 'cardigan' fabric (a double-bed fabric tucking one bed on each course), this creates a full and thick fabric common in clothing designed to keep the wearer warm. Alternatively, when combined with lace holes and needles out of action, tuck can produce a lacy and delicate fabric (**Figure 2.11 c** and **d**).

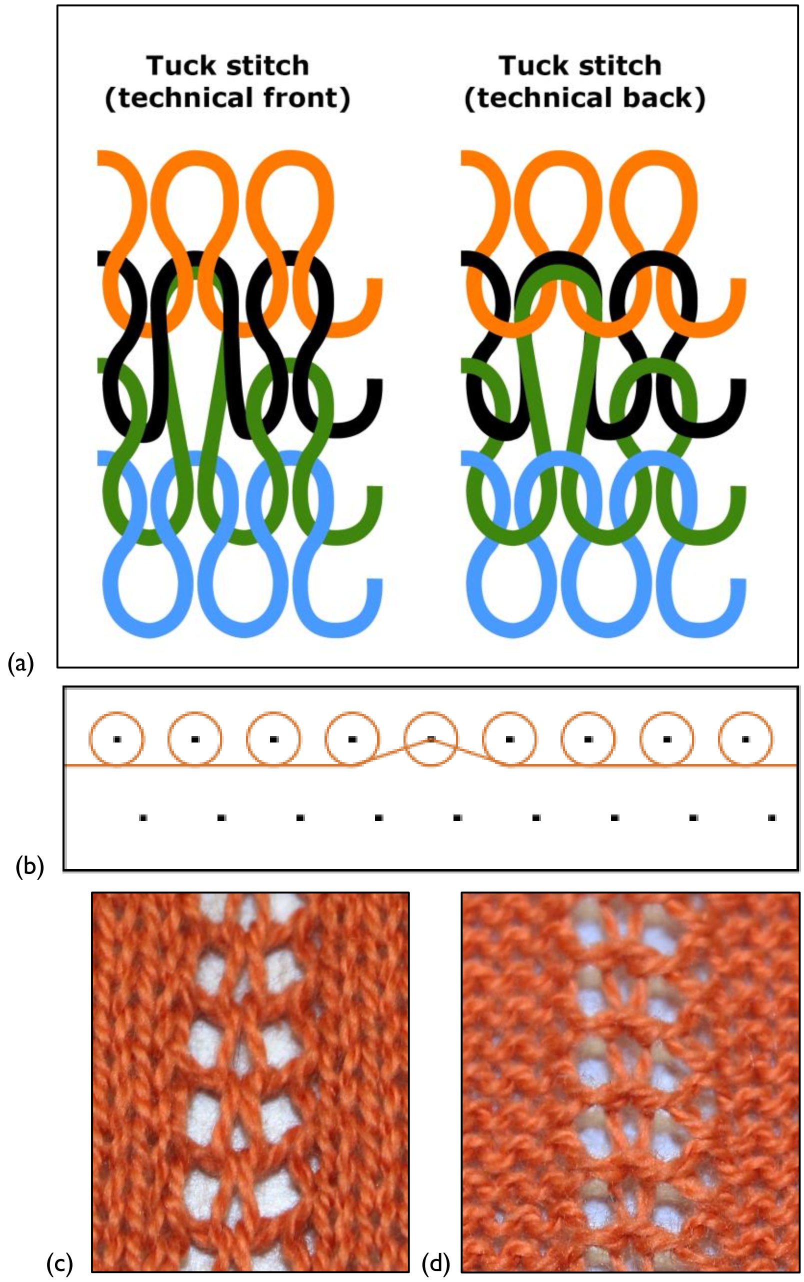


Figure 2.11 Tuck stitch structure

(a) Diagram of tuck stitch structure. (b) Knitting machine view diagram of single-bed fabric showing one needle being tucked, the stitch on the needle is from the previous course.

Photographs showing (c) technical front and (d) technical back of a tuck stitch pattern. There is a needle out of action either side of the tucking needle to give a more open fabric.

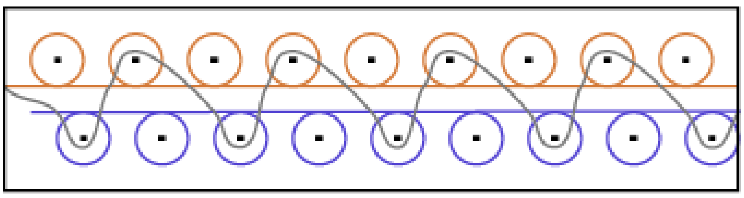


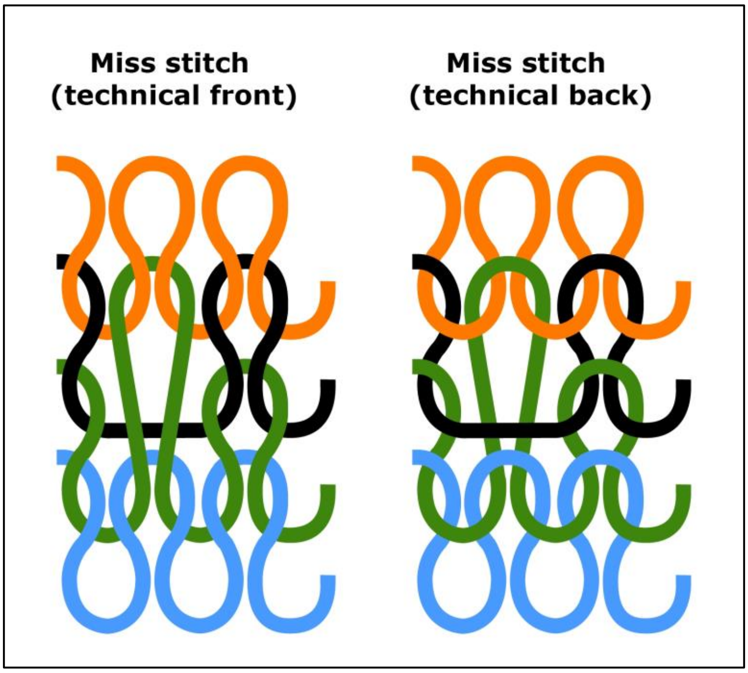
Figure 2.12 Spacer fabric showing a yarn being tucked between two separate fabrics on the front and back needle beds.

2.3.2.3. Hold/miss stitch

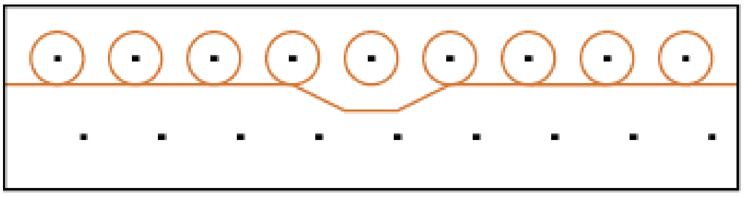
(Also known as: float, partial knit, fléchage, short course knitting, miss stitch.)

This technique is a varied and interesting one that can have wildly different effects. This method is achieved simply by knitting selected stitches, and not knitting others. The simplest is by 'floating' yarn , a method similar to tuck, where selected stitches are bypassed by the new course. Instead of tucking the yarn into the needle, it is floated past, leaving a horizontal float on the reverse of the fabric (as shown in **Figure 2.13a**). Like tuck stitches, this can make the fabric shorter in length because of the stitches that are not knitted.

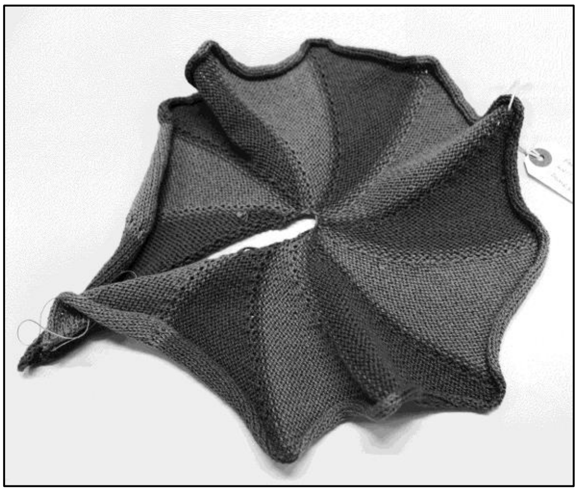
Partial knit (or fléchage) means holding certain needles without knitting them; this can shape the fabric. Elaborately-shaped structures can also be created to add texture or changes in direction (Tellier-Loumagne, 2005:101), as in a sock heel or toe, or to create circular shapes like the one seen in **Figure 2.13b** (Black, 2002: 177).



(a)



(b)



(c)

Figure 2.13 Hold stitch structures.

(a) Stitch structure diagram showing one needle being held.

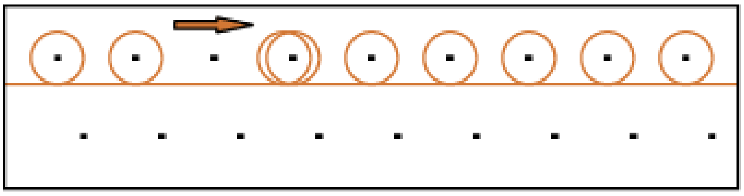
(b) knitting machine diagram showing one needle being held on single-bed fabric.

(c) Photograph of a circular effect created by partial knitting. Knitting part of the fabric width allows the number of courses to differ across the width of the fabric, creating irregular or triangular shapes.

2.3.2.4. Transferred stitches

Transferring stitches usually involves moving the loop from one needle onto the adjacent needle. Needles can be moved in groups, as in fully fashioning[10] on clothing or individually, as when making a lace hole. The stitch moved either moves onto an empty needle or an occupied needle, this needle then has two stitches on, as seen in **Figure 2.14a**. The needle that the stitch was moved from will remain empty. If left in use, the empty needle, when next to occupied needles at both sides, will have formed a new stitch after two courses of knitting. Another use for transferred stitches is to create lace holes such as those seen in **Figure 2.14b**; this is common in clothing and accessories and can be used to create patterning. When transferring stitches in large blocks, the wale and course direction is altered. This can be used to create zigzag or chevron effects. Transferring is also used in cable stitches and lateral transfer.

(a)



(b)

Figure 2.14 Transferred stitches.
(a) Diagram showing single-bed fabric with one stitch being transferred to the right.
(b) Photograph showing transferring of stitch to create lace holes.

[10] 'Fully-fashioned' is a term meaning knitted to shape. This is an alternative to 'cut-and-sew' and is usually indicative of a more expensive garment. Often, stitches are transferred in groups, which leaves a continuous wale at the selvedge, and makes small marks along the fashioning – either of overlapped stitches when narrowing, or a lace hole when widening.

2.3.2.5. Jacquard

Jacquard is a general term for fabrics, which use more than one yarn, often in different colours, to create pattern. Jacquards can be double-bed (such as bird's eye, ladder-back, tubular, blister, three-colour, etc.) or single-bed structures (such as intarsia, Fair Isle, etc.). Jacquards are commonly used to create patterns using colour, such as in intarsia shown in **Figure 2.15 -** a single-bed structure that can show large patterns of block colour without having to incorporate the alternative yarns behind, for example, Argyle sweaters. Another jacquard is Fair Isle, which will show a small scale, often banded pattern, limited to two colours per course – the yarn not in use is floated across the back of the fabric (McGregor, 1981). Double-bed jacquards incorporate the yarn not being used into a structure on the reverse of the fabric – the structure's name is usually indicative of this technique.

(a)

(b)

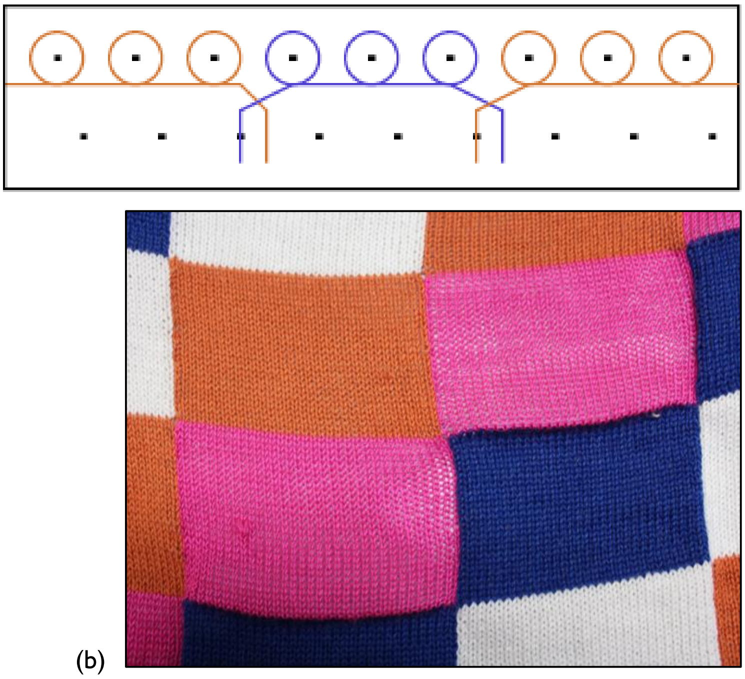
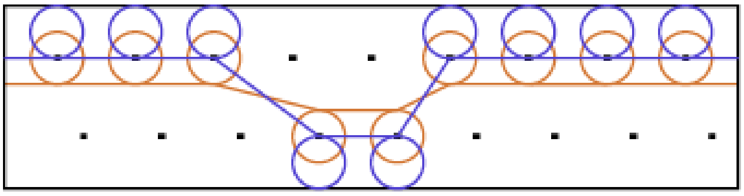


Figure 2.15 Intarsia stitch structure.

(a) Diagram showing intarsia with three yarns. Where the yarns meet they are twisted together and left free for placing in selected needles for the next course (b) photograph of intarsia using 4 colours.

2.3.2.6. Plating

Plating is a method of knitting two yarns at once so that one can be seen on the face of the stitch and the other on the reverse (as shown in **Figure 2.16**). The two yarns are knitted at the same time, but held in a staggered position during the knitting process (Ray, 2012: 58-59). This is a technique that can be used to create a pattern using a contrasting yarn. For example, a plated rib in two colours of yarn will appear as a vertical stripe when stretched with one colour showing on the face stitches and another on the reverse. In knitwear design, plating is commonly used to incorporate a yarn such as an elastomeric (or other technical yarn) to add a required property without having much impact on the external appearance of the fabric.

(a)


(b)


Figure 2.16 Plated stitch structures.
(a) Diagram showing relief pattern shown with plating. The upper, blue yarn shows on the reverse stitch and the lower, orange on the front stitch. (b) Photograph showing plating in stripes.

For further detail and for more stitch structures, see 'Structure Table' in **Appendix A** for further information on knitted stitches and their characteristic properties.

2.3.3. General knitted fabric properties

The properties that are desired in knitted textiles will be dependent on the final usage. However, there are properties, mentioned here, which are present in knitted textiles due to the core structure of the fabric. These properties play an important role in the designer's experiential understanding of knitting. For example, since all knitted fabric is inherently stretchable (particularly when compared with a woven structure), considerations about the application will be affected by this property. Additional properties will be developed by the designer/engineer/maker to suit their needs. Some of these may be controlled by the choice of knitted structure (as above), because different structures will vary in property (see **Table A.17** in **Appendix A**). Some properties will be controlled or dictated by the choice of yarn, tension, scale and finishing processes.

These inherent properties may be desirable to the chosen application, or they might be detrimental. However, it is the role of the knit practitioner to understand these properties, and to design or engineer the fabric to the best effect. The two examples below are the most common and relevant for understanding the inherent property of any knitted fabric.

2.3.3.1. Extensibility

Knit is by its definition a stretchy structure. This is what gives it an advantage in many uses over woven structures. The loop formation allows extensibility as it straightens out, allowing the fabric structure to stretch without the yarn having to stretch (Cooke, 2011: 38). This stretch is more pronounced in the course direction than in the wale direction. Because of this stretch, knitting is suited to tight-fitting forms. Knitted clothing can be made to fit closely without the need for extra seams or for complicated openings/fastenings.

There are certain structures that limit the extensibility of a knitted fabric but these will only lessen, not remove this property. If a knitted structure with controlled stretch is required, a warp-knitted fabric is usually used, or a rigid yarn laid in in the warp or weft direction in order to restrict stretch. Interlock and float stitches create less stretchy fabrics in the course direction. Conversely, adding structures like ribs will make the fabric relax to into a narrow, folded structure, which allows for a large amount of stretch (Cooke, 2011: 39). The same effect can be achieved in the length by using a purl rib. Both of these structures fold the fabric in a concertina effect, which is unfolded and extended. Recovery of knitted fabric (return to original dimensions) is not always reliable. Rib structures usually have better recovery than plain structures, which can be enhanced with elastic yarns. Fabric relaxes after knitting and can be altered by finishing processes such as washing, steaming and pressing (Cooke, 2011: 40).

2.3.3.2. Open structure

Knit has an inherently open, porous structure. This is due to the way the loops intermesh (as seen in **Figure 2.5**). The fabric is ‘composed largely of air space’, which gives excellent thermal insulation properties, but knitted fabrics are not waterproof or heat retentive and allow a high permeability of air and water (Brackenbury, 1992: 26-29).

2.4. Knit specific literature

Information about knitted stitch structures is common to knit practitioners from all disciplines, but literature about knit has various areas of focus and specialisation, which is often reflected in the language and information used. In order to understand the segregation of knit knowledge, it is important to highlight some of the differences in the literature from perspectives based in design, those based in engineering and those of non-knit practitioners. The individual perspectives of these different communities influence how knitting is perceived by wider audiences and how development in the field is focused. To be able to appreciate a pragmatic view on knitting, it is important to be aware of the different sides of the discussion directly pertaining to knit design, development and research.

2.4.1. Knit from a design perspective

In addition to descriptive literature available on machinery and stitch structures (as discussed previously in this chapter), Francis & Sparkes (2011) added a fresh perspective to the discussion of knit as a design topic by presenting a practical account of knitwear from a designer perspective. The contribution highlights a pragmatic approach of the 'fundamental principles' for weft-knitting design and manufacture (ibid.: 55) that is applicable to aspects of knitting from handcraft through to technical textiles. The authors respond to a lack of writing on the subject of knitting from outside a technical perspective and aim to explain 'diversity and complexity' of the subject in a way that is accessible to all users. The approach in this thesis echoes that of Francis & Sparkes in its motives of providing an accessible and transparent view of what knitting involves and how that might be used by different practitioners within knit or from different disciplines concerned with making[11]. From a knitwear design perspective, Francis & Sparkes cover both the creative and the practical (the artistic and the technical) areas of knitting. Their perspective includes experience of being in control of both the fabric and the form of the product and they emphasise that the designer should be knowledgeable of both 2D and 3D elements of knitted forms (ibid.: 61).

The relationship between 2-dimensionality and 3-dimensionality in knitting is important because the making of the material and the product may often be one inseparable concern - something that is often second nature in knit practice. In other design disciplines and in industrial practices, the combination of 2D and 3D may be split over several individuals, departments, experts or even companies, depending on the complexity of the product. For example, fashion designers or furniture designers are likely to buy materials from an external supplier to work with, whereas a knit designer would most likely knit a fabric (or have a fabric knitted) to specification, after considering the final outcome.

Francis & Sparkes also make a connection between misunderstanding of the role of the knit designer in creative industries and the lack of specialist education in the area. Specialist knit education is uncommon, because setting up specific knit courses requires expensive and large equipment. This lack of experience and understanding in education leads to perceptions of the knitting being split into 2D (textiles), 3D (fashion) and technology (engineering) (ibid.: 62).

In addition to the practice perspective of Francis & Sparkes, various doctoral theses have been written about knit design. Several of these discuss the problems faced by the segregation of schools of thought on the design and technical sides of the subject. One such thesis questions the categorisation placed on textile practices:

[11] Such as many art and design disciplines, particularly those concerned with constructing materials or with textiles.

> *The role of textiles is changing… What we are seeing is perhaps a return to the designer as a material innovator. Innovations and advances in textile fibres and tech are influencing how textiles are being used. Traditional techniques and technology, the ornamental and structural, and the micro and macro are blurring. Textile techniques, once associated with being hand-crafted are being transformed into high-tech automated processors using sophisticated and complex technology and machinery.*
>
> Underwood, 2009: 156

As the quote above shows, Underwood is aware of the new areas that knit design is becoming part of, but as a practitioner, she is chiefly concerned with the pragmatic structured nature of knitted forms using her background as a design practitioner and machine programmer. This combination of programming and designing is not common in the commercial industry, but can be found in academic practice, and is distinctly similar to a craft method as the designer has complete control over each aspect of the outcome.

Underwood explores the crossovers between form and structure as a methodological approach in a similar way to a 2001 thesis by Guy, written at an early stage in the development of practice-based design PhDs. Guy explored the use of inherent properties of particular knitted structures to shape fabric size rather than commonly-used methods such as shaping through fashioning and partial knitting. She relied heavily on experiential knowledge of fabric structures and the final outcome of the fabric after knitting (after the fabric relaxes into its structured shape).

Guy's study came at a time when practice-led[12] research was less common, which may have led to the following statement: '*[her knitted] samples were not created for their aesthetic value, it is the researcher's opinion that it is not appropriate to exhibit or evaluate them in these terms'* (2001: 264). This separation of technical decisions and aesthetic values can be seen as a clear example of segregating the possibilities of being aesthetic and functional. The nature of conducting research in knit has implications that a scientific method or discussion should be employed. In order to be accepted in a discussion of functionality, it may be considered necessary to strip away the discussion of aesthetics (though the fabrics in Guy's thesis are of great visual interest).

Like Underwood, Guy adheres to the idea that there is a need to push towards acceptance of design processes in the technical areas of knit, though this may be at the expense of aspects that are important to designers. This subjugation of design agrees with the state of the literary field described by Francis & Sparkes, who are in search of equality and accessibility of design practices within a complex subject field.

[12] Practice-led and practice-based research are often used as interchangeable terms, but practice-based may be determined by use of one's own practice to change external elements, whereas practice-led aims to provide new knowledge for that practice (Creativity & Cognition Studios: n.d.). Both highlight the role of the researcher's own practice in the formulation of knowledge (Rust, Mottram & Till, 2007: 12; Gray & Malins, 2004: 25). In this study, I propose that the method is both practice-led and practice-based.

Jane Scott (2012) studies knit for its structural usefulness in architectural applications[13]. Her work touches on a need to look at knit pragmatically and evaluate it for its structural integrity alongside its possibilities for aesthetic development. Scott considers experiential knowledge of knit design in developing new applications. She uses a design approach to conceive architectural knitted structures by focusing on suitable and integral applications of knit structures while considering the additional input of fibre properties. Scott's work is a good example of how experiential knit design can be transferred into areas outside fashion and traditional textile applications. This pragmatic approach, supported by Francis & Sparkes, Guy, Underwood and in this thesis shows the strength of a pragmatic, inclusive approach to knit design. Experiential knowledge gained through practice in knit design allows for informed and explorative work in areas outside traditional application of knit design knowledge.

2.4.2. Knit from engineering perspective

Literature about knitted textiles from engineering perspectives, including textile technology, textile engineering and technical textiles, adopts a different approach to the writing from design perspectives. In tone, the writing is usually objective and passive, indicating a scientific methodology concerned with 'fact' and provable 'truth' as in the manner of traditional, scholastic research (Wood, 2000: 45). In spite of these language choices, when concerned with textile products, the authors must often include considerations from qualitative perspectives. Statements made can refer to a broad need for comfort and aesthetic needs (as in Mielicka, 2011: 3) or refer to the nature of apparel industry needs. The merging of qualitative and quantitative perspectives is difficult, and one is often subordinated by the other, due to the cultural or academic motives of the author. The considerations of design do not often feature prominently in engineering texts, and the acknowledgement of aspects outside the interests of the text is usually limited to the scope of the knitwear industry.

From the perspectives of authors within engineering, the properties of a knitted fabric can be attributed to the structure, yarn and direction of the fabric[14]. The correct combination of these properties is vital to finding the appropriate structure for the desired application, or vice versa (as stated in De Araujo et al., 2011: 136). The words used to describe engineering considerations are inherently different from the descriptions a design practitioner might use, but the practicality is the same. The main elements missing from this description are those of aesthetic and tactile value of the yarn, which are likely to be high in importance for many design applications.

2.4.3. Knit from outside perspectives

Knitwear design is, arguably, the most commonly perceived outcome of knit for those outside the knit specialism. Knitwear possesses areas of interest in the combinations of design and technology, as well as having a significant commercial presence. Because of these areas, the knitwear design process has piqued interest from researchers who are not directly involved in a knit design process. Three such

[13] By incorporating wooden veneer into knitted pockets and applying moisture to distort the veneer, causing adaptable structures for architectural purposes.

[14] As the properties are different in course and wale directions.

cases of researchers from outside perspectives studying knitwear processes are discussed here as examples.

Claudia Eckert is trained in engineering and has undertaken substantial research on the processes of knitwear designers. Eckert's fundamental reason for this interest is that she believes there is a common process between engineering and knitwear design processes (Eckert & Demaid, 1997) (N.B. the process she studied is that of knitwear for clothing outcomes). Eckert & Demaid acknowledge a principal that is common to textile practices, but not always to engineering practices – that 'it is impossible to create a knitted sample without knitting the fabric' (1997: 106) since there is no satisfactory way to replicate all aspects of knitted fabric. This observation shows a gap between the knowledge preferred by some branches of engineering and the technology available to fully model a representative knitted fabric. Some attempts have been made in more recent years to model the movement and structure of knitted fabrics (for example, Xin, 2012) but they fail to capture the essence of a knitted fabric in all of its respects (stretch, 3-dimensionality, handle, drape, appearance, etc.). Even the visualisation software on Stoll's programming software struggles to show an accurate representation of a fabric when it has all the structural data in the system. The images in **Figure 2.17** and **Figure 2.18**, show that the actual fabric (as seen in the photographs) has many characteristics that the Stoll software fails to predict. As a design tool, this can be used to predict the appearance of stripes and jacquards but, when dealing with a complex fabric of any kind, it struggles to give an accurate representation. For example, a rib is always shown in a stretched flat state, rather than a drawn in, relaxed state. As Eckert & Demaid state, there is no substitute for knitting a fabric to produce a model of the structure, feel and appearance (1997:106.).

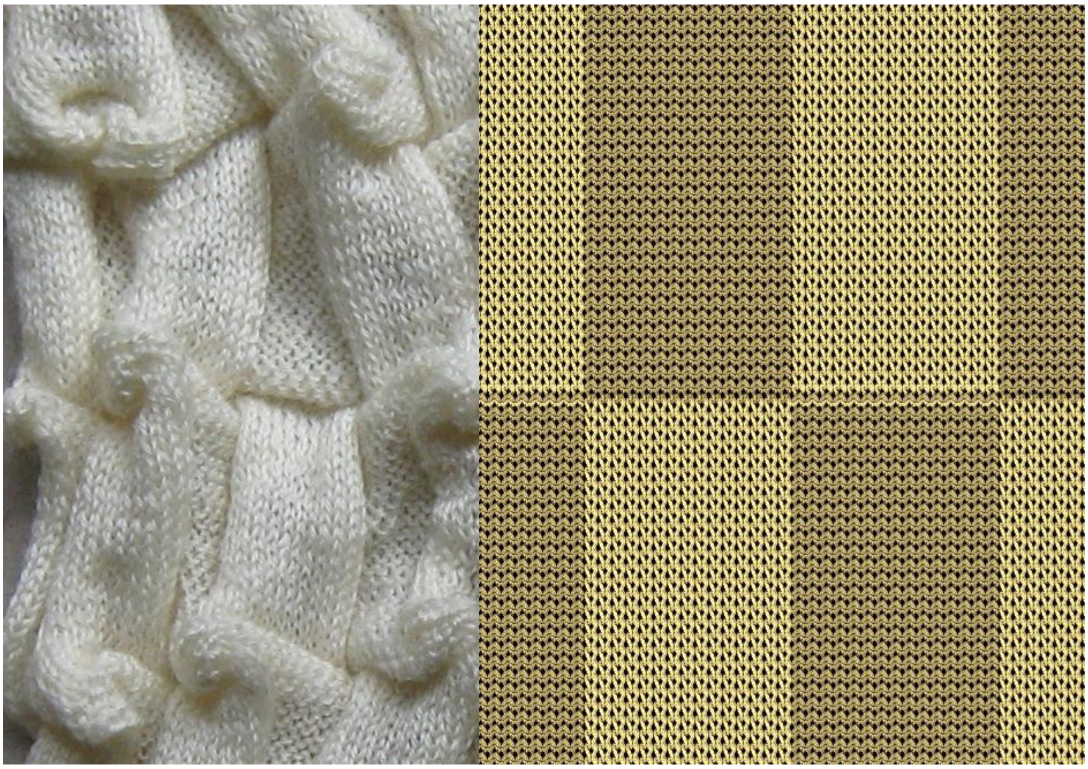


Figure 2.17 Photograph of Sample 4, 'Purl Rectangle' fabric (**Chapter 4: Stage 1**) compared with image taken from Stoll M1plus software in 'fabric view'

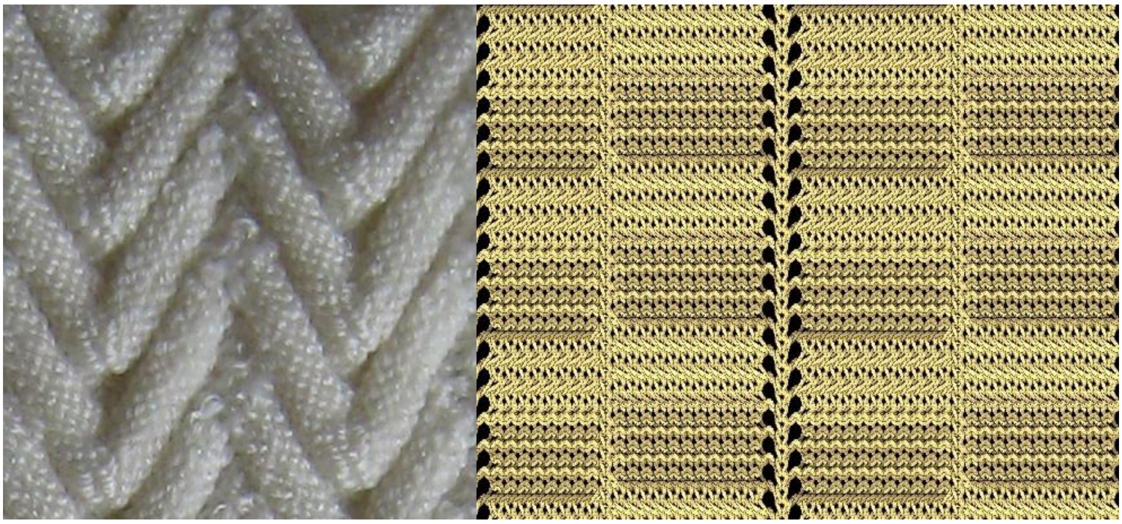


Figure 2.18 Photograph of Sample 6, 'Transfer Purl 4' fabric (**Chapter 5: Stage 2**) compared with image taken from Stoll M1plus software in 'fabric view'

Eckert & Stacey (2003: 357) offer a process model of knitwear design which pre-supposes a commercial fashion outcome and the various pre-requisites therein – i.e. a reliance on trend information, a division of labour through technical and design factions and an emphasis on the outcome pertaining to a fashion market and showcase (catwalk/magazines). But this does not work for all models of knit design. For instance, it does not work in conjunction with a craft method, where one person may be responsible for all the stages of design and production. Also, it does not adhere to the conception of textile design as art, as this is not always reliant on trend information, catwalk showcasing and often not reliant on technical support.

Another example of research from non-knit perspectives sees Sharp et al., from computing and design backgrounds, describe knitwear design as such:

> *…a good example of practical design – requiring designers to express artistic flair within pragmatic constraints…*
>
> Sharp et al., 2006: 184

This definition describes the complexity of the design process in knitwear design, and how those constraints are limiting as well as providing necessary involvement to trigger innovation and interest in the design task. From experience, I would add that it is not only the external constraints (such as cost, trend, production capability) that create these abilities in the designer, but also a set of fundamental constraints inherent to knitted fabrics as a whole and the personal preferences of the designer's style.

Another significant quality mentioned by Sharp et al. that could be applied to the whole of knit or textile design is the ability of the designer to visualise the end product in a seemingly 'complete' manner. This visualisation does not necessarily convey the complex understanding of what problems might be encountered and the experiential skill that the designer uses to evolve and transform with apparent ease (2006: 190). This indicates a co-existing 'visionary' and 'problem-solving' approach, which does not easily fit into existing, scholarly paradigms of research thinking. The designer is likely to know which obstacles are easily overcome and how to modify the design to adapt to other obstacles[15]. When presented with a knitted fabric, the making of a garment (as an example) is taken for granted. The designer is confident in their knowledge and some of the thought processes are deemed natural, or simple, leaving room to concentrate on other ideas and details.

The final example in this section of a non-knit specialist using knit at the centre of their research is the thesis of Paul Richards (2013). Richards uses the hand-knitting process as a basis for his development of case-based reasoning[16] in design. His background in computing and interest in artificial intelligence see him as an outsider to knit, but his research acknowledges the knowledge and adaptability of knitting as a method or methodology. Richards makes two salient descriptions of knit practice to illustrate his perceptions:

- 'Knitwear has both creative and technical aspects' (2013: 17)
- 'Knitwear is a creative domain where success is subjective: there are no mathematical formulae which can tell you if a cardigan is beautiful!' (2013: 18-19)

This thesis agrees with the definitions by Richards and sees them as useful evidence that the background of a practitioner need not narrow their appreciation of knit practice for its intricacy, variety and scope.

2.4.3.1. Perspectives on knit in summary

To summarise, the various perspectives discussed in relation to knit design highlight the following issues:

- Most areas do not show the overall scope of fundamental knit knowledge, each omitting some elements through lack of interest, experience or considering those elements to be unnecessary to their cause or lacking in rigour.
- It is possible for knit design to appeal to outsiders for its practical and pragmatic nature that bears similarities to other practices. The interest from external disciplines is not always represented in the knit design literature; it is often published in the area of the external discipline.
- The cases of non-knit specialists using knit as a case study in their research shows high engagement with and respect for the methods inherent in knit practices.

Considering these issues, this project focuses on a knit design specific approach with the motives to explore and communicate the process in manners that suit readers from other disciplines. Throughout

[15] This is a feeling supported by one knit practitioner in the final focus group from this study (FG4 in **Chapter 7**).
[16] An artificial intelligence method using experiential knowledge to solve new problems (Richards, 2013: 18).

this project, methodological discussions are made more important than particular product applications or outcomes.

2.5. Textiles

The term *textile* formerly applied only to woven structures, but is now more broadly used to encompass anything manufactured from fibres, filaments or yarns, including products using these as a 'principal raw material' (McIntyre & Daniels, 1995: 343). In some instances, the term *textile* encompasses items made, not using traditional textile materials, but those which use any material in combination with a traditional textile *technique;* for example, it may now be possible to classify some 3D-printed materials as textiles because of the structure they follow, rather than because they are produced using a yarn, fibre or filament.

2.5.1. Textile design – a definition

'Textile design is about designing all types of fabrics, by adding colour, texture and pattern for a particular customer, for a particular end use' (Sinclair, 1997: 32). This definition, in contrast to Spencer's definition, is used to define textile design from an insider perspective. In her writing, Sinclair talks about the particular skills a textile designer needs (outlined below).

- *Designing skills:* plan work; use CAD; consider aesthetics, visuals, tactile qualities, drape, texture; design for single products and mass-production; test products; develop specifications (technical drawings); evaluate products
- *Making skills:* Understand quality control and assurance; plan instruction for making; consider joining fabrics; use correct tools; finishing techniques; modify product; evaluate product
- *Knowledge and understanding of:* health and safety; environmental considerations; systems and control; fabric structures and performance; fibre and fabric properties; consumer needs (1997: 6-7).

These definitions show a wide range of different and challenging requirements placed on a textile designer and draw the definition of a textile designer in line with a designer-maker. As already stated, many of these skills are the same as for knit designers, fashion or product designers. Additionally, many of these skills also apply to those in textile engineering practices.

Some of the elements described by Sinclair are recurring qualitative ideas that appear to distinguish between the literature on textile design and that on textile technology. Winifred Aldrich also mentions these in her own book 'Fabric, Form and Flat Pattern Cutting', written from a designer's perspective, offering guidance to students of fashion and textiles. Aldrich specifically wrote this book to provide information that is useful to, and presented for, designers and pattern cutters in contrast to much of the technical literature available on the subject (2007: 9). The literature available previously tended to be overly technical or ambiguous in language or containing specialist designer language that is not always understood by other designers or technologists. Aldrich is a strong advocate that the best way to learn about textiles and to understand a concept such as drape is to handle fabrics and to learn about the different ways they behave. She also acknowledges that there are many ways to design pattern shapes (garment forms) and that often there is a combination of methods, however, knowing how a fabric will behave is essential to success (ibid.: 5).

The concerns of Aldrich and Sinclair that knowledge is paramount rather than the method of application, is something which is important to this thesis. Aldrich's idea that the fundamental understanding of fabric qualities is difficult and that it requires time, experience and qualitative understanding, recalls ideas in this chapter about the role of experiential knowledge, its importance and the problems situating it in formal, academic discussion.

2.6. Discipline and knowledge transfer

Similarly to Aldrich's writing, McCabe's thesis discusses the problem of knowledge transfer across subjects being impeded by language used by certain disciplines (2006: 175). Scientific knowledge is contained, not transferred, because of the vocabulary used to describe it and the way data is presented. I would go further and argue that the publications themselves in which articles are to be found cause significant problems within knowledge transfer. In a Knowledge Transfer Network event (Morris, 2012), speakers, myself included, supported the ideas that problems in communicating scientific knowledge are perpetuated by treating disciplines like 'islands'. Designers may be discouraged from presenting their processes to research audiences by the language and other conventions used in academic writing (scientific writing) and expected of researchers for publication. Designers may find the expectation to articulate their practice unnatural and may not consider their practical skills to be valued as research (Archer, 1979a: 18).

2.6.1. Defining design

Design is something that comes in various guises with the suffix 'design' (fashion design, textile design, product design, industrial design, etc.). But design is also something that is involved in, though arguably distinguished from, other disciplines such as science (see Farrell & Hooker, 2013: 483), art and engineering (see Archer 1979a; 1979b). The main indicators to the type of design that is being practised often boil down to an informal and possibly personal (or even arbitrary) selection of methods and/or methodology, rather than the materials and processes used or the outcomes created.

It could be assumed that the very core of what makes design is led from the methods deployed, but how is it so clear that these methods do not share many aspects in common with science or art or other disciplines? Where do these rigid distinctions of practice come from? A scientist may act as much upon trial and error, 'gut instinct' or subjectivity as an artist or designer, but in the dissemination this is not focused upon and an 'objective' approach is favoured[17]. Designers, artists and scientists can all be concerned with the production of physical things. Quantitative or qualitative analysis is not the sole domain of one subject over another, nor are the two mutually exclusive in any case. Is the distinction

[17] See Wood (2000) for further discussion on the possibility of objectivity and the place of 'rigour' in research.

merely an arbitrary one enforced by institutions and administrations? This study proposes that disciplinary rigidity is at times inaccurate, and mostly harmful.

Archer offers the perspective that a methodology may exist as a set of ideals and values rather than a rigid framework or a process (1979a: 17). Archer argues that even within quantitative research, there will still be values influencing the research (ibid.). He argues that as a design approach acknowledges these values, it is allowed to be freer in its process. A designer is used to working in a way uninhibited by the rigour of academic process, but is still expert in his or her own field/s. The suppositions and conventions that dominate academic literature can alienate designers and require significant adjustment of design practices to incorporate the language, structure and 'rigour' needed to publish in many journals and other forums.

These definitions of subject, discipline and methodology put up hurdles to achieving successfully interdisciplinary work, collaboratively, or individually. The lack of transparency and comparability across areas of research stifles the idea that knowledge can freely pass between subjects and researchers without difficulty. The topics chosen in research 'dictate a specificity in focus' that forces researchers to lose integration with other aspects, considerations or indeed whole areas of practice (Dahl, 2011: 425).

In discussing product design, Dahl offers the idea that when form and function are addressed simultaneously, one usually suffers with the promoted importance of the other. Indeed, many discussions of form and function are conducted with a bias towards one or the other. This is usually indicative of the original perspective of the author. Sabine Seymour's book 'Functional Aesthetics' (2012) is one example of literature promoting function in unison with aesthetic. The functions in the book however, tend to be limited in their scope to examples of qualitative and artistic functions – such as a performance or a fashion outcome where the research is usually conducted by artists or design practitioners.

2.6.1.1. Defining a design methodology

Existing methodological frameworks for design are often derived from or developed using social science (Gray & Malins, 2004: 30) or scientific paradigms (ibid.: 121). It is the position of this thesis that this is not suitable to represent the various methods and considerations needed when talking about design, or knit as a whole subject.

Bye offers a framework that has a primary focus on practice and the making of artefacts in textile design (2010: 213). Her approach is founded in the methods of design and the various considerations that come with it. Bye states that:

> *This approach is most directly related to a combination of quantitative and qualitative methods, with the incorporation of a practice element that becomes iterative with testing and defining the research problem. This iterative process is directly related to the design process.*
>
> Bye, 2010: 214

In this quote, Bye highlights the wide-ranging nature of design methodologies in terms of the designers' knowledge, thinking and doing. Bye believes that for design research to develop with 'appropriate knowledge, foundation and theories', the leaders of this research must be designers, so as to avoid distortion from external effects. The imposing of values from other subjects might hinder the design process with rigid, external values (2010: 210). It is not always the case that designers are the ones who carry out research that has an influential effect on public and academic perceptions of design (as with Eckert's and other research discussed in section **2.4.2.** and **2.4.3.**).

Bruce Archer wrote a short, but influential paper on the value of design methodologies and their inherent qualitative properties. He states:

> *I was concerned to find ways of ensuring that the predominantly qualitative considerations such as comfort and convenience, ethics and beauty, should be as carefully taken into account and as doggedly defensible under attack as predominantly quantitative considerations such as strength, cost and durability.*
>
> Archer, 1979a: 17

Archer's approach to defend the innate subjectivities of design resonates well with the aims of this thesis surrounding knit design methodologies. Archer and I both seek to promote qualitative methods into a formal capacity within a wider understanding of design practices, thereby giving validity and security to claims made from design or artistic divisions. Archer goes on to criticise the communication of design theories, which were inappropriately conveyed using 'words or mathematics or scientific notation alone' (ibid.: 18). This is a sentiment echoed by McCabe's thesis aiming to promote knowledge transfer between scientific and artistic communities within textile research which criticises the restrictive nature of scientific language in the promotion of knowledge transfer (2006: 175).

Archer also states that design is a 'distinctive process, comparable with but different to scientific and scholarly processes' (1979a: 18) and looks to the future, in hope that it will contain more on the subject of design methodology via more complete and inclusive means. In the years since Archer's writing, the area of design methodology is still somewhat lacking definition and application. Archer's ideas are important, not only in developing the ideas that would be taken forward, but also for illustrating the difficulty that has stopped full realisation of these ideas in the years since they were first published. The difficulty in recognising the worth of design processes and methodologies is a large, complex issue. Academic and commercial society is clouded by deeply-rooted disciplinary divisions, stemming from first experiences in education and continued into our 'parochial' careers (Schön, 1991: 60). This segregation entrenches our alignment with, and disassociation from, areas which may be both rewarding and related.

2.6.2. The debate in education

Education has a strong and influential bond with the idea of discipline; though these boundaries reflect changes in wider society and are in a constant flux of re-organisation and re-structure. This, according to Turner (2006), has led to a *post-disciplinary* society (corresponding to post-modernity) with each discipline now suffering from a lack of authority. In contrast to this idea, the idea of scholarly disciplines has become deeply rooted and little-questioned in contemporary practice (see Archer, 1979a and 1979b). Terms such as 'multidisciplinary' and 'interdisciplinary' have gathered momentum to fill the gaps caused by the deep segregations of study and practice.

There is evidence for the perpetuation of disciplinary division across creative subjects. 'Engineer' derived from the Latin word 'ingenerare' – to create, implying a creativity focus before it became one of the 'sciences'. (El-Mogahzy, 2009: 18). Similarly, there was no historic distinction between craft and industry, the differences largely being opportunistic through innovation and commerciality and never antithetical (Metcalf, 2007: 5; Jönsson, 2007: 242). Similarly, the Greek 'technê' meaning a skill, craft, technique or art (OED, 2014; Thornquist, 2012:12), provided a shared root for both technique and technology, of which technology grew to dominate the once shared meaning. This need for distinction between art and science is something brought about by a falsified necessity, which is clear in the work of many artists working happily within both domains or incorporating the two in novel and simultaneous ways.

With textiles sitting within both arts and science it becomes difficult to apply rigid distinctions here. Archer berates the use of scientific notation in design theory as inappropriate (Archer 1979a:18) . Archer saw education split into sciences and humanities, and in 1979 appealed for design as a third area. (1979b:18). Where design is certainly recognised now in education and industry, there is still some remaining stigma and confusion attached to knowing its correct place within scholarly activity. Whereas the values of art and design practices were once fully integrated into knowledge and scientific contribution, because of this disciplinary segregation, art and design have had to reposition and justify once more their contributions to knowledge, innovation and research practice at large (Press, 2011). The value held in the knowledge and approach of an art or design practitioner is not the same as, or measurable against, those of scientific, empirical practitioners; nor should it be. As Press states of artistic practitioners, their insights are not always predictable, but can be of immeasurable use:

> *In their pursuit of a more beautiful, useable and understandable world, art and design researchers provide essential pathways to a better and more economically sustainable future.*
>
> Press, 2011: 169

The issue with comparing the contribution of design (or more widely, humanities-based) practices to scientific modes of study, is the difficulty in quantifying 'return on investment' or contribution of design work to an institution or economy (Howells, 2011: 237). Design research can have impacts on areas much wider than the project's initial scope, and these impacts know no disciplinary bounds. Press gives the example of Elaine Shemilt's work with the Scottish Crop Research Institute to create artwork based around some of their data, which visually revealed previously unknown genome sequence information of a bacterial potato plant pathogen. Shemilt's artistic presentation of the data provided a contrast to the 'systematic and empirical' approach of the scientists, which led to a new method of looking at the data, which the scientific approach alone did not uncover (Press, 2011: 168-169).

Since Archer's writing (1979a; 1979b) calling for design to have its own area outside that of science or the humanities, there has been little mainstream movement in favour of design education. In a recent and upsetting governmental movement, the UK has reworked the art and design curriculum for compulsory education (up to the age of 16) to favour art and design history over contemporary and future-looking practice (NSEAD, 2013). The curriculum framework cited (Department for Education, 2013: 182-184; 192-197), omits the purpose of art and design subjects to provide context and critical thinking through action and engagement with historical and contemporary events and practices.

Under a political system which negates the worth of designers' work through policy implementation, it is of great importance that the valuable input of a design approach and of the designer is recognised as being multi-dimensional, forward-thinking, synergistic and capable of creating jobs and revenue, as well as international and individual advancement and enjoyment.

2.6.3. Textile and knit education

In knit design it is rare to find specialised courses prior to further education (FE) or higher education (HE) (based on the UK education system). This is likely to be because of the large amount of space and investment required to offer education on knitting machines. Development of machinery also happens rapidly, which makes keeping up to date with advanced knitting technology more difficult (Francis & Sparkes, 2011: 61-62). For these reasons, knit is unlikely to feature in school education (unless by using hand-knitting or domestic machine-knitting). When taught in schools and FE and HE institutions, knitting is often subsumed into textile design, where it may be given an artistic, craft aesthetic or fashion direction, depending on the course.

In HE there are a small number of specialist knit courses offered. To illustrate, a search on UCAS (UCAS, 2013) for institutions offering relevant undergraduate courses available for a 2014 start showed 1 for 'knit design', 67 for 'textile design' and 103 for 'fashion design'[18]. The figures for post-graduate study courses showed 5 knit and over 100 of both fashion and textile courses (UKPASS, 2013). These figures indicate the relatively small amount of specialist teaching on knit available. Some of the fashion or textile courses will offer advanced teaching in knit, but others will not.

This low number of specialist courses shows the strange position of knit as being between fashion and textiles, as well as within and outside them. It also gives support for Francis & Sparkes' concerns of knit being pushed aside by educational institutions. For this thesis, it offers an explanation for the inherent misunderstanding of what it is that a knit designer does, and what skills they can offer.

2.6.4. The science/engineering/design/art divide

As discussed already, the idea of disciplinary conflicts and misunderstanding is important to the position of this thesis and the research herein. In order to discuss this further it is necessary to

[18] Figures correct as of 25th July 2013. Terms shown denote search terms. UCAS registered institutions only shown, figures are offered as indication only.

approach the large and amorphous debate about the differences and similarities between arts and/or design and science and/or engineering.

The diagram in **Figure 2.19** shows an approximate conceptual framework of the debate surrounding the similarities and differences in art, science, design and engineering. The authors in the diagram are those whose writing has had direct relevance to this thesis. At the centre of the diagram are three concepts – *Artefacts, Knowledge and Practice* - that I find to be important to all of the disciplines, regardless of perspective. I believe that these similarities should be the key topic for discussion, rather than concentration on differences that are not always present.

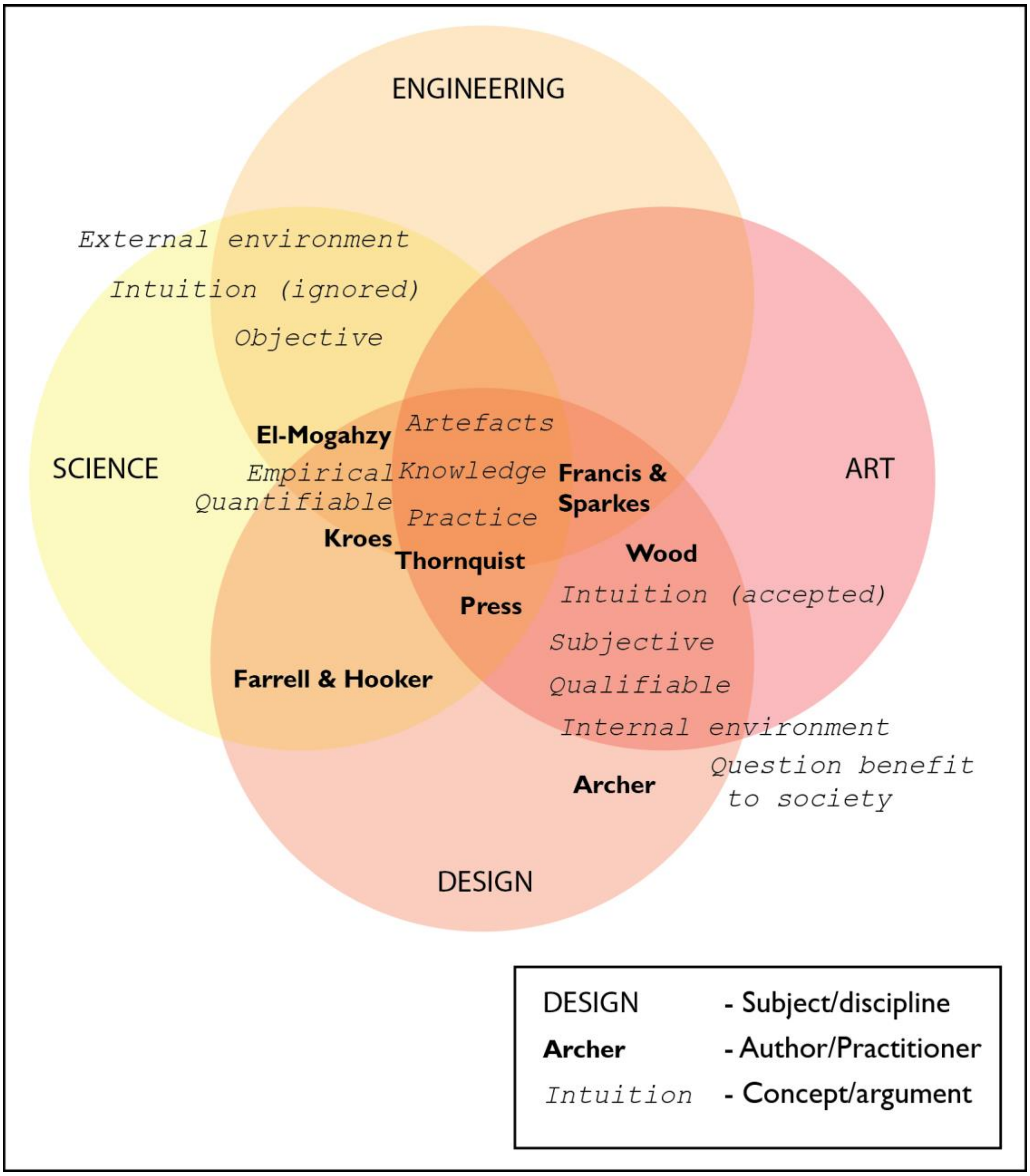


Figure 2.19 Representation of the conceptual framework of the science/engineering/design/art divide as mentioned in this chapter.

Clemens Thornquist (2012) questions the division of science and art in research modes and highlights certain areas where researchers are omitting large areas of relevant methodology in order to reflect on their own practice; such as artists reflecting on science outcomes, without scientific methods or scientists reflecting on art outcomes, forgoing art practice. Thornquist offers a key definition about what research into clothing (and by extension textiles) might mean outside a fashion, humanities or fine art context. He says:

> *…it is about the basic development of new techniques, methods and models of dress. ….rather than dressing different ideas in fancy clothing, basic research is about exploring the potential of dress through fundamental relationships between form and material, between technique and expression.*
>
> Thornquist, 2012: 11

This pragmatic definition concentrates on relationships between elements, prioritising neither form nor function over each other. He goes on to point out the relationship between science and art, technique and expression, and how it is not a matter of formalising the differences between arts and sciences, but realising how art can be, might be or is science and vice versa (ibid.: 12).

Thornquist ponders the moment at which the creative process starts (something that he does not try to answer), which can be realistically interpreted as an *ad hoc* factor in the design process. This ad hoc nature is not vilified for its subjectivity, but praised for the creative potentials it can bring to a design project.

Farrell and Hooker, in a related manner to Thornquist, question the diametric relationship of arts and sciences. They discuss differing perspectives in relation to the distinction between science and design. In this sense, the debate concerns the natural - previously assumed to be the scientific - and the artificial - previously assumed to be the designed. Farrell and Hooker disregard this distinction, as the artificial includes such large swathes of artefacts, including abstract concepts and things created by scientists from natural materials. In turn, artefacts are described in terms of their inner and external environments. In summary, the debate cites existing literature as assuming that scientists are concerned with the inner environment (or the workings) and designers more concerned with the outer environments (the function); the designers' main concern with the products' inner environment is that it enables 'the fulfilment of its intended outer purpose' (2012: 483).

El-Mogahzy offers an inclusive view of textile engineering that has design at its foundation (2009: 18) and is a deeply interdisciplinary field. His view is that textile engineering sits in an outsider position to other engineering subjects and hopes it will earn recognition in these areas through functional textile products (ibid. 22). He also believes that, as textile engineering schools move away from traditional techniques (citing spinners and looms), they lose links between the traditional and the functional. The two should be maintained in some sort of balance in order to successfully understand and develop advanced textile products (ibid. 401).

There are many issues raised in this debate, such as the differences in definitions of objects, roles and practices between practitioners from the same discipline and from others. This thesis aims to question the debate itself rather than to solve it, but the perspectives in this debate provide useful context to how disciplines are perceived, established and held onto in practice.

2.6.5. Interdisciplinary/transdisciplinary/multidisciplinary/cross-disciplinary research

In spite of the historical and contemporary difficulties in conducting work that spans several disciplines, there are many people who work in textiles as part of wider-reaching projects that encompass a range of disciplines - within these, there are well-publicised areas like technical textiles, architectural textiles and electronic textiles. In this section, I would like to keep discussion to groups that share a similar ethos to my research in order to situate this thesis into a field of related research.

To outline my own background in cross-disciplinary research is to talk about the project *Aeolia* (Kettley et al. 2010; Glazzard & Kettley, 2010), which ran from 2008-2011 at Nottingham Trent University and continues as a research group working on other projects. The *Aeolia* project sought to investigate the ideas of integration of individual craft and design practices across disciplinary subjects. The collaborative team consisted of nine practitioners across knit, weave, print, embroidery, fashion, interaction, engineering, product, sound and music. In this project, each person was considered to be the sole expert in their own field. Where a development in the largely fluid nature of the research required more or less input from particular members, this was accommodated, as well as additional members added to the team. The project began through trying to integrate a commercially available technology[19] into various textile media. When doing this, it was decided to split the research into two strands. The first, to integrate as successfully as possible the foreign technology into textile forms and the second, to create original textile technologies. Both of these focused primarily on experiential knowledge rather than trying to learn a new 'technological' way of working. The group worked successfully in this format, which involved taking the technology and working it back into the textile or the garment, rather than working towards the technological end. The showcase for the two strands was back body panels with integrated stretch sensors tightly fitted into the material (see **Figure 2.20**) and a garment created for use with a cellist, which incorporated a custom-knitted, conductive stretch sensor.

[19] a carbon impregnated rubber stretch sensor from Merlin Robotics (Merlin Systems, 2013)

Figure 2.20 Aeolia project. 2010.
L-R embroidered, knitted and woven back panels with stretch sensors.

The final outcome of these works culminated in presentations of the works and a small number of performances and demonstrations of the new, knitted stretch sensor technology. What made this project so successful was the management of the interdisciplinary nature – the ability of practitioners to be expert in their own field, acting with autonomy, but to have access to all relevant fields. It was left to a textile designer to create a technology, as this technology was textile-based. The role of the engineer in this scenario was to facilitate, not dictate, the final outcome or the processes. The research process rested on the use of a facilitator (Kettley) to co-ordinate this large group. Individual researchers held a large degree of responsibility for their own material and technical contributions.

There are many practising artists and researchers who have training in both engineering or scientific and art or design areas and whose work reflects these backgrounds. Similarly, there are researchers and artists who stem from one type of discipline and expand to include knowledge from other disciplines that they then add into their existing practices and skill sets.

With the Aeolia project, individuals were not expected to leave their areas of specialism, but to engage with the additional information required to develop multidisciplinary projects. This can be seen in contrast to a project such as Guy's (2001) (discussed in section **2.4.1.**) where the ultimate end clouds the individual's skills that are so important to the project's very existence. This results in the design concerns being subjugated by the desire to appear quantitative.

This integration has been the subject of two books by Sabine Seymour, one concerned with technology integration into clothing (2008) and the other with the relationship between function and aesthetic (2010). Seymour is keen to point out the disciplinary backgrounds of the researchers featured in *Functional Aesthetics*. The emphasis in her book is the importance of using practitioners from relevant disciplines in order to achieve something successful, be this a fashion designer for a fashion output, an artist for a conceptual output or an engineer for an engineering output. A noteworthy aspect of this method is that in many cases the output does not belong to one discipline alone and may belong to several.

The disciplinary divisions that are rife in design preconceptions and expectations are slowly being lessened by collaborative work, cross-disciplinary work and better understanding of other people's practices. The wide aims of 'knowledge transfer' deal with issues such as:

- collaborating with others
- understanding and appreciating their methods
- making meaningful contributions to work and literature outside single viewpoints or disciplinary areas
- connecting academic and commercial development or interests

Knowledge transfer has an important role in the work outlined in this thesis and will be discussed in section **2.6.8.** as well as throughout the research. A concluding section on the knowledge transfer elements of this thesis can be found in **Chapter 8**.

2.6.6. The gap between technology and design

Discrepancies, when distinguishing between the practices of engineering or technology and design in knit, can be illustrated through the educational research about students of scientific or design-based knit courses at university by Sayer, Wilson & Challis (2006). The research set a practical, making task to compare the methods of teaching and learning from a BSc (Bachelor of Science) Textile Design and Design Management (TDDM) course at the University of Manchester (UM) with students of BA (Bachelor of Arts) Fashion Design (FD) at Manchester Metropolitan University (MMU)[20]. This making task tested students' understanding of design practice in a 'hands-on' capacity through a simple design and making assignment. The task was to knit a seamless handbag using only the hand flat knitting machine. There were various specifications to be adhered to, as is common in design projects.

Sayer, Wilson & Challis found that three of the bags knitted were very similar in style, whereas two of the FD student's bags were significantly different in appearance from the others. The TDDM students had written process notes about the problems they had encountered and overcome, whereas the FD students had produced sketches, samples and mood boards. In addition to these differences in output, there was common feedback, among both sets of students, that the problem-based learning task was rewarding and enabled better understanding of a complex method (seamless knitwear design).

Similarly, when comparing students' learning style preferences from the same two Manchester Universities, Sayer & Studd (2006) compared BA Textile and Fashion students from MMU to the BSc TDDM students from UM. Students were asked to rate which learning styles they preferred – *Activist, Reflector, Theorist* or *Pragmatist*[21]. They also completed questionnaires on 'How do I learn best?' – *Visual,*

[20] The TDDM (UM) students were taught design mainly through lectures, and the FD (MMU) students through workshop experimentation.
[21] after Honey & Mumford's test 'The Manual of Learning Styles' (see Sayer & Studd, 2006)

Aural, Read/Write or *Kinaesthetic*[22]. What they found was that students from both universities preferred the same learning styles. When compared, both chose *Activist* as their preferred learning style and *Pragmatist* as their least preferred. Both sets leaned strongly towards *visual* teaching styles and matched closely in all answers, with a slight leaning towards *read/write* from the UM students (ibid.: 173).

The finding that two groups of students enrolled on different degree types, with different emphases and learning outcomes, in institutions with different leanings, prefer the same learning methods and consider themselves to be predominantly active learners is an interesting and possibly counter-intuitive result. At the start of the study, it was thought that the results from the two courses would be different, though they proved to be surprisingly similar. This implies that the emphasis placed on the separation of technology and design in both education and industry is not necessarily justified in the case of knitting.

The case for a lack of disciplinary segregation can be advanced from Sayer & Studd's studies into higher education by considering Schön's comment on career professionals. He states that, later on in an individual's career, specialisation can lead to a narrowness of vision (Schön, 1991: 60) where the individual loses the ability to see outside their specialism, possibly to the detriment of their practice. As with industrial practice, in education 'hard cases make bad law' (Polanyi & Grene, 1969: 78) and rigidity in disciplinary demarcation hinders development. Failing to acknowledge aspects of practice, because they do not fit with current theory in that area, does an injustice to the possibilities of both individuals within practices and the disciplines themselves.

2.6.7. Tacit and experiential knowledge

Tacit knowledge is an important aspect of many areas of design, but is more widely accepted in qualitative and artistic design than scientific and engineering design. Tacit knowledge is described as the ability to know more than we can tell (Polanyi, 1966: 5) and therefore does not adhere to traditional academic research principles that favour rigour, repeatability and stipulations of exact processes. Recalling his scientific background, Polanyi uses examples such as human faces' physiognomy to illustrate the difficulty of describing our reactions to, and the essence or character of things, rather than the physical properties of these things. He says this type of observation cannot be described fully by using either words or pictures – therefore, the understanding requires an inexpressible understanding of the whole, rather than the parts (ibid.). Niedderer also questions the sceptical treatment of tacit knowledge by traditional research practices. She sees tacit knowledge as being necessary to any development and communication of knowledge that should not be discredited for not fitting into 'research requirements' (2007: 10).

Experiential knowledge describes things learned through lived experiences – personal and embodied knowledge[23] (Niedderer, 2007: 9). Inherently, experiential knowledge is similar to tacit knowledge and development of tacit knowledge may be the result of an accumulation of experiential knowledge.

[22] after Fleming, 1996, 'VARK' (see Sayer & Studd, 2006)

[23] relatable to tacit, implicit and ineffable knowledge

The methods proposed by Aldrich (2007) to learn tacit and experiential properties of fabric through variety and involvement, support the case for tacit knowledge's important role in design (and, in particular, textile-related disciplines). Aldrich's methods for learning fabric properties hinge on the gradual accumulation of the knowledge needed to assess suitability of fabrics for applications. This builds up a store of experiential knowledge to apply to future decision-making in design (similar to the case-based reasoning used by Richards [2013]). Aldrich does not presume to tell the reader what they should be thinking or feeling about fabrics, but suggests a wide range of fabrics that will build up experiential knowledge of contrast and properties.

Putting such emphasis on the importance of tacit and experiential knowledge is an important difference between development and delivery styles of subjects such as art and engineering. This highlights the inherent differences between different practitioners about the practice and understanding of research and how it should be conducted and shared. This thesis values tacit and experiential knowledge highly and frequently refers specifically to the knowledge of individuals from their experiences in their own practices.

2.6.8. Knowledge transfer

Various initiatives exist to promote the transfer of knowledge between disciplines, or to open up knowledge from projects beyond their traditional scope, audience or format. Together with 15 Knowledge Transfer Networks (KTNs), the Technology Strategy Board Network[24] (TSBN) runs several initiatives to broker communication between businesses, academics and researchers (TSBN, 2014). The Materials KTN (KTN, 2014) has a specific interest in bringing research into new materials to commercial development, aiming to 'bring together the materials supply chain to accelerate innovation, improve global competitiveness and sustainability' (ibid.).

One example of an interest group set up within the Materials KTN is 'Auxetics Innovation'. Auxetic materials make up the focus for the practical element of this research project and are introduced in detail in section **2.9.** of this chapter. Similarly, smart materials, technical textiles and many more groups exist within the breadth of both the KTNs and the TSBN. These two entities have a governmental and business focus and prioritise innovation, science, health, economical and business objectives.

Another example of cross-disciplinary networks exists in networks set up to bring together particular design interests. One such example is the ArcInTex network (2014) run from the University of Boras, Sweden, which aims to bring together research from architecture, interaction design and textile design to create innovative and collaborative work. This network has European funding and a different set of priorities from the TSBN, with concentration on artistic perspectives and thinking with 'respect to techniques, materials, perspectives and design thinking' (ibid.).

[24] In connection with special interest groups and community networks

Various other groups and projects exist in universities and as businesses to promote knowledge transfer, multidisciplinary work and innovation within design, making, textiles, art and science. Some examples include:

- The Institute of Making at University College London looks widely at concepts of materials, making and maker involvement (Institute of Making, 2014).
- TIO3 in Belgium specialises in inspiring clients with textile processes and technologies or to start new businesses (TIO3, 2014).
- The 2013 Praxis & Poetics conference co-located conferences on 'Research Through Design' and 'Design for Pleasurable Products and Interfaces' with the aim to talk about practice in a non-discipline specific environment (Wallace & Yee, 2013).

The spread of knowledge transfer and other encouragement of interdisciplinary collaboration and communication show an exciting trend in both design and design research. **Chapter 8** of this thesis explains how the findings of this study aim to facilitate knowledge transfer and encourage wider dissemination of the findings.

2.7. Contemporary knit design research

In terms of contemporary research within knit design, there are several strongholds of development as well as individuals who are pushing boundaries in both commercial and academic areas. For example, researchers at the University of Boras, Sweden have a strong presence in developing textile research in 'Smart Textiles' and 'Fashion, Function, Futures' (F3) (University of Boras, 2013). The knitting and research facility is pushing artistic combinations of technology and knitted textiles, in which design research is practised independently from general textile engineering or scientific outcomes (ibid.). Some examples of the work at Boras around knitting include:

- Integration of heating/conductive elements that burn out sections of a tablecloth when actuated by mobile phone activity (Landin, Persson & Worbin, 2008)
- Using the effect of heat on fabric to design 2D, 3D and human interaction elements (Dumitrescu & Persson, 2011)
- Knitted garments for use as musical instruments, with comment on the significance of using the connection with the body to make sounds (Satomi, Worbin & Scholtz, 2011)

Other institutions that have an agenda in promoting the versatility and quality of both research and product in knit design include:

- The University of Southampton, which organises a series of conferences called 'In the Loop' These conferences aim to 'bring together disparate approaches to this single subject' and invite contributions from researchers, academics, knitters, designers, artists from all aspects of knit research (University of Southampton, 2013)
- Nottingham Trent University has emphases on advanced textiles – electronic and functional textiles with some collaborations with designers and manufacturers – and on creative textiles – focusing on 'Global Cultures, Digital Craft and Embodied Knowledge and Lace Heritage' (Nottingham Trent University, 2013)

- The Textile Futures Research Centre at University of the Arts London develops its research strategies through the subjects of 'science and technology, sustainable strategy, and well-being & social innovation' in regard to the future of materials and textiles. The areas remain open and investigate issues around human, material, societal and practical elements (Textile Futures Research Centre, 2014)

The existence of the four research groups listed above (among others) shows a strong relevance for the future of knit in both physical and theoretical epistemologies. The different approaches to categorising and developing work in knit and textile design show that, though the issue is complex, there is potential for diversity, knowledge transfer and fun in the development of knit research.

2.8. Technical Textiles

Though the research in this thesis is not specifically attempting to fit into the definition of technical textiles, it is a relevant area for comparison and discussion. The various interpretations and definitions of technical textiles make any classification of this (or other) functional textile research a problematic task.

2.8.1. Definition of technical textiles

As with the term 'textiles', the term 'technical textiles' is one with various opinions and connotations affecting an exact definition. Kettley (2011: 323) describes them as vastly ranging through industrial and small-scale applications with an indication on properties and specific end use 'over and above aesthetic consideration'. Kettley gives acknowledgement to the various ways in which a textile or a technical textile might be categorised. The fields of category range from disciplinary or application field, fibre or material, manufacturing process or various desirable properties. Braddock and O'Mahony (1998: 6) describe 'techno textiles' as contemporary textiles, which span the gaps between art, design, engineering and science – providing a more broad and romantic interpretation of the field.

Techtextil – the world's largest trade fair on textile technology breaks down technical textile into twelve 'application areas' based on their end application. Approximately put, these are as follows: agricultural textiles; textiles for building and construction; clothing and shoes; geotextiles for roads and civil engineering; home and upholstery textiles; industrial textiles for mechanical, chemical and electrical industries; medical and hygiene textiles; automotive and transport textiles; eco textile applications; packaging; protection and sport (Techtextil, 2014). Techtextil also categorises into eleven 'product groups' such as non-wovens, composites, coated textiles, etc.

There is still little clarity on a direct classification of technical textiles because of the multitude of subdivisions and terms. Within the subdivisions exists a range of companies, and within each company a range of products and techniques. The sole thing that links all technical textiles is that they contain or consist of textiles. The technical aspect implies that a technology or a functionality is prioritised above other properties, but the end uses for some of these technical textiles may be in the clothing industry as decoration or aesthetic (such as clothing with light or colour change). The areas of technical textiles that focus on yarns (such as bamboo fibres, or seaweed fibres for sustainability) are not far-removed from the traditional textile yarn industry.

With this difficulty in defining technical textiles, it may be best to keep in mind that technical textiles is a huge subject, which not only has the possibility to combine all of the discipline of textiles, but also many of the disciplines of engineering and science. The one thing it is not considered to cover is those applications, traditional in textiles, which, though functional in a way, are considered to be largely aesthetic. This includes textiles as artwork or as fashion items. Clothing, however, cannot be excluded; as has been noted, sport and leisure clothing as well as wearable technologies are key areas for investment and development.

2.8.2. Smart textiles

The term 'smart textiles' is as problematic as 'technical textiles'. Popular consensus suggests that smart textiles contain electrical components and can produce dynamic properties after electronic activation. The definition of smart textiles might be broken into smaller sub-categories:

- Passive smart textiles: textiles with additional features that do not alter the environment (e.g. optical fibres, conductive fabrics, etc.)
- Active smart textiles: have sensors to sense the environment and actuators to activate a response (e.g. colour-changing inks, shape memory alloys, etc.) (Ajmera, Dash & Meena, n.d.)

Considering these various definitions, the terms 'smart textiles' and 'technical textiles' encompass a large range of textile products and functions. Both terms could be classed as 'buzz words' caught up in inferred meaning around the latest technologies and developments, implying certain target markets and developers. Linguistically, the inclusion of specific jargon such as 'active', 'passive', 'actuators', etc. for smart materials may alienate makers from non-scientific or engineering backgrounds, who might be deterred from using such materials in their practice due to the unfamiliar terms used.

2.8.3. Other areas of 'technical textile' development

Other areas of development in smart and technical textiles that are not included in the definitions put forward by Techtextil (2014), are those pursued by art, craft, theory, interaction and designer-maker practitioners. Architecture has had a significant relationship with technical textiles. An example is the work of Jenny Sabin, specifically the knitted 'myThread Pavilion' comprising a vast network of knitted tubes to create a lightweight 'building' derived from sportswear (Sabin, 2014). Similarly, the process of knitting can be used as dividers for outside spaces such as fences (Volpi, 2014), which range from individual knitters using twine, to resin-coated industrial practices.

Essentially, the scope for technical textiles encompasses a great number of existing practices and could encompass many more. Projects such as those discussed by Seymour (2008, 2010) could be seen as technical textiles, but may choose not to be because of the connotations that come with the term. The research in this thesis may be seen to be technical textiles by some, but those terms are not used to classify it here.

2.9. Auxetics

2.9.1. Introduction

This thesis focuses on the practical application of design knowledge in a 'functional' field of knitted textiles. In order to demonstrate the adaptability and diverse potential in knit design practice, it is necessary to put the practice through a task to create functional 'artefacts'. Auxetic materials were chosen to be the focus of this practical work for several reasons:

- The field was considered to be lacking significant design focus (Morris, 2012).
- Auxetic systems are composed primarily of geometric structures, in similar ways to many knitted textile designs.
- Work published in the initial stages of this research (Liu et al., 2010) indicated possibilities for creating weft-knitted structures from engineering perspectives.
- The work published by Liu et al. (2010) used simple relief structures, commonly used in aesthetic knit applications.

What follows is a basic introduction to auxetic materials in order to explain some of the avenues of current auxetic research and development. The bulk of auxetic literature comes from scientific sources, however, the review herein will concentrate on relaying the basic elements without being reliant upon mathematic or geometric detail for description. Using descriptive language and images keeps the perspective framed in the practice of the designer, rather than those of scientists and engineers.

2.9.2. Definitions

The Poisson's ratio (PR) of a material is an engineering definition for the measure of the change in dimensions. As described by Whitlow below:

> *When a bar is subjected to a longitudinal stress a direct strain takes place in the direction of the stress. At the same time a strain will take place at right angles to the direction of the applied stress; this is termed the lateral strain. Where the deformations remain elastic, the ratio of the lateral strain to the longitudinal strain will be constant for a given material. This ratio is called Poisson's ratio.*
>
> Whitlow, 1991: 270

Whitlow states that the expected and common value for a conventional material is usually a Poisson's ratio of between 0.25 and 0.35 (ibid.). Any material with a positive PR value will display a contraction at a right angle to the longitudinal strain (the direction of the stretch), as shown in the upper portion of **Figure 2.21** where the material with the positive PR is stretched horizontally and shows a reduction in the vertical measurement (behaviour like this can be obviously seen when stretching an elastic/rubber band).

Mathematically, the Poisson's ratio is worked out by the following formula:

$$\text{Poisson's ratio (PR)} = -1 \times \frac{\text{transverse strain}}{\text{axial strain}}$$

Ashby, Shercliff & Cebon, 2009: 54

The axial strain is the change in measurement in the direction of stretch (i.e. by how much a fabric was extended). The transverse strain is the change in measurement in the transverse direction to the direction of stretch (i.e. by how much the measurement expanded or contracted depending on the fabric properties). Although this thesis uses minimal mathematics and keeps equations basic where possible (to make comprehension of numerical information as widely understood as possible), the PR value is worked out after some of the testing for comparison. Comparison is made between the PR results of fabrics, but also the presentation of information is compared between PR and alternative results (percentages, graphs and diagrams).

Materials with a negative Poisson's ratio (NPR) are also known as auxetic materials (first used in Evans, 1991). The adjective *auxetic* is derived from the Latin word *auxēticus* meaning increase or amplification (OED, 2011). These auxetic materials will show an expansion at an angle transverse to the stretch applied (as shown in **Figure 2.21** where the lower portion of the diagram shows the NPR material expanding in the vertical direction, transverse to the stretch in the horizontal direction; this is a contrasting behaviour to the positive PR material). Auxetic materials are sometimes referred to as anti-rubber or dilatational materials. For the purpose of this text they will be referred to as auxetic materials, with occasional reference made to Poisson's ratios.

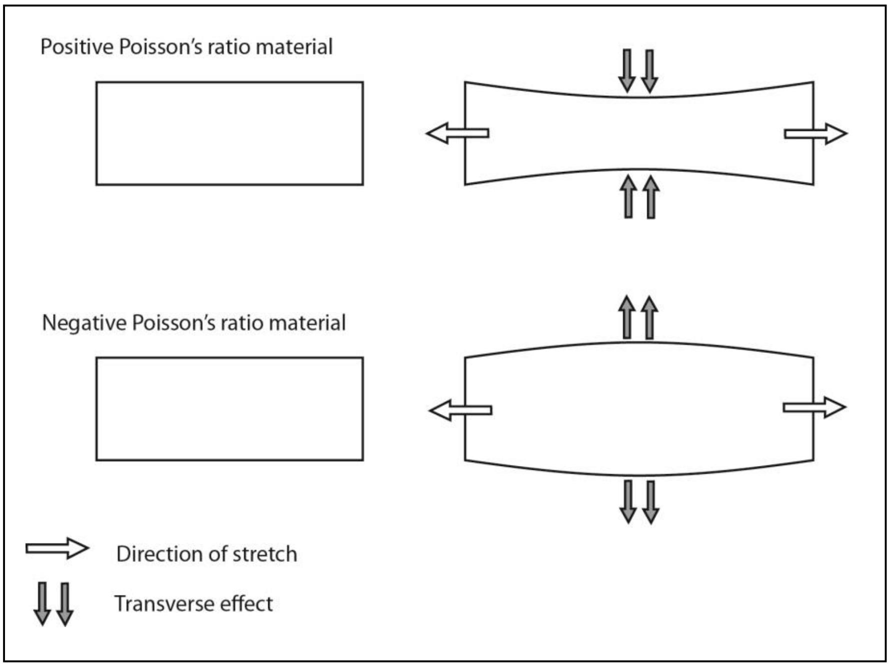


Figure 2.21 Visualisation of positive and negative Poisson's ratio in relation to material dimensions.

Auxetic materials were brought to the attention of a research audience in 1987 by Rod Lakes and his development of a polyurethane foam exhibiting a negative Poisson's ratio (Lakes, 1987; Mehta 2010: 9). Work on auxetic structures has since gradually expanded into various scientific areas, but has remained largely theoretical, with very few auxetic products available commercially. Of those that are available, none are thought to be purposefully engineered or designed for their auxetic properties (Glazzard & Breedon, 2014: 267). Some attempts have been made to spin out the research from universities into companies such as Auxetix Ltd. (discussed below) and Auxetic Technologies from University of Bolton (Alderson, 2011). But these have not managed to extend the understanding of auxetic materials into the commercial sector, as evidenced in discussion from a KTN workshop on the subject of commercialisation of auxetic materials (Morris, 2012).

An example of a spin-out company is Auxetix Ltd. (Auxetix Ltd., 2011) from University of Exeter. Auxetix is a development-based centre, which provides licenses for their auxetic material products. The areas Auxetix Ltd. aims to develop are in: aerospace; automotive – seat belts, cargo straps; construction – embedded sensors, concrete reinforcements; defence – blast-fabrics; healthcare – dental floss, medical sutures, pressure-sensing fabric; manufacturing; textiles and communications (Auxetix Ltd., 2011). Within Auxetix is an emphasis on auxetic textiles. The main development here is the auxetic yarn produced. This is a yarn consisting of a thick, stretchy yarn and a thinner, non-stretchy yarn (as shown in **Figure 2.22**). The two are wound together and when extended, the stretching yarn is forced to spiral around the taut, non-stretching yarn. This effectively widens the overall thickness of the structure and when used in combination begins to form auxetic structures.

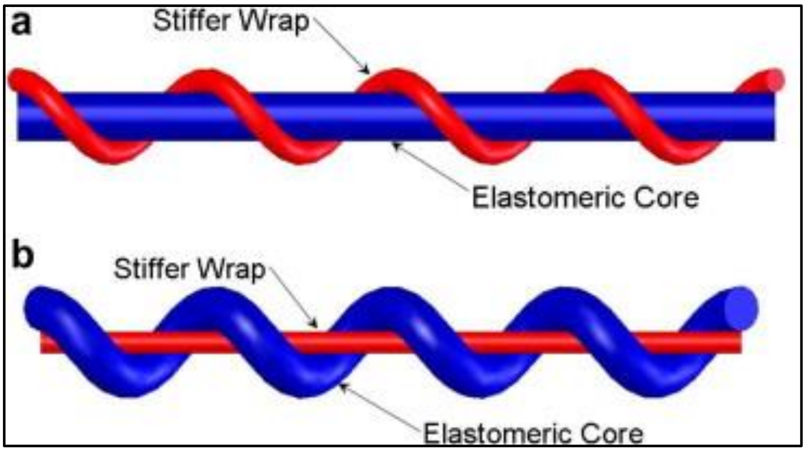


Figure 2.22 Double helix auxetic yarn shown at rest (a) and stretched (b). (Source: Miller et al., 2009: 652).

The potential benefits of this 'double-helix' (branded as 'Zetix') yarn technology are mainly channelled into the development of blast-protection fabrics. Using the Zetix yarn, woven into tight textile structures, this will allow holes to expand to let through some of the blast force of an explosion to prevent tearing of the fabric, but these will be small enough to keep out flying debris (EPSRC, 2010). Further to these advantages, there are applications cited in manufacture of seat belts that expand to spread the load of an impact to provide increased protection to passengers. Additionally, there is discussion of work in the area of medical suturing and textile composite materials, where the yarns used would expand when under force, so would be more difficult to displace than a conventional yarn.

2.9.3. Geometric models and structures

Another strand of auxetics research is that into the geometrics that exhibit the behaviour. In 2010, Yanping Liu and Hong Hu at the Hong Kong Polytechnic University published a summary of the advances in this area (Liu & Hu, 2011). They broke down auxetics into geometrical models and structures. The following section discusses literature important for understanding the field of auxetic materials and the areas in which it is being or has been explored. Different geometries, research projects, disciplinary areas and viewpoints are discussed to describe work that has formed inspirational material for the practical development in **Chapters 4-7** of this thesis.

2.9.3.1. Re-entrant structures

Re-entrant honeycombs or re-entrant hexagons were responsible for the auxetic behaviour of the first NPR foams (Lakes, 1987: 1039). This effect as shown in **Figure 2.23** is produced by elongating the zigzag of the horizontal struts, which then forces out the mesh of vertical ligaments to increase the open area of each cell.

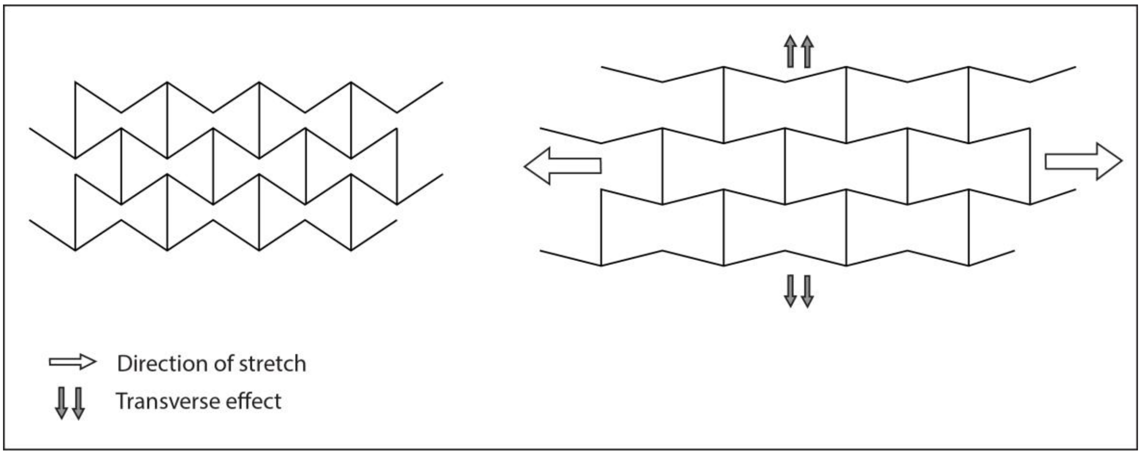
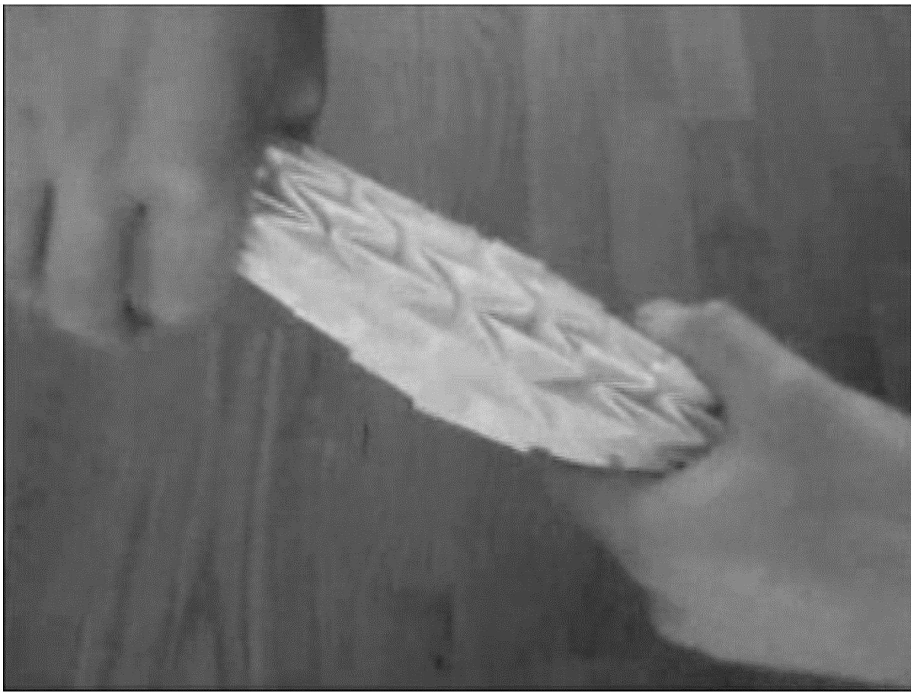
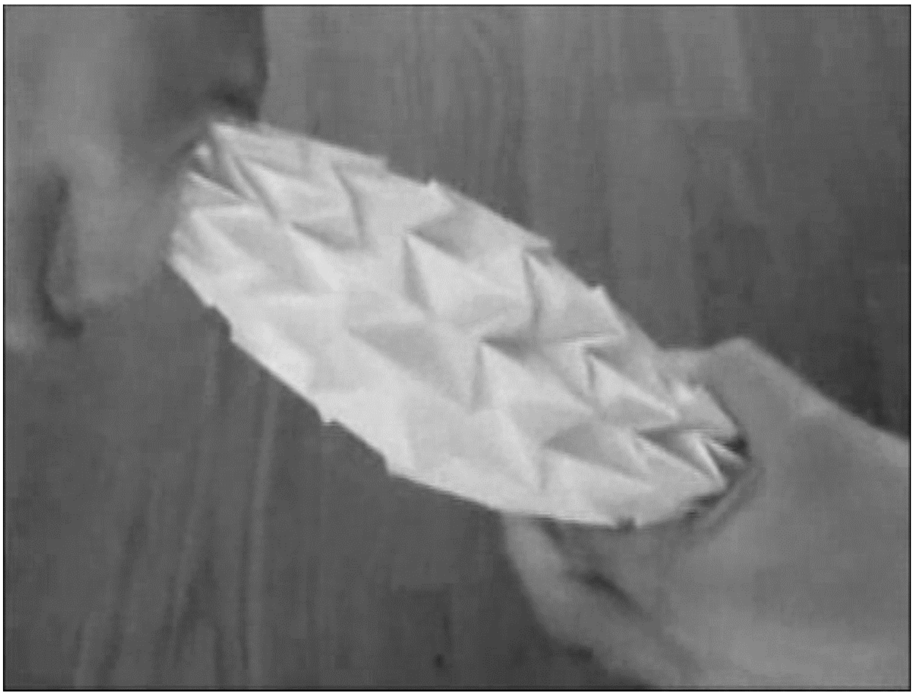


Figure 2.23 Diagram showing re-entrant hexagon structure.

There are various types of re-entrant structures, many of which can be represented in folded paper forms such as Miura Ori and origami. Daniel Piker, who works with geometric structures, has produced examples of paper folding that demonstrates an auxetic effect. Pictured in **Figure 2.24** is one example, shown in a video on Piker's blog (Piker, 2009a; Piker, 2009b). This structure is related to the geometrical structure in **Figure 2.23**. As shown in Piker's video, the folded paper is rolled into a tube and when a pulling force is applied, the diameter of the tube expands.



(a)



(b)

Figure 2.24 Stills from 'Deployable/Transformable Structures' video (Source: Piker, 2009b) showing folded paper, tubular, auxetic structure (a) unstretched and (b) stretched.

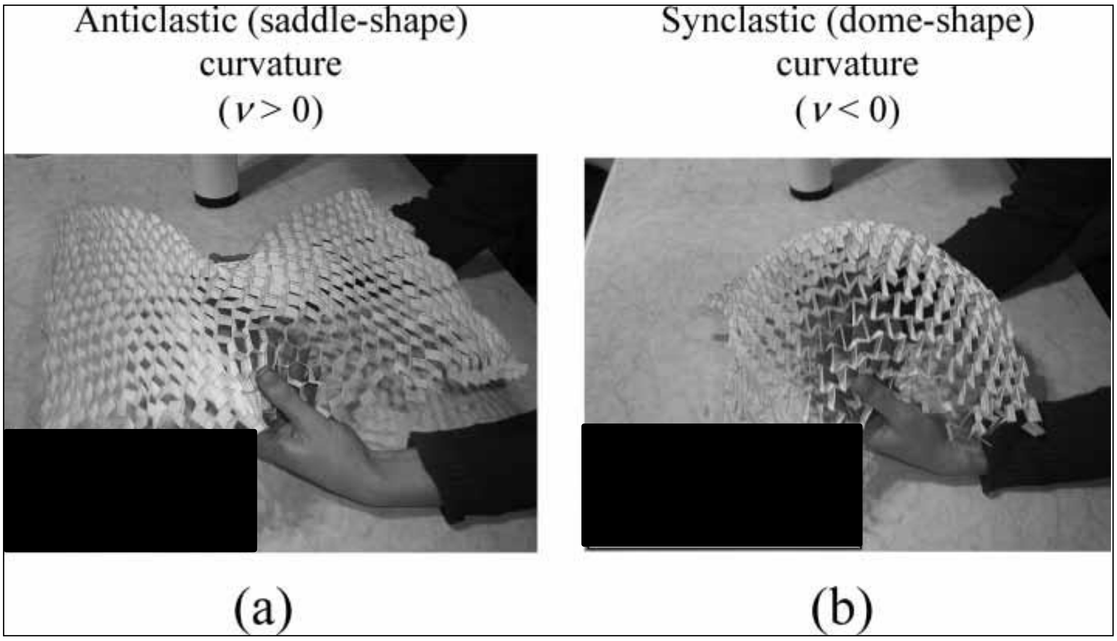


Figure 2.25 Honeycomb structures (Source: Alderson & Alderson 2007: 566). (a) conventional honeycomb and (b) auxetic honeycomb structures. N.B. 'v' refers to the Poisson's ratio.

One of the other noteworthy properties of an auxetic structure is that it shows a difference from conventional materials in the way it bends. The curvature of a conventional material can be seen in **Figure 2.25a** where the bend occurs in only one of the planes, forming a saddle-shape. In **Figure 2.25b** it can be seen that the material, when bent in the same way, shows curvature in two planes thereby forming a dome shape. This property has been cited as having uses in the forming of aircraft parts, without the need for excessive machining (Alderson & Alderson, 2007: 556).

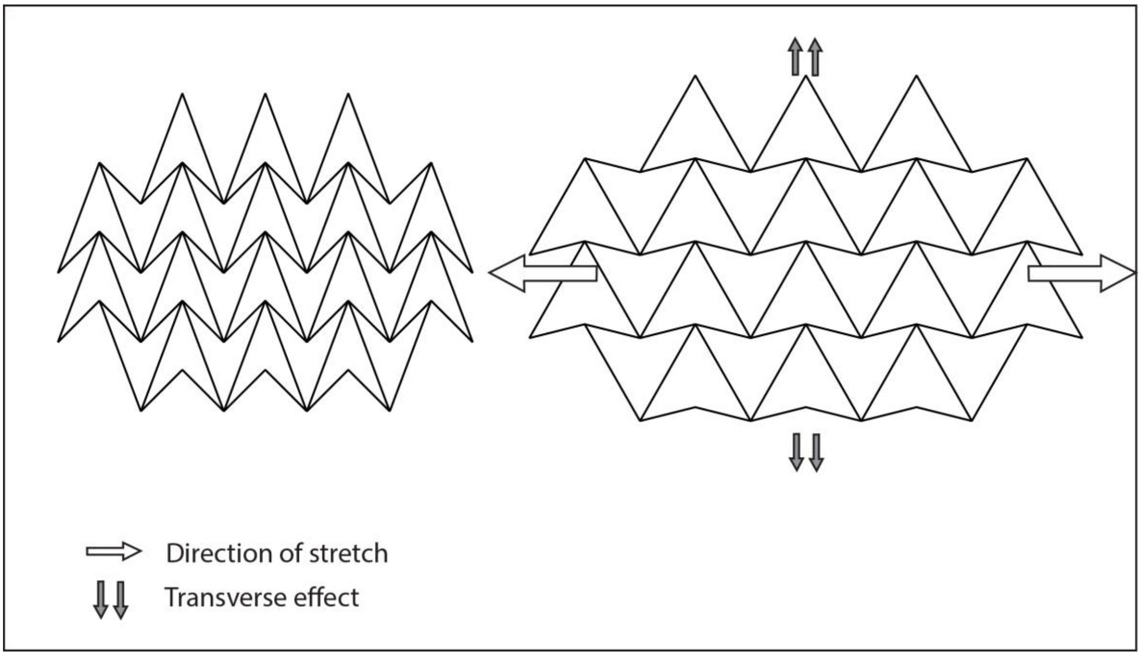


Figure 2.26 Diagram of double 'arrowhead' re-entrant structure.

There are many types of re-entrant structure identified so far in literature. They all work on the same principle of using a change in orientation to make ligaments to force each other in outward directions. Another example is seen in **Figure 2.26** in a structure referred to as a double arrowhead re-entrant structure (as derived through computational modelling by Larsen et al., 1996: 368).

2.9.3.2. Rotating units

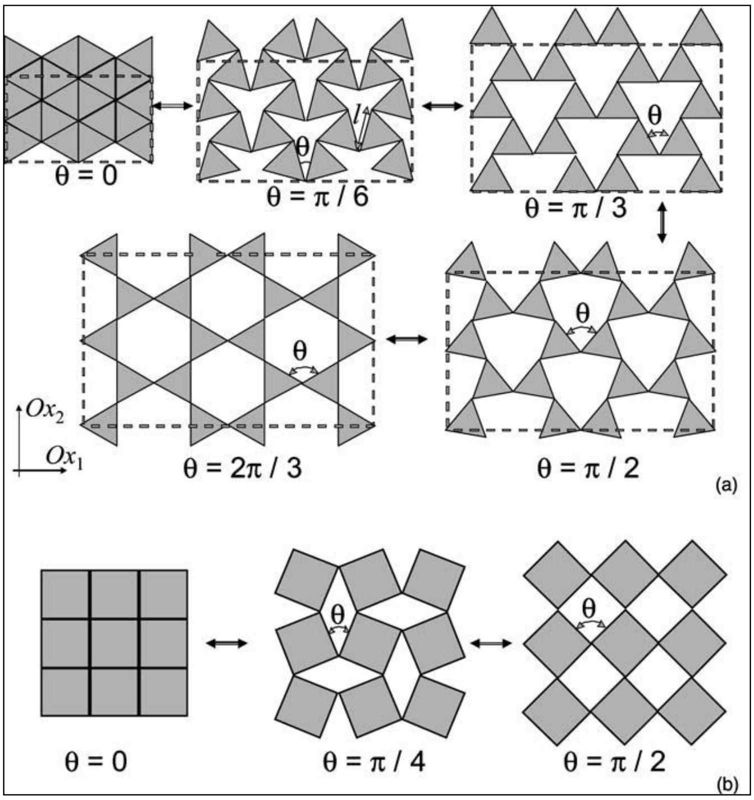


Figure 2.27 Geometry of rotating auxetic structures (Source: Grima & Evans, 2006: 3194). (a) 'rotating triangles' and (b) 'rotating squares' structures.

Joseph Grima (University of Malta, department of Chemistry) has also explored this subject.
As **Figure 2.27** shows, it is possible to create auxetic effects by connecting triangles or squares. Here the triangles (a) are strategically connected with 'hinges' at their points so that this structure can be compacted into a tight grid as well as being extended in both X and Y-axes. The connected squares (b) follow the same principle (Grima & Evans, 2006: 3194).

2.9.3.3. Chiral structures

Chiral structures are formed by connecting straight ligaments to central nodes. In **Figure 2.28** those ligaments are in the form of the sides of a triangle and the nodes in a circle. The ligaments are wrapped around the circles when the structure is relaxed. When force is applied, the ligaments can unwrap allowing the structure to expand rotationally, forcing out the area in both X and Y directions (Liu & Hu, 2010: 1054).

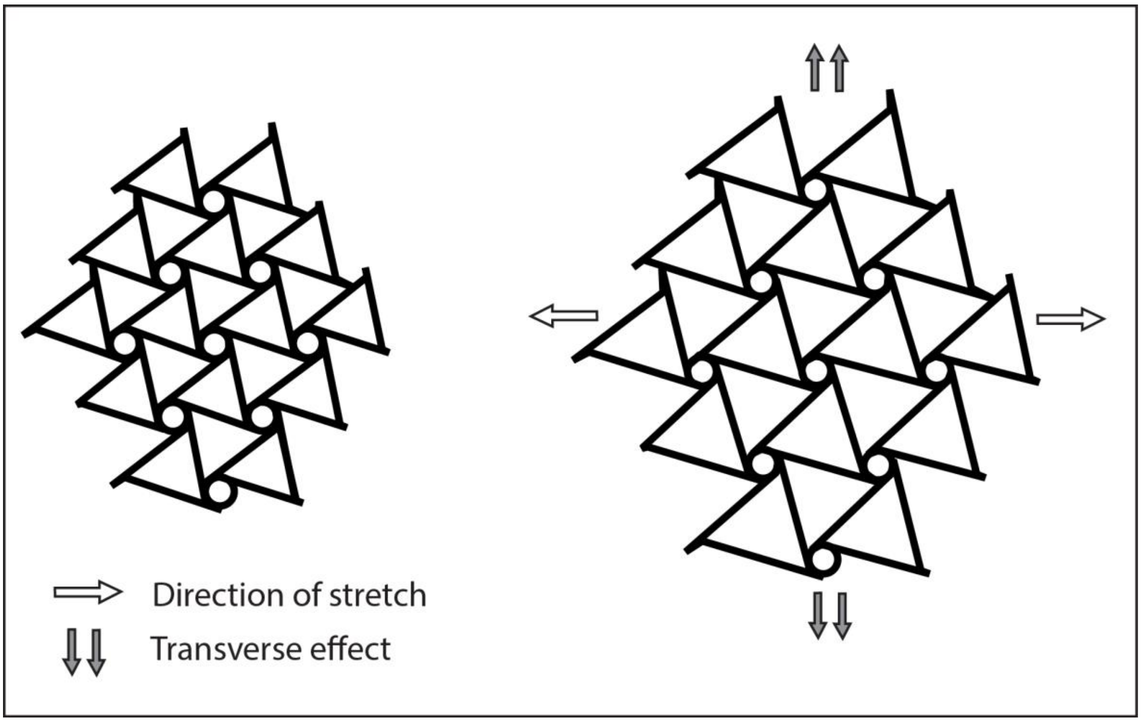


Figure 2.28 Triangular chiral structure with circular nodes.
The expansion occurs when the central nodes rotate and release some length of the ligaments from the spiral around the nodes.

2.9.4. Auxetics in textiles

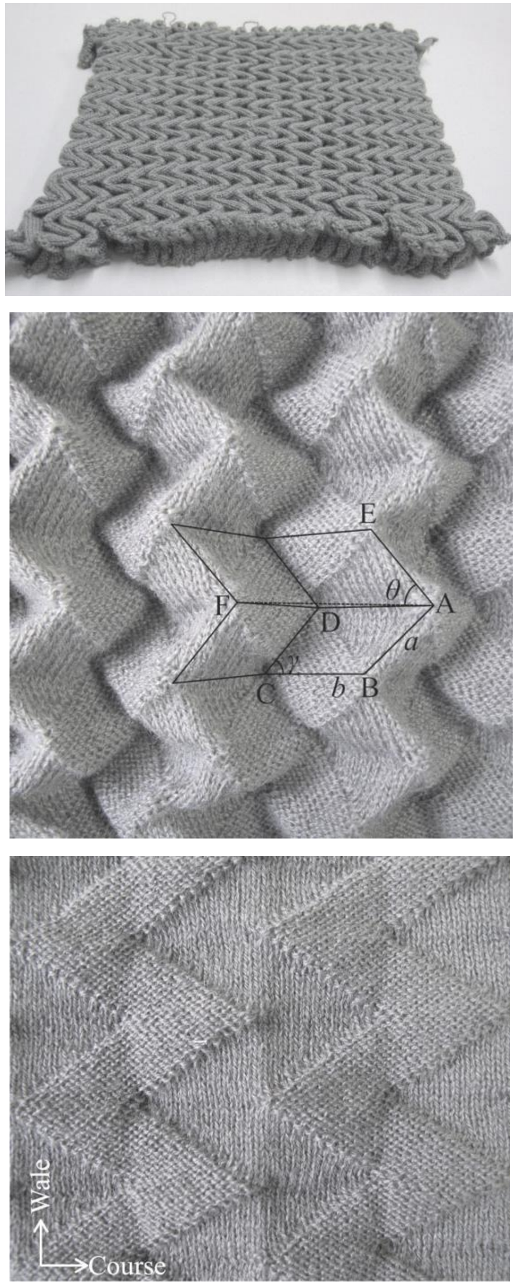
There is a small, but significant number of developments in the area of auxetic textiles. In the area of yarn development, there is the double-helix yarn, as mentioned earlier from Auxetix, which was developed in connection with University of Exeter and has been explored in use in woven bandages that either have a drug release capability, or have an auxetic indicator to show when a bandage is too tight (Materials KTN, 2011). Another example of auxetic yarn development featured in the work of Alderson & Alderson, who conducted work on extrusion of monofilament polyester, polypropylene and nylon for creating auxetic behaviour (2005: 29-34).

In terms of fabric production, Alderson & Alderson were also involved in the development of an auxetic warp-knitted structure based on the double-arrowhead re-entrant geometry (Starbuck et al., 2008), which used commercially available, conventional yarn (Alderson, 2009). Ugbolue et al. (2008), also using an approach governed by warp-knitting methods, have worked on developing auxetic fabrics for fibre-reinforced composites. Their aim is to produce auxetic structures from non-auxetic yarns. The development of auxetic yarns and auxetic textiles made from conventional yarns shows both interest in auxetic textiles and room for development within design perspectives.

2.9.5. Weft-knitted auxetic textiles

Auxetics research at Hong Kong Polytechnic University includes projects on: 3D auxetic textile structures, NPR knitted fabrics and intelligent impact protection based on 3D auxetic fabrics (Hong

Kong Polytechnic University, 2012). Liu et al. (2010) demonstrate the work of Hong Kong Polytechnic's development of a weft-knitted, auxetic textile, as seen in **Figure 2.29** and **Figure 2.30**.



(a)

(b)

(c)

Figure 2.29 Fabric C12-W12 by Liu et al. (Source: Liu et al., 2010: 860).
In (a) fully relaxed, (b) stretched and (c) fully opened states

The sample is knitted with conventional, non-auxetic yarns (in this case wool) on standard, industrial knitting machinery (a Stoll CMS 822 E7.2 in 14 gauge). The approach of the 2010 paper was entirely quantitative, with data being recorded at each stage and the results from the measuring being interpreted into series of equations and algebraic information (as in **Figure 2.29b**). This method suits conventions from textile engineering perspectives, but does not provide meaningful information for those from less scientific backgrounds like design, as discussed in focus groups in **Chapters 4-7**. Later in this thesis, extensive use of algebra is found to be a problem, not only for designers interviewed, but also acknowledged as 'off-putting' by more technical participants.

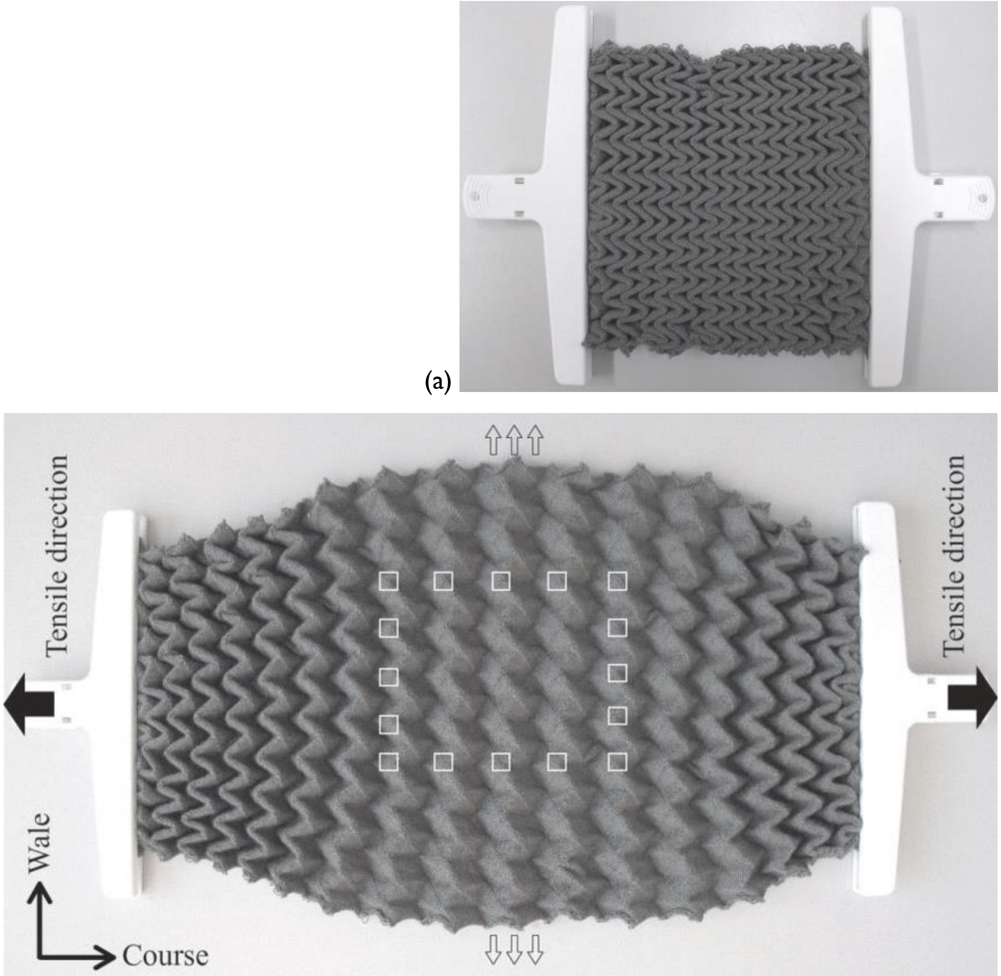


Figure 2.30 Negative Poisson's Ratio effect of fabric by Liu et al. (Source: Liu et al., 2010: 861). (a) fabric at rest, showing a dense, folded fabric. (b) fabric under extension showing auxetic behaviour

In a later paper from Hong Kong Polytechnic, this weft-knitted auxetic textile work is taken further with the manufacture and measurement of five more auxetic fabrics (Hu, Wang & Liu, 2011). Three of the fabrics are developed visually using reference from existing auxetic geometries; one based on a rotating rectangles geometry (Grima & Evans, 2006: 3194) and two on re-entrant honeycomb geometries (Alderson & Alderson, 2007: 566). The other two of the five new fabrics are more common to a generic knit design approach and use structures that show a 3-dimensionality when relaxed, and are likely to have been developed from experiential information based on observation of knitted relief structures. Hu, Wang & Liu name this type of structure as a 'foldable structure' from a 'structural disequilibrium' in the stitch structure (2011: 1495).

2.9.6. Design, developments and future work in the auxetics field

After attending an event run by the Materials KTN as part of the Auxetics and Related Systems conference in Bolton, UK in September 2012[25], it became clear to me that those most involved in the field of auxetic[26] materials identified a need to significantly increase awareness and visibility of auxetic materials (Morris, 2012:10). In this discussion, it was suggested that auxetic materials needed a 'champion' or a 'sexier' image – in other words, a high-profile outcome that would present the materials to the public or industry as a usable and desirable material.

The workshop and conference was mainly focused on auxetics for geometry, engineering, medicine and chemistry. There was a limited awareness of work in other fields such as design and art. As a delegate, I was the only attendee specifically from a design background. This gave me the opportunity to raise the idea that high-profile applications would be more quickly and easily realised through a design project. This suggestion was well received by the workshop participants, but did not seem to be something that had been seriously considered before.

The work conducted in auxetic research can certainly be seen to be of interest in design fields. As mentioned, Daniel Piker has worked with auxetic 'deployable' materials in computer modelling, paper folding techniques, mathematics and architecture, as shown in **Figure 2.24** (Piker, 2009b). Piker's structural outcomes are more design focused than those of the scientific researcher discussed in the previous section. Rachel Philpott also cited auxetic materials as an influence in her screen-printed, folded polyester work in deployable textile structures (2011: 31; 2013). Her work does not specifically concentrate on any major description of auxetic materials but, like Piker's, is inspired by geometries, which are then incorporated into an existing interest or practice. It is this development of auxetics for aesthetic and structural interest that provides support for the research discussed in this thesis. A scientist viewing auxetic structures as quantitative and a designer viewing them as subjective or qualitative is a key difference in the approach, but not necessarily in the quality of the outcome.

Norbert Palz has also completed research into 3D-scanning and printing for architecture design outcomes, by using auxetic systems as examples of structures that would be nearly impossible to manufacture by traditional hand-operated techniques (Palz, 2010). Palz is concerned with design processes and the ability to interact between contemporary and traditional manufacturing techniques, wishing his auxetic materials to be a 'new species of materials' (Palz, 2009).

With interest in auxetic materials extending into design areas, there is a hope and expectation that developments will become more tangible and accessible to a wider range of users. The aesthetic and structural potential for auxetic systems is large and currently under-developed. Architecture and product designs are likely candidates to show interest in auxetic materials and it is likely that fashion, apparel and textile design could easily use the information from both scientific and design research so

[25] The 4th International Conference and 9th International Workshop in Auxetics and Related Systems

[26] The workshop consisted of 40 delegates from academic, KTN and commercial institutions (list of delegates available in Morris, 2012)

far. Considering the processes, materials and developments in this thesis, the auxetic field has more chance to develop products that are auxetic in behaviour and incorporate auxetic material's inherently interesting aesthetic qualities.

The development of the auxetic field increasingly shows the aesthetic and material potential of auxetic structures, but still fails to articulate these in broad and inclusive contexts. For example, the work by Shim et al. uses silicon rubber to cast intricate chiral structures that are envisaged for use in creating switches and architectural materials (2013: 8202). Despite the clear aesthetic qualities of the materials produced, and the acknowledgement of design potentials, Shim et al.'s paper prohibits easy dissemination of ideas to non-specialist material scientists through its use of subject-specific language. A simple and pragmatic overview of the process and outcomes – refraining from the use of subject-specific jargon - would improve the capacity for dissemination from the paper. Similarly, the destinations of publication could be changed from a science-specific journal to a design journal or a magazine. This would greatly increase readership and interest. In following the conventions for design publication types, the language would need to be publication-specific and could therefore be understood more widely than when published in any one type of publication alone. This process is applicable to all subject specialisms; design papers also could benefit from such a summary – or in a more radical notion, an overhaul of favoured academic writing styles in all areas.

2.10. Conclusions

2.10.1. Conclusion on knit literature

The literature on knitted structures and processes is plentiful, but lacking in unification. The writing from qualitative sides often omits views from quantitative sides, and vice versa. Some elements such as the Loop conference (University of Southampton, 2013) represent the ideals needed to bring together different knit practitioners in a shared forum. Perhaps with the unity coming from a collective representation of knit as a subject, the diversity and potential for knitted structures would be better articulated to non-knit practitioners.

There can be a tendency with knit design to assume that the necessary knowledge is simple and can easily be attained through a hobbyist approach, which may be presented as a nostalgic and fashionable craft (Turney, 2009: 42). This approach ignores the dedication and skill required to have the knowledge required to be a professional within knit design industries (which may include the understanding of craft alongside machine manufacturing). A good knit design practitioner has a high level of practical, artistic, technical and application skills. They may be experienced in any subjects: arts, design, engineering, technology, programming, selling, writing, or even all of them. From a designer-maker perspective, it is necessary to be aware of the wide scope of your practice, but this is not always recognised by the designer-maker or by others. To introduce a Marxist concept, the means of production need not be separated, but may be unified in a skilled designer-maker, thus providing a sense of both social and technical competence, individual knowledge and satisfaction (Watson, 2003: 85-86). The skills of a designer-maker should not be underestimated by institutionalised tendencies to separate disciplines and knowledge.

2.10.2. Conclusion on textile and design literature

Many of the same observations apply to the literature on textiles and design. Disciplinary segregation and subjugation has left deep marks on the way that literature is presented, circulated and received. The knowledge transfer issue remains pertinent to how the future of textile and design development will proceed.

Though knit is, arguably, a core method of textile production, it does not always get the same exposure as other textile production methods. This might be a result of knit's situation between a fashion subject and a textile subject, sometimes leaving it excluded from discussion in both subjects, rather than always included in both subjects.

2.10.3. Conclusion on auxetics literature

The existing literature was reviewed for its relevance to design and its potential for use in work that uses subjective and aesthetic values. This range of existing literature on auxetic materials shows that there is still a long way to go before describing the full range of functions and application of auxetic materials. The largely theoretical development in the field lacks a sense of public engagement and awareness. There is a large range of methods for producing auxetic materials, varying from paper folding, honeycomb development, polymer science, micro-chemistry to textile methods.

These textile methods have, so far, been seen to include twisting of yarns to form helical yarns, weaving, warp-knitting and weft-knitting. There is no doubt that this range will expand in the near future with some of the polymer chemistry moving towards filament extrusion and the potential for textile finishing methods and with the addition of new technologies in production.

In addition to the problems of language use in overly subject-specific papers, the potential for a broad distribution of engineering literature related to auxetics is limited by the conventions of the journals and publications they appear in. For example, the scientific writing might favour referencing styles that omit paper titles (in favour of listing all authors involved), which makes knowledge dissemination difficult. As with Schön's concept of specialism leading to narrowing of vision (1991: 60), the issue of uptake of auxetic materials may be a victim of exclusivity in literature and the scientific field at large.

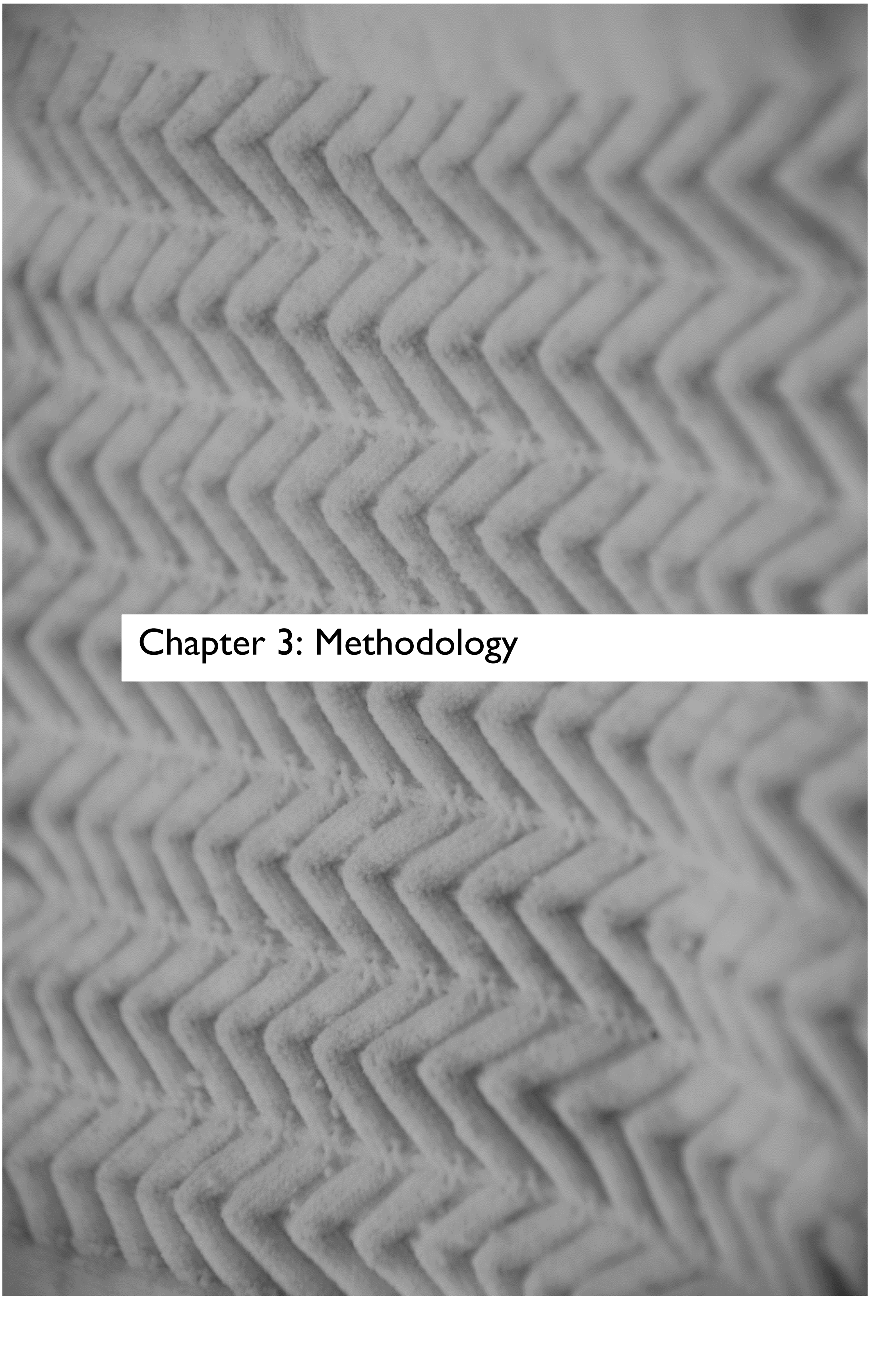
2.10.4. Chapter conclusions

Though the range of subjects visited in this chapter may seem wide-ranging, there is a pragmatic and simple core theme. Through the perspective of a knit designer, the links can be simple; they are predominantly about the practical application of knowledge to a given or chosen task. From a designer's viewpoint, existing literature fails to represent knowledge of both functional and aesthetic design considerations and methods. Collaborative work and literature holds potential for valuable contributions to further knit and auxetic development.

This is not to say that collaboration and interdisciplinary impacts are easy. Projects such as Aeolia (section **2.6.5.**) took considerably longer to produce a technical outcome than an individual practice would have taken, but the outcome exceeded the practices of the individuals. To be recognised (collaboratively, financially or by publication) in this type of work is usually down to considerable effort from the practitioners involved to learn and adapt information beyond their experience. It is the practical creativity in knit and textile design practices that I believe makes them suitable starting points to develop wide-ranging and pragmatic projects that can cross disciplinary interests. Whether either 'technical' or 'smart' textiles as terms fully encapsulate the diversity available in the field is open for discussion. The terms certainly bring together high levels of interest from industrial and commercial sectors and continue to hint at a field that is diverse, challenging and moving forward.

As a knit practitioner, I see form and function as inseparable qualities – each informing and creating the other. This view is more common in a designer-maker perspective, as the designing and the making go hand-in-hand for many knitted products. The form of a garment cannot exist without the function and the function cannot exist without the form. This epistemology of knit practice sets it aside from other disciplines in which practitioners have different emphases on separate stages of the designing and making process. The methodological implications of a knitter-designer-maker's approach will be discussed in more detail in the following two chapters.

In summary, knit and textile development is diverse, creative, technical and present in a wide range of disciplines, products and practices. The segmentation and lineation of language, outcomes and dissemination opportunities hinders, but does not stop the use of knit in imaginative ways, from the individual knitters, to the collaborative researchers and to the industrial giants.



Chapter 3: Methodology

3. METHODOLOGY

3.1. Introduction

There is an important distinction between the methodology of this thesis as a process and the methodology as an outcome. This thesis applies a knit design methodology based in practice and experiential knowledge, but in order to do so, this has to first be defined, supported and described. The process of explicating this knit design methodology is an outcome of this study.

As shown in the literature discussed in **Chapter 2**, there are several observations supporting the development of a bespoke methodology to cover all aspects of knit. The two main priorities to focus on are:

1. Explain and support a knit design methodology that acknowledges the diverse, tacit, experiential, creative and technical aspects of designing for, with or in knit.
2. Explain and support a generic knit methodology to apply to all applications of knit knowledge.

By producing a generic knit-based methodology, it will be possible to document the fundamental knowledge necessary to produce any form of knitted textile, for any application. Creating an original methodology is important for knitted textiles, as the pragmatic parameters of the knit design process make it dissimilar to any social sciences (from which field a large proportion of methodological format is developed or borrowed). Instead of borrowing from several methodologies in order to form a patchwork of existing methodologies from widespread sources, it is more suitable to build a bespoke methodology derived from practice, which takes into account how knitters think and act in different contexts (Harland, 2011:22). Likenesses to existing research methodologies are made, but not relied upon. This study, using a structure derived from practice-based research, evaluates the methods from my own practice for their suitability within this project, how to describe them, integrate them and whether they need any support from external (social science or science) methods (Gray & Malins, 2004: 30).

This chapter will discuss the objectives of this thesis with regard to the methodological contribution to knowledge and the practical methods and processes used to achieve the objectives. It will discuss the nature of knit methodology and the difficulties of representing a knit design methodology in diagrammatic form. Details of sketchbook and notation processes will be discussed for their roles in the development of knit designs and of design knowledge. A detailed overview of the practical processes, testing processes, data collection (from artefacts, testing and participants) and analysis will be included.

3.2. Methodological objectives

The key aim for this methodology is that the process of a knit design methodology be accurately represented from the position of the author (that is – a designer-maker perspective) while incorporating support or challenges from other practitioners, processes and evidence. In addition to this aim, there are four main objectives:

1. The first being that the results of any quantitative testing and experimentation can be articulated without the need for specialist language or mathematics. The quantitative testing methods in this thesis are inspired by or comply with ideas set out by predecessors in the field (Liu et al., 2010; Hu, Wang & Liu, 2011; British Standards Institution, 1992), so aim to be thorough and objective. Every effort is made to make execution, explanation and dissemination of each testing stage as clear and concise as possible. The use of specialised terminology is limited to that which can be unambiguously explained, and results are given with minimal mathematic and algebraic information.

2. The second objective is that the complex and vital relationship between the creation of knowledge and the making of physical objects in knitted textile design be explained. Through parallel strands of reflection, validation, discussion and showcasing, the relationship between practical and theoretical work will be extracted from an inherently tacit and instinctive process. The methodological process, both of knit design generally and for this study, will be discussed throughout this thesis. After each practical stage, the methodological discussion will be reviewed to incorporate the following elements in order to provide context and additional viewpoints:
    - personal reflection on the design process
    - observations of the fabrics
    - any information from testing
    - contributions from focus group participants

3. Thirdly, demonstrating the extent to which a knit design methodology is a meaningful mode of enquiry. By completing the research project using experiential knit design methods and processes, this will help to justify the position of knit design as a complex, unique and valuable process within the field of design research. The application of a design methodology to a technical task will demonstrate the transferable knowledge at the core of the knit design process.

4. The final objective is to explain the methodology in a pragmatic way that not only covers knitwear, knitted textile design and designer-maker experience, but also represents generic properties applicable to all knit disciplines. Documenting this knit methodology is important for knitted textiles, as the variable, mixed-method, pragmatic and practice-led, parameters of the process make it dissimilar to any social science methodology.

3.3. Important factors for this study

Several important factors are present throughout this study. Some are set out in the research design and some will evolve through the data collection and analysis.

From the research design (informing the study from the planning stage):

- The research is practice-led (experiential and tacit knowledge inform the making process to be documented).
- Research findings will be of a non-generalisable nature.
- The designer-maker approach is applied to a project outside a traditional design domain (field of auxetic textiles).
- The documentation will include tacit knowledge of the researcher and other participants.

From the researcher and participants (informing this study from the practical development stages – Chapters 4-7):

- Play is a key element in defining feedback and informing progression (play is a method of understanding the development and properties of fabrics through unrestrained physical handling and manipulation of fabrics [Glazzard et al, 2014]).
- The fabric development and dissemination work will uncover how experiential knowledge is used by participants and helps to form their expectations.
- The practitioner perspectives of researcher and other participants play an important role.

Though the study described here celebrates subjective perspectives and tacit knowledge, it aims to be descriptive and transparent. It is not a scientific approach but, inherently in the knit methodology, there is documentation, reflection and quantifying and repeatability. These aspects, however, are linked with a malleable and adaptive process rather than a protocol, not formulaic, but free to emerge from the processes, thoughts and actions.

3.4. Knit design methodology

Little exists in the way of a formal methodology that captures all of the elements of knit practice. What follows is an interpretation of my own practice, with reference, where relevant, to other methodologies in order to develop a comprehensive explanation of this approach. It is important to this thesis to not only document the approach used in this project, but to give an overview of the fundamental knowledge contained in knit practices. In addition to the information on relevant methods and methodologies explained in this chapter, consider the range of fabrics and structures shown in **Chapter 2** (section **2.3.2.**) in building a comprehensive understanding of the processes and outcomes of a knit practice.

3.4.1. Practice-led research

The research in this thesis comes from the perspective of someone who has had training in knit design. It is based in the practices of design and textile processes. It pertains to both the practice of the individual researcher and the production of artefacts. The main focus is on the perspective of the researcher in her own practice, but there are opportunities to interrogate other methodological practices and my own reflections on my practice by documenting the opinions of others in focus groups. These focus groups consider the perspectives of other knit designers and engineers, as well as product design and engineering practitioners (use of multiple methods and perspectives for triangulation and to monitor subjectivity [Gray & Malins, 2004: 31]). The viewpoints of others will be used in synthesis (or antithesis) with my own observations to inform each subsequent stage of practical and theoretical development. Following each practical stage, a summary of the theoretical development derived from the focus groups informs changes and considerations for the next chapter.

3.4.2. Similarity to grounded theory

Grounded theory contains similar elements to the research in this study. As with grounded theory, the findings of this study are not aiming to be generalisable and lean away from quantitative, objective information associated with scientific methods. The theory generated comes directly from the data; in this case, the data are the knitted artefacts produced, reflections on my practice, the quantitative and qualitative data learned from them and the input of focus group participants and other contributors to the discussion through meetings, conferences, presentations, etc. A designer-maker may not repeat each project in the same manner, but the approach used in each project becomes valuable knowledge in the formation and execution of new projects. This study did not follow a Grounded Theory framework, but used several elements of Grounded Theory to support the methods used from a practice-led, designer-maker approach. Subscribing to an existing methodology in its entirety would not allow the freedom to use and document a designer-maker approach to knit without compromising on aspects (for example, the freedom to trust tacit knowledge in the development of fabrics).

The research here follows a practice-led approach, with the researcher playing a key role in the generation of knowledge (Rust, Mottram & Till, 2007: 12). Because of the practice-led approach, there is immersion in the data during the generation of knitted artefacts and the design and analysis of focus groups. A manual method of transcription and coding encourages involvement with the focus groups' responses, allowing for sufficient involvement with data to allow conveyance of the 'essence' of participants' responses rather than verbatim accounts (Strauss & Corbin, 2008: 47).

As with Grounded Theory, this research is not tied to a single epistemology, theory, method of data collection or analysis (Charmaz, 2006: 178) but uses decision-making based on banks of experiential and tacit knowledge from a history in knit design practice. Data in this thesis is collected (in the form of focus group and artefact creation) and analysed simultaneously (ibid.: 5). Theory is developed through analysed coding[27] of qualitative information at the end of each focus group. The coding from each stage is then re-addressed at the end of the data collection stage (after four focus groups) and re-evaluated in light of the overall groups of categories (ibid.: 60).

3.4.3. Other related research methodologies

The process of a knit design methodology is iterative with reflection and feedback causing action (as in Action Research in Kolb, 1984:23). The sampling stage[28] of knit design is a direct example of reflection on and revision of actions and processes.

[27] Examples of the coding process can be seen in **Appendix E**.

[28] The knit design process is iterative and cyclical containing many feedback loops (Eckert & Stacey, 2003: 357). Eckert & Stacey show a diagrammatic representation of the knitwear design process including complex networks of feedback loops,

Pragmatism also plays a key factor in this research. Simply put, 'pragmatism'[29] is a good descriptor for practice-based and applied design work because of its meanings of realism and practical, achievable goals. In terms of a knitting approach, the use of the tacit and experiential knowledge discussed in **Chapter 2** provides a vital method for knowing the most desirable way of producing a given knitted artefact. The most desirable method will vary depending on the stipulations of each project. It is my opinion that a knit practice is an inherently pragmatic approach. A knitter or knit designer deals with a large number of variables for even a straightforward project. This leads to a well-considered use of appropriate knowledge and ability to adapt and evolve the working process or final outcome, as needed. A designer-maker is particularly pragmatic in their approach to knit projects as they are in control of the process from conception to completion and will have to negotiate each issue encountered to find the best outcome. As a pragmatic approach dictates, a design approach in knit may not solely rest on the pre-determined ideals and values of the designer, but may rely on changing information in the course of the project. Even approaches to knitting that are extremely radical or conservative in their approaches require pragmatic considerations of the fundamental knowledge and process at the core of knitting practice.

Knitting any artefact involves consideration of technical, practical and aesthetic considerations. This mixed-method approach is present in the practical development stages, analysis thereof and in any theoretical design and development. An approach from either quantitative or qualitative methodologies alone would not represent the range of priorities present in both the experience of knit design practice, and the individual perspective.

This pragmatic, designer-maker approach is similar to a craft methodology. The practitioner's experiential knowledge of materials, processes and potential applications is key to any developing outcomes. Therefore, the approach to design follows a logical (but adaptable) design route, made possible by a 'true understanding of the product in question' (Sullivan in Rees, 1997: 125). Though they are not usually combined, a craft methodology and problem-driven (or industrial) methodology are not mutually exclusive (Jönsson, 2007: 241). As with industrial or scientific practice, craft practice may have an end-use (problem) identified at the start of the design process and other external factors to consider (cost, time, profit, etc.).

3.5. The thesis methodology – practical development

The following chapters (**Chapters 4** to **7**) outline the practical development stages (Stages 1-4). The theoretical work will be informed by the practices of design, reflection and analysis from these practical development stages. The outcomes of these stages will be compared with expectations and reactions from my own experience and from the experiences of others involved in the project. The thesis methodology takes a natural and free form, as it moves through both practical, making stages and theory generation from data.

[29] Excluding connotations from and associations with philosophical, linguistic, mathematical and other specialised subjects.

After each practical and theoretical stage, reflection is carried out on that stage and the project as a whole. During reflection, it may become apparent that adjustments or enhancements need to be made to the methods (an iterative, feedback process). For consistency and coherence, the theoretical contributions are reviewed as a whole after the completion of each stage and again after completion of the four stages. The reader can assess the results using their own knowledge and experience and it is not expected that any two readers will experience this project in the same way.

The methodology in this thesis aims to present a description of how one might carry out the following:

- a knit design methodology
- a designer-maker methodology

This methodology is also expected to be transferrable and may provide useful contrast or support to practitioners from the following areas:

- crafts
- technical textiles
- textile design
- textile engineering

The mixed and complex nature of the methodology in this thesis mirrors the methodology used in designer-maker practice, where the designer-maker makes each decision based on many variables and on a large amount of experiential and tacit knowledge. The approach of this thesis is described in the following section.

3.5.1. Practice-led/practice-based, design-maker methodology

The design of this research follows a practice-led, knitted textile designer-maker methodology. This was learnt through a knitwear design education and practice. The approach is both practice-based and practice-led, in that it is both informed by my practice and aims to impact on the practice of knit (generically and as a designer-maker). There are few references to generic knit methodologies, so a supporting material is drawn from knitwear design process (Francis & Sparkes, 2011; Eckert, 1997; Eckert & Stacey, 2003; Stacey, Eckert & Wiley, 2002; Black, 2002; Brackenbury, 1992), textile design process (Tellier-Loumagne, 2005; Sinclair, 1997), textile technology and engineering processes (El Mogahzy, 2009; Sayer & Studd, 2006; Sayer, Wilson & Challis, 2006; Spencer, 2001) alongside personal responses from the researcher and focus group participants specialising in design or textile subjects.

At its simplest, the design method is a largely cyclical arrangement, which allows fabric and theoretical development to go through various phases of reflection and adaptation. The methodology combines the pragmatic method of making with qualitative and quantitative analysis of fabrics, testing and responses from the researcher and others. The perspective used is that of a ‘designer-maker’ (Howell, 2013) rather than necessarily being a specific type of designer or engineer (e.g. knitwear designer, fashion designer, product designer, etc.). Each stage of research is approached in this manner, using pragmatic and practical methods of realisation.

In this study, the practice and knowledge of knitted textile and knitwear design becomes the methodology and informs the design process for practical work. The practice-led, designer-maker knowledge also informs the design of the subsequent testing and analysis stages.

Inherent in this designer-maker knit methodology is a combination of several key components:

- **The use of visual inspiration and design methods** (as used in knitwear and textile design practices detailed in Eckert & Stacey, 2003).
- **The creation of physical artefacts** (making fabrics or products – in order to both generate and test theory; and as a manner of documenting and appraising the making process.).
- **Assessment of fabrics/products for quality, appearance, suitability for purpose etc.** (consisting of qualitative and/or quantitative methods of appraisal, including presentation of products to audiences).
- **A cyclical process of making and assessing** (data analysis feeds back into the making and dissemination processes).

The list above acts as a simplified model of a generic knit methodology and may not be suitable for all knit uses without the addition of extra considerations (such as applied engineering or apparel design). The statements in brackets following each stage describe how my practice in this project uses these stages to develop the practical work.

A possible criticism of the designer-maker approach could be that the level of complexity of designs might not be as advanced as the combination of a skilled designer and a skilled technician, but the problems encountered between technicians and designers in communication and compromising are not encountered by a designer-maker. A designer-maker does not need to communicate the thought process behind modifications to another practitioner, and can rely on experiential and instinctive thoughts to develop ideas. These experiential and instinctive ideas can be lost in the communication of ideas to other individuals (as explained in Eckert, 2001).

3.6. Methods used in this study

This section gives an overview of the methods used in this study. The written order gives an indication of the order of the methods but, due to the cyclical nature of the project, there is frequent movement, overlap and repetition of processes.

1. Literature review

A review of contemporary and well-established items of context will form the explanation of how this research is timely, relevant and original (as detailed in **Chapter 2**). The context draws on different practical, theoretical and disciplinary areas to give a broad overview of elements of importance within this study, its aims and objectives. Reflection on the literature provides the rationale for the design and making work and highlights opportunities where alternative types of information would be beneficial additions to existing literature.

2. Sketches, notes, video and photographic work

A record is made of the approach to the practical project through series of explorative drawings, photographs and detailed note-taking of processes, design decisions, outcomes and technical information.

Visually recording this data is important to provide the focus group participants and the reader of this thesis with the required information to form their own, qualitative responses to the fabric samples and creative process. The documentation methods surrounding the fabric are derived from my own practice in knit, where sketching, photographing and note-taking (qualitative and technical) are common methods in design development. In addition to the visual records of the process and outcomes, a technical record is kept of the fabric development in detailed tables including, where possible, examples of the Stoll programming language (directly related to stitch notation). Excerpts from this information can be found throughout **Chapters 4-7**, and detailed notes in **Appendices B** and **D**.

3. Knitting

Knitting is the key method of practical development. The designing and knitting of artefacts enables this project to realise the methodological objectives. The production of fabrics provides physical 'proof' of concept by using a designer-maker approach that satisfies a function determined by a field based in science and engineering.

4. Measuring

The importance of measuring to this design project is in providing evidence of the desired auxetic behaviour. Measuring is done in both a preliminary way (to give indication that fabric is auxetic) and in a rigorous way (to give an indication of how auxetic a fabric is, and to allow comparison between fabrics)

5. Reflection

Reflection is an important stage in this, and any knit design process. It refers to any stage of thought between one action and the next, or when making changes or repeating a previous action. This might be a tacit reflection, such as tightening a fabric's tension after a trial is knitted, or a larger process of re-addressing the format of the practical stage at the end of each stage.

6. Dissemination

Work is disseminated at several stages during this project; at conferences, in publications (see **Chapter 8** full details on related publications), in focus groups and in individual meetings or assessments. This dissemination allows the practical and written work to be regularly exposed to outside parties in order to receive feedback from them on aspects such as aesthetics, tactile elements, auxetic behaviour, contributions to knowledge, etc.

3.6.1. Free form knowledge transfer and development

The nature of this project allows free development of the project to incorporate interesting evolutions (such as the two projects described in **Chapter 8**). This freedom is in place to allow for opportunities for knowledge transfer and dissemination. The opportunities encountered are not only a possibility to develop new work, but feed back into the theoretical development. By developing work in different settings (academic, explorative, material-led, structure-led, etc.), there is increased scope for understanding, engagement and further development. The dissemination opportunities test the responses to this work from different communities of practice.

3.6.2. Subsequent stages, analysis and evaluation

The contributions to theoretical knowledge will be derived from the combined outcomes of focus groups, practical work, reflection and from other opportunities (minor projects, publications, conferences, etc.). The use of dissemination as a method adds to a new form of knit design practice – it is an evolution from my existing, making practice to a practice that challenges pre-conceptions through language, knowledge and material. The discussion on the methodology, research design and outcomes achieved will reflect on the aims of the thesis. Comments on the methodology will assess how successful it has been and what impacts this will have outside this thesis.

3.7. Sketchbook and knit notebook pages

The following sections from sketchbooks and knitting notebooks for this research project show the experimental and developmental processes from the initial design stages. The practice that is shown in these pages is based on my personal methods in designing this project. Where other knit design practices might use mood boards for influence, here, auxetic geometries make up the main visual inspiration. These auxetic structures are translated into sketches and plans, informed and inspired by experiential knowledge of knitted stitch structures.

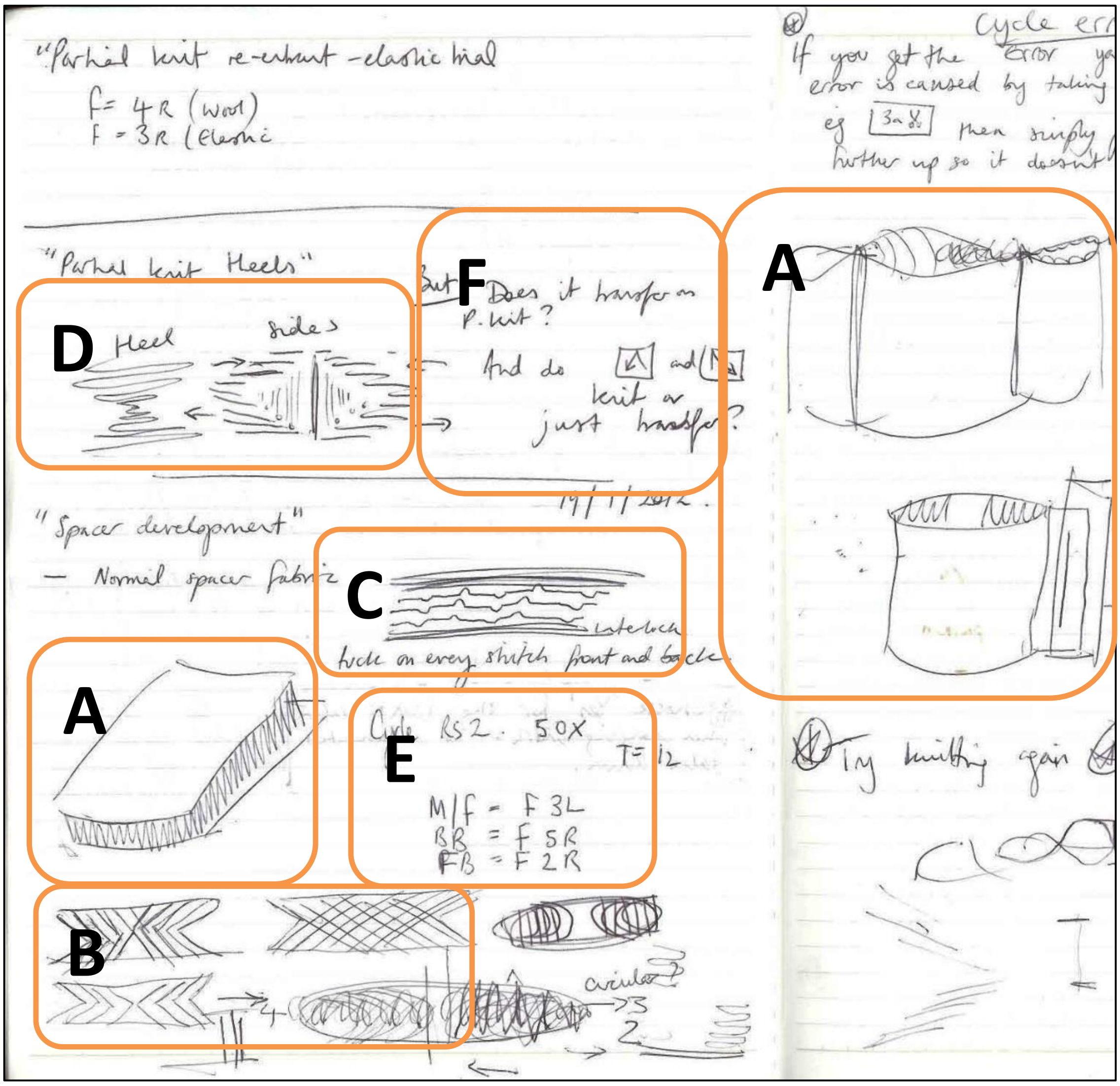


Figure 3.31 Page showing how sketches take the form of visualisation drawings (A), cross-sections (B), needle-bed diagrams (C) and theoretical yarn paths (D) alongside machine notations (E) and reflection (F).

The comparison of different representations of complex information helps rationalise and develop an idea to fruition. The combination of all of these elements on a single page shows a complex and non-linear thought process.

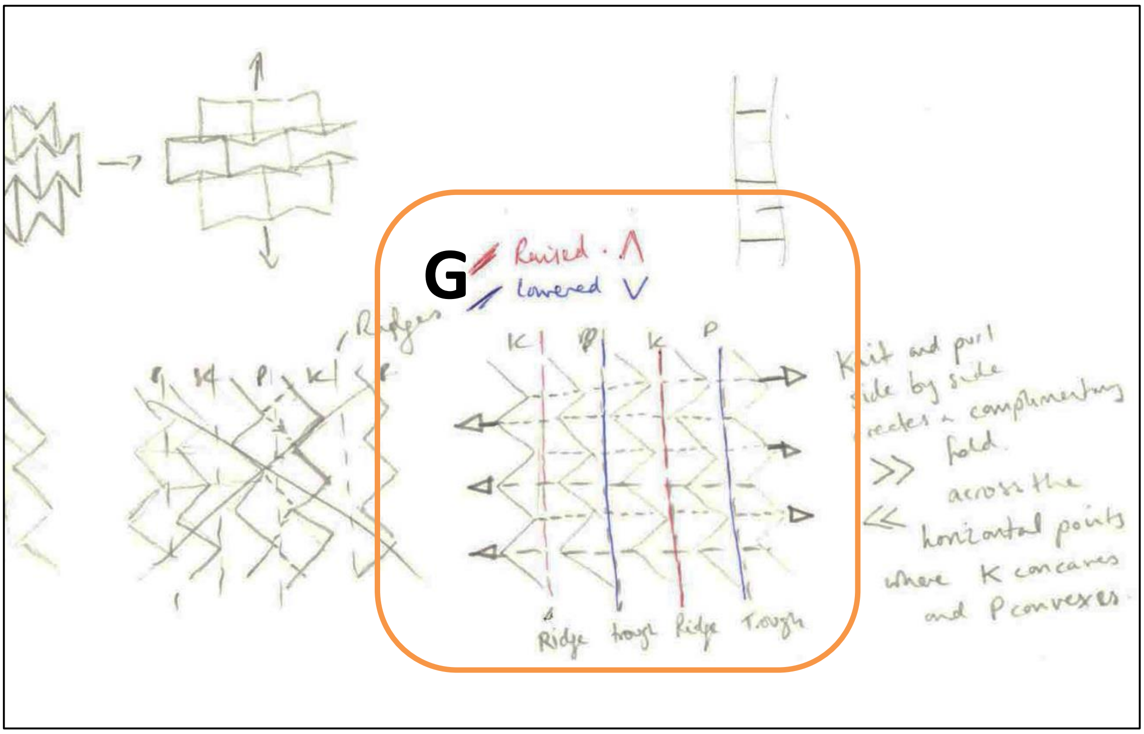


Figure 3.32 Sketchbook page showing how sketching has use in making sense of existing work (G) Sketch shows analysis of work in Liu et al. (2010).

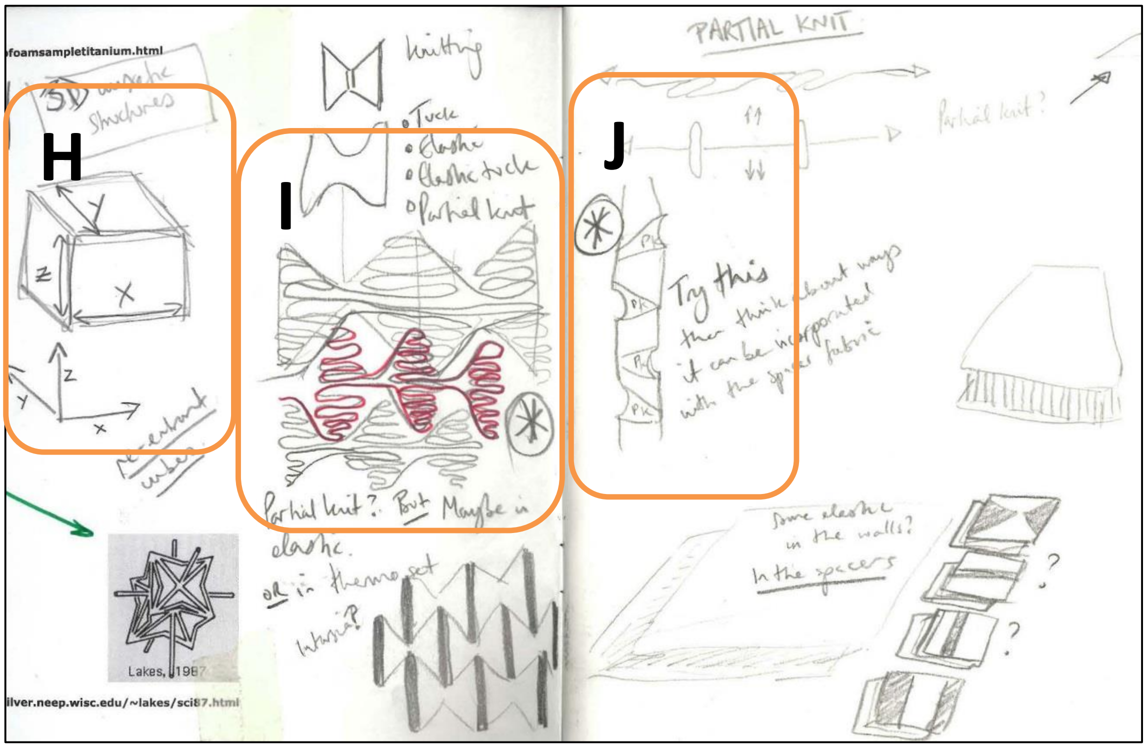


Figure 3.33 Sketchbook page showing how many ideas can be presented at once using visual reminders of relationships between axes and shapes (H), stitch structures (I) and pattern placements (J).

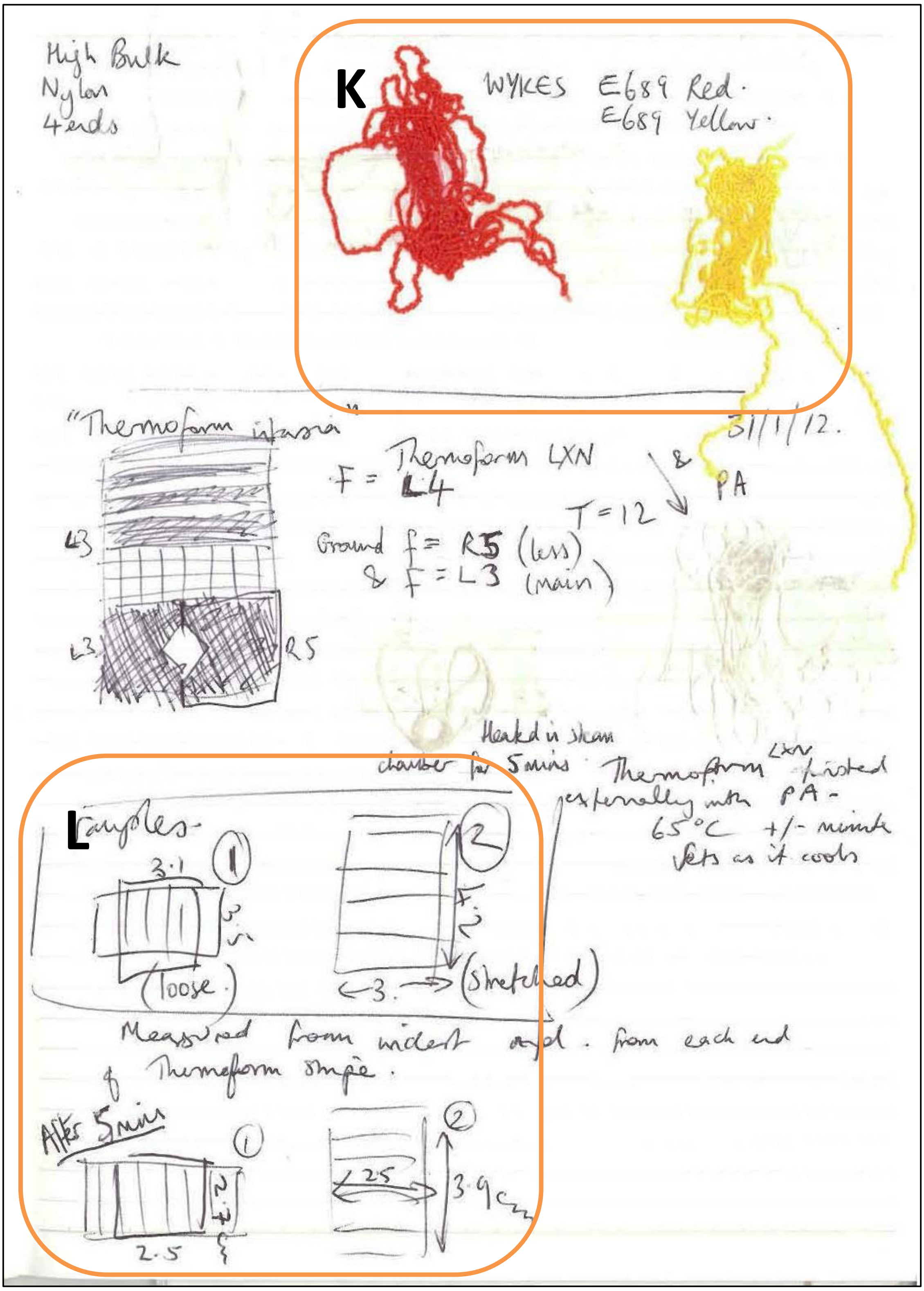


Figure 3.34 A typical page from a document, which becomes a sketchbook, logbook, technical notebook and ideas book in one.

The inclusion of yarns (K) acts as a reminder of their properties and a link between the relevant fabric and its notes. Sketches may also be used to predict behaviour of unusual materials or structures (L).

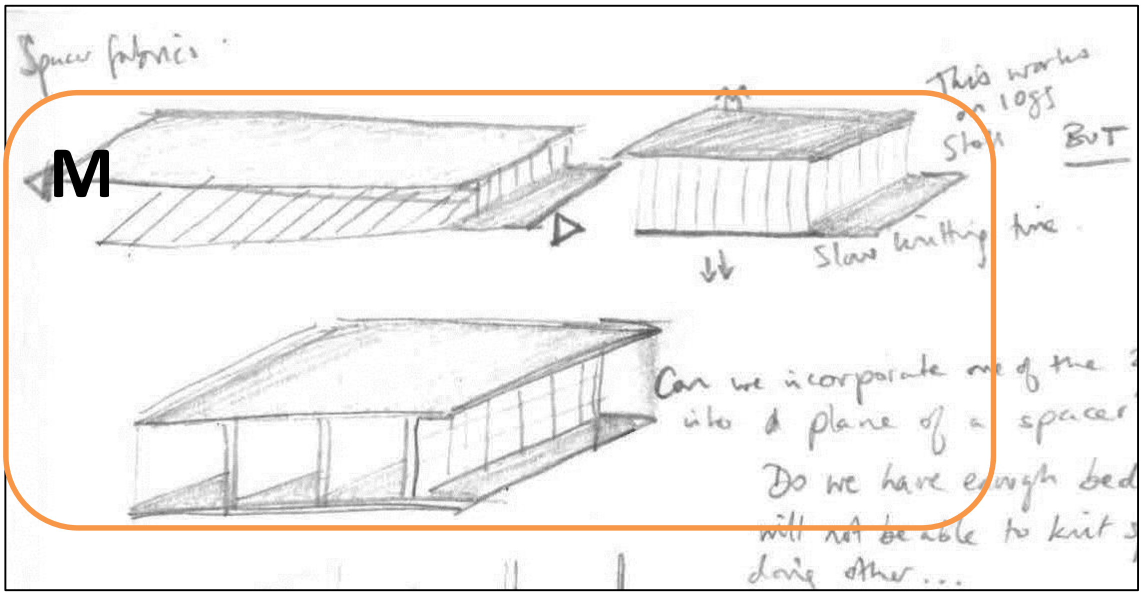


Figure 3.35 Sketchbook page showing how sketching is used in thinking about each element of the design process.

The testing of structure ideas, fabric shapes, knitting machine limitations by visualisation (M). The page of sketchbook in **Figure 3.35** shows a thought process behind the spacer fabrics developed in **Chapter 6**.

Figure 3.31 to **Figure 3.35** show a range of the benefits of an unstructured sketching method to allow free interpretation, development and application of complex ideas. Several key aspects of the sketching and notation process include:

- personal notes on future developments, successes, failures and alterations
- technical sketches of stitch structure
- sketches of yarn path, as shown in red in **Figure 3.33** (approximated for complex structures, but the path a yarn will travel, when traced out on paper can highlight any issues that might arise, or check that the structure will knit as intended – this is a way of modelling a structure through sketching)
- cross-sections that show how the knitting will appear on the machine during knitting
- needle bed/stitch chart notations (as shown in the boxed area in **Figure 3.31**) to develop how the idea becomes a practical reality
- notes about the machine, tensions, yarn, etc. used
- rough sketch models of the overall appearance/effect of the finished fabric
- ideas of shapes, ratios, pattern repeats, etc.

These sketches, in their complexity and simultaneous nature, visually describe the nature of my design process. Visual methods of designing alongside technical information, thoughts about aesthetics, sketches of the internal and outside views of fabrics, pattern placement and programming information all occur at the same time and are not differentiated by any sign of a linear organisation or progression of thoughts. The relationships between these processes are not hierarchical, nor are they formulaic; one does not always accompany, precede or follow another. The order of methods varies for each project.

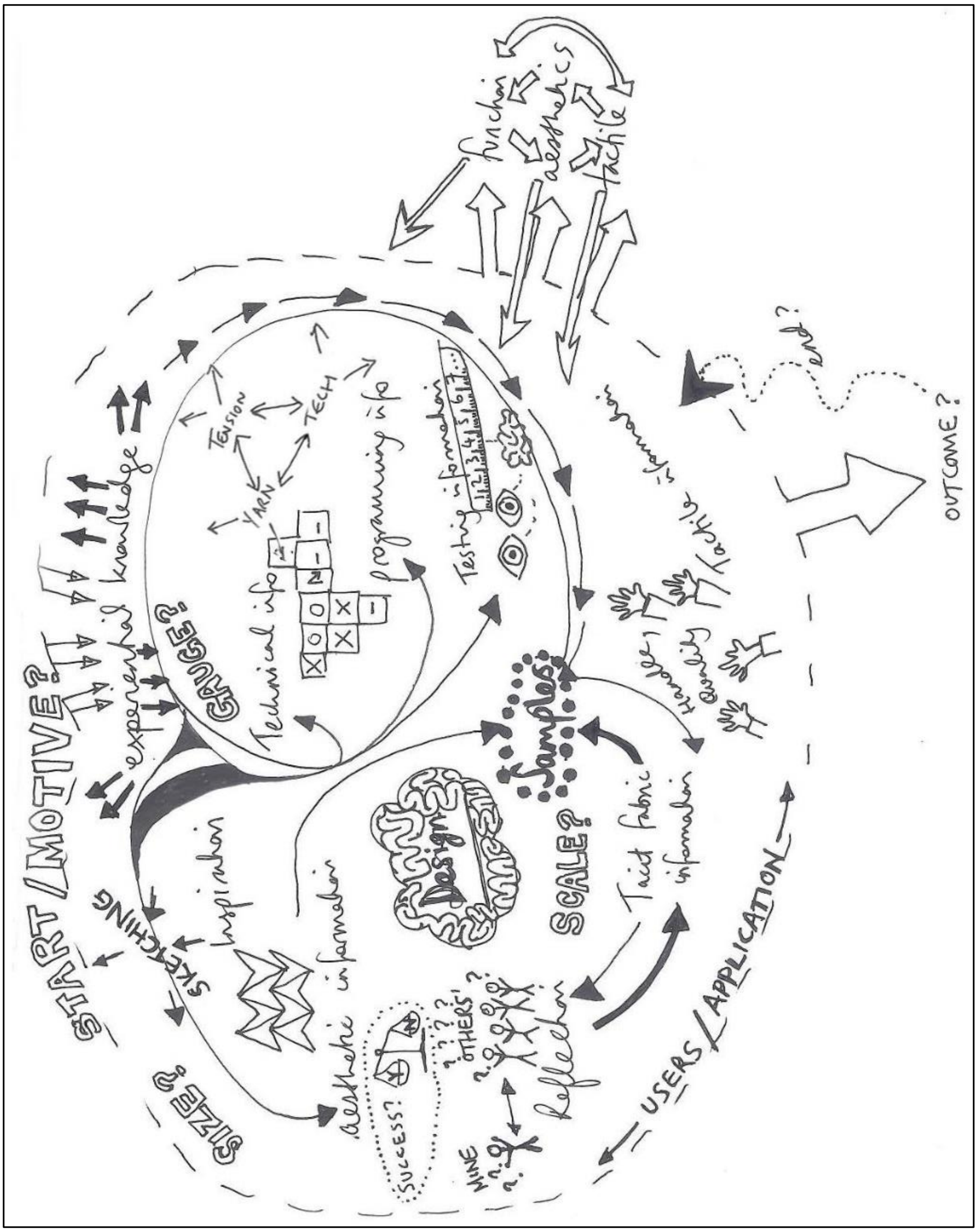


Figure 3.36 Diagram of methodology as an approximate sketch. The sketch shows a non-hierarchical, non-linear relationship between elements. The process has no defined start or end as the order of events is dictated fully by the project.

Since the beginning of this study, several attempts have been made to visualise the methodological process in the form of a diagram. Initially, the diagrams were used as tools to visualise my own process to myself and then to communicate this process to others (the earlier attempts at visualising the methodological process can be found in **Appendix G**). The visualisation of a methodology proved to be highly problematic due to the non-linear, cyclical, variable, adaptive and chaotic nature of the process, drivers and outcomes. The motivation behind designing a methodology diagram or visualisation is to provide both written and visual forms of information, where possible, to enable different interactions and responses from different readers.

Because of the free-form nature of the design methodology, the visual representation of the design methodology of this project may be best represented as a sketch. As shown in **Figure 3.36**, the methodology, when represented as a sketch, shows a non-linear representation of thoughts and processes that have interlinked relationships. Importantly, the elements are not necessarily hierarchical in nature – nor do they always have the same importance in different projects. The most important elements are the ones that have the most links to them – as they are more likely to be important within more (or all) projects.

As shown in the image, some of the considerations in the design process have direct effects on other elements of the design process, though these effects do not always follow the same directions. For instance, decisions about tension, yarn and machinery might be dictated by other circumstances, but also the yarn, tension or machinery (once they are determined) may have knock-on effects on other aspects, or each other. For example, if the aim was to make a very close-fitting garment, this might affect the choice of yarn to an elastic yarn – this would affect the tension and the machinery requirements. If the aim was to produce a range of designs for fashion outcomes, any number of considerations might be the starting point for the design (e.g. colour, stitch, texture, shape, garment, yarn, etc.).

The important advantage of this methodological representation over the previous attempts at representations is that the individual elements are not hierarchical or time-ordered. The design method is an intrinsically personal and complex process that cannot be easily divided in order to be visualised. A methodological diagram that incorporates a freedom of order and a complex network of possible routes and outcomes is more accurate, though this may not appeal to practitioners who favour regular and scientific approaches.

3.8. Knitted fabrics

3.8.1. Knitting/sampling or production of artefacts

The production of knitted fabrics forms the most important process in this project. Because of the nature of a craftsperson or a designer-maker, the need to trial products physically is vital to test thoughts, ideas and processes. One objective of this project - to demonstrate that design knowledge is suitable for producing 'functional' or 'technical' textiles - rests on demonstrating this through making. In order to show the theory's validity, it is necessary to create physical examples that can be compared with those physical examples produced via other methodologies (namely, engineering, scientific or mathematical).

A key difference between engineering approaches and a knit design approach is the role of modelling in the design practice. As shown in the sketchbook images (**Figure 3.31** to **Figure 3.35**), design models can be quick sketches showing forms and structures. Knit production using flat-bed machinery has a relatively quick set up process (compared with weaving and warp-knitting), so modelling an idea for a fabric is easy to do through the physical making of it. This can be a much simpler and more straightforward approach than computer simulation, despite advances in modelling knit structures via knit programming software [Hunter, 2013a; 2013b]). Using a design approach, physical modelling allows for quick assessment of whether a fabric has worked to expectations, or if it requires some alteration.

This study uses its practical element as a 'proof of concept', so the making stage is an extended version of an exploratory sampling stage. The aim of each fabric development is to produce an auxetic structure – this behaviour marks the test of whether a fabric is successful for this study. The making of fabrics is paramount to the understanding of a physical idea in many of these cases. Where a sketch will show the general shape of a fabric and predictions of the behaviour, the simplest and most informative method of testing an idea about a knitted fabric is to knit it. The experiential knowledge of a designer is used to approximate the outcome of a design, but the realisation of a physical sample shows up discrepancies between the design idea and the physical reality (a difference that is difficult to model, as shown by the Stoll visualising software in **Chapter 2**, **Figure 2.17** and **Figure 2.18**).

3.8.2. Materials used

Materials used in this knitting process are chosen for their properties, which include: fibre type, strength, elasticity, aesthetic, thickness, handle, twist, rigidity and suitability for use on the chosen knitting machinery. The materials are selected using knowledge gained from previous experience of working with those materials.

For example, wool was chosen for the initial sampling (in Stage 1, **Chapter 4**), as it is known to work well in knitted structures due to its light elasticity and twist applied during the spinning process. From previous experience of using wool for knitting relief structures, it is known to give good definition of structures (more so than a more dense and non-elastic yarn such as cotton, which gives a less three-dimensional overall result). Liu et al. (2010) use wool in the development of their relief structures for these reasons. In both cases, the knowledge of an experienced knitter can justify the use of particular fibre-types or yarns for knitted structures.

After initial trials with wool, other yarns were chosen for their inherent properties, in order to work towards the desired auxetic effect. For example, polyamide monofilament was used for its rigid structure, where it was thought a stiffer fabric would help the auxetic effect by encouraging better folds in a purl rib, when used as a stripe. Covered elastomeric was used to give a density and stretch (with various degrees of resistance) to the fabric.

Auxetic structures are activated by extension (or stretch), therefore using yarns with varying properties of elasticity was an appropriate area for experimentation. By experimenting with these yarns, based on results from trials, it is possible to make more focused decisions about thickness, ends used (number of yarns knitted at once, affecting thickness), strength (e.g. of elasticity), tension, etc. This discussion of yarn choice will be addressed throughout this thesis, when appropriate.

3.8.3. Machinery and equipment used

For repeatability, electronic, flat-bed, knitting machinery was used for the practical sampling stage. Though it is worth noting that the electronic machinery is not central to this study and the knowledge may be transferrable to different methods of knit production. The use of Stoll knitting machinery in this project is justified for the following reasons:

- Creating relief patterns on a manually-operated knitting machine is a time-intensive task due to transferring of multiple stitches by hand. Using electronic machines allows for quick sample production, allowing for a greater variety to be made.
- Samples can be easily adapted to incorporate a slight change (for example, of yarn, tension, pattern scale, etc.) This allows a fabric to be quickly replicated with a change in one variable, making comparison of the different fabrics easier.
- Stitch size is well regulated on these machines, which leads to comparable fabrics.

The programming of the samples in this study was completed by the designer (under guidance from, and with support of specialist technicians). This led to full control over the knitting process and allowed for quick revisions of programmes for re-knitting with variations.

3.9. Assessment of samples (measuring, testing and focus groups)

The assessment aspects of this study include both quantitative measuring of samples and collection of qualitative opinions from my own personal reflection and discussions with other practitioners.

The quantitative measuring will aim to show a direct relationship between the stretching of a fabric in one direction and the expansion of the fabric in a transverse direction. The testing is based on visual measurement and uses measuring devices (tape measures and steel rulers), photography, calibration and image analysis. The testing setup is designed to be simple to avoid generating too large an amount of data.[30] Certain tests are repeated for consistency, but others are done with the aim of demonstrating quantitative evidence of auxetic behaviour.

Sight-based measurement is used to complement numerical measuring. This works on the principle that, if the fabric can be seen to be expanding in a transverse direction to stretch, then it is auxetic. This sight-based test is similar to experiential and qualitative methods of fabric analysis (Aldrich, 2007) and is a satisfactory method for aesthetic aspects of knit design.

Focus groups are used to capture qualitative responses to the fabrics. At the end of each practical stage, a focus group is held to discuss the samples from that stage and any testing results available. The focus groups are semi-structured and capture comment on the fabrics, processes, methodology, disseminations, etc. The qualitative, quantitative and personal assessments create the basis for the theory building found at the end of **Chapters 4-7** and discussed in the conclusion in **Chapter 9**.

[30] In line with the objective of presenting information in a style suitable for practitioners from different backgrounds. A balance is sought between qualitative and quantitative data.

3.9.1. Issues with testing

Saville stated that the values obtained by textile testing 'are not expected to be exactly the same' each time, and the tester should apply appropriate statistical criteria to check whether results fall within an acceptable spread of values (1999: 3). This questions the purpose of rigidly testing the textiles. For the purposes of testing fabrics in this study, it is determined to be sufficient for results to act as a proof of concept – illustrating a general auxetic effect. The testing is not meant to be minutely accurate or to demonstrate precise repeatability, but to make a considerable effort in making an objective and demonstrable test. With that in consideration, the fabrics are tested to an accuracy of 1millimetre and variances in the results are expected.

The difficulty in testing knitted fabrics arises from the large number of variables in knitted fabrics. Some of these include different stitch structures relaxing differently. These include different fibre types relaxing differently; tension or stitch length; finishing processes; yarn stiffness etc.

In addition to these variables, some additional variable elements can be proposed that make consistent and repeatable production and testing of knitted fabrics problematic[31]. The tension on the yarn as it is fed through the knitting machine may have unpredictable variables (such as unquantifiable tension masts, adjustments in threading, alignment of the yarns in threading, etc.). Similarly, ambient variables may have an impact such as room temperature; whether the machine has been running already; humidity; etc. may affect the final fabric. Yarn may be affected by the cone it is on, or the way it is wound. The welt (starting structure) of the fabric may affect the amount the fabric stretches after knitting (e.g. a rib welt is more stretchy than a tubular welt, and the tension of the 'set-up' course will affect those). The knitting machine applies weight, or 'take-down' (using 'combs' and 'rollers') to the fabric, to enable the knitting process. The take-down will need altering for different structures and different yarns (e.g. elastic yarns greatly affect take-down requirements). It is also possible that, in a given structure, with a set of variables determined, the needs of the fabric/machine and the properties of the fabric will change depending on the size of the piece of fabric knitted.

Because of these variables, it is extremely difficult to produce exactly replicable fabrics, and in turn, exactly replicable tests for those fabrics. It was not possible to conduct the development in this study in a fully-controlled environment. It was possible, however, to produce these fabrics in a creative, lively and improvisational environment, one that is familiar to a designer-maker or a design practitioner.

The testing stage puts joint focus on attaining qualitative responses and quantitative results. This is necessary to represent the practice of the designer-maker in making qualitative, quantitative, objective and subjective analysis work together seamlessly and tacitly.

[31] Some observations are in specific reference to electronic machine knitting and the Stoll CMS machines used in this study

3.10. Quantitative testing

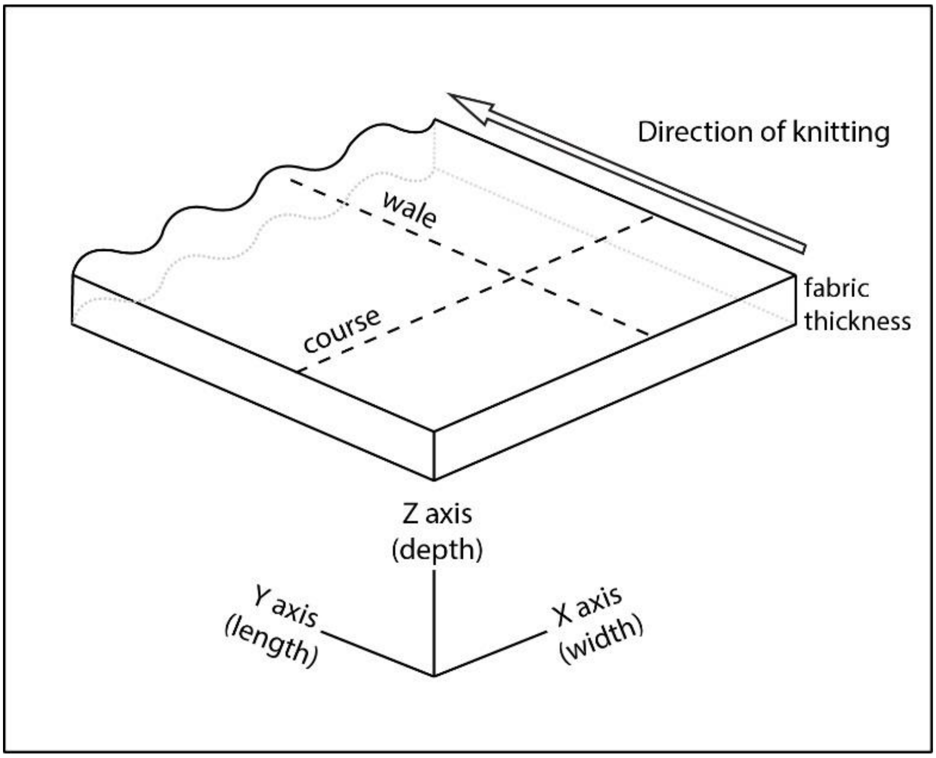


Figure 3.37 Attribution of dimensional axes to knitted fabric.

In order to discuss testing methods, it is necessary to define some common knowledge and key terms from related subjects. **Figure 3.37** shows how the course direction, wale direction and thickness of fabric can be attributed to X, Y and Z axes. This shows a clear comparability of knit terms to generic engineering and design terminology. The axes described above will always relate to the same dimensions of the fabric, rotating the fabric will not re-assign the axis information as the width, length and depth are determined by the structure of a knitted fabric and its orientation.

Quantitative testing was carried out on samples, in order to be able to present transferable fabric information to a more scientific community and to prove the claims of auxetic behaviour. Initial testing was conducted using metal clips to stretch the fabric and tape measures (as shown in **Figure 3.38**). This provided a quantitative indication of functionality of the fabrics before the later testing stage described later in this chapter. As the primary concern of the testing is to prove the concept of designing auxetic fabrics, seeking a high degree of precision was not deemed necessary. Therefore, using a metal ruler or calliper to an accuracy of 1mm was considered suitable.

Figure 3.38 Photograph showing preliminary testing set up.
This fabric is being stretched along the Y-axis.

After the preliminary testing stages, a test rig was developed to suitably clamp and measure the fabric samples. The main considerations for the design of the test rig were:

- Provide a secure grip of the varied range of fabric structures and yarns.
- Be able to secure the clamps in place at various distances apart on the board.
- Allow samples to be measured flat to minimise sag from vertical suspension (main factor against using available tensile testing machinery).
- Make a simple, easy-to-use design that would not require specialist machinery or engineering knowledge. This aims to contribute to the knowledge transfer element.

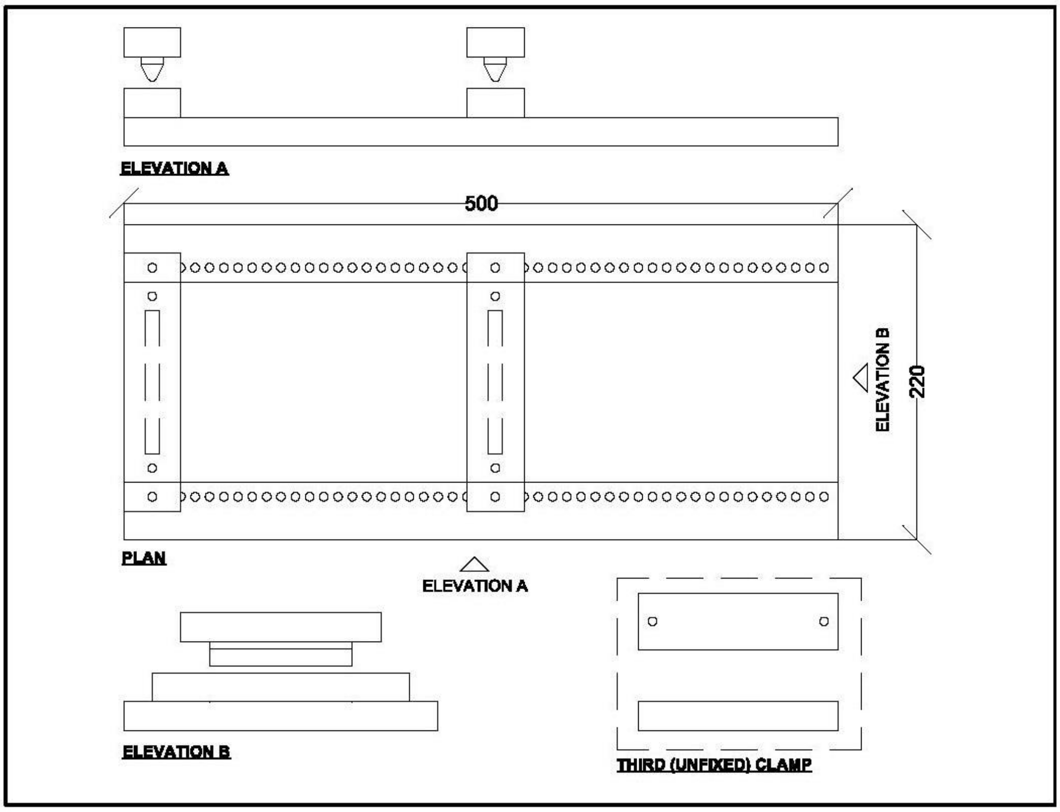


Figure 3.39 Specification design drawing of test frame[32].

The design of the testing system, frame (**Figure 3.39**) and process, was based on testing principles determined in Liu et al. (2010) and British Standards Institution (1992). The final testing stage did not use the pointed clamp sections from the test fame in **Figure 3.39**, as the overhang obscured the fabric and could have led to slippage.

The area of fabric used for the testing is focused on a 10cm square in the centre of the fabric. This is informed by a method used in knitted textile design to determine the stitch width and length (where the number of courses and wales within a 10cm square are counted and divided by 10 to indicate the number of needles and courses which would be required to produce a fabric to the desired size). The 10cm square is marked out in the centre of the fabric as a precaution to avoid interference to the results from the edge or selvedge of the fabric (which may have different properties from the centre, due to take-down or fabric curling).

[32] N.B. the pointed section of each clamp was not used in the final testing due to the overhang obscuring the edge of the clamped area. This obscuring might lead to un-noticed fabric slippage. The final set-up is shown in **Figure 3.40**.

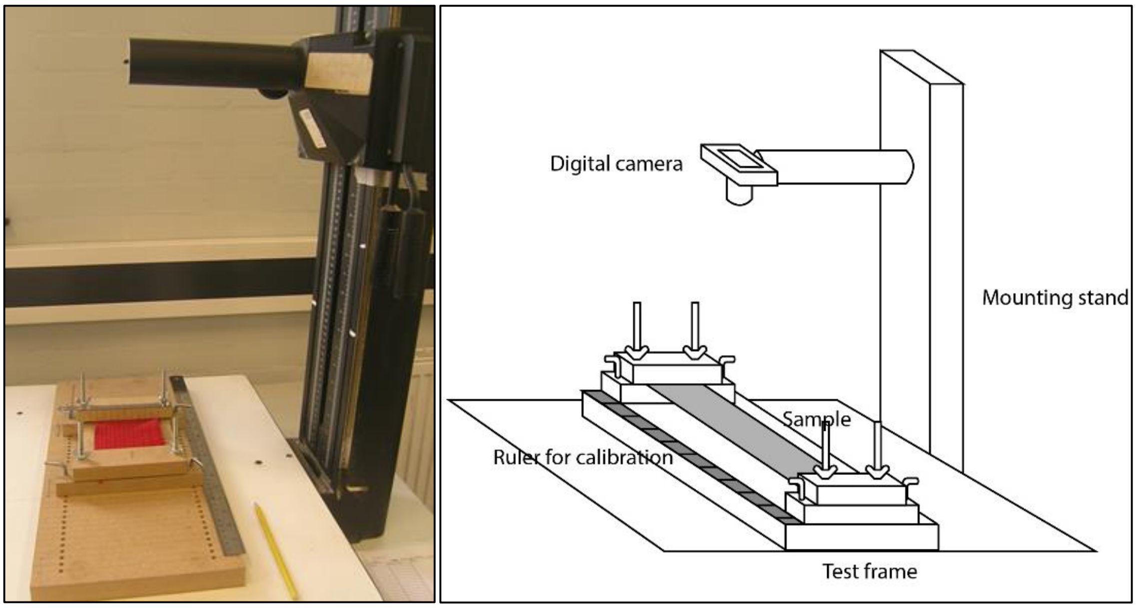


Figure 3.40 Photograph and diagram showing testing set-up and image capture.

A full trial of the testing method (as shown in **Figure 3.40**) was carried out on a fabric sample. Following this trial, testing was carried out on select fabrics from practical Stages 1-4 to represent the range of stitch structures, yarns and auxetic behaviour (from visual perception and preliminary testing).

1. The fabric is marked with pen or pencil using a 10cm square template (laser cut in Perspex). Marks are made every 1cm around the perimeter of the template.
2. The fabric is then clamped into the test frame, keeping the markings close to the clamps.
3. A piece of wood is placed under the sample to keep it elevated to the height of the clamps.
4. The clamp is moved 1cm for each extension and pegged in place.
5. Fabric is measured against original position to ensure it has not slipped during repositioning.
6. A photograph is taken at each extension.
7. The extension is repeated until the fabric shows substantial resistance to further stretching (this value will vary greatly between different structures and yarns).
8. The fabric is removed from the clamps and allowed to relax (relaxation is determined by the 10cm square returning to its original measurements).
9. The fabric is rotated 90° and tested against the other axis.

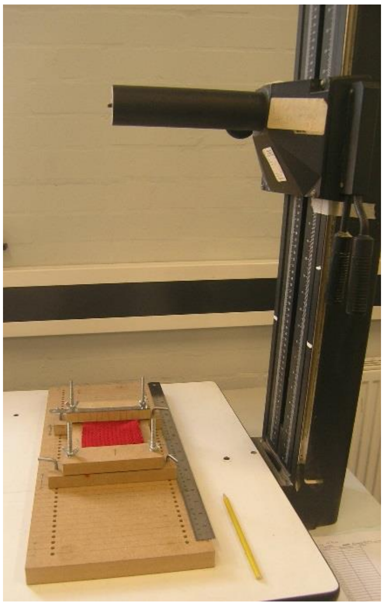
It should be noted that the method listed above proved difficult to implement for testing expansion in the Z-axis. For Z-axis expansion, visual evidence can be found in the videos supporting this thesis and the video stills used in **Chapters 4-7**..

3.10.1. Testing of stages 1-4

- To bring an objective, quantitative and repeatable element to the assessment of the knitted samples.
- To be able to directly compare and represent the auxetic properties of samples.
- To provide the information in a way that is in keeping with satisfying the scientific audience in the larger knowledge transfer objective, while retaining the visual and practical information for a textile and artistic audience.
- To develop ways of presenting the aforementioned information to the artistic and design audience to satisfy the larger knowledge transfer objective.

In **Chapter 7**, there is a discussion of the testing of a selection of samples from across **Chapters 4-7** using the method described below. The results of this testing are predominantly discussed as graphed information to give a visual representation of the auxetic behaviour (as in Glazzard & Breedon, 2014). Further quantitative information from these tests can be found in **Appendix F**.

3.10.2. Testing process

- Mark the sample with a marker pen at 10mm intervals around a laser cut 10cm x 10cm template.	
- Tighten sample into the clamps of the test frame. - Camera is mounted onto stand and frame is fixed to the base. - Steel rulers are attached to the frame along length and width to provide calibration and reference for the photography and analysis. - Samples are then stretched 10mm in each extension. - The extension process continues until the sample shows significant resistance to further stretching – this method is not meant to replicate the force of a tensile tester or other industrial testing facilities. - A reasonable force is applied that relates to human actuation. - Photographs are taken of each 10mm extension along the test frame.	

- After the range of extension for the sample has been reached the photographs are exported to a digital image analysis software (Cell^B).
- Measurements are made on this software between marked points. The sample is then measured vertically between the markers – these are referred to as the 'lines'[33] in the analysis. This measurement gives simple indication of the transverse effect as a direct result of extending the fabric.
- N.B. Due to the 3-diemsional nature of the fabric the markers may spread out to form an irregular line (as in the figure opposite). Taking a constrained measurement (in this case, the vertical distance between markers) rather than an arbitrary measurement (e.g. from marker 1-1) gives more comparable results.

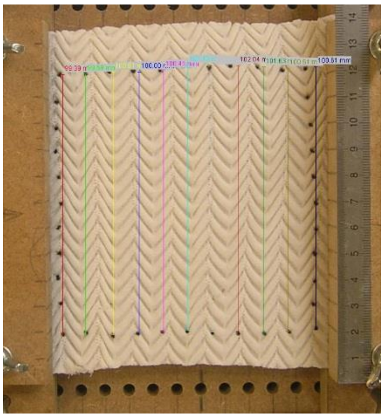


Table 3.1 Illustrated process of testing knitted fabrics for auxetic behaviour.

3.10.3. Graphed/numerical results

The data from the image analysis is collected into spreadsheets using the Cell^B software. From there, the information is gathered into a combined spreadsheet (as in **Table 3.2**) showing the sets of values from each extension side by side. The extension (Ext.) shows how many times the fabric has been stretched 10mm, i.e. Ext. 0 is the fabric at rest, Ext. 6 is the fabric stretched 60mm from the position at rest. The lines 1-11 refer to the 11 lines between the points marked on the sample that are transverse to the direction of stretch.

	Vertical distances Y axis TP4 Zimmerman (3 ends 14gg)										
	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8	Line 9	Line 10	Line 11
Ext. 0	93.06	91.84	93.27	92.65	94.08	94.29	92.86	93.27	92.65	91.43	89.18
Ext. 1	91.67	94.51	96.14	95.73	96.75	97.76	97.36	95.93	94.31	92.48	89.84
Ext. 2	93.28	94.91	98.57	98.78	100.61	101.02	100.20	97.76	96.33	94.09	88.59
Ext. 3	93.06	96.12	100.20	98.57	101.22	101.22	100.20	100.20	97.55	93.47	91.43
Ext. 4	93.28	97.76	100.61	101.02	101.22	101.02	100.61	100.00	96.95	94.09	90.43
Ext. 5	93.25	97.34	100.61	100.20	101.02	101.23	101.02	99.18	97.14	94.48	90.59
Ext. 6	93.46	97.14	98.98	98.98	100.82	100.61	99.18	98.77	96.52	94.48	91.00
Ext. 7	92.64	95.91	99.39	99.18	100.00	100.00	98.57	98.16	96.32	93.25	91.62
Ext. 8	93.05	95.91	97.55	96.32	98.36	98.98	97.55	97.14	95.71	93.66	90.80
Ext. 9	93.25	95.30	97.14	97.55	99.59	98.98	98.77	97.75	96.93	93.46	90.80
Ext. 10											
Ext. 11											

Table 3.2 Example of a section of the results from image-analysis testing.

[33] The 'lines' are between marked points, they do not follow courses or wales exactly. Lines are used to measure expansion transverse to the stretch, which could be measured in either X or Y-axis.

It is worth noting that the measurements of the vertical lines when at rest are not anticipated to be the same, due to the 3-dimensional nature of the fabric at rest and the effect of this on the marking of the measuring points. Plotting each line measurement separately in the graph allows for the shapes of the curve to be compared (i.e. whether there is growth [auxetic behaviour] or reduction [non-auxetic behaviour] in the measurements). Variations and inconsistencies in the results are likely due to the three-dimensional nature of the fabrics allowing for considerable movement of the structure's surface during extension. This may include shifting and compensating of structure, shape and pattern – these variations stop the curve appearing smooth.

The graphs in **Figure 3.41** and **Figure 3.42** show examples of the types of graphs shown in **Chapter 7**: they feature 11 transverse measurements plotted against each extension of 10mm. Each line (labelled 1-11) represents the changing measurements of one of the vertical lines measured in the image-analysis software. As can be seen in **Figure 3.41**, for this graph there is a tendency for the vertical measurements to increase to a point (showing auxetic behaviour) and then decrease again.

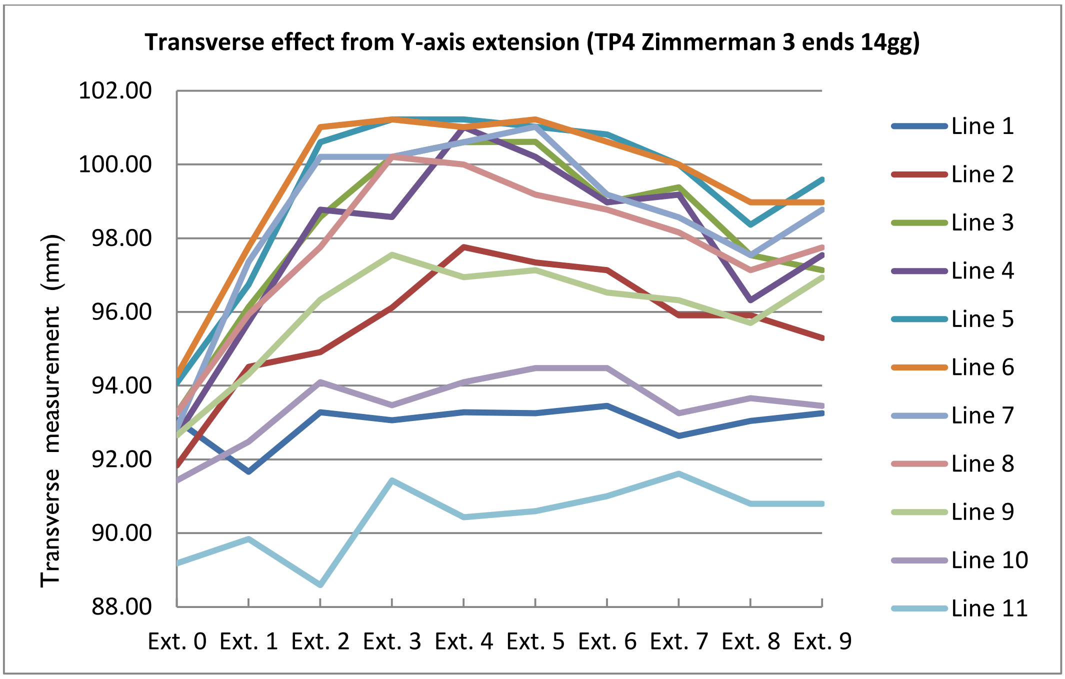


Figure 3.41 Example of a graph showing results from the spreadsheet in **Table 3.2**.

The clamps from the test frame constrain the vertical movement on the sections nearest to them. So, in a row of lines numbered 1-11, lines 1, 2,10 and 11 are likely to be the most constrained (as can be seen by their less pronounced movement in **Figure 3.41**) and lines 6 and 8 (nearer to the centre of the testing area) move in more pronounced curves. Because of this issue of constraint from the frame clamps, as part of future work, a less constraining testing method would be proposed.

With a conventional knitted structure, a non-auxetic effect or a positive Poisson's ratio effect would be expected. That would present a graph such as **Figure 3.42**, which shows an overall decrease in the vertical measurements of lines 1-11 over the course of the extensions.

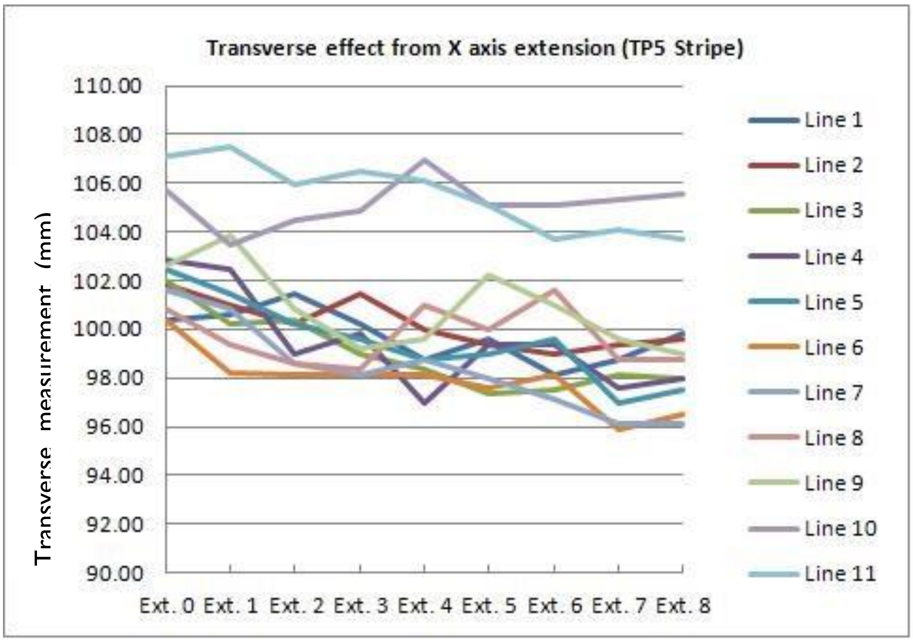


Figure 3.42 Graph showing test exhibiting positive Poisson's ratio (non-auxetic) behaviour.

Full testing information can be found in **Chapter 7** and **Appendix F**. Values, graphs, photographs and other information can be found during the discussion of each sample.

3.11. Qualitative testing

The qualitative testing of samples and methods is of great importance to this study. Allowing subjective responses from the researcher and from various participants is essential to the designer-maker process to assess aesthetic and tactile properties, as well as decisions informing yarn choice and pattern adjustments. Qualitative judgements can be used to decide whether a fabric is auxetic in the first instance (by sight) before carrying out quantitative testing to produce numerical results.

3.11.1. Focus groups

The use of focus groups serves to provide differing opinions on the progress of the practical work. Through semi-structured questioning, the participants offer contributions on how they perceive the project to be structured; where they see the relevant contributions to knowledge and development; whether any of the materials or ideas could be used in their disciplines or practices; and how the approach used is different (or similar) from their practice. These focus groups aim to reduce the effects of subjectivity and idiosyncrasy (from the design of a person-specific, practice-based project) to the overall worth and contribution of this research.

By getting input from different practitioners at regular stages in the research, there is an opportunity to regularly disseminate findings (thereby checking the language, visual data and knowledge transfer suitability), incorporate feedback and external perspectives into the overall theoretical and practical development of the thesis. This study does not aim to speak about creative practices in a generalisable manner, but does aim to illustrate a complex breadth of practice and perspective that does not necessarily adhere to well-documented and prevalent ideas of discipline, practice, understanding, methodology and discussion.

3.11.2. Rationale

The focus groups seek input from a number of practitioners from related fields on how they react to this work:

- From a design/engineering/commercial/textile/knit/craft/art perspective – does this work have differences/similarities to their own?
- Does this work interest them?
- How does the presentation of information affect these judgements?
- How do ideas of discipline/material/process/aims affect these judgements?
- It aims to capture gut reactions and informal reactions to fabrics (aesthetic, tactile, positive negative, etc.) in order to capture authentic reflection from others.

Another main objective of the focus groups is to encourage discussion about knowledge transfer. Gathering reactions from different practitioners from different disciplines and different stages in their careers gives a valuable insight into the role of knowledge and methods of presentation in practical research and development. By questioning the methods known and used by practitioners and authors in these fields, there is a justification for using alternative methods of presenting information.

The focus group is also a method of qualitative testing. Individual reactions to the samples are fed back into the design process (in the case of focus groups 1-3, whereas focus group 4 informs future work and evaluation). These responses form part of the assessment feedback loop. This method tests some of the most subjective concepts of this thesis, such as aesthetic and tactile information, to consider not only my own individual opinions, but also to include those from others for comparison and contrast. Via this validation process, the views of others can be integrated into the methodology, thereby making the overall contributions to research less individually subjective.

3.11.3. Participant selection

Participants for the focus groups are chosen by different methods. The first three focus groups recruit participants through advertisement. Because participation was advertised to practitioners from a large art and design college at NTU only, all participants had relevant experience in research or practice and no screening process was needed.

The first group (FG1) uses a convenience sample of a mixed disciplinary group of Master's degree students. The group provides a mixture from artistic and scientific backgrounds and students working towards Master's of both Arts (MA) and Science (MSc).

The second focus group (FG2) is a self-selecting sample from Master's students who had been informed of the study and volunteered their contributions to the discussion. Again, this provided a mixture of disciplinary backgrounds and current practices.

The third group (FG3) is a self-selecting group made up of PhD and Master's students who responded to a request for participants. The request for participants included information about the work being involved in textile design, this led to there being a larger proportion of people from textile disciplines. From these textile practitioners, there is a mix of those from artistic and scientific backgrounds.

The final group (FG4) contains professional practitioners in textile design, textile engineering (including auxetic materials), craft, architecture and knitwear design. These participants were approached individually for their contributions, to ensure a mix of disciplinary background and of professional and academic experience. The final focus group tests theories developed up to that point about how information can be transferred.

3.11.4. Coding, validation and assessment

Coding forms an important part of the analysis of this work. It allows complex ideas from participants to be grouped together and be meaningfully compared[34]. By comparing the thematic coding throughout the four focus groups, it is then possible to consolidate the themes for analysis to allow easier recognition of trends and significant data points.

Focus groups, alongside other methods of dissemination (presentation, conferences, academic papers, etc.), provide opportunities to receive critical feedback from external practitioners. This critical feedback forms part of the design process and may be incorporated into feedback loops and have impacts on the subsequent stages of the practical or theoretical development of the project.

3.12. Dissemination

Information produced through this study is disseminated to various audiences in a number of different ways. Firstly, through the focus groups, as described in the previous section, secondly to individuals during official monitoring stages and meetings, then to conference audiences through posters and presentations, and finally in published articles.

Below is a full list of the published articles (to date) relating to this study:

- GLAZZARD, M. and BREEDON, P., 2014. Weft-knitted auxetic textile design. *Physica Status Solidi (b),* 251 (2), 267-272.
- GLAZZARD, M. and BREEDON, P., 2013. Exploring 3D-Printed Structures Through Textile Design. *In: Research Through Design 2013 Conference Proceedings, Gateshead, UK, 3-5 September 2013.* Northumbria University, pp. 51-54.
- GLAZZARD, M., 2012. Reclaiming a Knitter's Perspective. *In: Defining Contributions 18 May 2012.* Nottingham Trent University, pp. 25-30.
- GLAZZARD, M. and BREEDON, P., 2012. Designing a Knit Methodology for Technical Textiles. *In: Smart Design: First International Conference Proceedings, 22-24 November 2011.* Springer, pp. 103-108.

[34] Examples of the coding process can be seen in **Appendix E**.

In addition, the work has been presented at the following events:

- Research Through Design, 3-5 September 2013, Baltic Centre for Contemporary Art, Newcastle upon Tyne and Gateshead, UK (Poster, exhibition and paper presentation).
- Arcintex network meeting, 25 February – 1 March 2013, Aalto University, Helsinki, Finland (Poster and workshop).
- 4th International Conference on Auxetics and Related Systems, 4-6 September 2012, University of Bolton, Bolton, UK (Paper presentation).
- College Research Conference, 28 June 2012, Nottingham Trent University, Nottingham, UK (Paper presentation).
- Defining Contributions, 18 May 2012, Nottingham Trent University, Nottingham, UK (Paper presentation).
- 1st International Conference on Smart Design, 22-24 November 2011, Nottingham Trent University, Nottingham, UK (Paper presentation).

All of the methods of dissemination test the relevance of the results and the language used in different fields and to different audiences. Presentations and publications are made for design, science or mixed audiences. This means that the language used must reflect all aspects of the work, while using appropriate and transferrable language (i.e. non-specialist, where possible).

3.13. Methodology conclusions

This study rejects the application of pre-defined methodologies from other disciplines and practices. In this case, the methodology is derived from the practice of a designer-maker of knitted textiles. The methodology is inherently creative and incorporates qualitative response from the maker and others. In close relation to the qualitative elements, quantitative aspects are necessary to fully carry out a project in knit (due to the complex and technical nature of knitted structures, especially when machine knitted). Because of the aim to produce auxetic, knitted textiles, the quantitative analysis must be in place to demonstrate that the fabrics are displaying the auxetic behaviour. However, because of the designer-maker perspective in the methodology, the testing in this study aims to present any qualitative or quantitative data derived from the testing to be simple and easily understood by a wide range of other practitioners.

One main outcome of this aim to produce shareable information is the production of visual methods of displaying auxetic behaviour – such as graphs and drawn diagrams. The numerical information may also be presented as a percentage of increase rather than a negative value (as in NPR values).

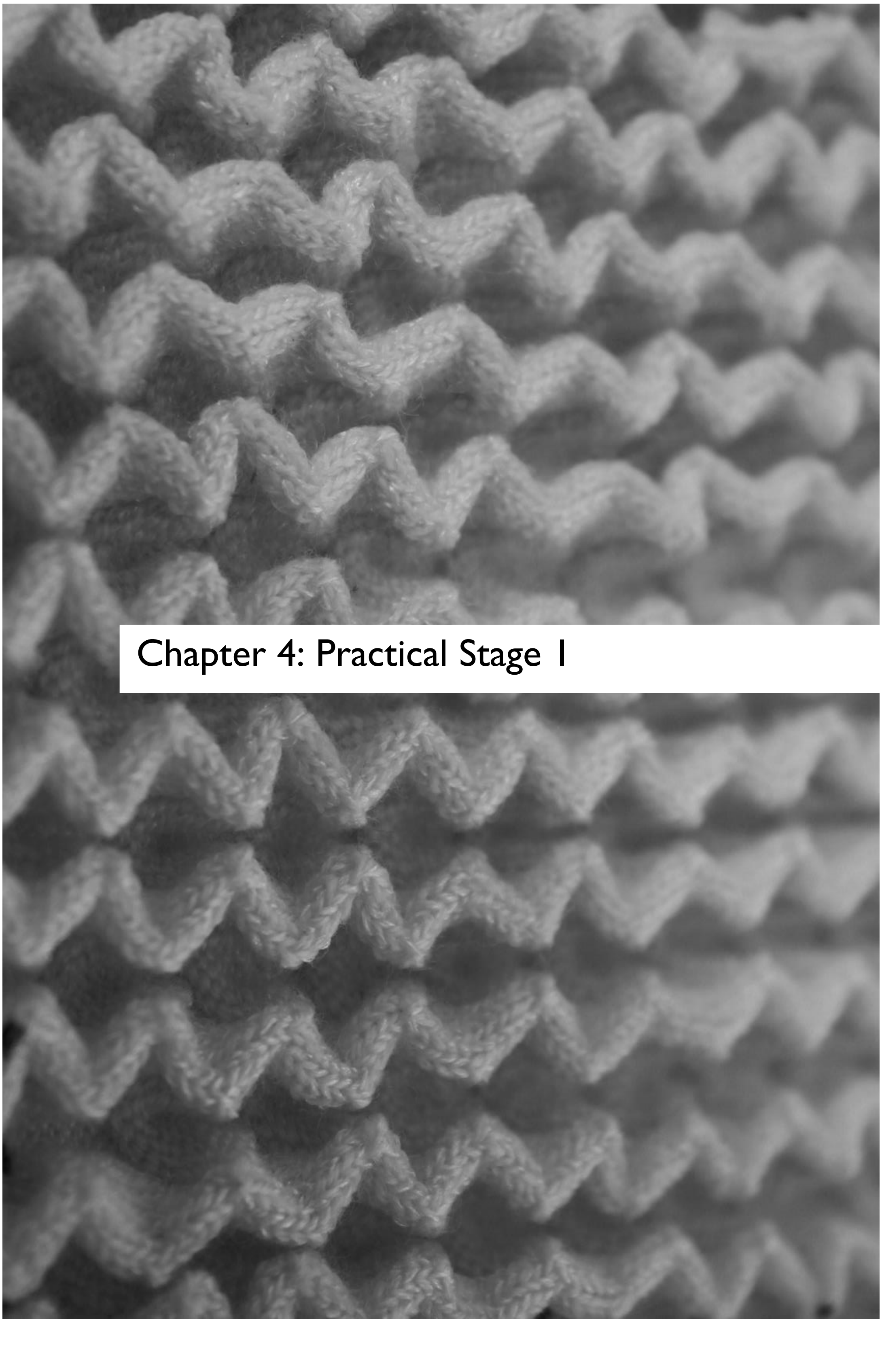
The use of photography and video (in the supporting information for this thesis) to present information is another alternative to the existing methods in auxetic literature. These methods fit well with the desire for visual information from a designer-maker perspective. In lieu of being able to handle the fabrics personally, the videos may give the reader an insight into the handle and physical properties of the fabric. These aspects are important for design applications that are not only interested in the quantifiable information surrounding a fabric, but also in the aesthetics and movement of fabrics.

3.13.1. Methodology in future chapters

Validity of the application of the testing methods for these fabrics, as described in this chapter, will be questioned further throughout this thesis. Qualitative observations from me and other practitioners in formal and informal settings will provide a context for the quantitative test results and frame their place within this research. Human knowledge and reaction to fabrics will be the primary testing and reflection method in the practical development stage of the project.

The iterative approach to methodology building (or documentation) and theory building will be discussed at the end of each practical development stage for any observations, developments and changes which will be put into effect for subsequent stages. In the concluding sections of this thesis, the use of an experiential designer-maker methodology will be evaluated and the testing of information by various methods will be evaluated against the knowledge transfer element.

Chapter 4: Practical Stage 1



4. PRACTICAL STAGE 1

4.1. Introduction

In order to test initial hypotheses, a pilot study was conducted. The process and findings of this pilot study are discussed in this chapter. At the end of the chapter there will be reflective and summative information on the success of the format of the pilot study, and how it informed the main study.

The initial hypotheses for the pilot study were:

- Auxetic textiles can be produced using experiential weft-knitted textile design knowledge.
- Discussion of these textiles can be directly linked to information about existing auxetic textiles (both knit and non-knit).
- Discussion and dissemination of auxetic results can use the language and conventions of the design discipline used to develop them.

4.1.1. Format for study

The pilot study took the format outlined in the methodology chapter using knit design practice, in which knitted samples are produced, appraised and tested in an iterative and cyclical manner. Four auxetic fabric samples are discussed in detail in this chapter and further information on the other sampling trials from this stage can be found in **Appendix B**. This then culminated in a feedback session using a focus group with participants from various disciplinary backgrounds (in this case, Master's students in scientific, design and making related disciplines) in order to evaluate and critically assess the working stage.

4.1.2. Aims of the pilot study

- to test the proposed programme of study
- inform which parameters to test in samples
- discover whether initial objectives for the project have changed, or if the original hypotheses need refining
- develop initial theory to interrogate through further focus groups and sample development (Collins, 2010: 164-165)

4.2. Design of pilot study

4.2.1. Inspiration and beginnings

The starting point for the pilot study was taken from the paper published by Liu et al. (2010) titled *Negative Poisson's Ratio Weft-knitted Fabrics* (as described in section **2.9.5.**). This paper outlined an investigative study at Hong Kong Polytechnic into the production of weft-knitted auxetic textiles. There were several reasons for using Liu et al.'s paper as a starting point for the pilot study and fabric development, including:

- The fabric described used a simple, relief structure with a strong geometric pattern (geometric patterns have featured prominently in my previous design work).

- The perspective of the authors was quantitative and incorporated views from textile engineering. This allows for direct comparisons of outcomes of weft-knit auxetic fabrics achieved through different processes.
- Liu et al.'s paper omits any comment on the aesthetic, tactile and qualitative properties of the fabrics described within. This contrasts with this thesis' aims to describe technical work to art and design audiences as well as representing artistic concerns to science audiences.

The pilot study began by replicating the sample described in Liu et al.'s paper (2010). The sample was replicated in order to appraise the handle and the movement of the fabric. Liu et al.'s paper expressed the auxetic effect with photographs, statistics and detailed mathematical analysis, but in order to experience and assess the fabric in a way conducive to my knit design knowledge, it was preferable to be able to handle the fabric first hand and draw my own conclusions on the effects.

Liu's sample was knitted on a 14gg Stoll CMS knitting machine using 2/28 superwash wool[35] and so was replicated using the same yarn type and machinery at Nottingham Trent University's (NTU) knit department in early 2011(the replicated sample is shown in **Figure 4.43**). Liu et al. had provided a graphed pattern for the knitted stitches used, so it was possible to replicate the sample exactly and using equivalent or identical machinery and materials.

As described in Liu et al., the pattern was in a zigzag arrangement of face and reverse loops. This was in a planar form, though the 'fabric after knitting tended to curl and form three-dimensional geometry…due to structural disequilibrium of the face loops and reverse loops' (2010: 858). This particular nature of knitted material is well known to practitioners used to dealing with knitted fabrics. It accounts for the significant curling of edges on jersey fabrics, which can cause difficulty in make-up or garment applications.

Liu et al.'s fabric makes use of some key aspects of knitted fabric and stitch structure. Experienced practitioners in knit will understand that knit fabrics tend to curl and distort at the selvedges and where face and reverse stitches meet. Within a fabric there are two key points to remember about interplay of face and reverse stitches. They are:

1. On a horizontal axis/course the face stitches will protrude and the reverse stitches recede (as with a rib fabric).
2. On a vertical axis/wale the reverse stitches will protrude and the face stitches recede (as with a purl rib fabric or garter stitch).

After replicating Liu et al.'s sample and observing the simple design creating an impressive three-dimensional and auxetic effect, it was possible to conceive designing my own auxetic fabrics. Liu et al.'s fabric acts as influence, inspiration or a launch-pad for some of the fabrics produced and explained in this chapter.

[35] Machine-washable wool

4.2.2. Measuring methods used in pilot study

Starting with the replication of Liu et al.'s sample, further fabrics were then developed based on the principles discovered. This process included:

- taking into consideration the geometric make-up of the graphed stitch structure and optimising the interplay between knit and purl stitches
- close observation of small sections of the knitted fabric
- analysis of observations in combination with experiential knowledge
- reflection on each stage of the process

Samples are measured using a preliminary measuring system[36]. This measures across the widest point of the fabric (between the selvedge edges) in both relaxed and stretched states (as explained in section **3.10.** of **Chapter 3** and shown in action in **Figure 4.47** in this chapter). Liu et al. (2010) have shown that the negative Poisson's ratio can be shown, until the expansion reaches an apex (where the fabric resembles a flat, conventional fabric) and then the Poisson's ratio will change to become a positive value. As these first stage samples are all based on a folding principle, they will be stretched until they reach this apex of expansion to show the widest possible transverse measurement.

N.B. Samples are always approached from the angle which they have been knitted on the machine i.e. the length is the measurement of the Y-axis and the width is the measurement of the X-axis.

4.3. Knitted samples

The samples described in this section are accompanied, where relevant or possible, by a representation of the programming information (a repeated unit from the Stoll programming software), a photograph of the sample, observations on the fabric and salient testing information. The names of the samples are given numerically in order to denote chronology and order of development. The name in brackets by the sample number reflects the descriptive name (used for saving files in the programming stage) to identify the properties or intentions behind a sample. Where specific information from the later stages of the study (focus groups, dissemination or development in this or future chapters) is relevant, this may be included in the discussion of each sample.

[36] The 'preliminary' testing shows approximate measures (due to the methods and tools used). The testing system is developed further after the completion of Stages 1-3.

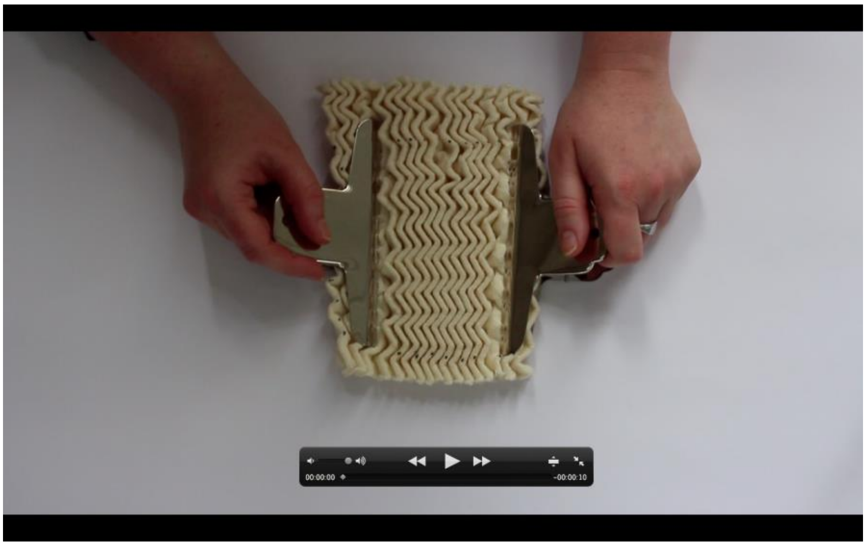
4.3.1. Sample 1a

After replicating Liu et al.'s programming and knitting a test sample (named Sample 1), an elastomeric yarn was added to the wool yarn used in the original study. This addition was based on experiential knowledge acquired through designing knitted fabrics for use in clothing, where adding elastic is a common method in clothing industries for adding stretch and recovery to fabrics and forms (Aldrich, 2007: 27). It was found through visual and tactile appraisal that the addition of elastomeric had given a different quality[37] (a closer stitch structure) to the sample and what seemed to be better recovery[38] (the sample can be seen in **Figure 4.43**). The alterations made to Liu et al.'s sample is the first instance in this study of using experiential knowledge in the design and development of these function-focused fabrics.

To provide a point of comparison for future results of testing the auxetic behaviour, sample 1a was measured using the preliminary measuring methods (using clips to stretch and tape measures to record information). The auxetic effect displayed showed an extension to 436% of the original measurement in the X-axis given an expansion to 153% of the original measurement in the Y-axis.

In addition to the comments made by Liu et al. in their original paper (2010), it is possible from re-knitting the sample from their specifications to assess the fabric qualitatively. Qualitative responses are used from my perspective (acting as an expert in knit design) and from participants in focus groups. My observation at the time of knitting, suggests that the fabric could potentially be used in a great number of aesthetic or fashion applications, even those which do not require an auxetic effect. The fabric would work well to cover the form of a body through expansion and allowing the moving folds of the fabric to settle over three-dimensional forms.

[37] 'Quality' here referring to a knit term used to describe tension and stitch density of a fabric rather than a value judgement.
[38] How well or how quickly the fabric returns to its original size and shape after being stretched


(a)


(b)

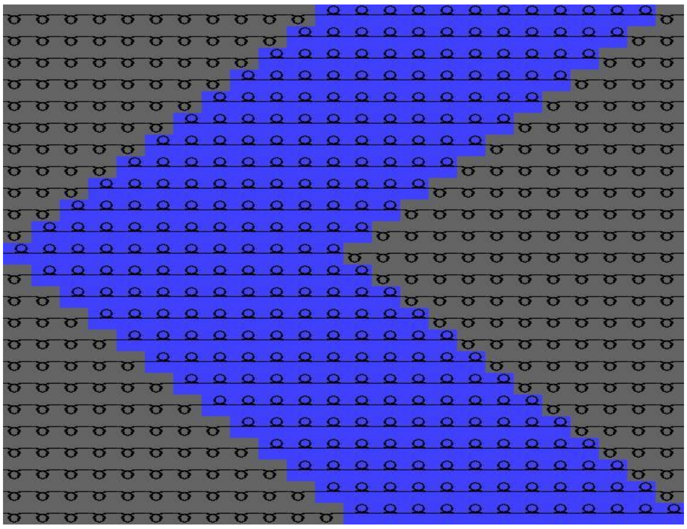
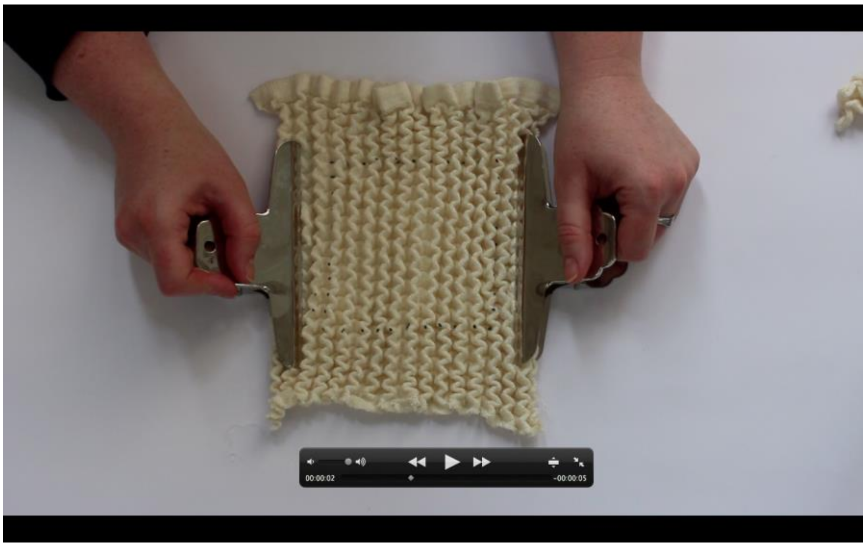

(c)

Figure 4.43 Sample 1a replicated from Liu et al. 2010 using wool with addition of elastomeric (a) at rest, (b) stretched in X-axis, (c) Stoll programming chart.

4.3.2. Sample 2 (Purl zigzag stagger)


(a)


(b)

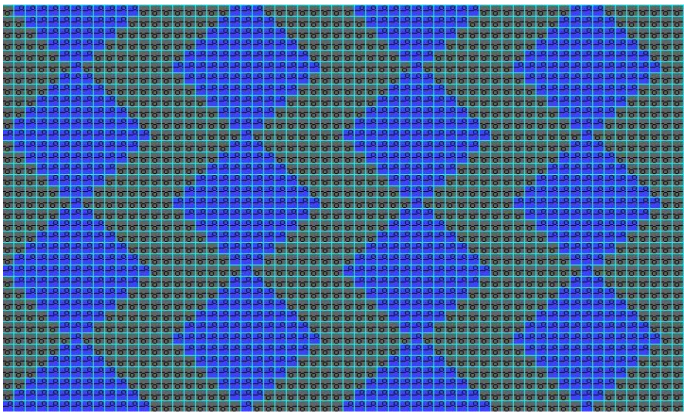

(c)

Figure 4.44 Sample 2 in wool and elastomeric at rest (a) and stretched in X-axis (b) with Stoll programming chart (c).

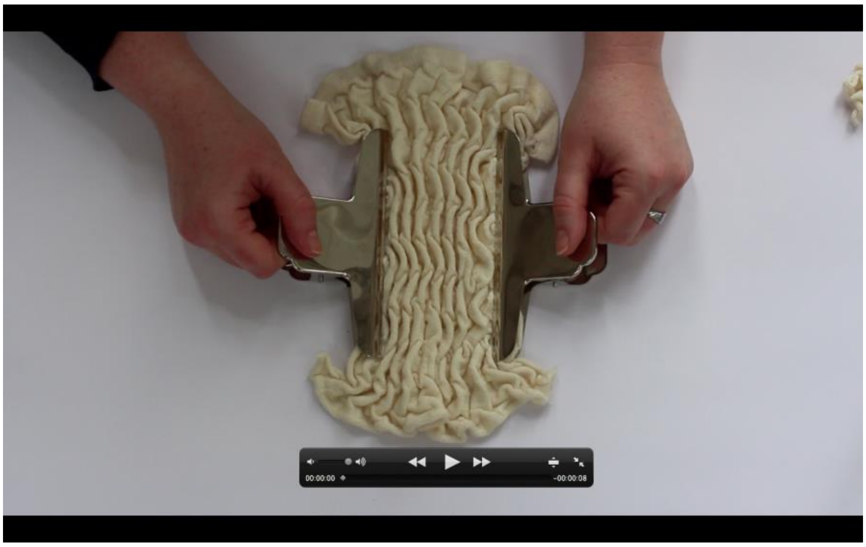
Sample 2 was inspired by Liu et al.'s sample but was set in a staggered formation to test whether the folding effect was achieved by an accumulation of the repeated pattern motif. The proportions of the pattern were kept the same as the original samples but this pattern is laid out as a drop repeat (see chart in **Figure 4.44**) that gives a staggered version of the zigzag pattern.

The results from this sample were not as defined as Sample 1a. but still displayed some auxetic effect. The transverse expansion in the Y-axis of the fabric was 111% from an extension of 248% in the X-axis (compared with Sample 1a's 153% expansion from a 436% extension). It is worth noting, in this case, that the extension was not as large as in Sample 1a, so the auxetic effect was achieved through less stretch (comparatively).

As well as displaying a limited auxetic effect, Sample 2 exhibits good three-dimensional properties which are manifested in a 'cell' type structure. In terms of visual and tactile appraisal the sample was found to be pleasing[39] and, due to the cell structure, could be used for applications requiring embedding of objects or materials. The dense fabric form is 'springy' to the touch with an effect that inspires the user to play with it. The aesthetic of the fabric is significantly different from that of Sample 1a, but I found the appearance of both to be pleasing.

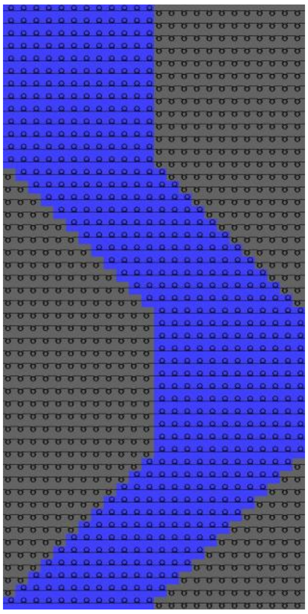
[39] My own response to the fabric written in the evaluation matrix (**Appendix B**) during reflection on the fabric's success

4.3.3. Sample 3 (Purl zigzag S)



(a)

(b)



(c)

Figure 4.45 Sample 3 in wool and elastomeric at rest (a) and stretched in X-axis (b) with Stoll programming chart (c).

Sample 3 is a copy of Liu et al.'s original zigzag pattern with the points of the zigzag elongated with square panels to stretch out the pattern. The aim of this was to produce the same effect as the original sample but with an 'S' shape instead of the pointed zigzag (as seen in **Figure 4.45**).

With this sample it was assumed that there would be an auxetic effect, though it may be less pronounced than that of Sample 1a. Indeed, there was an auxetic result, showing a 112% increase in the Y-axis after a 392% extension in the X-axis. However, even with the elastomeric, the sample recovery was slower than that of Sample 1a, sometimes requiring some manipulation to fold back into neat pleats. In spite of this functional downside, the fabric has proved popular, aesthetically, among those[40] who have been shown the sample base. The aesthetic appearance is pleasing and could be likened to something like a heat-set pleat or crêpe fabric.

In this sample the auxetic function is not very pronounced and requires manipulation to reset but as the fabric is developed from Liu et al.'s original work, it is interesting to begin to see a range of fabrics that vary in both appearance and auxetic effect. The variations in both appearance and auxetic behaviour come from small, intuitive alterations to the programme, while retaining the essence of the original stitch pattern. The use of minor alterations giving such differences sets a good precedent for the potential for further development around knit/purl relief patterns in this study.

[40] As part of the methodological objective to disseminate, contextualise and support the information from the fabrics by showing the samples to focus groups.

4.3.4. Sample 4 (Purl rectangle/basket weave)


(a)


(b)

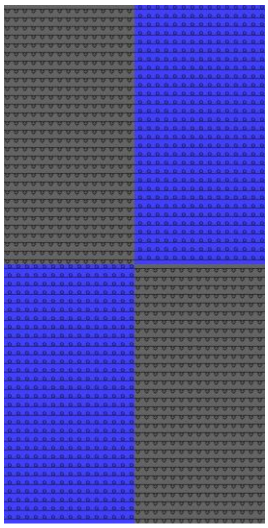

(c)

Figure 4.46 Sample 4 in wool and elastomeric at rest (a) and stretched in Y-axis (b) with Stoll programming chart (c).

Sample 4 takes leave from following the pattern used by Liu et al. and draws on experiential knowledge learned through time designing knitted fabrics for garment or aesthetic purposes. The 'basket-weave' or 'chequerboard' pattern is a common hand and machine-knitting sample (Tellier-Loumagne, 2005: 137), which is often used in clothing and accessory design. It is made up of alternating squares or rectangles of face and reverse stitch (shown in the chart in **Figure 4.46**). These squares or rectangles can be made in any size, but for the purpose required here it was decided to keep them to small units (15 needles by 30 courses) so as to maximise the effect of the twists.

As is known from previous design use by the author, this stitch structure, under the correct conditions (yarn structure, tension, gauge and proportion), has been known to twist into spirals at the point where the corners of the four unit squares meet. This creates a 'springy' and highly textured fabric (as can be seen in **Figure 4.46a** and **Figure 4.47**). This fabric is able to be pulled back into a flat piece of knitting and, if desired, can be permanently pressed flat with steam. Several smaller samples were tried using this same principle in different pattern layouts (for example using the face/reverse stitch confluence in 'T' shape patterns), but they were not as successful as this initial attempt.

What is exciting about Sample 4 is that it demonstrated a closer relationship between the extension and the expansion than the previous samples. An expansion of 145% in the X-axis was attained by extending the sample 130% in the Y-axis. This shows an auxetic effect similar to the one shown in the Liu et al. sample, but with less than a third of the extension required[41]. The auxetic behaviour can be seen in **Figure 4.47**. As with Sample 1a, Sample 4 was popular with focus group participants for this stage of the research.

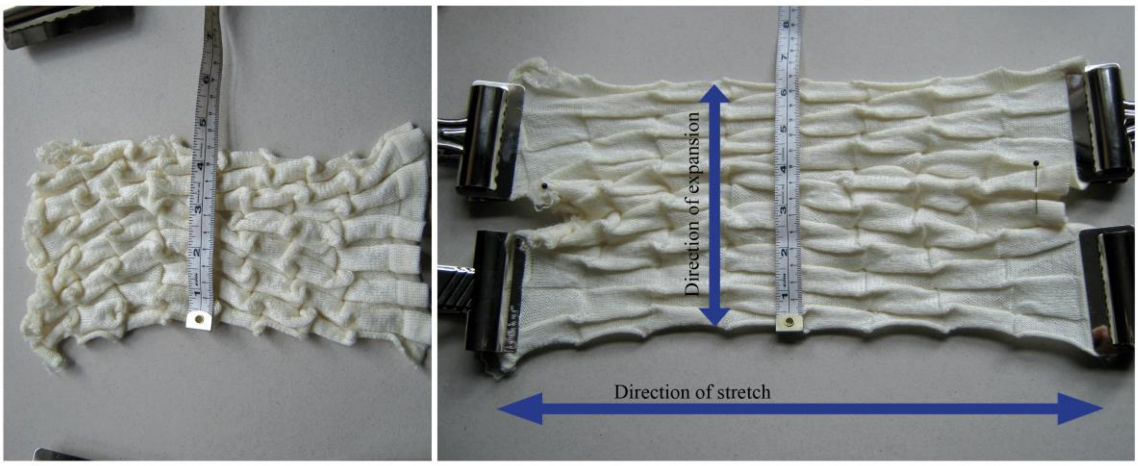


Figure 4.47 Sample 4 showing auxetic effect using preliminary measuring methods.

[41] Sample1a – In X-axis 153% Expansion, 436% Extension.
Sample 4 – In Y-axis 145% Expansion, 130% Extension.

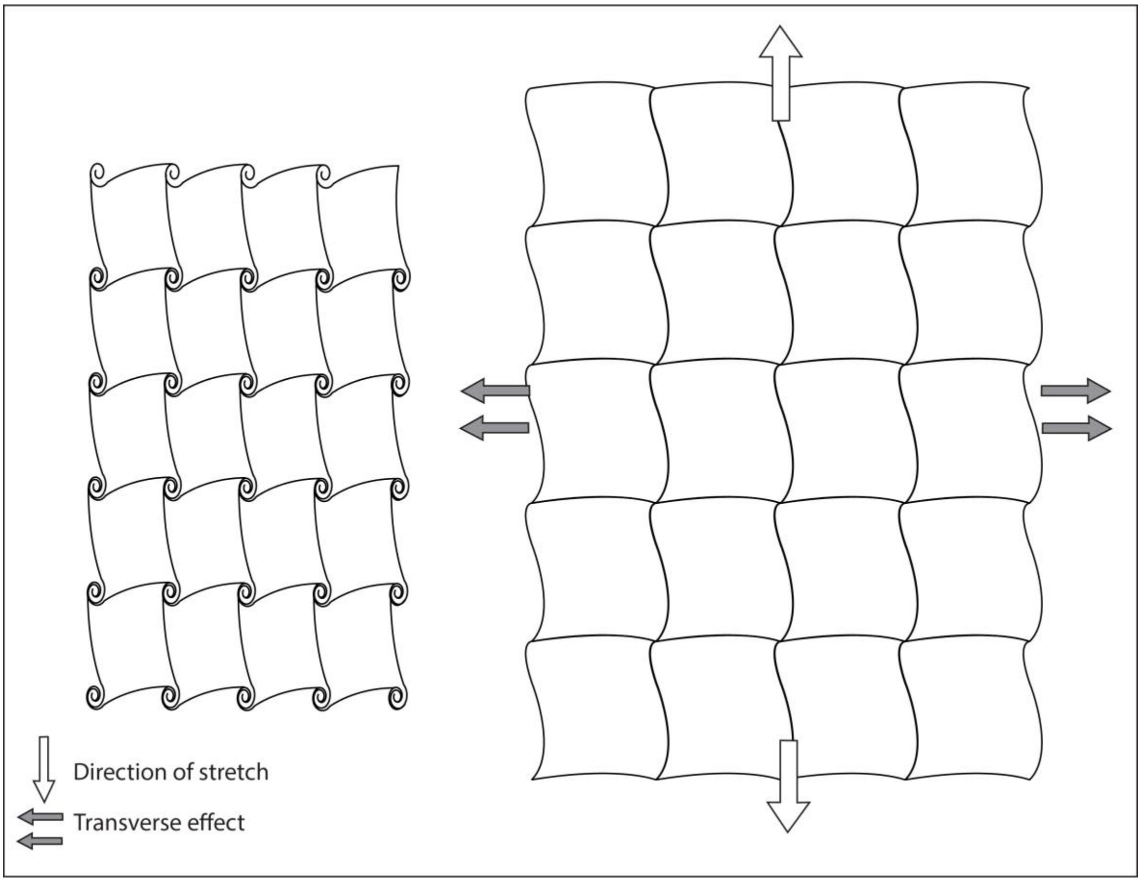


Figure 4.48 Diagram of behaviour by Sample 4.

The diagram shown in **Figure 4.48** proposes that Sample 4 works on the same principle as the chiral honeycombs consisting of triangles and circles (see **Figure 2.28** in literature review or Liu & Hu 2010: 1054). However, because this knitted sample is a solid fabric rather than a series of ligaments, it has been drawn to reflect the essence of the behaviour. In this case it is a chequerboard style, which turns into spirals at the intersections. When the fabric is stretched, the spirals straighten out providing extra area in the X and Y directions.

4.3.5. Sample 5 (Purl Diagonal)

(a)

(b)

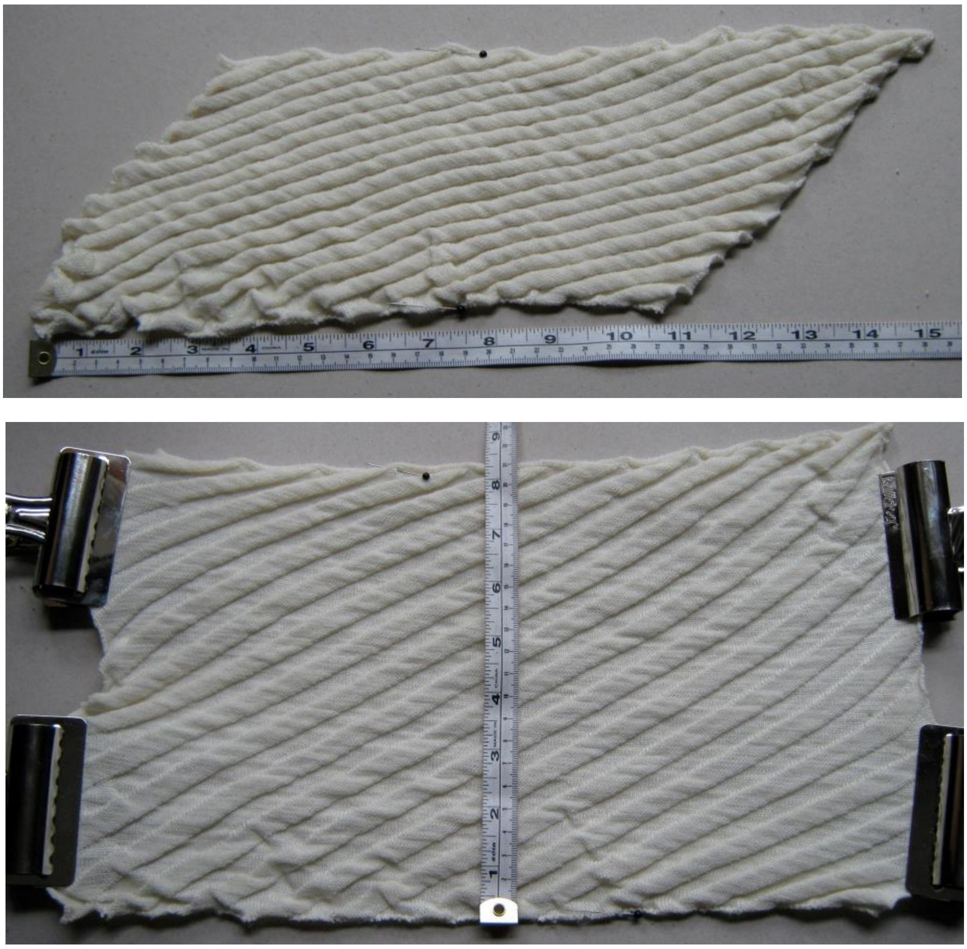


Figure 4.49 Sample 5 in wool and elastomeric (non-repeat pattern – 12K, 12P moved along one needle every one course) shown at rest (a) and stretched in X-axis (b).

Sample 5 returns to the principle explored by Liu et al. (2010), about the diagonal, folding properties attained through relief stitches. It also incorporates some experiential knowledge from previously working experimentally with knitting machines in relation to purl ribs (stripes of reverse and face stitches, which create a horizontal rib effect). By showing in Sample 1a that a three-dimensional effect is achieved within diagonal relief lines, which can also be seen in horizontal relief lines (purl rib) or vertical relief lines (rib), then it implies that, by continuing a short section of the diagonal line shown in Sample 1a across the width of the fabric, then a similar effect will be made to that of a rib or purl rib. This speculation is shown to be true in this fabric. The resulting fabric is aesthetically interesting as the overall shape of the fabric distorts from a rectangle (the shape of the programme) to a rhombus shape.

Interestingly, Sample 5 may be seen to be very auxetic, or it may be seen not to be auxetic, dependent on the method used for measuring the samples[42] (the stretch of the fabric is based on a rotational movement rather than a stretching, so the fabric rotates from the rhombus shape in **Figure 4.49a** into

[42] The auxetic behaviour of this and several other samples in this thesis is shown in 'one principal fabric direction' similarly to those discussed in Hu et al., 2011: 1495.

a more rectangular-shaped sample in **Figure 4.49b**. This does not have much of an increase through extension, but shows significant expansion in the direction transverse to the stretch).

When stretched in the X-axis and measured across the widest part, there is a significant expansion in the length (187%) and an extension of 143% in the width. However, when measured across the entire width of the fabric, as if it were enclosed within a rectangle, the total width does not change when extended. This may be seen as an auxetic effect in that it expands in the length, when stretched in the width, but it may be seen as rotation or shear[43] effect rather than extenstion. As explained in section **2.9.3.**, auxetics work on auxetic behaviour includes rotating principles and the growth effect of Sample 5 is significant enough to be documented here.

Through discussion of Sample 5, questions are being raised about how auxetic behaviour is defined and illustrated. This discussion is continued through this thesis and is an important outcome of the research.

4.3.6. Reflection on sample stage

The samples that were most successful were invariably the simplest of the samples. The basket weave of Sample 4 and the diagonal lines of Sample 5 took into consideration designing and making methods from previous experience through a background in knit design. Samples 2, 3 and 5 were based on some of the scale and proportion principles in the original Liu et al. programme used in Sample 1a. Sample 4 was derived from experiential knowledge and was known to have distinct three-dimensional folding/twisting properties at the intersections between face and reverse stitches.

A summary of the auxetic behaviour in this chapter can be seen in **Table 4.3**. Where an auxetic result was found (i.e. the transverse direction measurement became longer during stretching than it was at rest), it is highlighted in the table. The percentages in brackets show how much the fabric was extended or expanded in relation to its original measurements.

[43] 'Shear' indicates the amount the fabrics distort in warp and weft (Aldrich, 2007: 25). The shear is often a diagonal distortion such as a square becoming a rhombus or vice versa.

Sample name	At rest width (X) (mm)	At rest length (Y) (mm)	Width / X-axis stretch		Length / Y-axis stretch	
			extension (X) measurement (mm)	transverse (Y) expansion measurement (mm)	extension (Y) measurement (mm)	transverse (X) expansion measurement (mm)
Sample 1a (Liu et al.)	80	150	349 (436%)	230 (153%) PR = -0.159	-	-
Sample 2 (Purl zigzag stagger)	145	190	360 (248%)	210 (111%) PR = -0.071	-	-
Sample 3 (Purl zigzag S)	90	220	353 (392%)	247 (112%) PR = -0.042	-	-
Sample 4 (Purl rectangle/ basket weave)	110	226	-	-	294 (130%)	160 (145%) PR = -1.320
Sample 5 (Purl diagonal)	270	111	385 (143%)	208 (187%) PR = -2.052	-	-

Table 4.3 Summary of auxetic outcomes from testing results from practical stage 1.

Table 4.3 shows the results of the preliminary testing of the fabrics from this chapter. The auxetic effect is represented as a percentage increase and the Poisson's Ratio (PR) result is shown for comparison (full calculations of the PR can be found in **Appendix C**). The percentage value is an indication of the largest transverse expansions available from those samples. Presentation of these is important in offering a non-specialised alternative to understanding the aspects of a PR. The relationship between the percentages gives an indication similar to the PR result.

To explain the PR values, a negative value shows that the fabric has a negative Poisson's Ratio (NPR), or an auxetic effect. The larger the magnitude[44] of the number, the more 'efficient' the relationship between the extension and any expansion. For example, out of the auxetic fabrics, Sample 3 shows the least magnitude (the PR result of -0.042 can be compared to a relatively high extension to 392% giving a

[44] Magnitude denotes a value's distance from zero. 10 has a greater magnitude than 1 and -10 has a greater magnitude than -1.

relatively low transverse expansion to 112%) and Samples 4 and 5[45] the greatest magnitude (sample 4's PR result of -1.320 is comparable to the percentage relationship where the sample is extended to 130%, giving a 145% expansion). Therefore, Samples 4 and 5 may be considered the 'best' auxetic results (the most efficient Poisson's ratios) of this set of fabrics.

The values expressed as percentages give a simpler indication of the possible extent of the auxetic behaviour, but need to be taken into account together to indicate how auxetic a material is (what the PR value would indicate). The values in **Table 4.3** show only the NPR and percentage values for one instance of measurement (measurement of the fabric at rest and the widest expansion). It is my opinion that the PR values, though descriptive, require both fundamental and specialist mathematical or engineering knowledge to understand with ease. The alternative of a percentage relationship, although it involves considering two numbers instead of one, is something more widely understood and easier to visualise. The final focus group (FG4) tests these theories on mathematical understanding and preference.

4.4. Methods of documentation

As can be seen by the sample appraisals for each fabric, a mixture of quantitative and qualitative assessment has been used. It was decided that an evaluation matrix (inspired by and adapted from Pugh, [1991: 77] to incorporate room for elaboration on findings and discussion) might be used to document the samples in the manner of a product designer. A common aim of this method is to attribute scores to products in order to weight them against one another. In this study it was not appropriate to score the fabrics against each other in anything other than auxetic effect, but side-by-side comment on my observations of aesthetic, tactile, quality, technical information and any testing results was considered helpful. A section of the evaluation matrix can be seen in **Figure 4.50** and the full versions in **Appendix B**. The excerpt in **Figure 4.50** gives an indication of the types of notes made during the knitting stage and the decisions made on how each fabric might be developed. The information is technical and reflective and would be used for my own reference during developmental work.

[45] When sample 5 is measured as previously discussed

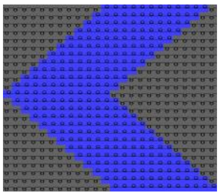
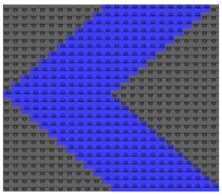
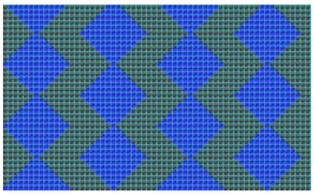
Sample number, name, thumbnail.	1, Hong Hu Zig Zag purl (acrylic)	1a. Hong Hu (zig zag purl wool)	2, Purlzigzagstagger.
	 	 	 
Needles	250	250	250
Rows	250	250	250
Machine	14 gauge Stoll	14 gauge Stoll	14 gauge Stoll
Tension	12	12	12
Yarn	2/28 Acrylic	2/28 lambswool & lycra (1 end)	2/28 lambswool & lycra (1 end)
Static height (mm)	270	150	190
Static width (mm)	60	80	145
X axis stretch height (mm)	342 (126%)	230 (153%)	210 (111%)
X axis stretch width (mm)	403 (672%)	349 (436%)	360 (248%)
Y axis stretch height (mm)			
Y axis stretch width (mm)			
Reason for knitting	Recreation of Dr Hong Hu's sample from the paper [HU, H., et al., 2010. Mechanical Properties of Composite Materials Made of 3D Stitched Woven-knitted Preforms. Journal of Composite Materials, 44 (14), 1753-1767] to see whether or not that sample did everything it claimed to on the paper. It seemed fantastical for a stitch which had been knitted before for aesthetic value and in textile and clothing design and was so simple.	Recreation of Dr Hong Hu's sample from the paper [HU, H., et al., 2010. Mechanical Properties of Composite Materials Made of 3D Stitched Woven-knitted Preforms. Journal of Composite Materials, 44 (14), 1753-1767] Using wool like Hu had done. To increase form of fabric using the twist in the wool, increase elasticity with wool (after acrylic sample). Lycra added to improve recovery	Staggered version of sample 1 and 1a. Wanted to see if the offset pattern would have a similar effect, or whether the pattern relied on accumulating in rows. Thoughts during planning of samples: Kept the proportions the same. Did graphed pattern as a drop repeat
Adjustments	Used acrylic for ease of knitting. Tension was changed to suit yarn. Results clearly work. The acrylic is disappointingly limp. Wonder on the usefulness of an auxetic knitted fabric – which when stretched fully will begin to stretch the flat fabric (as knit does) to become unstable porous material (stated by Liu et al as an 'axial strain curve')	Lycra	Adjustments made:. None. Larger sample knitted after trial piece to see if effect would be better over large scale. Added lycra also to improve return and shape retention How thoughts have changed: Effects are good. Auxetic effect is not as strong (although extension is less than in sample 1/a), but still displays auxetic properties.
Overall thoughts aesthetic, tactile and auxetic behaviour	Good, very impressive 3D effect. Good recoverability. Interesting folding pattern – not along the lines of K/P contrast. This fabric could potentially be used in a great deal of aesthetic or fashion applications where the auxetic effect may or may not be an advantage. eg. it could expand to cover a body just as easily as an other application.	Lycra does add recovery of shape. Also makes the shape shorter and wider. Zig-zag is more defined. Fabric feels better, more solid. Better than the acrylic. Better than a small pure wool trial. Lycra added effects assumed from experience. Lycra was added due to the sample looking slack and exhibiting some recovery and shape retention, but due to previous experience with knitting fabrics, I thought that adding lycra would add some more stability to the fabric. In my opinion this is an improvement on the original wool samples.	Fabric is dense and springy to touch. The 'cell' like structure potentially useful for applications. I feel the sample is aesthetically pleasing as well as having a good 3-D structure.
Developments	Knit in wool as Hu did. Add lycra for increased stability and recoverability.	Try other samples with similar effects	Try other samples with similar effects.

Figure 4.50 Example section of evaluation matrix for data storage and comparison in pilot study stage.

4.5. Focus group stage

Focus group 1 (FG1): 14th April 2011 (duration: 1 hour)

After the first sampling stage a focus group was undertaken for the following purposes:

- To meet the research objectives of 'incorporating the views of others' (see section **1.1.2.**)
- In order to test the work and the language on practitioners of different backgrounds (see section **1.3.**)
- to experience feedback from practitioners from different backgrounds
- to discuss methodological processes in relation to the samples
- to critically assess samples
- to inform second sampling and assessment stages.

4.5.1. Selection of participants

Participants were chosen largely due to disciplinary concerns. For the pilot study the participants were students on a Masters level course which combined elements of product design, engineering and architecture, which offers a Master of Science (MSc) or a Master of Art (MA) route at the student's discretion.

The group featured:

- The author/researcher,
- 5 Master's students from various disciplinary backgrounds featuring a mix of those opting for MSc and MA routes
- Textile Design lecturer
- Product Design lecturer.

The focus group (FG) began by an introduction to my background and the aims of this study. Participants then introduced themselves and their work with attention paid to whether or not they considered themselves aligned to a particular discipline/disciplines. Discussion during the focus group was kept semi-structured with topics being introduced and developed as appropriate. The fabrics from this practical stage were introduced (including the replication of Liu et al.'s sample) to the participants after the initial disciplinary discussion. Participants were encouraged to interact and play with the fabrics and asked to respond to them – Questions included the following:

- Did they like the fabrics?
- Could they use the fabric in their work?
- What changes would they like to see to the fabrics?
- How might they make the fabric more relevant to their discipline or their own work?

The focus group was recorded using a sound and a video recorder. The information was then transcribed and coded. During coding, the information was analysed to reveal themes of conversation.

The themes were determined from the data and used qualitative interpretations of the essence of each response (rather than using specific terms to categorise).

The analysis of the focus group starts with coding into themes of information (as shown in **Table 4.4** which can be grouped into larger 'parent themes' for comparison with other focus groups in visual and graphical ways.

4.5.2. Focus group themes from analysis

Parent theme	Sub themes	FG1: number of responses
Physical	Properties	9
	Material	18
	Scale	3
	Structure	5
Knowledge	Knowledge	5
	Knowledge transfer	0
	Understanding	1
	Experiential	20
	Tacit	2
Qualitative	Qualitative	1
	Tactile	4
	Aesthetic	9
	Emotional	1
Quantitative	Quantitative	1
	Results	0
Applications	Applications	18
	Industry	1
	Fashion	4
	Function	2
Communication	Communication	4
	Language	1
	Simile	2
	Collaboration	1
	Education	1
Discipline	Discipline	16
	Practice	0
	Methodology	14
	Process	22
	Design	0
	Engineering	3
	Craft	1

Change		3
Positive		10
Negative		6
Total		188

Table 4.4 Themed responses from focus group 1 (FG1).

4.5.2.1. Positive and negative responses

The participants gave mainly positive responses to the samples/project. These positive statements were generally linked to potential applications and to the aesthetics. In spite of a discussion on auxetic material no responses to the auxetic nature of the samples were made. There was indication of the participants being impressed by some of the possible techniques and potential forms mentioned (3D, shape-knitting etc.). One participant saying that the textile samples resembled his work in positive ways.

Negative responses were partly to do with the aesthetic – with one suggestion that the samples looked like bandages – suggested reasons being the ecru colour, the elasticity and the knitted texture. Some participants thought that textiles were not the right material for their disciplines, because they were seen to be too soft, or that they were not capable of the strength or complex material structure required for non-textile practices. Another negative suggestion was that the fact that textiles needed to be made by a particular process (knit/weave) - this was seen as a limitation.

Participants were very tentative in handling the samples and it was not until after 40 minutes that they were comfortable handling the samples and thinking more about tactile and material properties surrounding them. With these participants, there was not much mention of tactile properties; a different approach would be expected from textile designers.

4.5.2.2. Application

Common themes were application and process. In terms of application, many contributions were made alluding to potential applications. Many of these suggestions were within the textile or fashion disciplines, rather than in participants' own disciplines. Some of these fashion-based applications were inspired by, and similar to other applications that participants already knew of, such as 'magic gloves' or origami. The participants did not engage with the fabrics as an open-ended material exploration and instead found this approach confusing, apart from the embroidery designer present, who found potential in the fabrics while being less application-driven than the product designers. Application was the most commonly volunteered subject when discussion was left open and un-structured. It could be assumed from this that application is a major concern to these practitioners from their experiences in design. Interestingly, although no specific question was asked of participants to come up with an application, some participants assumed that they were expected to think of product applications for the samples.

4.5.2.3. Process

Some reference was made to traditional textile processes and whether or not it would be suitable to integrate those processes into the participants' design work. This process discussion was wide-ranging and specific to disciplines. Some textile process terms such as weaving and sewing were used, sometimes incorrectly, but offered evidence that these were processes that participants were familiar with from their everyday lives.

Fabric treatment processes were briefly mentioned as a possible route. One participant from an engineering background spoke about her enjoyment of dress-making as a hobby. She described the process of knowing how to interact with fabric and seams, as if they were tacit knowledge. She likened this form of making to making a truss or a beam, but simply using different materials.

4.5.2.4. Material Properties

Material properties were discussed in relation largely to application. These were described in terms of 'hard' or 'soft' or in terms of specific material requirements needed for products (conductivity, insulation etc.). There was some questioning of whether there could be a substitution of materials (e.g. paper) into the textile form or of the suitability of textile materials when using certain types of finishing processes.

4.5.2.5. Discipline

The participants' decision to take a Master of Science or a Master of Arts route was discussed, with three choosing MSc and two choosing the MA. All participants described their disciplinary backgrounds; the MAs had come from interior architecture and toy design and the MScs from ergonomics, computer/electrical engineering and structural engineering. In spite of these varied backgrounds, all considered themselves to be 'designers' rather than 'engineers' (though not necessarily in all contexts). There was talk about fashion and textiles as a discipline, where there was some underlying assumption about the textiles being used in a fashion context as opposed to a 'practical sense'.

One of the most interesting comments was from the engineering graduate in response to being asked 'Can you see yourself to be a designer now, after being an engineer, or do you consider engineering to be design?' she said:

> *I think it's kind of like a spectrum and the problem is with design education in the UK, that they polarise these two disciplines and it needs to be more of a spectrum and people need to be more rounded and understanding of different processes…*
>
> Engineering and design student, 2011

going on to say that she was becoming more interested in the 'user' of the design and the artistic considerations. She mentioned having a 'battle' to get a holistic view into design education and to get 'engineers and technologists to appreciate the value of aesthetics' in spite of a lack of enthusiasm for the appearance, so long as the product or design 'works'.

4.5.2.6. Communication

The previous comment led on to a key observation concerning communication between practitioners about subjects. The participant, when explaining to her engineer colleagues/friends about making dresses, likened the processes to making 'a truss or a beam, but instead of working with aluminium, steel and rivets, you're just working with silks and threads.' This is an important observation that an easy way to communicate in many circumstances is the relating of knowledge to the specific area of the individual's understanding.

4.5.2.7. Experience

Additional to each participant's own background experience there was discussion of knowledge gained through experience. Several times it became evident that the participants had a great degree of specific knowledge coming from their various backgrounds in academia and industry. In some cases it was difficult to get the participants to acknowledge this tacit knowledge and none of them was aware of the term 'tacit knowledge' previously. Some tacit knowledge was described in terms of choosing interior architecture materials by tactile and aesthetic values, or knowing the behaviour of certain engineering materials. One reference was made to more senior professionals assuming a correctness in their knowledge based on industry experience.

There was definite acceptance that there was a need to appreciate the knowledge of other professionals or of other disciplines. Mentioned twice was the role of the architect – as the designer – in relation to technical and engineering requirements.

4.5.2.8. Aesthetics

Aesthetics were another recurrent theme. One view was that the aesthetic *can* be of more value than the function – though function is undeniably needed. One view from the textile practitioner was about incorporating the aesthetic value holistically into the project. When talking about tacit knowledge and implied knowledge, aesthetics were commonly mentioned. Aesthetics was also the only 'non-functional' property mentioned by the group, whereas the researcher and the textile practitioner also mentioned tactile properties.

When asked to describe qualities of the knitted samples, aesthetic qualities were the most common, in spite of the declaration of several participants that aesthetics were of less importance than functionality in their practices. There was a contradiction in responses that led to a consensus that aesthetics were not important to practice, but important to consumers (and were important to the participants when responding to the fabrics). When talking about product design in general, one participant stated:

> *No-one gives a damn about function, so long as it doesn't break down….the form is what everyone cares about when looking to buy, you have to factor it in*.

Engineering and design student, 2011

The role of aesthetics to the participants was complicated. Generally, people seemed divided on the importance of aesthetics, though all used it as a default appraisal method during the discussion.

When participants were asked simply if they liked the knitted samples, their response was based largely on the aesthetic – possibly because they found it difficult to imagine a use outside an aesthetic one (in spite of a few having been suggested in earlier discussion), or because it was an easy way in which to appraise something that they did not have much specific knowledge about.

4.5.2.9. Methodology

Finally, methodology was one of the last themes to emerge. One topic discussed which properties were taken into consideration when designing a product or object, the function, the aesthetic or other desired qualities. When discussing previous industry experience, the idea of using value judgements as a method was deemed appropriate, and, when talking of dress-making, the engineer likened the method of creating a dress and a beam. These observations imply acknowledgement of the importance of experiential and practical knowledge in the making of physical objects.
A suggestion in relation to why engineers were not keen to use non-scientific methods was a testing-based consideration, that there was an ease of mind achieved by using laboratory tests and scientific appraisal, especially when working with products with a duty of liability to the consumer.

When asking about how participants appraise their work, one described a change over the course of the Master's programme[46], from a graph-based, testing method to a more qualitative, user-centred method and how it is perceived by others.

The final point on methodology was about the integration of different methodological skills of different practitioners – for example to get in-house structural engineers into architecture practices so as to inform from an engineering or quantitative perspective into an architecture or qualitative perspective, or vice versa. It was suggested that it would be an example of 'best practice' to have in-house input from both technical and design professionals.

4.5.3. Conclusion on analysis

With an evident urge to appraise the samples based on their visual appearance, the group identified several of the same themes that came up when shown to more textile-oriented assessors at a later project assessment stage. One suggestion was that the samples are knitted in other colours and other materials. This could be done by developing samples so that one is repeated using various colours and yarns in order to see the effects of these changes on the specific stitch structures. Any change in yarn is likely to significantly change tactile, aesthetic and functional qualities.

It is an interesting result that participants declared functionality to be important to their practices, but did not address (or check) the auxetic functionality of the fabrics available to them. There were large discrepancies in the idea of the participant as designer and user, with the designer being interested in

[46] The participants were in the final term of their Master's studies, 3 months before submission.

function and the user in aesthetic. Similarly, the role of expertise in an area affected how deeply the participants engaged with the discussion. Participants did not class the fabrics within their areas of expertise, so were limited in thinking of how the fabrics could be used within their practice. The fact that the material in question was a textile was an immediate limiting factor for some involved who struggled (or did not try) to apply the knowledge or structure into their areas of interest.

This leads to the posing of a question: is it really possible to integrate the appraisals of quantitative and qualitative information? A knit design background is interesting in its combined and fully integrated use of quantitative and qualitative considerations and assessment throughout the design process, though it may be true that one of these elements often overtakes the other in priority. In the combining of appraisal methodologies (functional, aesthetic, quantitative, qualitative, etc.), it may be that one element becomes covert and one overt, though both are required in a large number of cases.

4.5.4. Implications for project methodology

From this focus group, several ideas have been raised towards interpreting future information in this study both from my perspective and from that of others:

- Qualitative and quantitative methodology are both present and important in practical and appraisal work.
- Both elements are not always apparent – one may be obscured by the other, or not recognised by the practitioner.
- Though the fundamental knit knowledge may not yet cross into other disciplinary areas, applications for fabrics can be envisaged.
- There are language barriers between the related design subjects.
- Physical properties are of high importance, whether viewed subjectively or objectively.

In the following section, the analysis and observations from the practical development stage and the focus group will be considered for their role in the overall understanding and realisation of this study's aim and objectives.

4.5.5. Theory building

The theory as drawn from the data in Focus Group 1 (FG1) and obtained through practical experimentation and reflection is outlined below in **Table 4.5**. The 'proposition' column shows ideas that guide the research – these may be initial ideas supported by evidence found through the research, or ideas generated through the research. The 'evidence from data' column shows the piece of data that supports or informs the proposition. The 'outcome and actions' column shows how this idea is developed, either at this stage or in the subsequent stages of the study.

Proposition	Evidence from data	Outcome and actions (from across duration of study)
Design and experiential knowledge is appropriate to produce knitted auxetic materials.	Samples 2, 3, 4 and 5	Make explicit the role of design knowledge to the production of fabrics.
Background of FG leader and preconceptions about fabric may cause more fashion applications and discussions than other areas.	Fashion applications were common among participants. Some acknowledged that this was what they thought the fabric was for.	3D-printed materials provide non-fashion application for structures.
Participants who may have had trouble in visualising uses for fabric in their own areas, may desire a gradual move towards familiarity in order to envisage applications.	Colour and material type influenced responses and limited inspiration.	Use and discuss and a wide range of materials and variations.
Tacit appraisal is important, at least as an initial or developmental reaction.	Tacit appraisal is important to all participants, though not overtly understood by practitioners.	Include and draw attention to tacit responses.
Disciplinary allegiance may be overt (but does not exclude influences from other areas).	Individuals acknowledged the influence of their backgrounds on communication and appraisal.	Include and value perspectives of researcher and contributors.
Physical and tactile resemblance is important to appraisal (as seen with simile/metaphor in FG2).	Positive and negative responses were sometimes associated to resemblance to objects from the participant's experience.	Include important physical and tactile information to allow these responses.
Disciplinary background and focus group format may impede handling. Inclusion of dedicated textile practitioners will give a different response.	Participants were tentative about handling fabrics.	Use mixed groups and encourage a more informal focus group set up.

Limited textile process understanding leads to negative connotations.	Textile processes were seen to be a making limitation.	Use of textile structures in different materials and via different processes. Encourage more comprehensive understanding of processes – illustrate range and potential.
A pragmatic comparison can be made from textile or fashion design to other making disciplines. Knowledge transfer (KT) can be helped by relating understanding to others' specialisms.	Dress-making was likened to engineering, using a substitution of materials and processes.	Generic comparison may help to inform understanding of processes. Use different ways of presenting information to encourage understanding.
'Polar' design disciplines may not be the best way to teach design.	Polarisation of design disciplines is a problem. Education systems should aim to be more inclusive leading to better understanding.	Cover different disciplinary bases in thesis to encourage understanding. Look for more developed solutions.
Aesthetic and sensory responses can be an important contributor to reactions and value judgements.	Aesthetic properties were important to the participants – especially when taking a product through to market, in appraisal and reaction.	Include aesthetic/sensory comment where possible.
Tactile properties are not important to all practitioners.	Tactile properties were not important to this group of participants.	Less tactile emphasis needed for non-textile practitioners.
Value judgements are often used by and important to practitioners – this links in to tacit knowledge. Individuals' expertise is an important source of information.	Value judgements deemed appropriate in practice at making and assessment stages.	Include own value judgments and acknowledge those of others. Recognise own expertise and that of others.
These practitioners rely on testing (mainly quantitative) and measuring to back up their designs.	Engineering practitioners rely on testing when liability could be a problem.	Acknowledge the importance of testing to certain communities, practitioners and applications.

Mixed-methodology can diversify innovation and development in design work. Addition of other methodologies to own practice can be beneficial.	Mixed-methodology was important to participants – some had changed from quantitative to include some qualitative and others acknowledged the importance of collaborative work in development.	Indicated possibilities for mixing of methodologies – highlight examples of this.

Table 4.5 Theory building from focus group and practical data.

4.5.6. Changes to study and focus group as a result of the pilot study

The subsequent sample stages of this study will include more emphasis on material and other variations such as scale, pattern and visual alterations. This will complement the feedback from both the first focus group and meetings with supervisors and examiners at an interim assessment stage[47]. These changes will be manifest in the knitting of samples in a range of materials for both their aesthetic and tactile qualities as well as the effect this might have on their auxetic nature. Samples will continue to be informed by experiential knowledge and assessed via the proposed methods. The evaluation matrix will continue to be used for the subsequent stages.

In the focus group there will also be changes in the subject or disciplinary background of participants recruited. It is desired to have a range of practitioners from product design, textile design and knitwear design. Over the course of the next focus groups this will expand to include engineering, textile and design students and professionals.

4.6. Knowledge transfer

After the end of the pilot stage Hu, Wang & Liu[48] released a paper (2011) stating that the 2010 (Liu et al.) paper had been based on Miura Ori origami patterns and then proceeding to add to the range of weft-knitted auxetic fabrics by turning attention to rotating shapes and re-entrant hexagons. The second paper described the addition of elastomeric yarn to some of the acrylic samples, an alteration that I had made to the fabric from their first paper (due to my experiential garment-making knowledge). This subsequent acknowledgement indicates the presence of these considerations in the development process, though they were not explicitly stated in the original publication.

In this study, the subsequent chapters describing practical development stages will include detail on the progression of testing considerations after initial testing and reflection. Because of the feedback from

[47] A project approval meeting was conducted by the NTU graduate school after the first 6 months of the study to discuss and approve the direction of work.
[48] Liu and Hu are part of the same research group at Hong Kong Polytechnic. The papers are written by similar teams, but have different lead authors.

participants favouring quantitative testing, it is worthwhile including more detailed and meaningful quantitative data in discussion and publications.

Adopting proposed changes for Stage 2 of sampling onwards will encourage greater engagement from focus group participants and other practitioners who see the fabrics and information through dissemination. Added visual interest and variation, as well as alternative yarns providing different aesthetic and tactile qualities, will enable the fabrics to appeal to different types of practitioners and provoke different responses. This will help align the work to the objectives of incorporating viewpoints from other practices to identify specialist and generic needs within design practice and knowledge transfer.

During this pilot study, a research paper for a Smart Design conference[49] saw the first public dissemination of this auxetic fabric development to a mixed design audience. During the presentation, videos of the fabrics moving were used to show auxetic behaviour to the audience. The percentages showing auxetic behaviour from the preliminary fabric measuring were presented (and published in the proceedings) to indicate auxetic behaviour. The simple mathematical information and visual representations received positive feedback from the conference audience and corroborated the usefulness of simple and visual information to be featured throughout this study.

4.6.1. Personal reflections

The undertaking of a pilot study allowed me to reflect on a methodology that, though familiar, was being applied in an unfamiliar situation. The notation of technical information and the generation of reflective information are common to my design practice, but have not previously been explicitly recorded in the same documents. The collation of the information from this pilot study into a tabulated form (the modified evaluation matrix format) will help keep information from this stage clear and relevant in the development of subsequent practical stages.

4.7. Chapter Conclusions

After beginning a complex area of study, which draws upon many different contexts, aspects and knowledge from sometimes opposing disciplines, it is necessary to assess how well this has been addressed. The primary aim of this pilot study was to attempt to work together all the strands of proposed research to see how they interconnect. It asked whether conclusions can be drawn from the combination of practical, theoretical, quantitative and qualitative strands; and also what conclusions can be drawn about the role of each individual strand.

Regarding the production of physical, auxetic artefacts, there are obvious successes in the production of four new auxetic samples in the forms of Samples 2, 3, 4, and 5. Some of these were largely influenced by the work of Liu et al. (2010) but utilised a different method of design than in the original study. This combination of designing for structural or pattern aesthetic and experiential knowledge has proved to be successful in the construction of auxetic, weft-knitted samples.

[49] 1st International Conference on Smart Design, NTU November 2011 (Glazzard & Breedon, 2012)

An inevitable part of the outcome of this process has been an increased awareness of the methods employed, both within traditional areas of knit design for fashion or aesthetic purposes, and within designing knit for functional or engineering purposes. This has added strength to the plausibility of using methods from aesthetic knit design in the production of functional textiles. As discussed for Sample 1a, experiential knowledge from knit design has achieved results in improving usability of fabric from the scientific viewpoint (the addition of elastomeric to Liu et al.'s sample[50]).

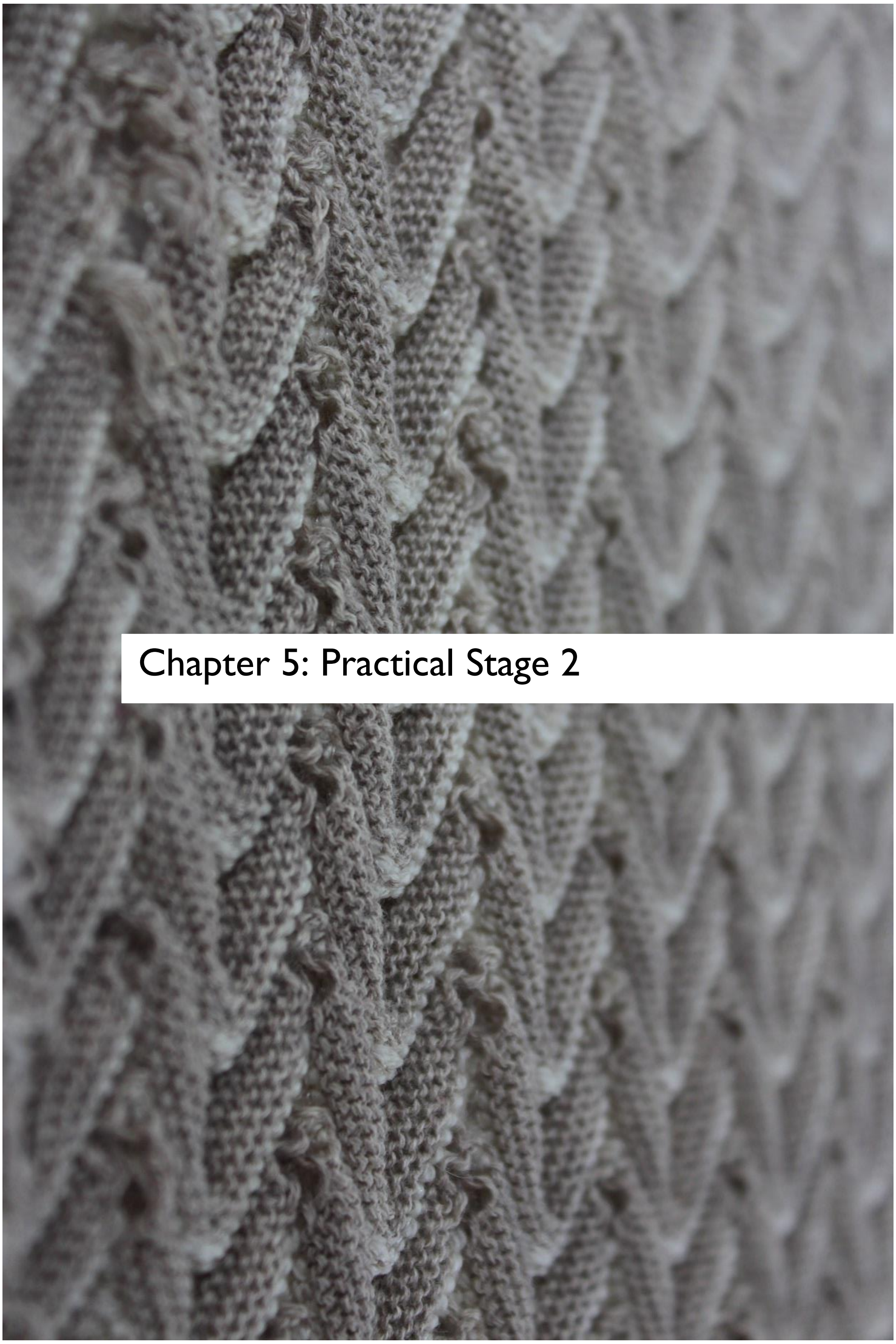
The methods of documentation have been key in trying to express both the similarities and the differences in the various approaches to creating functional knitted fabrics. It has been difficult to coherently combine the different approaches and this will require further work through the following stages of research. In laying out the results on one sheet in the style of the spread sheet/evaluation matrix, it has been useful to have objective and subjective information on one page; however, at this stage they are still not fully integrated. This opens discussion as to whether quantitative and qualitative can (or should) be combined in this way; whether there will be the correct audience to receive such information and whether this makes the research appear overly complicated, potentially alienating certain readers. To return to the main aim of this study to 'assess the value of a knit design methodology', it is necessary to persevere to present this mixed information in inclusive and integrated ways in order to represent the mixed-method nature of a knit design process.

The first focus group was successful as a research method, but requires development. Although there were interesting responses to do with discipline and methodologies of appraisal, there were still many questions left unanswered. Participants need to be encouraged to think in different ways about the featured fabrics and allowed to respond in a variety of ways to certain questions (such as those about discipline and their own practices). The subsequent focus groups will be carried out with a more diverse range of participants including those from textile-based or more design-focused disciplines. Some of the participants from the pilot study found it difficult to relate to textile processes, or appraise the aesthetic or tactile elements. It is hoped that in an environment with a greater mix of disciplines, that the discussion will become more lively and varied around appraisal and perspective. How to encourage non–textile practitioners to engage with textile processes, materials and thinking will be an outcome of this research.

The fabric sample set from this stage has shown significant promise for development. Development began from the initial replication of Liu et al.'s fabric and this led to variations and also inspired departures into original auxetic structures. From this experimentation with fabric and stitch structures, there were several non-auxetic samples, (which displayed ranges of three-dimensionality,) there were also some samples that displayed noticeable auxetic effect.

[50] Though in a later paper Hu, Wang & Liu (2011) added elastomeric yarn to their samples, this was not in the first paper and was published after the completion of this pilot study. Liu et al. and Hu et al.'s teams both contained knitting experts so the experiential knowledge used to include elastomeric is comparable, but may have different motives and be acknowledged differently.

The pilot study tested the proposed methods for obtaining information necessary to document a methodology structure for knit in relation to transferrable and adaptable knowledge. For this purpose the pilot study was a successful format. After minor changes, the methods will be refined to uncover both more wide-ranging and more focused input. Due to the success of the pilot study, the results of this stage will be included in the final results of the study.



Chapter 5: Practical Stage 2

5. PRACTICAL STAGE 2

5.1. Introduction

Stage 2 develops the practical and theoretical findings from the production of auxetic, knitted materials in the pilot study (**Chapter 4**). The format for Stage 2 remains largely unchanged from the pilot study but fabrics are further developed through experiential knowledge and using feedback and personal reflection and focus groups from Stage 1.

5.1.1. Information from pilot study

The initial trials from Stage 1 used wool and elastomeric yarns known through experience to work well with knitted structures. In this chapter there is greater emphasis on the choice of yarns used for knitting samples. This includes the tactile, aesthetic and performance-based properties of the materials used, in response to the feedback from focus group and assessment stages. When different materials are being used, the measuring and appraisal of samples remains standard to allow for comparison of materials on both auxetic and subjective results.

The inclusion of experiential knowledge from knitted textile design has been positive in the development of this study. This knowledge is a central concern to the development of the overall thesis. The use of knit design knowledge is continued and reflected on during Stage 2 where its role will be emphasised. This informs the sampling stage as well as the methods of appraisal of samples in terms of subjective values.

The evaluation matrix style of sample documentation proved to be a useful method as it allowed for the inclusion and organisation of both qualitative and quantitative data. The data can then be cross-referenced and compared. For the focus group in this stage (FG2), participants are drawn from a more diverse disciplinary background, which includes the addition of textile practitioners as well as those from product and engineering backgrounds.

5.1.2. Format of stage

The process of Stage 2 and the methods used are largely the same as in the pilot study in Stage 1. The main change for the knitting stage is that, rather than taking lead from an external research paper, original designs are derived from experiential knowledge or based on geometric, auxetic information.

5.2. Knitted samples

The samples detailed in this chapter show the overview of the processes and structures developed. The fabrics featured in this section are those that are successfully auxetic. For information about the other fabrics that show the design development process please see **Appendix B**. As with Stage 1 the fabrics are discussed in relation to their success in the making process, aesthetic qualities and auxetic behaviour. The numbering of the samples continues in sequence for the samples featured in the main body of the thesis. The names shown in brackets can be used to identify the samples amongst the full sample sets in the appendices.

There are two main stitch structures featured in the samples outlined below. Those named Transfer Purl 4 (TP4) are all variations on one stitch structure. Some of these variations take place in the programming[51] and some in the yarn selection. Samples called Transfer Purl 5 (TP5) are also variations on one stitch structure.

5.2.1. Sample 6 (Transfer Purl 4 [TP4] version 2)


(a)


(b)

[51] E.g. In order to add stripes to a Stoll-programmed fabric the change must take place at the programming stage rather than at the machine.

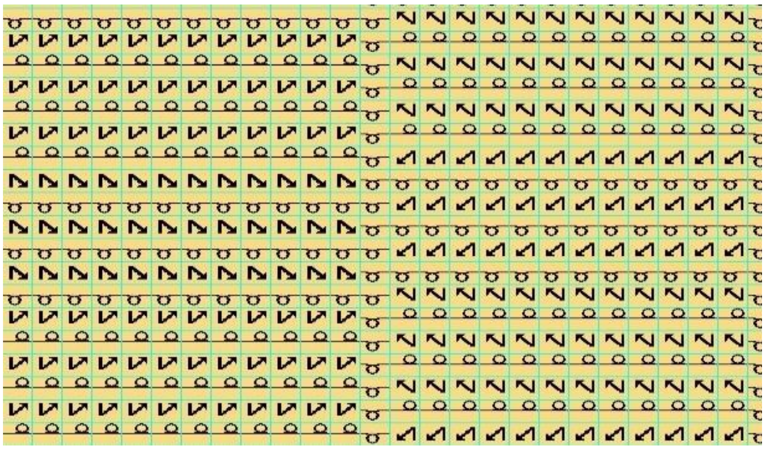
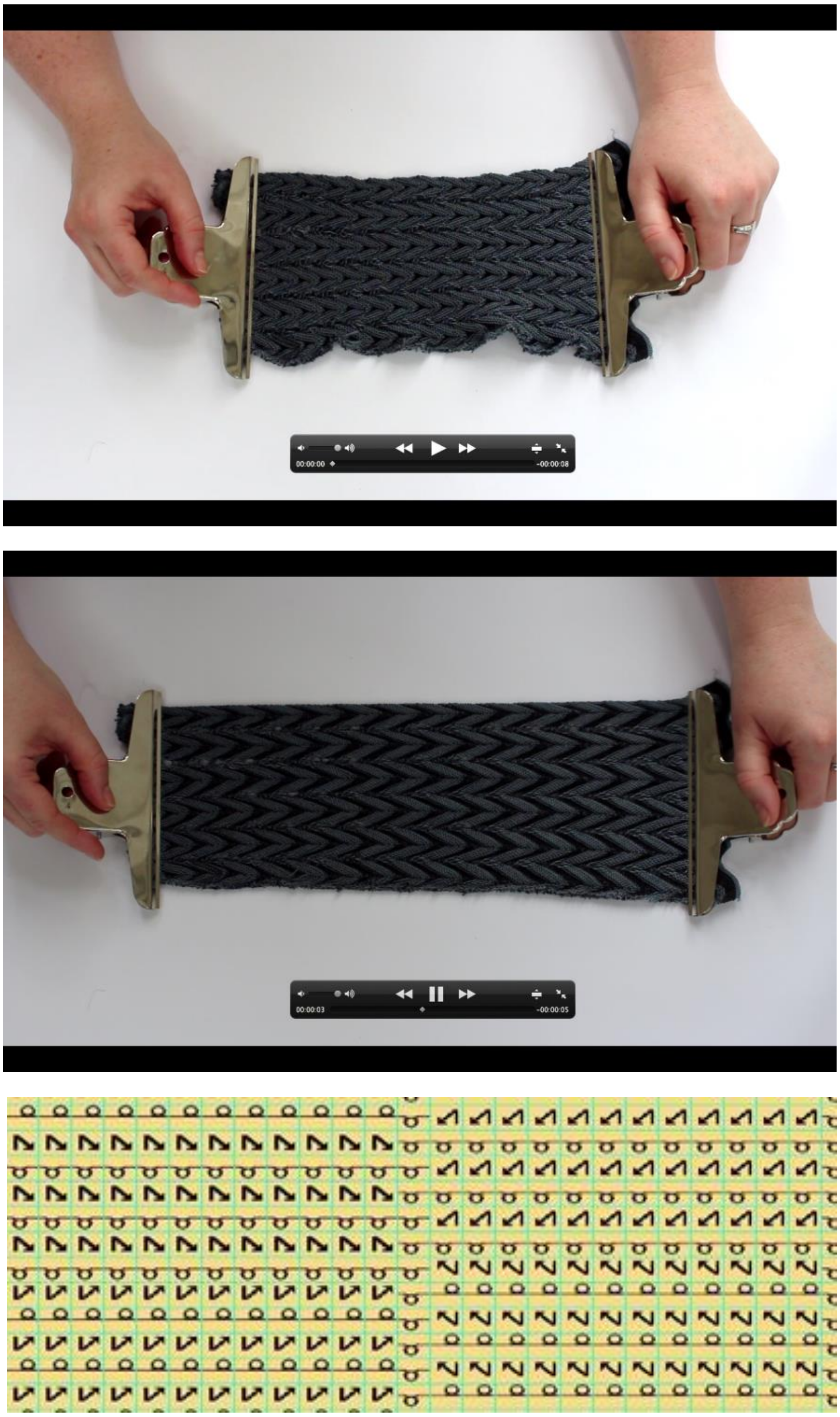
(c) 

Figure 5.51 Sample 6 (Transfer Purl 4 v2) knitted in wool and elastomeric at rest (a) and stretched in Y-axis (b) with Stoll programming chart (c).

The double arrowhead pattern from auxetic literature (as shown in Larsen et al., 1996) was used as inspiration for auxetic knitted fabrics. Initial, literal interpretations of this pattern (such as using the pattern information directly transposed into a relief or transfer pattern) resulted in flat, non-auxetic fabric. Because of this unsuccessful attempt, a re-interpretation of the double arrowhead pattern was developed using experiential knowledge. The idea of purl rib was continued from Sample 5 and the zigzag 'arrowhead' aspect was added by repeatedly transferring sets of stitches towards a central needle (this gives the horizontal zigzag effect shown in **Figure 5.51**).

During preliminary measuring of Sample 6, extension in the length (Y-axis) to 151% was found to cause expansion in the width (X-axis) to 113% of the original measurement. The visual effect of the fabric is partly that of the double arrowhead, and partly like a rotated version of Liu et al.'s (2010) auxetic relief fabric (due to its more regular zigzag effect).

5.2.2. Sample 7 (TP4 Version 2 [plated wool/nylon])



(a)

(b)

(c)

Figure 5.52 Sample 7 (TP 4 v2 plated wool/nylon) knitted in black wool plated with blue nylon. Shown at rest (a), stretched in Y-axis (b) and with Stoll programming chart (c).

In reaction to feedback from Stage 1 calling for more colour and pattern variation, in Stage 2 simple knit design techniques (in this stage plating and striping) were explored and discussed for their effects on aesthetic and auxetic outcomes. Sample 6 and 7 use the same programme and stitch structure (seen in the charted information in **Figure 5.52**) with different yarns used to knit the fabric.

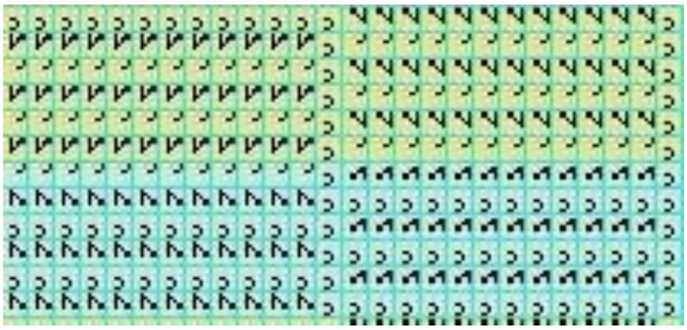
In Stage 1, plating was used to incorporate elastomeric yarn into the fabrics. Plating can also be used to highlight the contrast between the face and reverse stitches (method discussed in section **2.3.2.6.**). This can introduce a colour element, but also different fibre types to provide texture or other qualities to the fabric. In Sample 7, the two yarns plated together have different colours and yarn compositions. **Figure 5.52** shows black wool plated with blue nylon. Due to the stitch structure the reverse stitch is showing more on the fabric, so the blue nylon is more prominent. One advantage of adding a plating to an auxetic fabric, is that when stretched, as well as the fabric increasing in size, there will be a visual indicator showing the black yarn being exposed as the fabric structure opens and expands. The effect from the plating when the fabric is stretched adds an interactive feel to the fabric and a distinct aesthetic behaviour.

Preliminary auxetic measuring from this sample showed an extension to 158% in the Y-axis and an expansion to 113% in the X-axis. This gives a similar result to the fabric knitted in wool (with elastomeric), meaning the change of yarns did not greatly affect the auxetic effect in this case.

5.2.3. Sample 8 (TP4 polyester stripe)

(a)

(b)



(c)

Figure 5.53 Sample 8 (TP4 with stripes of polyester) knitted in polyester and wool/elastomeric Shown at rest (a), stretched in Y-axis (b) and with Stoll programming chart showing stripes (c).

Sample 8 also incorporates colour and yarn interest into the TP4 fabric with the addition of stripes. As with plating, adding stripes can be used for incorporating changes of colour or texture/fibre composition.

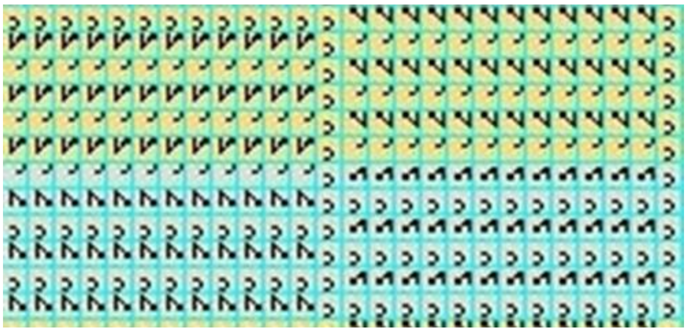
Similarly to Sample 7, when stretched, the visual effect is linked to the auxetic effect. The stripes are placed so they correlate with the sections of the purl rib (as seen in **Figure 5.53** where the creamcoloured wool comes forward and the grey polyester recedes). In **Figure 5.53** the prominent colour is the cream, but turning this fabric over shows the grey to be prominent on the other side. When Sample 8 is stretched, the prominent colour will make way to expose more of the recessive colour – adding an extra visual, interactive element to the auxetic behaviour when stretched (as with the plating in Sample 7). I found that the effect of adding stripes to this fabric made a visually interesting structure (Sample 6), into a very visually engaging fabric.

As with the plated sample, the change in fibre type did not greatly alter the auxetic effect when shown in preliminary measurements. An extension to 148% in the Y-axis gives an expansion to 115% of the original size in the X-axis.

5.2.4. Sample 9 (TP4 Version Monofilament)

(a)

(b)



(c)

Figure 5.54 Sample 9 (TP4 version monofilament) knitted in polyamide monofilament and wool with elastomeric.
Shown at rest (a), stretched in Y-axis (b) and with Stoll programming chart (c).

Sample 9 substitutes the grey polyester in Sample 8 for a polyamide monofilament (Samples 8, 9 and 9a use the same programme [shown in the chart in **Figure 5.54**] but are knitted in different yarns). The principle of auxetic fabrics unfolding (as with the samples in Stage 1) may be likened to the geometries from auxetic literature, comprising units with ligaments that force the structure to unfold or unfurl. Samples 9 and 9a experimented with variations in yarn stiffness to encourage sections of the fabric to 'push out' against one another.

Polyamide monofilament used in knitting provides a stiff structure without as much drape as a fibrous yarn would have. The polyamide monofilament yarn, however, does not provide a distinct 3-dimensional structure like many yarns with fibrous content do. If knitted with only a polyamide monofilament, the stitch structures used in this study result in flat, featureless fabrics. For this reason the monofilament was used in stripes (as seen in **Figure 5.54**), which allowed the wool and elastomeric to provide the 3-dimensional structure and the monofilament to provide a contrast in stiffness and texture helping to push against the rest of the structure.

The aesthetic of the fabric I found to be particularly pleasing, with the monofilament making 'transparent' sections, which increased in area when stretched (when viewing the technical front of the fabric in this case). The fabric becomes more transparent and porous as it is stretched. Out of the samples in Stage 2, this yarn and structure combination (after preliminary measuring) was found to be the most auxetic. An extension to 160% of the original size giving a transverse expansion to 126%.

5.2.4.1. Sample 9a (TP4 version monofilament 2)

Sample 9a was a repeat of Sample 9, but with the tension on the polyamide monofilament tightened. This was intended to make the stiffness of the monofilament sections more pronounced, but in reality made the sample difficult to knit. This meant the knitted fabric had many holes in it. In the preliminary measuring an extension in the Y-axis to 152% caused an expansion in the X-axis to 117%. Though the fabric was in many ways unsuccessful, I include the information here to demonstrate how much difference changing one aspect such as the tension can cause. Though the fabric was auxetic, it was considerably less auxetic than Sample 9, though the only change was a tightening of one point[52] on the tension of the monofilament. It is worth noting that although some variations (like tension) may produce large changes, other variations (like changing the yarn) may act differently. A change in yarn could produce a slight change (such as between the auxetic effects of Samples 6, 7 and 8) or a noticeable change (such as the larger auxetic effect in Sample 9 than that in Sample 8).

Because of this unpredictability in knitted structures, experiential knowledge is vital when judging the pros and cons, and when making adjustments to a fabric. Because a designer-maker is in control of all decisions surrounding the artefact being made, they will need to keep notes and samples that build up a better understanding of changes in each project. These notes can be seen in **Appendix B** and sketchbook pages in section **3.7.**

[52] Tensions are often changed in increments of 0.5. Tension adjustment varies greatly, but changing the tension by one point is not likely to be seen by an experienced knitter to be a radical change in tension.

5.2.5. Sample 10 (Transfer Purl 5 [TP5] Version 2)


(a)


(b)

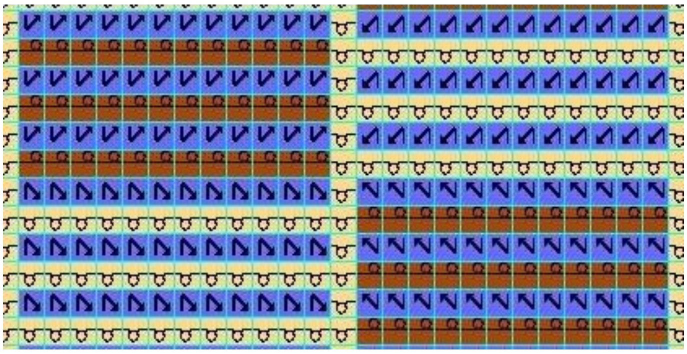
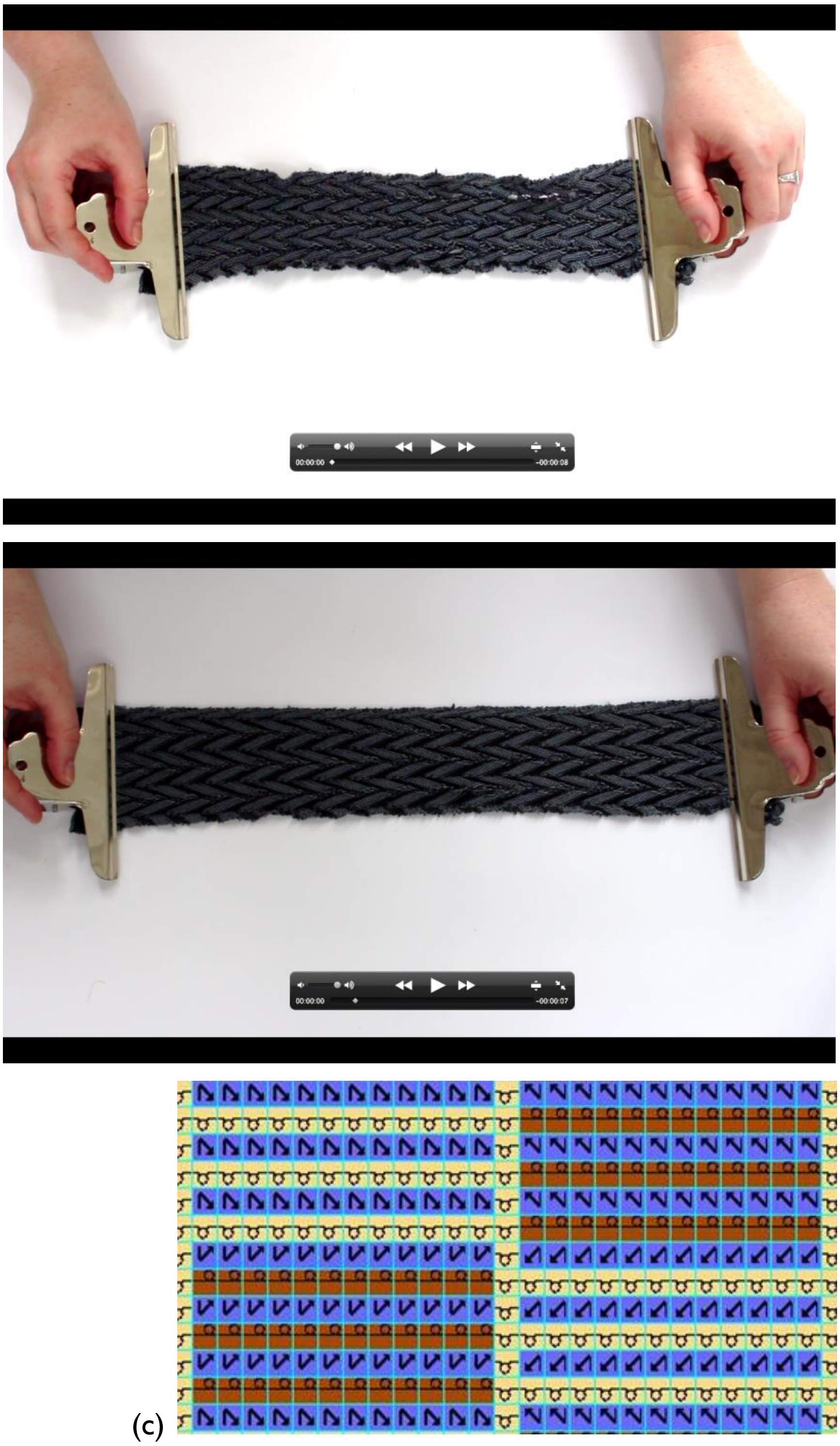

(c)

Figure 5.55 Sample 10 (TP5 v2) in wool and elastomeric at rest (a), stretched in Y-axis (b) and with Stoll programming chart (c).

Sample 10 introduces a development from the TP4 samples. Transfer Purl 5 (TP5) is a variation on TP4 where the purl rib is not continuous, but staggered. The face and reverse stitches create blocks, which interleave and become a 'herring-bone' pattern (as shown in **Figure 5.55**). On the surface, this pattern is reminiscent of the rotating-squares geometry from auxetic literature (Grima & Evans, 2006). When stretched flat, however, the structure itself is more like a staggered zigzag pattern or a basket weave pattern (like in Sample 4). I found the visual result to be pleasing and traditional. It is reminiscent of traditional designs such as ‘herring-bone’ tweed, brickwork or tiling.

When stretched and measured, a Y-axis extension to 152% showed an X-axis expansion to 111%. This stitch structure also shows an auxetic effect, though the effect is less pronounced than those of the TP4 samples.

5.2.6. Sample 11 (TP5 Version 2 [plated])



(a)

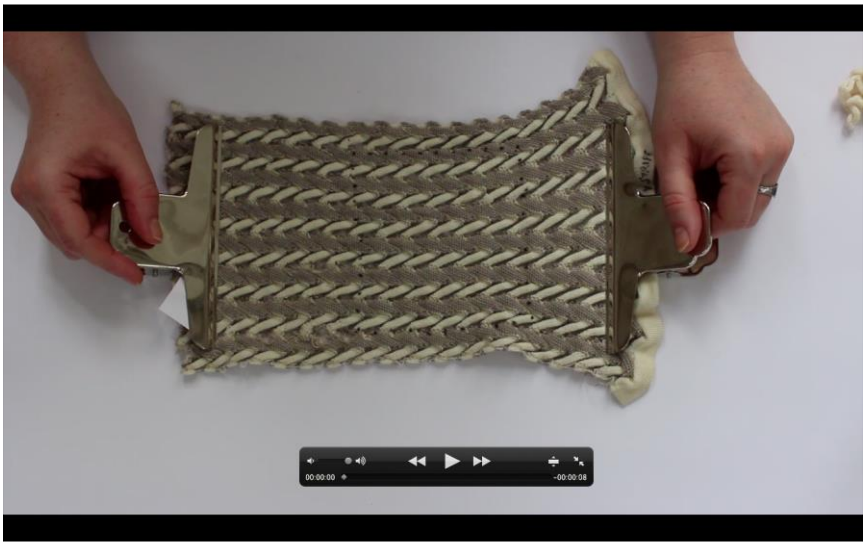
(b)

(c)

Figure 5.56 Sample 11 (TP5 v2 plated) knitted in black wool and blue nylon. Shown at rest (a), stretched in Y-axis (b) and with Stoll programming chart (c).

As a plated version of the TP5 structure, Sample 11 shows a similar result to the plated sample version of the TP4 samples (Sample 7). This plated version of TP5 gives much the same auxetic effect as Sample 10 (Y-axis extension to 152% and X-axis expansion to 112%). The interesting aesthetic qualities (as seen in **Figure 5.56**) at rest and when stretched are still present as with the TP4 plated version, but the distinction between the face and reverse stitches is not as pronounced due to the change in stitch structure.

5.2.7. Sample 12 (TP5 Version Stripe)



(a)

(b)

(c)

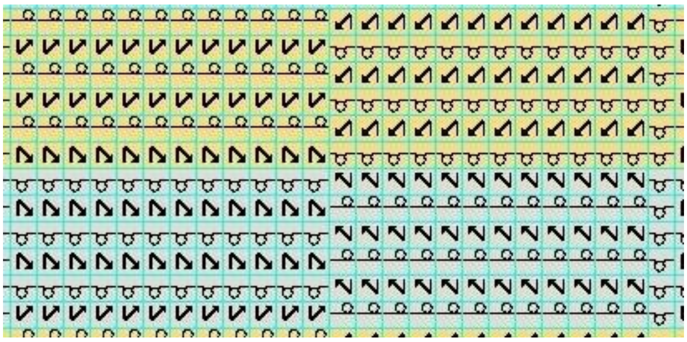


Figure 5.57 Sample 12 (TP5 Version Stripe) knitted in polyester and wool/elastomeric at rest (a), stretched in Y-axis (b) and with Stoll programming chart (c).

In Sample 12, a stripe is incorporated into the relief pattern. A contrast colour polyester stripe is added that alternates with the cream wool stripe in co-ordination with the changes between face and reverse stitch stripes (the purl rib element of the sample). Because the purl rib in this fabric is broken, the stripes are also broken by the way the structure forces certain stitches forwards and backwards.

As with Samples 10 and 11, the surface appearance at rest is that of a herringbone pattern. The addition of stripes to the stitch structure produced the appearance of having columns of contrast colour (as can be seen in the grey and cream columns in **Figure 5.57**) giving the illusion of vertical stripes in the fabric. When stretched, the fabric shows a regular, horizontal zigzag contrast. This effect is aesthetically interesting and can be altered in subsequent stages by changing the colours and the scale of each unit (currently 6 courses by 12 wales). Again, the auxetic effect remains similar to the other versions of the TP5 fabrics with a Y-axis extension to 141% giving an X-axis expansion to 112%.

5.2.8. Conclusion on practical stage

As this study leads towards Stages 3 and 4, there will be a continued experimentation in materials and scale for auxetic, tactile and aesthetic effects. In addition to the reflection on the samples produced in Stage 2, the preliminary measuring is discussed in **Table 5.6** to demonstrate the findings quantitatively.

Table 5.6 shows the results of the preliminary measuring for Stage 2. Of the TP4 fabrics (Samples 6 - 9a), Sample 9 has the most auxetic behaviour. From the TP5 fabrics (Samples 10 -12), Sample 12 has the most auxetic behaviour. The most significant increase in auxetic behaviour came from the addition of monofilament to the TP4 structure.

Sample name	At rest width (X) (mm)	At rest length (Y) (mm)	Width / X-axis stretch		Length / Y-axis stretch	
			extension (X) measurement (mm)	transverse (Y) expansion measurement (mm)	extension (Y) measurement (mm)	transverse (X) expansion measurement (mm)
Sample 6 (Transfer Purl 4 [TP4] version 2)	160	240	-	-	365 (151%)	180 (113%) PR = -0.240
Sample 7 (TP4 Version 2 [plated wool/nylon])	115	310	-	-	490 (158%)	130 (113%) PR = -0.225
Sample 8 (TP4 polyester stripe)	165	320	-	-	475 (148%)	190 (115%) PR = -0.313
Sample 9 (TP4 Version Monofilament)	155	300	-	-	480 (160%)	190 (126%) PR = -0.376
Sample 9a (TP4 Version Monofilament)	145	280	-	-	430 (153%)	170 (117%) PR = -0.322
Sample 10 (Transfer Purl 5 [TP5] Version 2)	150	256	-	-	388 (152%)	167 (111%) PR = -0.220
Sample 11 (TP5 Version 2 [plated])	105	325	-	-	493 (152%)	118 (112%) PR = -0.240
Sample 12 (TP5 Version Stripe – polyester & wool)	152	327	-	-	460 (141%)	170 (112%) PR = -0.291

Table 5.6 Results of preliminary measuring of samples from Stage 2 for auxetic behaviour. The highlighted cells show where auxetic behaviour was achieved. Poisson's ratio shown as PR value.

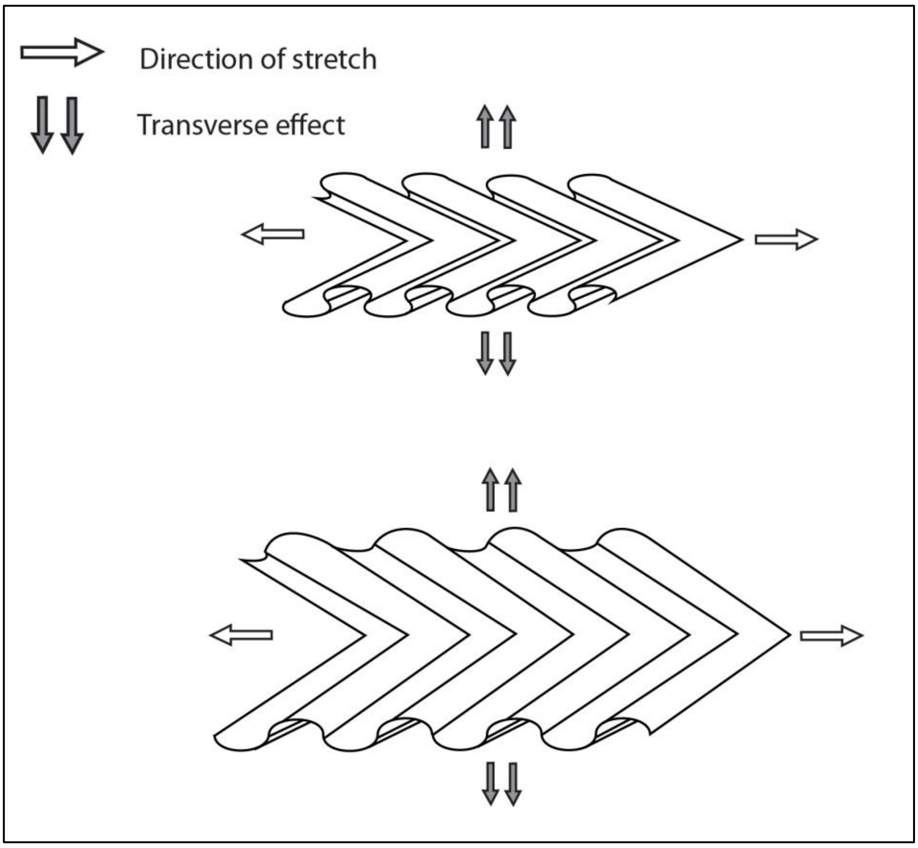


Figure 5.58 The structure from TP4 represented in diagrammatic form.

The fabric structure known as TP4 was found to be a significant and interesting structure in this study. The diagram **Figure 5.58** shows my representation of the action of the auxetic behaviour from this structure. The diagram is based on tacit understanding of the fabric, rather than technical reproduction of the stitch structure. This diagram forms the basis of 3D-printing work described in **Chapter 8** and is used as a way of describing the auxetic effect of this fabric to participants in focus group 4 (**Chapter 7**). The pictorial diagram is presented here as an alternative to mathematical auxetic geometries.

The design in this practical stage developed beyond looking at existing auxetic fabrics and geometry design for inspiration. Instead, the development focused on applying experiential knit knowledge into design interpretations of auxetic geometries. The ability to imagine significant changes and visualise outcomes through design is an important part of the design process (Eckert & Stacey, 2000: 526), as is recognising the discrepancies between inspirations, plans, programmes/patterns and the final outcome. The double arrowhead in this stage acted as a design inspiration rather than a rigid guideline. Reflection, analysis and development are key methods during the practical knitting stages of this study and this stage demonstrates a journey through how a knit designer may approach a design task. Variations through sampling are an important process to develop knowledge and understanding of materials and structures.

Experimentation with different yarns and yarn combinations within the same structures (TP4 and TP5) mostly showed only minor changes in the auxetic effect as described by preliminary measurements. In one case, substituting a yarn with very different properties (those of a stiff, polyamide monofilament, in place of a soft, fibrous, multifilament yarn) increased the auxetic behaviour substantially. In contrast, some yarns (such as cotton or the monofilament when used for the whole fabric) did not create a textured and auxetic fabric, but a limp and uninteresting fabric that was not pursued.

Experienced knitters (or makers of any kind) will know how difficult the making process can be. Material and artefact can both behave in unpredictable, changeable or even fickle manners. This is shown through the practical development in this stage that in spite of experiential knowledge in the knit field, the results of some experiments (across the whole practical stages) provided counter-intuitive results. Because of this tendency for knit to behave in unpredictable ways, this thesis questions the use of rigid rules for modelling and predicting behaviour of knit structures. Large numbers of variables carry different impacts and weighting, making knit a complex and difficult subject to master. If favouring deductive methods, each variable may be explored, but as can be seen in the results of changing the yarns for each stitch structure in Stage 2, not every variable will make a noticeable change to the results and the number of variables adds serious limitations to the time to explore creatively. It is my opinion that the best way to deal with the unpredictable and complex errors that knitting throws at the maker is to embrace them and to be adaptive, reflective and inventive. An adaptive, reflective approach is capable of seeing the discrepancies between actions and their effects and respond. I believe experiential knit design knowledge to be largely based in understanding those discrepancies.

5.3. Focus group stage and analysis

Focus group 2 (FG2): 27th October 2011 (duration 1 hour)

As with the pilot study, a focus group is used to discuss the fabric samples and receive feedback on the fabrics, results and processes from the study. Each focus group is cumulative and features samples from the current stage and the previous stages. The focus group was recorded with audio and video recorders.

Due to the interesting results from FG1, the format of focus group 2 (FG2) had no significant change from FG1. FG2 contained similar questions to FG1such as:

- How might you use these fabrics/structures in your own practice?
- If you would not, how might you change them or enhance them?
- What are your initial reactions to the fabrics?
- Do you consider yourself to be part of one or more disciplines?
- Do you consider yourself to be a designer?

The main addition to FG2 was an informal task that asked participants to indicate where they considered their practice to be situated on a line showing design at one end and engineering at the other end (results from participants are shown on this line in **Figure 5.59**).

5.3.1. Selection of participants

A call for participants was sent out to a wide range of Master's and research students, though scheduling problems resulted in a small group of 6 participants from across Smart Design, Product Design and Textile Design. The participants consisted of:

- The author/researcher
- MA Smart Design student – background in woven textile design
- MSc Smart Design student – background in product design
- MA Product Design Innovation student – background in product design
- MSc Smart Design student – background in chemical engineering
- MA Fashion and Textiles student – background in textile crafts, knit and felting.
- Lecturer in embroidered Textile Design.

5.3.2. Analysis – Themes

The analysis of the focus group starts with coding into themes of information (as shown in **Table 5.7** and which can be grouped into larger 'parent themes' for comparison with other focus groups.

Parent theme	Sub themes	FG2: number of responses
Physical	Properties	13
	Material	9
	Scale	1
	Structure	3
Knowledge	Knowledge	8
	Knowledge transfer	3
	Understanding	0
	Experiential	2
	Tacit	1
Qualitative	Qualitative	6
	Tactile	6
	Aesthetic	6
	Emotional	2
Quantitative	Quantitative	4
	Results	1
Applications	Applications	10
	Industry	2
	Fashion	4
	Function	2
Communication	Communication	3

	Language	2
	Simile	1
	Collaboration	3
	Education	1
Discipline	Discipline	13
	Practice	6
	Methodology	14
	Process	6
	Design	1
	Engineering	0
	Craft	0
Change	Change	3
Positive	Positive	6
Negative	Negative	0

Table 5.7 Themed responses from focus group 2 (FG2).

5.3.2.1. Methods

The dominant theme of the focus group was the methods used in participants' respective practices and their reflection on wider disciplinary practice. Participants gave the impression of not having a very clear idea of the methods practised in disciplines other than their own (or even in other areas of their own disciplines). When individuals mentioned their methods, clarity was sought from others on various processes, elements, and ways of handling or thinking about materials. One participant from a chemical engineering background cited the use of material databases for material selection, which was common practice in chemical engineering where materials' physical attributes are not a major concern (or when materials are problematic, as when dealing with hazardous substances). This was a technique much at odds with the textile practitioners' methods. The textile practitioners were surprised by the lack of opportunity to interact with the materials chosen in a tactile or aesthetic capacity.

One product designer suggested that my methods used to make the batch of knitted samples (without an application or purpose specified at the beginning) as 'not the normal or the main way of going about designing something' based on their experience in product design education. Though an alternative point of view was offered from an engineer about the choices of the method being 'solution driven' or 'problem driven' with the samples here being solution driven. Attempts were made to liken one person's practice to another's in order to aid empathy and understanding.

The textile practitioners all accepted a general similarity in the preferences they had for design methods. The general consensus was that combining the methods of other disciplines would contribute a positive effect when working on any project, especially a collaborative project. Several participants were enrolled on the same Smart Design masters course[53], and found the exposure to different methods educating and rewarding. Generally, where the methods used or discussed were unusual or unfamiliar to participants, each responded inquisitively rather than dismissively.

5.3.2.2. Properties

As with FG1, the subject of material properties was a common theme. The two participants with textile backgrounds were both explicit in talking about the fact that they assess the properties (such as strength, size…) of the textiles they are making during development. The product design and the chemical engineering participants would both assess the material or mechanical properties of any material before undergoing a process of ideation – looking at 'where the properties suit the function' (something which is not always possible when constructing textiles, which require several processes before the material properties can be analysed[54]). The property information in textiles was considered by the group to be an important factor if the fabric is going to be replicable or suitable for the desired outcomes. From my own perspective, I would add that factors, such as the yarn choice and the fabric quality, are property driven, as, if those properties are not taken into account, the fabric will not meet the high specifications required by designer or client for almost all uses. The impression given from the product and engineering backgrounds, regarding the use of the material tables, was that qualitative properties were not as important as the mechanical and material properties.

The textile practitioners were keen on qualifying fabrics in terms of visual and tactile properties, whereas the others were often content with written information, possibly not seeing physical samples until several steps along the design or development process.

The knitted sample properties were appraised both in tactile and visual manners by all participants. The mechanical property of the auxetic behaviour was soon forgotten from discussion and the focus was on how the materials felt and looked and what connotations they had with individuals – including the non-textile practitioners.

5.3.2.3. Applications

Applications were a common theme despite the lack of any direct questions about applications for auxetic fabrics in the focus group format. The general instinct of participants was to propose a standard fashion application, though it may have an extra element such as movement or growth inspired by the auxetic nature. Curtains that change size were another suggested application.

Application was also discussed in relation to the methodology used; one concept was designing for a purpose, and how that process or purpose might change as the fabric develops. One textile practitioner said that 'the fabric might not change a lot, but what it's for might change', as she goes through the development.

[53] The course promotes interdisciplinary work and group projects.
[54] The material properties cannot always be estimated from yarn alone and must sometimes be derived from the final textile material (e.g. a polyamide monofilament is non-porous, but a knitted fabric is porous).

A further observation on application focused on the properties of the fabrics from Stage 2 that showed a change in colour when stretched. One participant suggested that the ability of a fabric to change colour concentration could be used to make adaptive interior design panels, which allowed for a change in warmth or mood.

5.3.2.4. Discipline

Discipline was a recurring theme due to the nature of the focus group question plan. Participants tended to align themselves with one or more disciplines. This gave a ground from which to defend their own methods and to enquire about other people's. Many statements were backed up by referencing a discipline to align it to, so it would be clear why a participant was making those statements. Similarly, disciplinary information could be used to speculate about the reasons that other people made certain statements.

The other interesting area of disciplinary discussion stemmed from statements about 'clients' or 'stakeholders', the idea being that the stakeholder (or person instigating the project/providing the material) would restrict your thinking to within the discipline they came from. By stating my own disciplinary background, I had partially limited the discussion to ideas of fashion and textiles. This same discussion also implied that the input of the stakeholder was higher than that of the designer, who has to consider the client in all developments (this being more prevalent in commercial settings, and is debatable in the area of craft). The stakeholder/designer relationship in many ways questions the importance of the discipline and method of the designer in a situation where the stakeholder holds all of the power.

A repeat of the discussion from the first focus group about the science (or engineering) and art (or design) debate occurred. One participant said that interdisciplinary projects work in engineering and art if you are 'down to earth, but at the same time [use] your imagination and [are] creative'. Discipline also arose in connection with the theme of communication and how interdisciplinary approaches would 'broaden horizons' with positive outcomes such as learning how to communicate with each other. The chemical engineer commented that a blurring of barriers between disciplines allowed new knowledge to be created. He went on to suggest that science doesn't communicate with other disciplines, and that bringing disparate groups together would be a welcome development.

In another discussion about disciplines, one participant referred to the dichotomy she faced between her roles as artist and designer. This often caused her to think about the same task in different ways (i.e. from opposing perspectives towards the same outcome).

5.3.2.5. Materials

Materials were a common topic in discussion, mainly in relation to one of the other themes, such as the selection of materials in the method of using material databases. The choice of materials was a strong context for discussion, with some suggestion of using other materials when knitting fabric samples.

5.3.2.6. Knowledge

Knowledge was an important topic in this group, underpinning several of the other themes. Many statements were indicative of specialised or tacit knowledge in each participant's own disciplines, for example one textile practitioner knowing a lot about technical structural knowledge where another textile practitioner knew about fibres and felting processes.

The idea of tacit knowledge was raised in the focus group questioning, but as with FG1, none of the participants already knew of the term. Participants stated that tacit knowledge exists within specialists and influences the way they 'play round' with materials. This was acknowledged to be difficult to communicate to others in collaborative contexts as specialists may not share common reference points.

5.3.2.7. Aesthetic & Tactile

Participants were quick to use aesthetic judgments, including those participants from outside textile design or design practice. This was the most common form of appraisal, with the functional appraisal soon fading out of discussion. The idea that the designer needs to be able to make value judgments on materials before going into production was seen as important.

Tactile elements were discussed, and other value judgments such as the samples being 'warm', 'soft' or 'cosy' were heard. The members of this focus group were more 'hands-on' with the samples than those in FG1 and seemed to be more willing to make pure value judgments and accepting their gut responses than the last group's tendency to give scientific responses. Though the reason for this is not clear, it is thought that this may have been encouraged through the minor alterations to the questioning since FG1 in conjunction with the general personality of the group's individual participants.

5.3.2.8. Qualitative & Quantitative

Both quantitative and qualitative methods and considerations were accepted and used in the discussion. One textile designer stated that in her practice there is a need for repeatability and logging accurate, technical information in order to achieve that, but mostly judgments had roots in qualitative analysis. Her method was a mix of these aspects, which she found useful in creating and documenting new ideas through her practice and experience.

Overall, the discussion was mainly qualitative. The way in which participants appraised the samples and used terminology (such as 'warm and soft', 'cosy') put value judgments onto the samples. After the recording ended, the participants continued to talk informally about the samples and decided on their 'favourites' and created more experimental 'play' with the fabrics to test the movement and behaviour.

5.3.2.9. 'Spectrum' Task

Participants were asked to plot their practice on a line showing 'design' at one end and 'engineering' at the other end (as inspired by a comment from the pilot study focus group) the results are shown in **Figure 5.59** below:

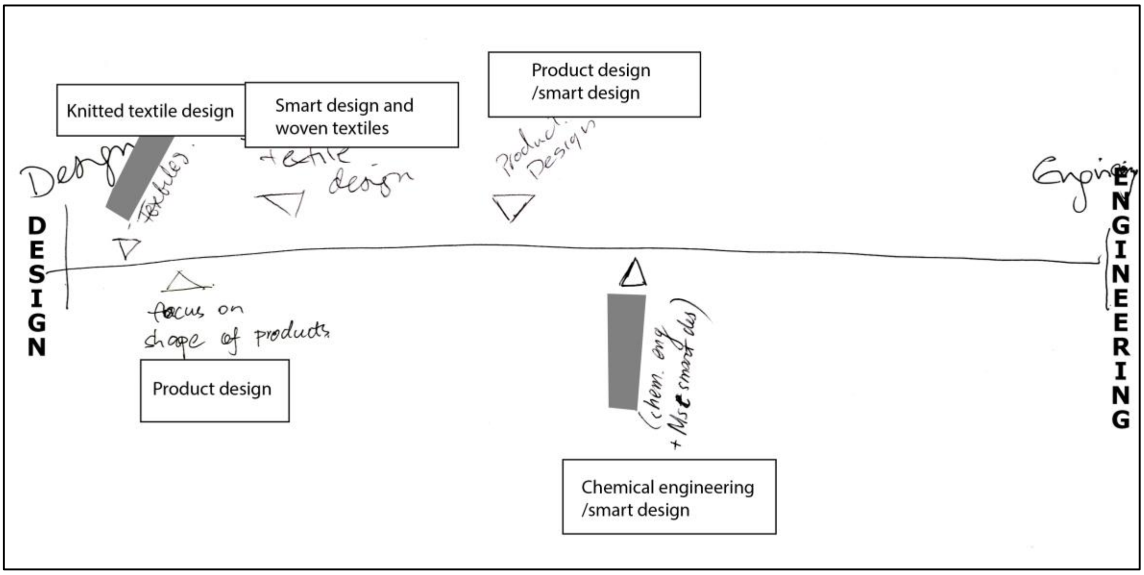


Figure 5.59 Image from focus group of Design - Engineering spectrum, showing participants' responses labelled by their self-described discipline(s) (stated at the beginning of FG2).

What is interesting about the responses to this task is the leaning towards the design end of the spectrum; even the chemical engineer is close to the middle of the scale. Also it is worth noting that none of the participants put themselves entirely at the design end of the scale. This shows an acknowledgement of the other elements individual practitioners bring to their work. It also highlights some of the problems with using specific terminology to define discipline and practice. In **Figure 5.59** the marks of the two product designers are not close to each other on the spectrum, nor are the two textile designers.

There was a further discussion about the impracticality of the 'spectrum' task – one reason being that it could be said that a practitioner 'is the line' and can therefore cover the whole spectrum, or that there is no line, or that a practitioner could exist at several points on the line at any given time. The task itself is a 'polar' question and does fit in with processes from 'repertory grid' design concepts that ask participants to choose from 'elements' (in this case a choice of disciplines) and study the 'constructs' applied to the decision-making process (Fransella, Bell & Bannister, 2003: 15-18). This comparison with repertory grids highlights the case that different terms (elements) have different meanings (constructs) to different participants, so it is worth asking participants for clarification on their meaning of the practice they declared during the introductions at the start of the focus group.

In spite of limitations from this task, the question helps to characterise the focus group and enable comparison with other groups questioned. There is scope to develop this written exercise method into focus groups 3 and 4 and to use the reflections from individuals to give further insight into the personalities of both individual participant and groups.

5.3.3. Focus group analysis conclusions

FG2 produced similar responses and results to the pilot focus group. The participants in FG2, made up largely of design Master's programmes, were open-minded to a wide-ranging discussion. One of the most salient points to come out of this data is the willingness of participants to incorporate other practices into their discussions and to recognise a range of methods and perspectives within their own practices.

As practitioners in design, the participants recognise that disciplines are prominent and important in developing understanding of working practices and in aligning (or contrasting) individual views to those of others. The issues of discipline and specialism can have huge impacts on how practices are perceived, practised, understood and shared. The participants expressed that shared 'community[55]' in a discipline gives a sense of a shared understanding among these practitioners and explains how even those disciplines without formalised methodologies (such as knit) can still have a shared practice and a shared experience.

5.3.4. Reflection on analysis

As seen in the literature review of this study (**Chapter 2**, section **2.6.**), disciplinary segregations are inherent to education and industrial practice in design, although the definitions surrounding disciplines are not always clear. A general openness existed in the two focus groups so far that indicated a desire to conduct multi-disciplinary work and understand the methods of other practitioners.

Ideas of discipline greatly affected areas for discussion in both focus groups. The presentation of my fabrics, coming from a textile design perspective, immediately influenced the discussion, causing it to stay within fashion and textile design contexts, rather than any other discipline that uses textiles (such as interior design, composite engineering, medical textiles). The language I used in the discussion may have influenced the participants to keep discussion to within what they perceived my particular disciplinary interests to be. Comment from the focus group about aesthetic elements kept the conversations away from topics of functionality.

5.3.5. Adjustments for third focus group

There will be substantial adjustments to the format for the third focus group. The format for focus groups 1 and 2 was very similar and therefore did not give rise to a lot of new information. The spectrum exercise worked well in encouraging a new range of ideas. This type of exercise is developed further and given more importance in focus groups 3 and 4.

After discussion with an advisor[56] (present in FG2) regarding methods that could be employed in the next group, the following suggestions were made:

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[55] See Wenger (2000) for discussion of the importance of 'communities of practice' within social learning and structure. Disciplines, and experience of them through education and employment, produce and perpetuate this sense of a community of shared practice.

[56] An advisor from my supervisory team for PhD study.

- Withhold information about samples' auxetic behaviour until they have been appraised by the participants. This aims to result in some key words derived from the samples and observation on the importance of quantification.
- After this, give participants some information about auxetic materials and the nature of the samples on the table and ask them to appraise again.
- The spectrum exercise encouraged a different level of engagement in participants. It would be beneficial to carry on the 'spectrum' idea and create variations on the straight line exercise, for example: using a triangle, including 'art', Venn diagrams or a number of different diagrams and ask participants to indicate their practice in each chart.
- The presence of more knitters would be beneficial to test some of the observations made so far – the one present from FG2 showed many agreements with the project's hypotheses about the nature of knit and knit design methodologies.

5.4. Theory building

The theory as drawn from the data in Focus Group 2 (FG2) and obtained through practical experimentation and reflection is outlined below in **Table 5.8**, which follows the same format as the theory building table in Stage 1 (section **4.5.5.**).

Proposition	Evidence from data	Outcomes and actions (from duration of study)
Design and experiential knowledge is appropriate to produce knitted auxetic materials.	Samples 6, 7, 8, 9, 9a, 10, 11 and 12.	Make explicit the role of design knowledge to the production of fabrics.
Having a choice of information makes it easier to explain work that crosses disciplinary boundaries.	Agreement of participants that different information is helpful to different people. Being able to choose information to best suit helps understanding.	Publish work with different information styles. Publish same work in different areas using information tailored to the publication style.
Practitioners are not necessarily of a single discipline, but disciplines are thoroughly engrained in practices.	Hand-out exercises showed no evidence that any participants thought of themselves as belonging to a single discipline. However, in spoken responses, participants aligned themselves with particular disciplines.	Seek multi-disciplinary outcomes. Seek ways of crossing disciplines in discussion and dissemination.

Background of FG leader and preconceptions about fabric may cause more fashion/textile design applications and discussions than other areas.	Fashion applications were common among participants.	Explore fabric and materials that are less aesthetic/'fashion' to encourage diversity of responses. Limit information about fashion/textile design in FG introduction.
Methodological background can affect all subsequent work, not only related work. Methodology and background is summative.	A knit design practice participant uses artist and designer practices. Textile/smart design participant retains textile design considerations in her new smart design practice.	Multi-disciplinary information is useful when speaking to specialised audiences.
Textile design process considers elements of designing simultaneously.	Textile design practitioners acknowledge the process of designing the fabric and the product simultaneously. The process is not linear.	Consider diagrammatic version of methodology to include parallel/iterative considerations.
Tacit appraisal is important, at least as an initial or developmental reaction.	Tacit appraisal is important to all participants, but may be limiting when talking to those outside their own discipline.	Include and value tacit responses.
Disciplinary allegiance may be overt.	Individuals acknowledged the influence of their backgrounds on communication and appraisal.	Include and value my own perspectives and those of contributors.
The order of preference for tactile and aesthetic values may come earlier in textile practice than in engineering – where mechanical properties are more important.	Physical attributes of materials were less important to engineering background participant than to textile practitioners. Textile practitioners assessed these properties throughout development.	Encourage availability of both physical and mechanical information. A data set can be made to include physical data – photos, videos, descriptions etc.
Subjects may not discuss practices openly or simply with others.	Understanding of disciplinary practice of others was limited. But exposure to other practices was welcomed and considered beneficial.	Encourage the open discussion of methodological practice among mixed groups. Discuss my practice openly.

Tactile and visual responses are important for all participants.	Tactile and visual responses are common to all participants. Participants trusted 'gut' reactions.	Tactile and visual discussion should be included where possible.
Open-minded approach must be used with own practices when working on innovative projects.	Individual, interdisciplinary projects require the practitioner to think in diverse ways and from different perspectives.	Encourage transparency in approaches of own work and in those of others.

Table 5.8 Theory building from focus group and practical data in Stage 2.

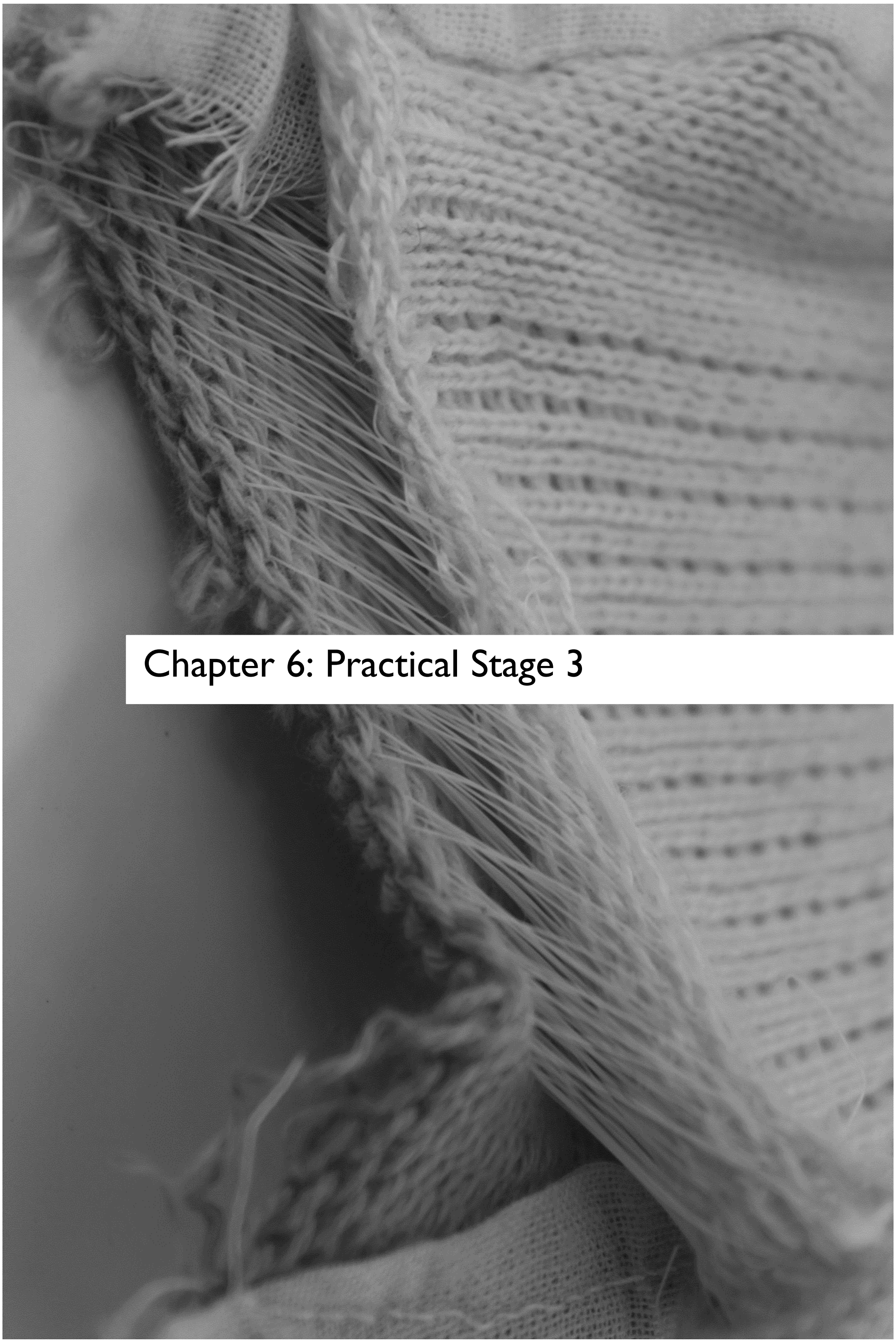
5.5. Chapter conclusions

The use of opinions gathered in Stage 1 validates some of the design decisions made during Stage 2 of fabric development. Suggestions, such as altering the yarn choice to give a different appearance (comment on colour choice and 'bandages' from FG1), follow the same design decision-making process that would be used in an extensive sampling stage (exploring colour, texture and aesthetic).

The development of further original auxetic fabrics demonstrates the explorative capacity of the knit design methodology. The methodology includes the ability to trial and adapt existing geometries, as well as using experiential knowledge and confidence to develop new auxetic geometries.

To facilitate the knowledge transfer aspect of the research further, it is important to frame questioning and discussion in a discipline-neutral manner as much as possible. The next focus group (FG3) makes further comment on the disciplinary preferences of various types of practitioner and sees more detailed information about specific design practices and priorities.

Chapter 6: Practical Stage 3



6. PRACTICAL STAGE 3

6.1. Introduction

After investigating methods of creating auxetic effects in the width (X-axis) and height (Y-axis) during Stages 1 and 2, Stage 3 investigated creating expansion in the depth of samples (or expansion in the Z-axis). This process was carried out through the use and modification of spacer fabrics.

6.1.1. Spacer fabrics

The principle of a spacer fabric sees two separate fabrics (wall fabrics), knitted on different needle beds that are connected by tucking a filament (usually a monofilament [Spencer, 2001: 376]) between the beds, joining the two fabrics together (this can be seen in **Figure 6.60**). The length of the joining yarn and the distance apart of the tucks determines how far apart the wall fabrics are. They can be short and join the two fabrics, or longer to give a gap of variable length between the two separate fabrics (Ray, 2012: 284).

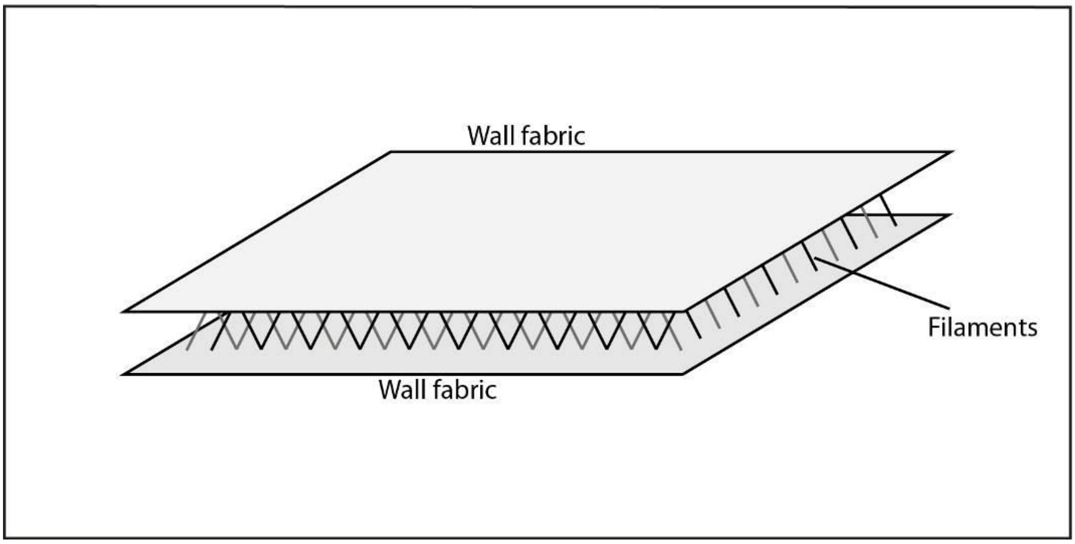


Figure 6.60 Diagram showing structure of conventional spacer fabric.

Spacer fabrics are usually used in applications concerned with the production of thick fabrics (spacers have uses in applications involving compression e.g. footwear, sportswear [Yip & Ng, 2008: 359] and insulation, e.g. sound absorption [Dias et al., 2007]). This connection with fabric depth makes them a suitable starting point from which to investigate making fabrics that have an auxetic expansion in the Z-axis. Weft-knitted spacer fabrics are usually filled with filaments that are tucked in a zigzag formation (at a variable angle) between the two wall fabrics. This method for machine-knitting spacer fabrics is simple and fairly quick (compared with fabrics that require large amounts of transferring, for example). A common goal of creating spacer fabrics is to form a dense structure by packing as many filaments into the central space as possible.

The idea behind an auxetic spacer fabric depends on the ability to increase the thickness (Z-axis) of the fabric using application of stretch. By programming the knitting machine to tuck in the filament yarns so that they are all positioned in the same direction and angle, it will create a set of diagonal central filaments. The fabric can be pulled at opposing corners, straightening out the filaments (until they are at a right-angle to the wall fabrics) to create a much thicker depth of Z-axis. The filaments in this auxetic spacer fabric can be adapted to give different maximum lengths.

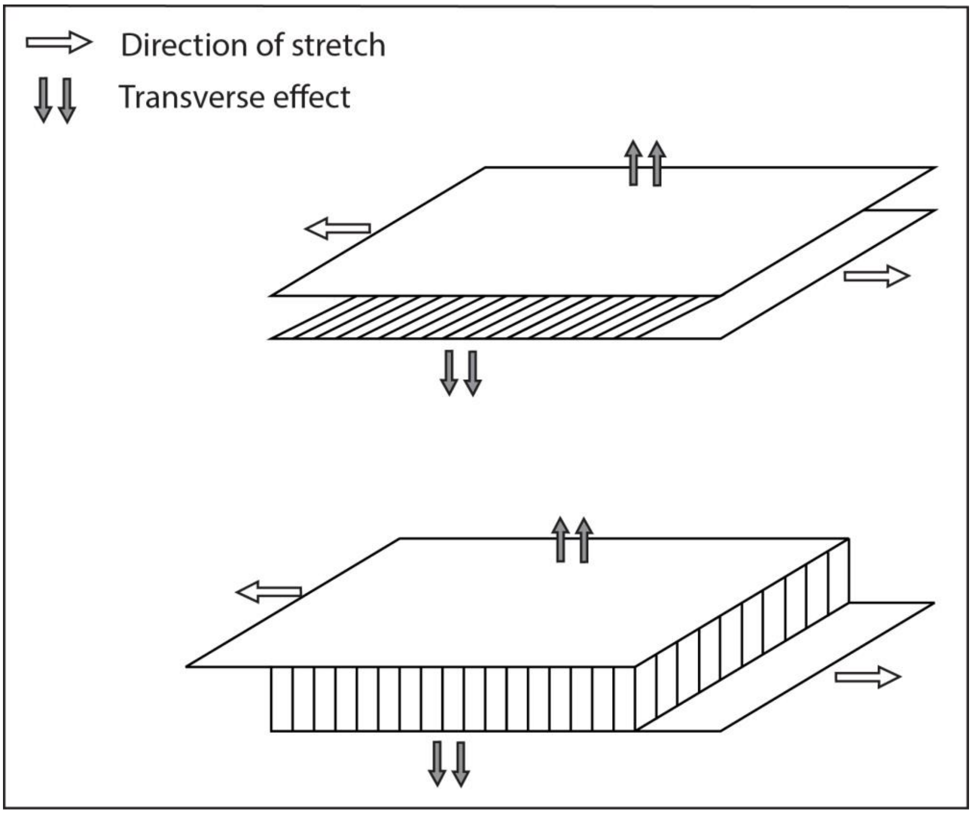


Figure 6.61 Diagrammatical representation of auxetic spacer fabric

The auxetic spacer fabrics for this project are inspired by auxetic geometries that use rotation to expand – like chiral effects and rotating units (explanations in section **2.9.3.**). My making and research background has frequently featured issues of stretch, expansion and rotation. This aided the design process in developing ideas for fabrics that would expand through rotation.

6.2. Significant fabric samples

Developing variants on the auxetic spacer fabric was more difficult than developing variants on the fabrics in Stages 1 and 2, because of the complexity of the spacer fabric structure. The spacer structure limits how the fabrics can be varied and only slight changes can be made while retaining the structure. A notable example of this limitation is that, when knitting a spacer fabric on a knitting machine, the structure uses both needle beds simultaneously; therefore it is not possible to incorporate relief structures (such as those in Stages 1 and 2) into the wall fabrics.

Technical information on the samples featured in this chapter, as well as details of the other fabrics knitting during Stage 3 can be found in **Appendix B**.

6.2.1. Sample 13 (Bulk test 2)

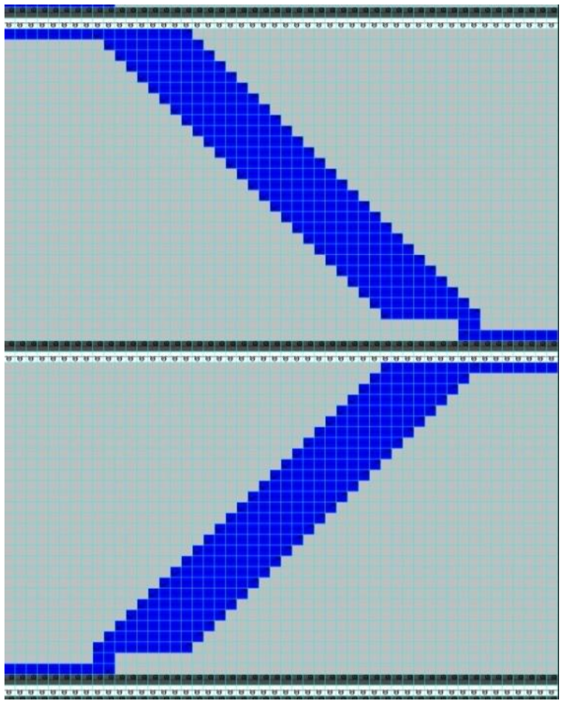
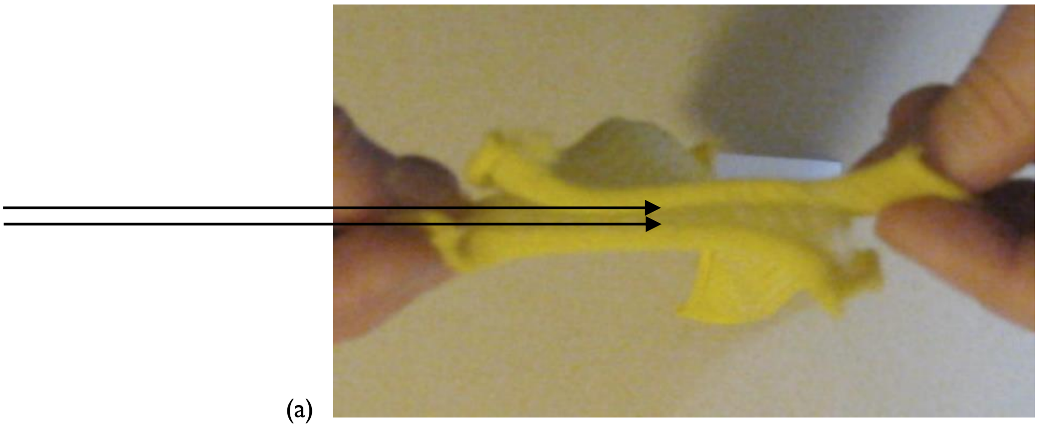


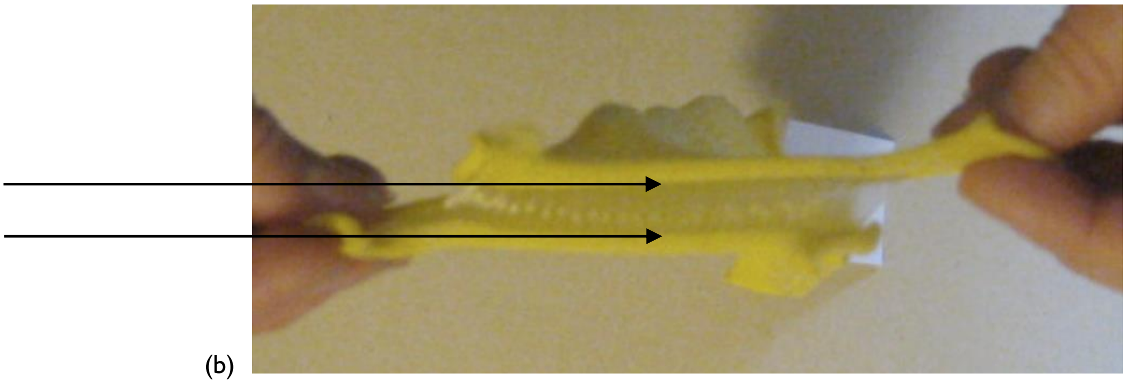
Figure 6.62 Stoll programming chart for Sample 13. Blue colour shows short floats[57] (6 needle) of monofilament being tucked in. Charts with longer filament floats can be found in **Appendix B**.

The initial spacer fabric (Sample 13), as shown in **Figure 6.62** and **Figure 6.63**, was immediately successful in showing auxetic behaviour. It was knitted in nylon for the plain wall fabrics (plain, single-bed construction) with polyamide monofilament as the inlaid yarn. These yarns were chosen for their strength and reliability in knitting. In addition to their strength, these yarns were chosen after feedback from FG1 and FG2, suggesting that synthetic yarns would encourage the participants to think of samples in a less textile or fashion-orientated context. Sample 13 showed the desired auxetic behaviour when extended from diagonally opposite corners. As can be seen in **Figure 6.63**, the diagonal filaments are rotated by moving the wall fabrics in opposite directions. At the largest expansion, the filaments stand at right angles to the wall fabrics and give the full length of the filament to the thickness of the fabric. This distance can be changed by the length of the float between tucks. To illustrate the effect of this change in float length, the fabric programmed in **Figure 6.62** would give a Z-axis measurement the length of a 6 needle float. A larger Z-axis expansion could be achieved by using a longer float length (examples of programming charts variations on float length can be found in **Appendix B**.

[57] A float is when a yarn is carried without being knitted. This leaves a horizontal length of yarn on the technical back of the fabric. In a spacer, the technical back of both wall fabrics faces the centre, they are 'back-to-back'.



(a)



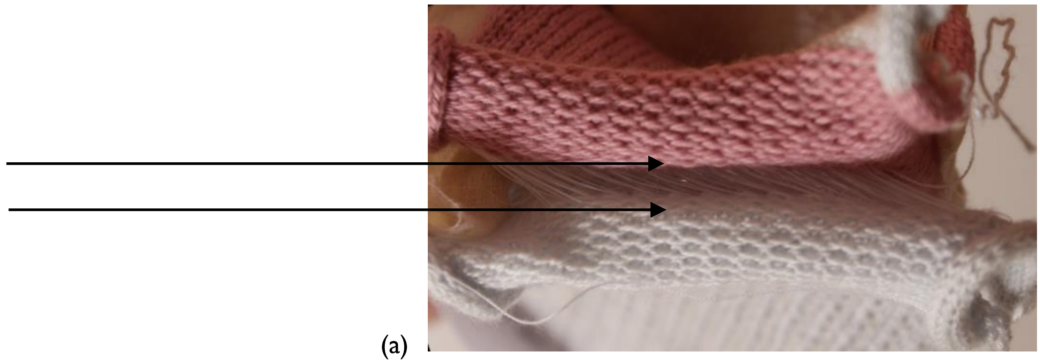
(b)

Figure 6.63 Sample 13 knitted in nylon with polyamide monofilament in centre. Stills from video showing fabric at rest (a) and stretched from diagonally opposite corners (in X-axis) (b). The arrows show where the filament ends (the thickness of the wall fabric is distorted by the plain fabric curling at the edges in this image)

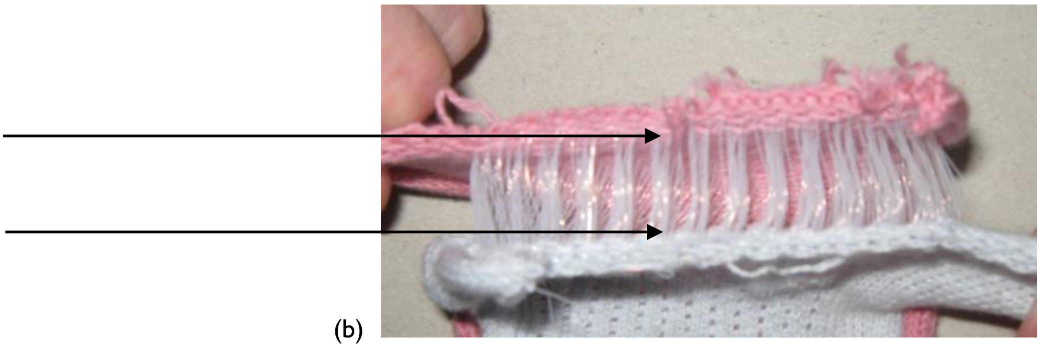
Sample 13 is visually unremarkable on the outside. The interesting elements of the fabric occur within the centre of the fabric. From the external appearance the fabric looks like plain, single-bed fabric. In Stage 4, variation will be made to change the external appearance of this auxetic spacer fabric.

6.2.2. Sample 14 (bulk test 2b)

Sample 14 repeated the previous sample using cotton yarns for the wall fabrics. A half-gauge single-bed structure was applied to these wall fabrics to combat the stretch of the fabric when force is applied[58]. Sample 14 was also successful in its intended auxetic effect. Using a thicker monofilament meant that the spacer required significantly more force to achieve the right-angle relationship of wall fabric to filament (this is shown in **Figure 6.64**). The thicker filament also emphasises the auxetic effect visually by keeping the wall fabrics more rigidly separate than in Sample 13. The differences between Samples 13 and 14 indicate the possibility for a range of end uses for these auxetic spacer fabrics dependent on the force required for actuation, the stiffness, and the depth required.



(a)



(b)

Figure 6.64 Image of Sample 14 (bulk test 2b) in cotton and monofilament at rest (a) and being stretched (in X-axis) (b). This fabric is made with thick monofilaments in the centre. N.B. the wall fabric in the pictures looks large because it is curled. The thickness of the fabric is marginally wider than the filament areas (indicated by the arrows).

The time required to knit this auxetic spacer fabric is many times longer than the time needed to knit a conventional spacer, but in a commercial, industrialised environment, machine and program modifications could be made to speed up the process (e.g. knitting two monofilaments simultaneously during a course of knitting could significantly decrease the knitting time).

[58] The floats in a half-gauge fabric reduce the number of loops and therefore the amount that fabric can be stretched.

6.2.3. Other spacer experiments

The other experimental spacer structures (shown in **Appendix B**) did not show auxetic effect. One example of an unsuccessful variation used elastic yarns in the wall fabrics to increase the density of the monofilament centre (the elastic contracts and forces the monofilament lengths into a smaller area of wall fabric). This density distorted the direction of the monofilaments. The elastic also caused problems with balancing the opposing forces needed to stretch the fabric, due to the elastic yarn used.

6.3. Results

The programming to make 'bulk test 2' as an original auxetic spacer fabric was immediately successful. The only significant changes to the program were the use of a half-gauge structure in the wall fabrics to increase stability, and variations in the length of the floats in the monofilament. This allowed longer or shorter lengths that would alter the eventual height of the Z-axis expansion.

6.3.1. Materials

Materials used in this stage of practical development were more synthetic than the materials used in Stage 1 and 2. Nylons, elastomeric yarns and polyamide monofilaments were used to create fabrics with a 'technical' look and feel (in response to feedback from Stages 1 and 2). Cotton was also used (as in Sample 14) to give strong wall fabric with limited extension in the yarn. This limited extension would allow the auxetic spacer structure to move rather than allowing the yarn to stretch[59]. In Stage 4 there is scope to experiment with different aesthetic combinations – though this is mainly limited to striping and colour on the wall fabrics.

6.3.2. Testing and further work on spacer fabrics

Because of the limitations in being able to vary the wall fabric structure and the lengthy knitting time of these fabrics, the development of this sample stage was not explored into many variations. It may have been possible with additional time to develop further variations on the auxetic spacer fabric.

One of the avenues for development that was proposed was to combine the relief structures from Stages 1 and 2 with the spacer fabric from Stage 3. It was not possible to try this at the time due to the machinery available. Relief structures and spacer fabrics each require both needle beds, so a machine with capability to knit on four beds simultaneously would be required.

Spacer fabrics can be the subject of various tests, including: compression, bending, air-permeability, thermal conductivity, stretchability, etc. (Yip & NG, 2003: 360) depending on the desired outcome. The regular tests were not considered suitable for ascertaining auxetic behaviour. Quantitative testing of the auxetic behaviour of these spacer fabrics also proved to be difficult. In order to measure the thickness (Z-axis) of the fabrics, a measurement needed to be taken from the centre of the fabric. This was difficult to do without applying pressure onto the fabric (and affecting the measurement). One possibility would involve cutting the fabric to be able to measure the centre of the fabric from a cross-section

[59] Cotton has little stretch or 'give' in the fibres. Wool has some elasticity and elastomeric yarns are highly stretchable.

view, but this would cause unravelling of the tuck structure. A final option was the suggestion of laser-measuring for the samples. The use of laser-measuring would go against the objective of this study to use simple and easily-articulated methods. The measuring stages for Stages 1 and 2 used low-technology equipment and simple mathematics.

In Stage 3, subjective, visual acknowledgement of the auxetic effect is considered to be sufficient. The annotated images in **Figure 6.63** and **Figure 6.64** clearly show the change in thickness through stretching. Video examples of these samples being stretched can be found in the supporting information for this thesis.

6.4. Focus group stage and analysis

Focus Group 3 (FG3): 3rd March 2012 (duration: 1.5 hours)

FG3 shows a change from the previous two focus groups. Written tasks were developed from Stage 2 with the aim to collect different types of responses from participants. The participants were individually asked to answer questions about their discipline(s), and answer questions about the fabrics, both individually and in pairs. Group discussion was then used to encourage diverse, collaborative conversations to elaborate on individual ideas.

Additional questions and changes for the participants of this focus group included:

- Asking participants to indicate their practice on a Venn diagram, a triangular and a linear spectrum (shown in **Figure 6.65**).
- Asking the participants to appraise samples in a written exercise.
- Asking participants to appraise samples in pairs (with a partner from a different disciplinary background).
- Asking participants about their methods of appraisal in different tasks.
- Information about the auxetic behaviour of samples is withheld until some initial appraisal has been conducted.

6.4.1. Selection of participants

FG3 used a self-volunteering sample. A request for participants was sent out to students of design at Master's and PhD level and researchers in the design areas at Nottingham Trent University. The final group consisted of:

- The author/researcher
- Research assistant in digital textile design for functional use - background in craft
- MA Knitted Textiles student – background in science
- PhD student in fashion knitwear
- PhD student in product design and energy consumption
- PhD student in smart fabrics - background in textile technology
- PhD student in fine art and photography
- MA Branding and Identity student - background in industrial design and product design
- PhD student in fashion business model and sustainable design

- PhD student in craft as practice working in knit
- PhD student in graphic design
- Lecturer in Product Design **-** background in craft and jewellery

6.4.2. Focus group 3 analysis

The third focus group took a different approach to the previous two. Participants were sourced mainly from the PhD cohort at NTU across a wide range of design-based disciplines (specifically: fine art, product design, industrial design, textile engineering, embroidery design, knitwear design, graphic design, education, textile design and economics).

The format of the data collection also included new elements, such as leaving the participant relatively uninformed about the samples they were being shown until after they had made some responses. Parts of the questioning involved using group work and asking participants to indicate practice on visual representations of disciplinary preference/subject area. An outline of the spread of responses can be seen in **Table 6.9**, which shows themes such as *properties, applications* remaining common among FG3 responses, as they were with groups in FG1 and FG2, and themes of *aesthetics* and *methodology* becoming more common. Analysis of the discussion is written in the sections below and focuses on common and significant responses from the individual, paired and group discussions.

Parent theme	Sub themes	FG3: total number of responses
Physical	Properties	36
	Material	19
	Scale	0
	Structure	15
Knowledge	Knowledge	4
	Knowledge transfer	14
	Understanding	3
	Experiential	4
	Tacit	4
Qualitative	Qualitative	8
	Tactile	28
	Aesthetic	44
	Emotional	5
Quantitative	Quantitative	8
	Results	3
Applications	Applications	36
	Industry	1
	Fashion	9
	Function	12
Communication	Communication	0
	Language	1
	Simile	19
	Collaboration	1
	Education	3
Discipline	Discipline	13
	Practice	1
	Methodology	7
	Process	25
	Design	1
	Engineering	7
	Craft	3
Change	Change	13
Positive	Positive	23
Negative	Negative	19

Table 6.9 Coding of responses from focus group 3 discussed in detail below.

6.4.2.1. Hand-out exercise

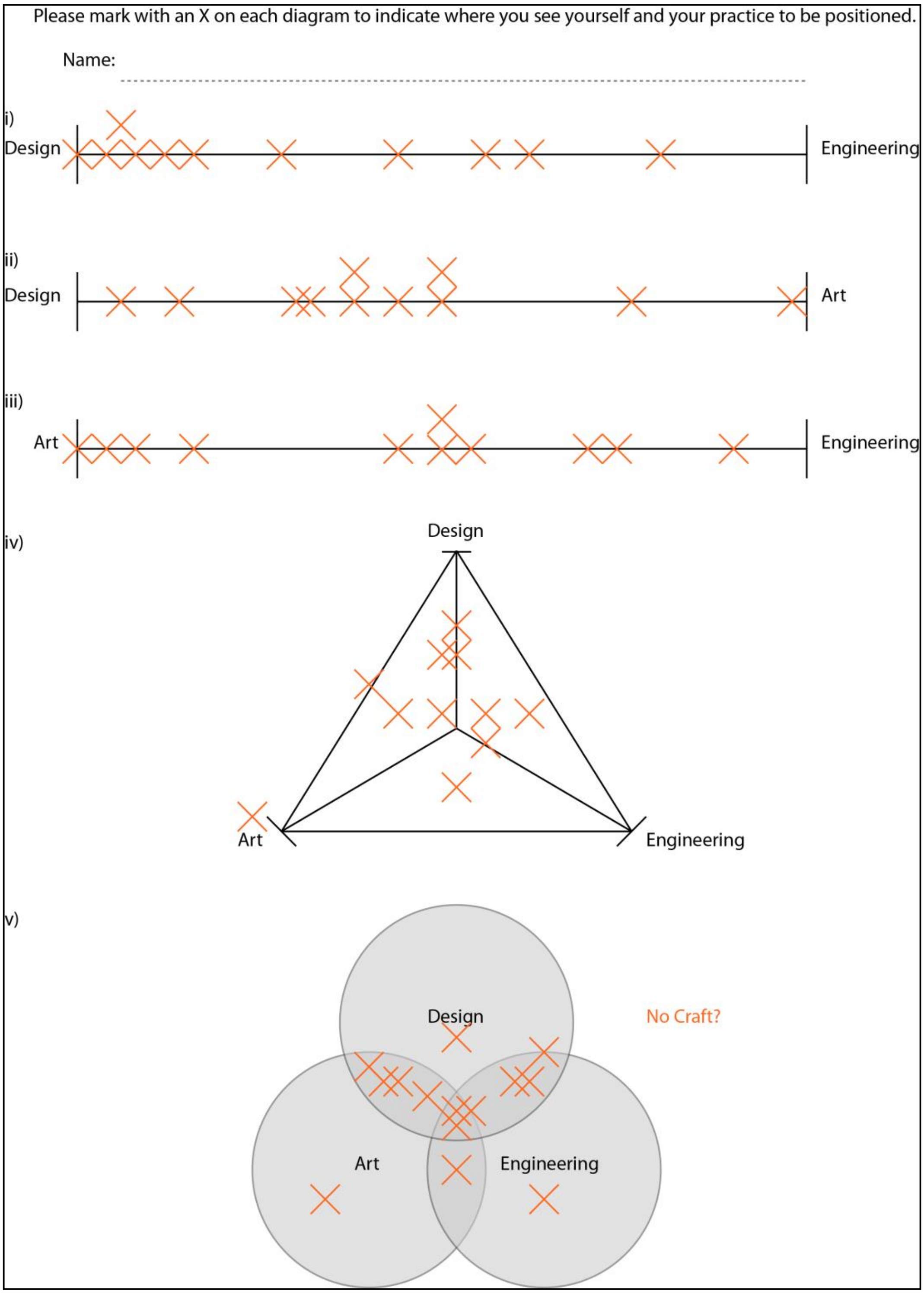


Figure 6.65 Summary of hand-out for focus group showing all responses.
N.B. participants may have made more than one mark on the diagrams.

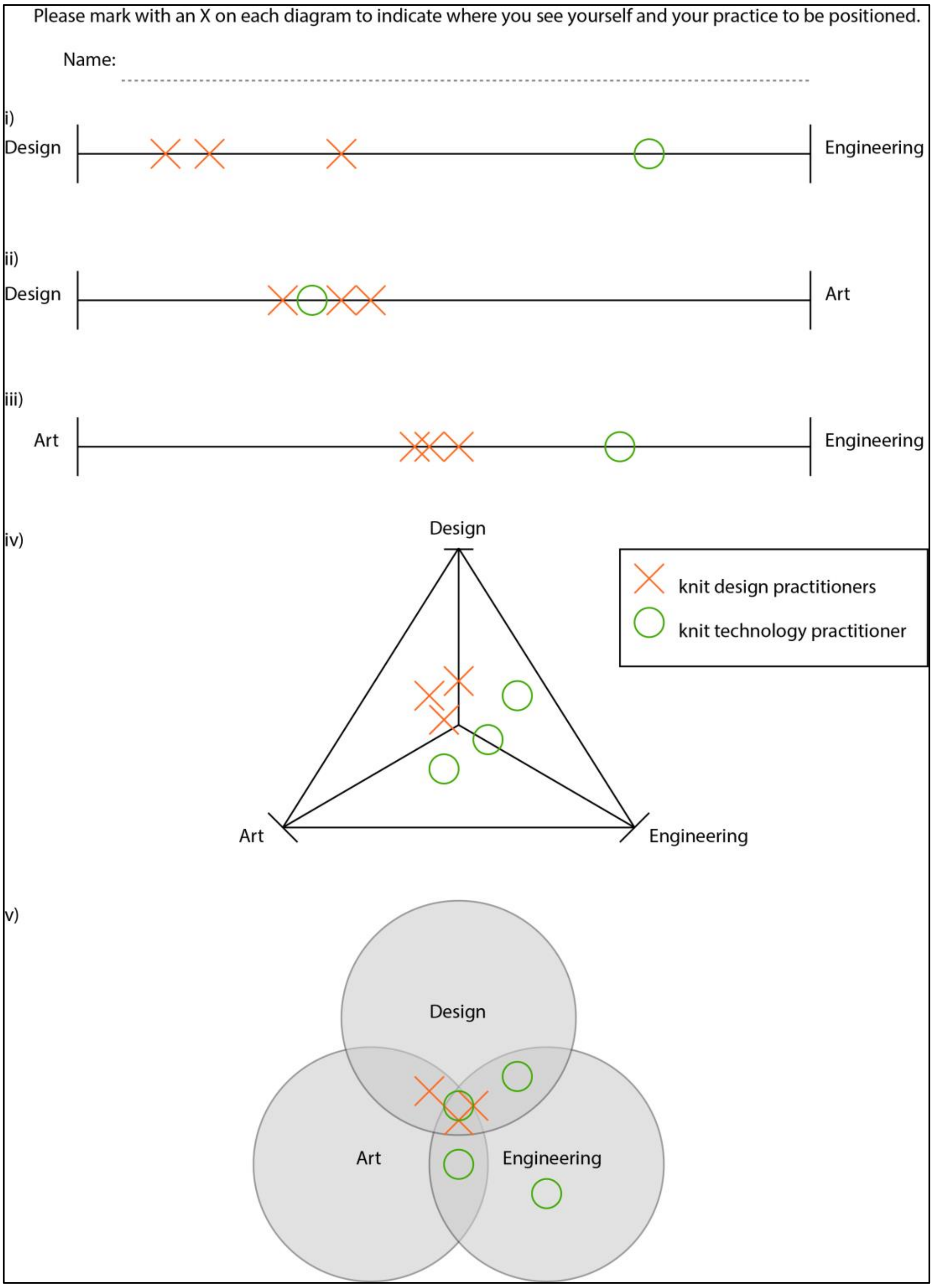


Figure 6.66 Summary of hand-out responses from knit practitioners.
N.B. participants may have made more than one mark on the diagrams.

FG3 incorporated another written task about discipline, developed from the task in FG2. This time the spectrum added art to the spectrum, along with design and engineering, to assess how the participants viewed their practice when presented with an extra choice. When asked to mark on three types of chart where participants considered their practice to be based - between art, design and engineering - there was a mixed set of responses. As can be seen in **Figure 6.65**, the most noticeable comment is that participants were not strongly fixed in their disciplinary declarations, as most of the responses were situated between the rigid disciplinary extremities. Most responses acknowledged a mixture of the three disciplines. Some participants made several marks on the hand-out exercises, showing that they may have thought of their practice as being in different, distinct disciplines, rather than an merger of disciplines.

The three knit practitioners who specialise in knit design all had very similar responses in this exercise. They all favoured ‘design’ over ‘engineering’, but all classed their practice as between art and engineering. The one who specifically focused on knitwear for fashion gave responses furthest removed from ‘art’, classifying knit design as more of a combination of design and engineering, than being about design and art. The responses that classed knit design more as art than engineering, were those looking at knit in ways not directly fashion-related, but still aesthetic and design orientated. All of these responses acknowledged a mixture of ‘art, engineering and design’ for knit practice. The knit and textile technology specialist also used the three disciplines when responding, as shown in **Figure 6.66** by the circular marks.

The categories of art, design and engineering were chosen due to my own ideas of what knit design entails. Had ‘craft’ and ‘science’ also been included, responses from participants may have been different. Only three options were also chosen in order to make the diagrams simple to navigate. With the addition of other disciplinary options, the diagrams may lose their simplicity and usability.

6.4.2.2. Properties

In the individual and group tasks, ‘properties’ was a common theme. Discussion on properties mainly focused on visual or tactile properties. Other reactions related to aspects like the properties of a fabric when ‘played with’ or ‘sensed’. Presumed properties were also discussed, for example, the spacer fabric might change its heat-retaining properties when stretched. One comment questioned how changing the scale of the fabrics and levels of stretch (in something like a clothing application) would affect qualities like weight and drape. The participants agreed with the comments from FG1 and FG2 that the yarn used changes the participants’ response to the fabric significantly.

The textile-engineering practitioner commented on how the innate properties of a yarn will give different impressions of what will be produced. For example, wool will provoke thoughts about warmth and indicate clothing, but a synthetic fibre will provoke other uses. He proposed that it is possible to learn something about the design or designer by looking at the materials used.

Both the textile engineer and the knit/science background practitioner suggested that, had they been in their own (scientific/laboratory) environments, they would have used tools and equipment to analyse the fabrics for their materials, density and other properties.

6.4.2.3. Aesthetics

In FG3 the most common theme was the aesthetic of the fabrics. Responses frequently focused on the colours and the patterns used; these were generally split into either positive or negative reactions or simply observational, such as stating the colour. Discussion also turned to how people tend to use aesthetics as a tool for appraisal. Since the exercises given to participants were to appraise the samples by whatever means they chose, most people opted firstly to appraise by qualitative, aesthetic standards and this approach was repeated throughout the session.

A notable example of the use of aesthetic appraisal was the tendency of this group to use similes to describe certain attributes of the fabrics, this happened 19 times across spoken and written responses. Examples of this included stating that a variation of TP4 fabric in covered elastic: 'looks like…net curtains (ruched)' or a 'dreadful 1950s swimming costume'. Other examples were also combinations of applications and similes or metaphors. These were things like 'shin pads', 'used for household cleaning', 'ice cream wafer' or 'it reminds me [of] a sock'. This habit of likening a fabric to either a use or an object that it was similar to was something that was common and used as a tool to provide a shared understanding of how an individual was analysing the sample in front of them. This is similar to the study by Eckert & Stacey, '*Sources of inspiration: a language of design',* where designers develop common reference points to convey complex descriptions (Eckert & Stacey, 2000: 526).

6.4.2.4. Tactile

Some participants commented on the changes they had in their perceptions of the fabrics after they had touched them. Tactile properties influenced some of the applications that were proposed, especially in fabrics that used synthetic fibres. The synthetic fibres (in this case: polyester, covered elastomeric and polyamide monofilament) generally received a negative response in relation to their tactile properties.

Tactile appraisal was said (along with aesthetic appraisal) to be something we are born with rather than something we are taught.

6.4.2.5. Applications

As with the previous focus groups, talk of applications featured frequently. Again, as with the other focus groups, participants were not asked to offer any comment on potential applications. The offering of applications may be related to the focus group format (and perception of what the purpose of this type of discussion is) or it may be a trait related to the practical, creative disciplines that these participants have come from.

Suggested applications from this group included:

- 'Plus size' clothing, or clothing that would grow with you during times of weight gain, or through age-related growth (to prolong the life of a garment to be able to be worn through different sizes and scales of the body)
- Suggestion that samples could be used for any number of garments (how they could be constructed as 3D objects)
- Sportswear
- Use in architectural spaces
- Engineering applications/geotextiles (spacer fabric)
- Bra cup (spacer fabric)

- A neck warmer, a skirt, tube top, wrist band, scarf, blanket or gloves (several of the garment shapes mentioned by non-apparel specialists were of simple construction)

In addition, the following section about 'similes' will give insight into further applications. There was also discussion about the purpose (or the necessity) of establishing an application in the design process.

6.4.2.6. Simile

Regularly in this focus group there was a tendency to liken the fabrics to particular objects or feelings. This simile or metaphor style response has featured to a lesser degree in earlier focus groups (e.g. a comment likening samples to 'bandages' in FG1). The responses are generally based on visual and tactile stimuli. One spacer fabric ('circular interlock' in **Appendix B**) that had a repeated 'S' shape cross section and a thick core was likened to an intestine, a swimming float and a shin pad.

The 'simile' comments were not always positive or negative, but often a way of describing something by way of a shared understanding, as in Eckert & Stacey (2000). Some responses negatively linked the fabrics to an association, e.g. the red elastic version of TP4[60] was likened to ruched net curtains or 'old' swimming costumes and the uncomfortable feeling from wearing them. Similarly, that same sample was described as having the potential to make 'a great sexy skirt'. Importantly, here the responses do not necessarily focus on all the aspects of the fabrics, but may separate aspects such as the look, the feel, the knowledge of the material or the manufacturing process.

The 'simile' response was most common in the written responses where it may have been an easier way to describe a complex reaction. It also became an easy way to describe the results of the written exercises to the group. On occasion, other similes used were adjectives such as 'wintry', 'concertina', 'crunchy', 'old-fashioned' etc.

Other ways of expressing the fabric were more mood-orientated. One participant in the written responses specifically commented on 'mood: sporty, rollerblades, wristbands for sports'. Another said of one fabric (in reference to being old-fashioned or 1930s) that if it were a woman, she would be called 'Edith' or 'Enid'.

Overall, the responses in this focus group were more formulated into complex and abstract notions when compared with the previous two groups.

6.4.2.7. Process

As this focus group contained several textile and knit practitioners, there was a strong emphasis on the process used to create the fabrics. This ranged from very specific textile-based enquiries (e.g. wondering how it was knitted, what material was used…) to specific comments on the structural make up, manufacturing process and properties of the fabrics.

[60] A video of this sample titled: 'TP4 red elastic Y-axis stretch.wmv' can be seen in the supporting information.

6.4.2.8. Making

One knit practitioner with a scientific background applied a scientific methodology to her knitting routine. The following quote describes her making process, which she described as a scientific approach:

> *What I do at the moment is I have a whole list of samples I want to make, but I haven't got very far down the list because I've done the first one and I think, that's not quite how I want and I need to make alterations and it kind of goes like that, but then last year when I was doing a lot of the more preliminary research for it I was wanting to knit, say certain shapes like spirals or something so I'd come up with a methodology of just changing one thing in a whole series, but just changing it gradually in the whole series. So I'd make the whole series and then I'd evaluate it all as if it was one sample.*

Knit design practitioner from science background, 2012

This scientific method still allows for innate, tacit creativity to create non-scientific, artistic outcomes. In this sense, the method is not a limiting factor. The process works in much the same way as a cyclical process from a design field, and the results may yield similar outcomes. This systematic method could be applied to any textile project, and bears similarities to the approach used in this study. A key difference in the methods in this study and those that the scientific participant described, is that my methods are not scientific. They share many characteristics, they are systematic, qualitative, quantitative, methodical and led by experience-based reflection. In my practice this is not science, I practise this as design.

Another salient comment concerned specific methods of designing for knitwear (knitwear design practitioner) and how the designer is developing both the fabric and the garment (or outcome) simultaneously.

A practitioner from an industrial design background agreed with this perspective, saying that the fabric in this case was 'semi-developed' and instead of starting with yarns, in her view they would be starting with a fabric. She acknowledged that the outcome would be different depending on whether the design process starts from the yarn or the fabric stage.

6.4.2.9. Analysis

One knitwear practitioner commented on how she went about her process of analysis. She proposed that she had a set order in analysis with visual first, followed by tactile. But she said the tactile could then change this process. The tactile elements would determine whether or not something was to be considered a 'fashion fabric' or not. In this case she determined the Stage 2 to be fashion fabrics with a 'really lovely handle' but the spacer fabric was, after tactile analysis, deemed unsuitable as a fashion fabric. After this decision she would question 'what else it could be used for'.
She also went on to say:

> *… but I've been taught how to assess knit from a very technical point of view. So if you'd said you wanted me to tell you how it was made or what it was made of etc., then I would have come at it from a very different point of view. But because we've not been asked to do that, that's not what you first want to do. So I was taught those skills (analysis), but not the skills I've just used (reaction).*

Knitwear design practitioner, 2012

This comment implies a very tacit sense of being able to appraise qualitatively and that these things are not (or cannot) be taught. The exercise in the focus groups is intentionally vague to allow the participants to interpret the term 'appraise' in their own way. Here, having not been specifically told to appraise technically, the participants went on to appraise in purely subjective ways. The textile engineering participant backed up this idea by saying that the desire to look at and feel the fabric is something we are born with.

6.4.2.10. Methods (preference)

Tactile and aesthetic discussion makes up a large proportion of the qualitative data collection for this study. Both feature heavily in the responses from this focus group. First responses from participants were, invariably, about the appearance or the touch of the fabrics. This is an obvious way of collecting responses without the aid of a lab or workshop environment. Measuring devices were provided in the form of rulers, measuring tapes, set squares, magnifying glass, calculator and a stitch counter. None of these items were used by the participants.

6.4.3. Discipline-led discussion

Some comments and discussion from this focus group did not fit well into any of the themes, but require documentation here.

6.4.3.1. Differences in understanding materials

The most heated discussion came from a participant challenging the use of the question 'what is it for?'. She had experience of being asked this question in previous work, as explained in the following quote:

> *I get the 'what's it for?' question all the time – I'm just really interested. Somebody said before – would you have asked that of wood? If those had been samples of metal would you have asked – what's it for? Would anybody have asked what's it for?.... what if as a jeweller I'd brought along some tubes, some wire and some sheet?*

Craft and design practitioner, 2012

The response from the group was that the metal material suggested had not been 'manipulated', that they were 'raw materials, not the results of [my] efforts,' and that the fabrics had undergone a 'design process.' When it was pointed out that a metal tube, wire and sheet had also been processed and/or designed, the consensus was that those processes were somehow less than the design that had gone into these knitted fabrics. The perceived design process in the knitted fabrics limited participants' abilities to imagine uses and developments for the fabrics. Because the fabrics are new to the participants, they may be seen as 'finished' products. This is something that might change with a sense of increased familiarity with the fabrics. An attempt was made to present the fabrics in FG3 without ceremony, in an informal manner to the participants.

As a textile designer and maker, I would argue that most fabrics have the same potential for outcomes. As I have the appropriate knowledge to develop a fabric into a product or a garment, the 'what is it for?' question does not occur to me often. A fabric can be suitable for many uses, not only the uses for which it was originally made. The group certainly saw the fabrics as existing in a semi-finished state – more advanced than yarn and not as finished as a garment or product. The discussion of the metal tube, showed a desensitisation to thinking of some readily available materials as already having been processed.

When asked how he would appraise a piece of wood or metal, a product design practitioner answered that he might talk about the weight, or the volume. When asked about the fabrics, he said that, according to his background, the fabrics were 'really a fashion item that we don't really link with quantitative feedback'. This highlights discrepancy in the understanding of practices of other design subjects.

6.4.3.2. Responses from textile backgrounds

Textile design practitioners were largely aesthetic in their responses and concerned with the processes by which the fabrics were made. Some of the comments were limited in their interpretation of the design process and how an application was not needed to initialise a design project; that material could be the basis for a design, as could a stitch structure or a yarn.

6.4.4. Differences in responses and comment on knowledge transfer between participants

When put into pairs to appraise the samples, some of the participants had difficulty communicating an example from the transcript being 'he used a lot of terms I don't know' (from a non-textile artist paired with a textile engineer).

Individuals were quick to acknowledge that their backgrounds had affected the way they communicated with each other and the way they related to the fabrics. Below are some responses relating to knowledge transfer:

- 'from my background…I wouldn't feel comfortable using [the tape measure/measuring equipment]'
- 'I think it's more our background [than the researcher's] that influence us [in the way we look at the samples].'
- 'for those people who don't have that much knowledge of knitting, we just look at it as a fashion, so we don't really expect any… I wouldn't expect myself to give any quantitative feedback, only subjective.'
- That using a ready-made [designed] fabric would be restrictive for a lot of people

Problems with communication between people of different backgrounds were not common, as most participants seem to communicate in shared and simple language. The only difficulty discussed was between a textile engineer and an artist.

6.4.5. Conclusions of analysis

As with the previous focus groups, FG3's participants took it upon themselves to put a strong emphasis on naming applications for the fabrics. This seemed to be a natural progression for the design practitioners. Among the suggested applications, there is still a tendency to propose existing fashion or clothing outcomes (e.g. maternity wear, tube skirts, etc.).

The assumptions of the participants in this group affected their responses greatly. In some cases disciplinary background dictated how the tasks and the fabrics were perceived, for example, one product designer only saw the fabrics as 'fashion items', even after explanation of the fabrics' auxetic behaviour was given. Over the duration of the study, there has been a tendency to limit the perceived usefulness of the fabrics to items of apparel and accessory.

6.4.6. Evaluation of FG3

In a small focus group, quantifying the results may be skewed to the responses of participants who speak most often or repeat certain points. The written responses, when added to the verbal responses, help to alleviate this problem by providing equality amongst responses from different participants within the group. The written and spoken results have been shown separately in **Table 6.10**. The written exercise provided equal opportunity for all participants to provide feedback.

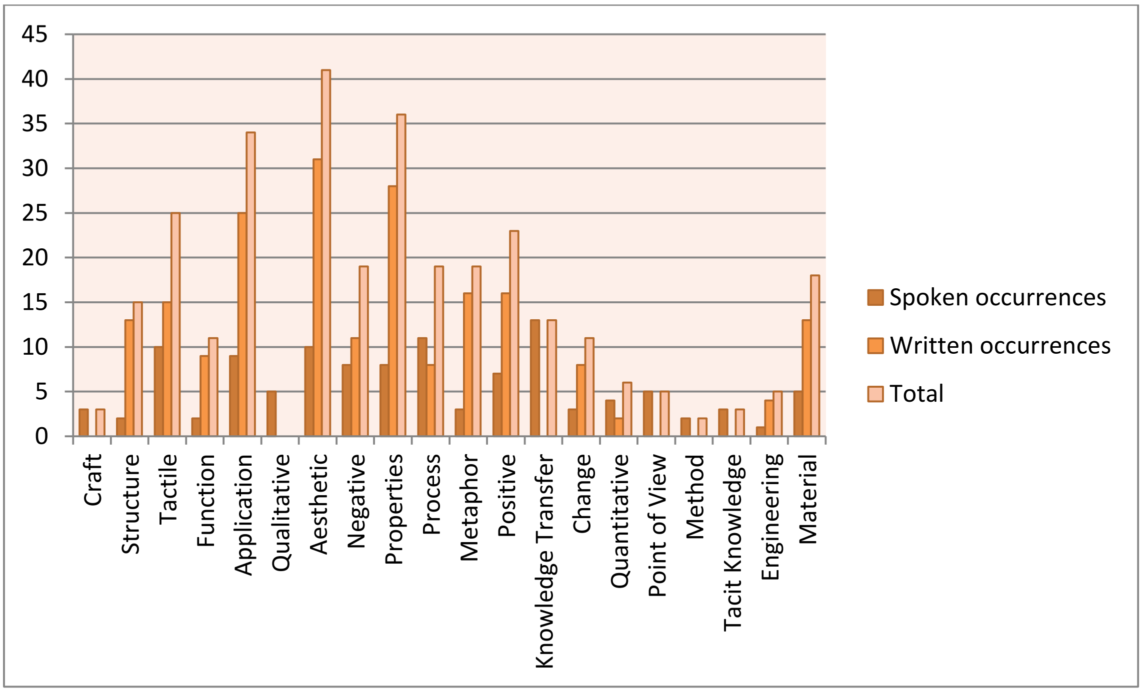


Table 6.10 Written and spoken responses to FG3 shown separately.

Pairing participants in one exercise provided interesting responses to samples. Additionally, the paired task and discussion helped to highlight to the group the varied opinions and voices used in analysis and appraisal. This made the final discussion more informed and encouraged understanding of knowledge transfer.

6.4.6.1. Changes to focus group design

The final focus group will target specific participants to cover the range of disciplines involved in knit design considerations. The hand-outs will be modified for the final group. These will be adapted to incorporate more about the backgrounds and to focus more on the ideas of knowledge transfer. Withholding the information about the auxetic properties of these fabrics did not provide significant changes in findings from FG2 and will not be continued for FG4.

6.5. Theory building

Table 6.11 shows the theory as drawn from the data in Focus Group 3 and obtained through practical experimentation and reflection is outlined.

Proposition	Evidence from data	Outcome
Design and experiential knowledge is appropriate to produce knitted auxetic materials.	Samples 13 and 14	Make explicit the role of design knowledge to the production of fabrics.
Quantitative analysis depends on the equipment available. Practitioners may have particular methods, not a generic need to quantify.	Engineer and science practitioner would have tested fabrics with their own equipment, but did not measure using simple measuring devices.	Discuss types of data rather than measuring samples in FG.
Samples can imply a ‘preciousness’ that prevents them being seen as materials with wide potential.	Participants thought of fabric as a developed material; not as a useable material and not an end-product.	Present more samples, more variations in material and placement to show flexibility and range.
Illustrative descriptions help participants to communicate a shared understanding about complex ideas.	The use of similes and metaphors played a strong role in describing samples.	Link finding to Eckert & Stacey research (2000: 526). Explore alternative descriptions for information.
Tactile information is important to the understanding of a textile. This is most important to design practitioners.	Tactile appraisal often changed responses based on aesthetic appraisal.	Aim to include physical samples where possible (e.g. exhibitions, conferences).

Methodological background can affect all subsequent work. Methodology and background is cumulative.	A knit design practitioner uses a scientific method in designing fabric.	Multi-disciplinary information is useful even to specialised audiences.
Practitioners are not necessarily of a single discipline	Hand-out exercises showed no evidence that any participants thought of themselves as singly disciplined.	Seek multi-disciplinary outcomes. Acknowledge importance of mixed-discipline approach.
A range of textures and colours will expand the scope for ideas and applications	Feedback from each focus group.	Continuation of experimentation with colour, materials and scale in Stage 4.
The process of a design project is dependent on the starting point.	Different participants acknowledge different starting points (e.g. semi-developed material, yarn, etc.) influencing the final outcome.	Compare research project with generic stages of knit design.
The relative 'newness' of technical textiles as materials may make them seem 'job-specific.'	Fabric was treated differently from other materials such as wood, metal and plastic. The expectation for use was more limited.	Compare research project with generic stages of material development.
Knitwear design process creates different elements simultaneously.	Knit design practitioner acknowledges the process of designing the fabric and the product simultaneously. The process is not linear.	Consider diagrammatic version of methodology to include parallel/iterative considerations.
Tacit appraisal is important, at least as an initial or developmental reaction.	Tacit appraisal is important to all participants	Include and value tacit responses.
Disciplinary allegiance may be overt (but does not exclude influences from other areas).	Individuals acknowledged the influence of their backgrounds on communication and appraisal.	Include and value perspectives of researcher and contributors.
Subject specific language can cause problems for multi-disciplinary groups.	Some communication problems between individuals stemmed from language use.	Avoid jargon where possible. Where not possible, include alternatives.

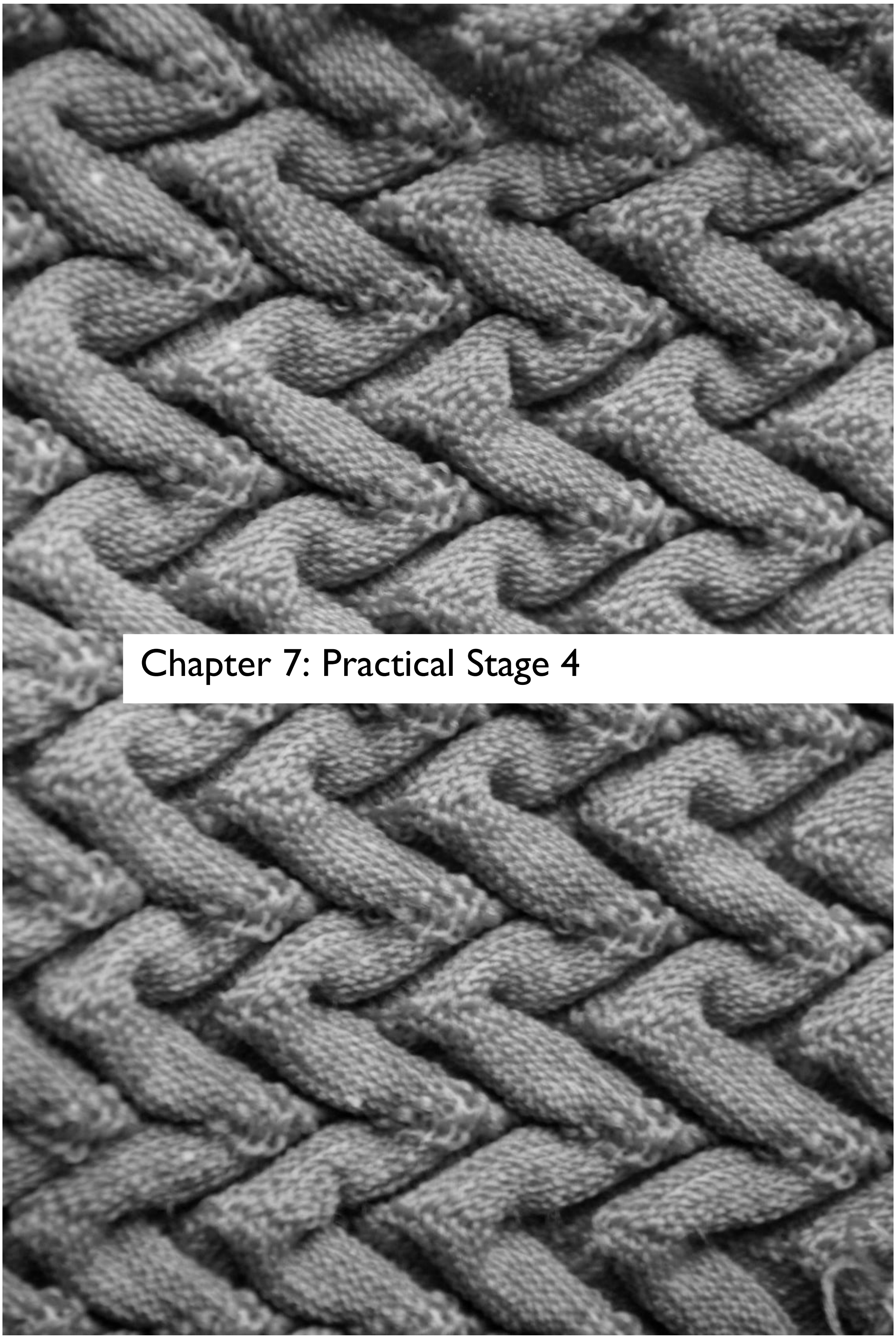
Table 6.11 Theory building from focus group and practical data in Stage 3.

6.6. Chapter conclusions

The development of fabric in Stage 3 encountered more problems than in Stages 1 and 2. Because of this, the sample development stage produced fewer auxetic fabrics than the earlier stages. One noticeably auxetic structure was achieved. This auxetic spacer fabric has possibility for variants to the scale of the filaments and the pattern of the wall fabrics (resulting in Samples 13 and 14). Some further variation will be conducted in Stage 4 of the fabric development.

The auxetic spacer fabric from Stage 3 is significantly different from the fabrics in Stages 1 and 2, as well as from fabrics developed by other researchers in auxetic textiles work published so far. The auxetic effect has not been measured by quantifiable means, but can be viewed to be auxetic in its behaviour when seen physically, in photographs or in video. This study aims to promote alternative methods of viewing auxetic behaviour (thereby challenging the nature of how to design functionality) - a fully qualitative, human method of attributing auxetic behaviour is seen to be a reasonable alternative to quantitative testing.

Chapter 7: Practical Stage 4



7. PRACTICAL STAGE 4

7.1. Introduction

After the first three stages it was decided to take the fourth stage into an exploration of materials and proportions.

The reasons for this were as follows:

- Feedback had come through in focus groups wanting to see different scales and different materials to enable participants to envisage different applications and take different experiences away from the fabrics.
- These variations facilitate the main aim of the research, which is promotion of knowledge transfer.
- To provide further proof of the concept that these technical materials can be aesthetic, designed, can appeal to wider audiences and be improved/adapted using experiential knowledge from design perspective.
- To continue the technical exploration for auxetic effect under different circumstances.

In this chapter, a record is presented of the final knitting stages with sixteen knitted samples discussed. Quantitative measuring of a selection of samples from across Stages 1-4 is presented to offer objective and numerical alternatives to the subjective visual representations of auxetic behaviour so far. By presenting graphs of auxetic behaviour in addition to the percentage and visual data seen so far, a versatile set of information is available to appeal to different practitioners and publications. The combined body of work from Stage 4 and the fabrics and supporting information is discussed with the final focus group (FG4).

7.1.1. How fabrics are developed from Stage 3

Stage 4's experimentation with materials and pattern elements demonstrates the diversity and variability of the fabric swatches. This variety adds an important range of qualities as incentive to design practitioners to incorporate auxetic materials into design applications.

Based on feedback from Stages 1-3, it was thought that presenting fabrics in various materials, pattern, colours, proportions etc. would encourage a diverse response from focus group participants from different backgrounds. The responses of the participants in FG4 showed that colour and material variation did have the desired effect in encouraging more enthusiastic responses from participants.

Some fabric samples were designed to look more 'technical'. This involved elements such as using synthetic yarns (e.g. a covered elastomeric or polyester), a fine gauge knit and a small stitch size, using a plain white yarn to best display stitch structure and using a uniform stitch structure.
Some fabric samples were designed to look more 'artistic'. These fabrics used contrasts in colour, contrasts in yarn types, variations in the placement of the patterned areas (all-over, central, in shaped sections, etc.) and the use of bright and bold colours to inspire thoughts towards different applications.

In preparation for the final focus group, some of the samples were seamed into tubes, by using a linker to make a chain stitch, as is typical in knitwear manufacture. This demonstrates a variety in presentation of the fabrics. In FG3 comments were made comparing the fabrics with a material like metal that might be available in wires, sheets and tubes. So the production of a tube was thought to aid visualisation of the fabrics as either raw, semi-prepared or fully-prepared materials. Since a tube is a vital component part of many knitted garments, yet not a complete product in this case, it might inspire thoughts of more three-dimensional uses for the fabrics.

For the focus group, a selection of the fabrics[61] is shown to most comprehensively represent the range of fabrics and variations available.

7.1.2. Variations explored during this stage

The variations in this explorative section of the research project concentrated on logical experimentations in knit practice. Changing simple elements of the fabric gives ranges of different effects. The samples were tested qualitatively with focus groups and videoed to show auxetic effect. Videos showing the fabrics in movement can be found in the supporting information for this thesis.

7.1.2.1. Yarns

Ranges of natural and synthetic yarns have been explored over the 4 stages of this research. In this final stage, the yarn choices will be dictated by which yarns give good aesthetic[62], tactile and auxetic results. The potential for experimentation with yarn is very large, and during this research there is not the scope for exhaustive trialling of yarn types.

7.1.2.2. Scale

Variations in proportion and scale will be achieved by changing the machine gauge or the pattern/stitch structure dimensions as well as the size of the piece of fabric. By using elastic yarns or yarns of different thicknesses and densities, it is possible to alter the scale by changing the yarn type.

7.1.2.3. Aesthetic patterning

Stripes, plating and placement of pattern in plain grounds will be used to provide aesthetic variation. Striping can be used in line with and against the pattern. Variation can be made by mixing auxetic and conventional structures in the same piece of fabric.

The samples in this stage will be discussed in groups relating to their original samples from Stages 1-3. The stitch structures remain the same as or slightly varied from the structures from Stages 1-3. A thumbnail image referring back to the original fabric development is shown next to each heading.

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[61] To show successfully auxetic fabrics, but also a range of auxetic behaviour, structure, appearance and materials.

[62] Opinions on qualitative properties are my own in the development stage and from the participants in the focus group stage.

7.2. Significant sample variations

The 16 samples discussed in this chapter are selected to display significant, interesting, visual, textural and auxetic results. Notes on the full trials and the variations considered can be found in **Appendix D**.

7.2.1. Samples 15 and 16 (Purl zigzag stagger) – from Practical Stage 1

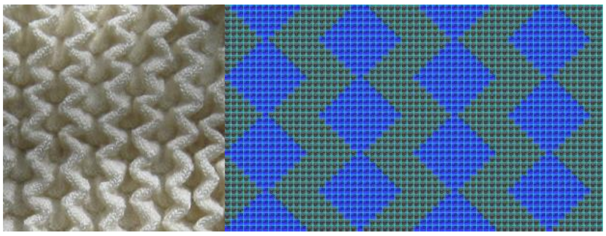
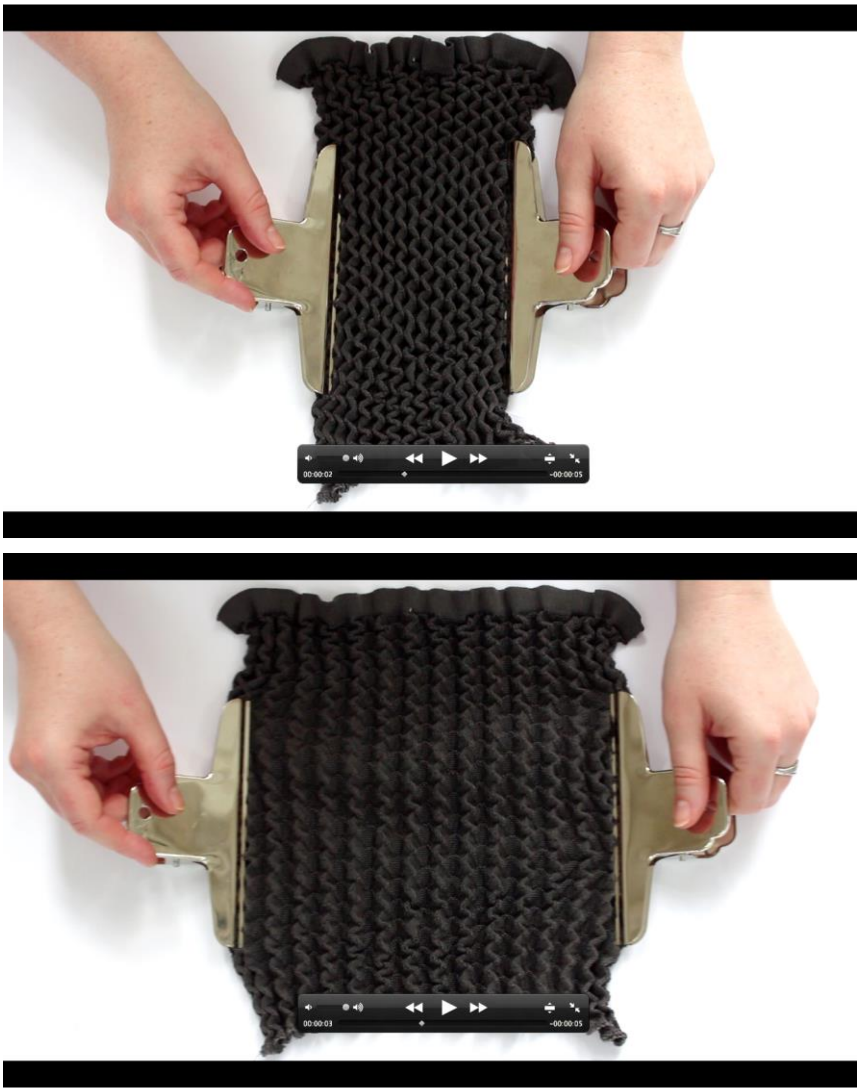


Figure 4.44 (Chapter 4)

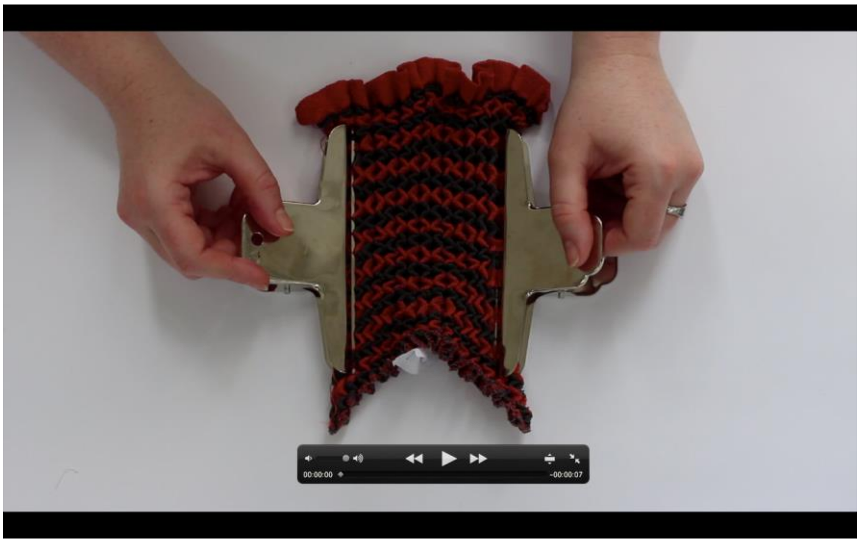
The main variations of the purl zigzag stagger sample (a variation from Liu et al.'s [2010] paper) use yarn and slight patterning variation. The auxetic results from initial testing were present, but not very pronounced, so significant developmental work was not explored. **Figure 7.67** (Sample 15) shows a grey polyester sample plated with elastomeric yarn to improve return and increase structure definition. The elastic yarn used for plating is wrapped in fine, black polyester and the colour contrast provides a subtle impression of the relief pattern when the fabric is pulled flat. The striped version in **Figure 7.68** (Sample 16) shows another potential for aesthetic patterning. The stripes in this sample highlight the details of the stitch structure. Both variations retain the definition of the original sample in Stage 1. Samples 15 and 16 display the same honeycomb effect and thickness as the original fabric (Sample 2).



(a)

(b)

Figure 7.67 Sample 15 (Purl zigzag stagger) in grey polyester plated with elastomeric yarn at rest (a) and stretched in Y-axis (b).



(a)

(b)

Figure 7.68 Sample 16 (Purl zigzag stagger) in stripes of grey and orange polyester at rest (a) and stretched in Y-axis (b).

7.2.2. Samples 17-19 (Rectangle Purl) – from Practical Stage 1

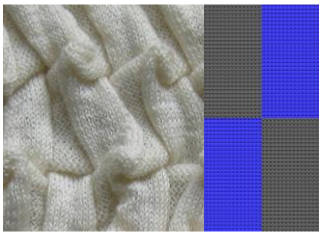


Figure 4.45 (Chapter 4)

Variations were knitted on Sample 4 (Stage 1). **Figure 7.69** (Sample 17) shows how the method of plating with elastic yarn (when knitted with polyester) added an inconsistency to the final fabric. The irregular pattern is caused during the relaxation of the fabric after it was removed from the knitting machine. Though the programmed pattern is regular, and in other yarn variations (such as in Sample 4 and Sample 18) the fabric appears regular, the elastic in this version causes the structure to be more dense and forces some of the peaks to flatten or to point to the other side of the fabric. Sample 17 was also stitched into a tube, which showed a good auxetic effect (as shown in **Figure 7.70** in the stills taken from a video of this sample being stretched. For video see supporting information for this thesis).

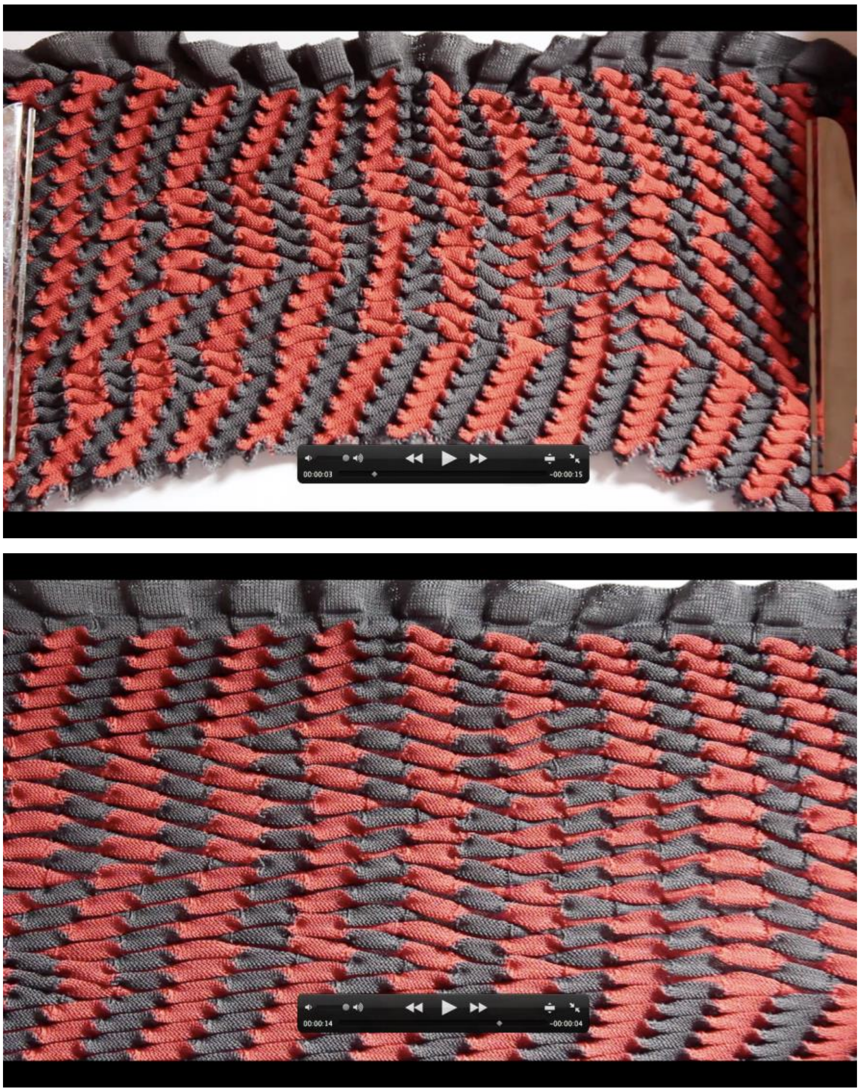
Figure 7.69 Sample 17 (Rectangle purl) Regular pattern plated with elastic, giving an irregular appearance.

(a)

(b)

Figure 7.70 Stills from video showing Sample 17 in grey polyester with elastomeric (a) at rest and (b) stretched in Y-axis.

In **Figure 7.71**, Sample 18 can be seen with stripes of grey and orange polyester. The twist in the pattern causes these to resemble vertical stripes when the fabric is relaxed. If stretched flat, the stripes are seen to be horizontal. It is worth noting that the sample in **Figure 7.70** shows stretch being applied to the Y-axis (along the wale direction) and the images in **Figure 7.71** show stretch being applied to the X-axis (course direction). Both photos show expansion in the transverse direction.



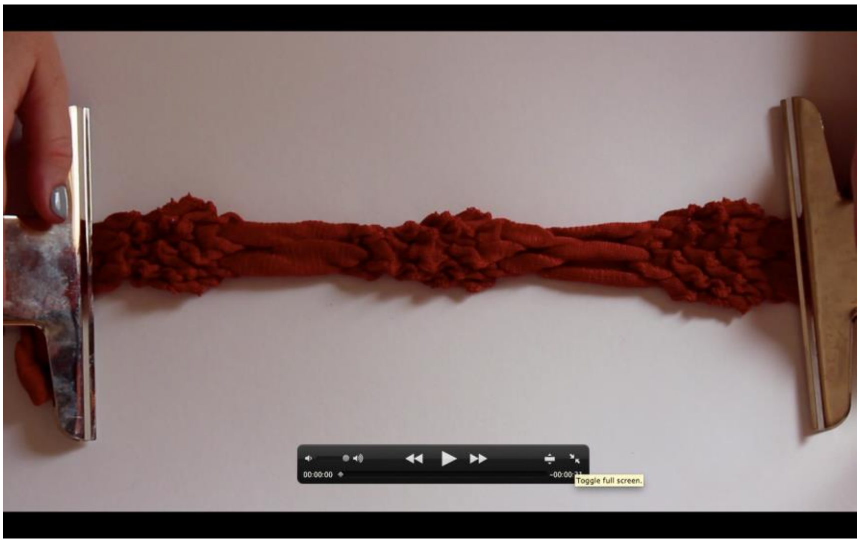
(a)

(b)

Figure 7.71 Sample 18 (Rectangle purl with stripes) in grey and orange polyester (a) at rest and (b) stretched in X-axis.

The variation shown in **Figure 7.72** (Sample 19) uses the auxetic structure (rectangle purl) in sections with plain knitted fabric in between[63]. When stretched, the unfolding of the auxetic relief structure demonstrates the natural tendency of the plain fabric to curl. This fabric has a strong visual effect when stretched as shown in the stills in **Figure 7.72** and the accompanying video.

[63] A version of sample 19 using rib sections in between the auxetic structure can be found in the supporting information in a video titled: 'Sample 19 (double-bed) Y-axis stretch.wmv'



(a)

(b)

Figure 7.72 Sample 19 (Purl rectangle) in sections with plain jersey shown at rest (a) and stretched in Y-axis (b).

7.2.3. Samples 20-26 (TP4) - Practical Stage 2

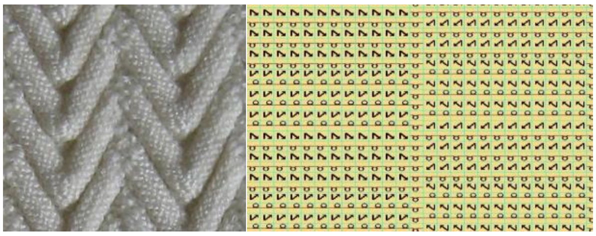
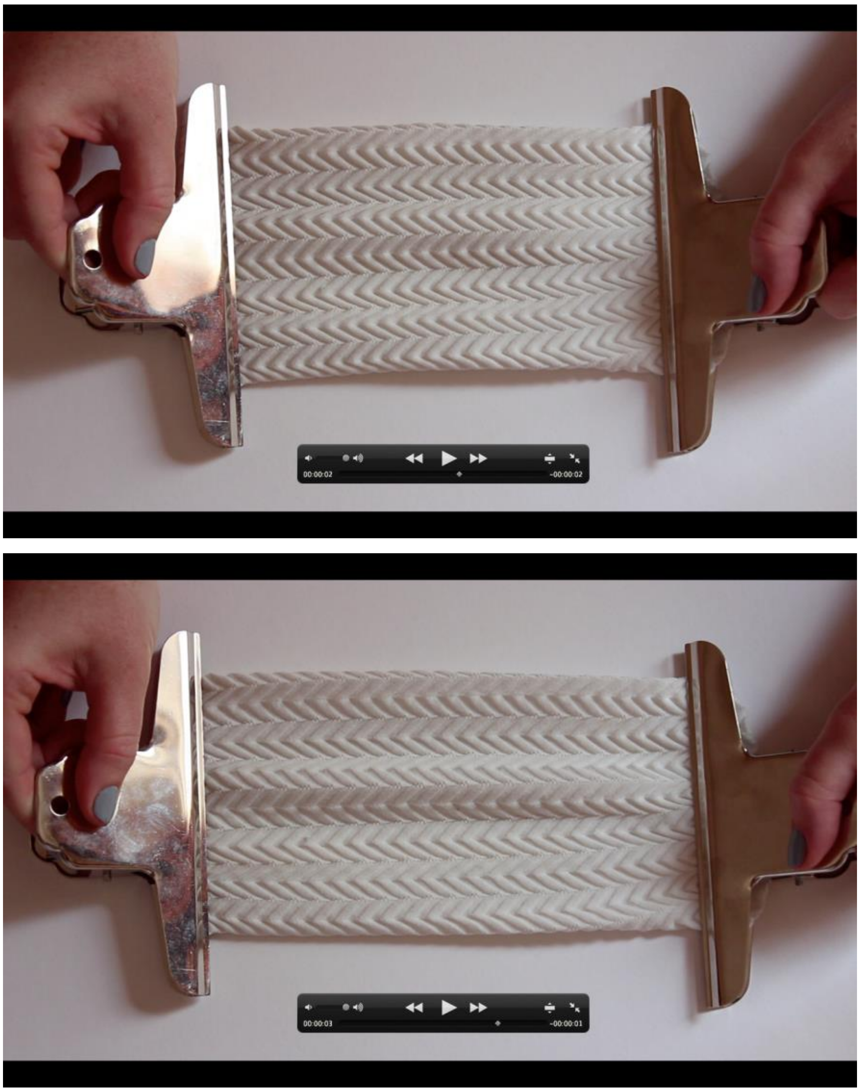


Figure 5.51 (Chapter 5)

The stitch structure known as TP4 (Transfer Purl 4 – Samples 6-9a in Stage 2) was one of the most successful structures in the previous developmental stages. Building on earlier variations during Stage 2 with plating, striping and yarn variation, Stage 4's experimentation builds on structural variations and strategic use of yarn. Shown in **Figure 7.73** and **Figure 7.74**, Sample 20 is knitted in a fine-weight covered, elastomeric yarn (3 ends of yarn knitted together). In this fabric, the elastic drastically reduces the overall scale of the pattern and the fabric, leaving the fabric looking like it was knitted on a much finer machine. During preliminary testing and handling of the fabric, auxetic behaviour showed when stretched in the X or the Y-axis. The results of this testing are discussed further in section **7.3.** of this chapter.

Figure 7.73 Sample 20 (TP4) knitted in 3 ends of Zimmerman elastomeric yarn.

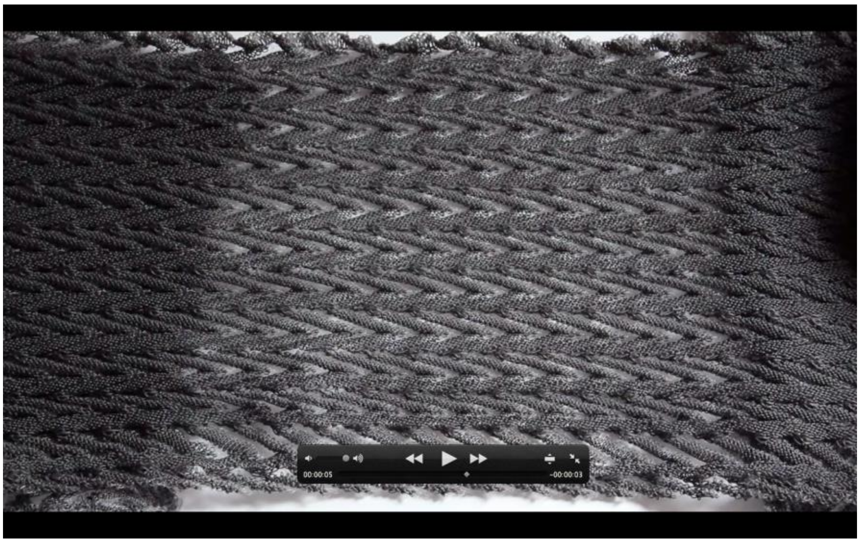


(a)

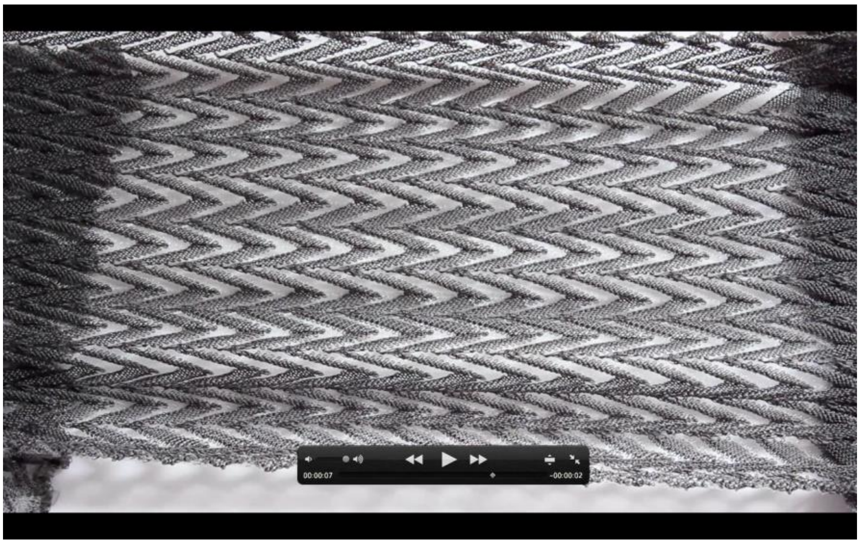
(b)

Figure 7.74 Sample 20 in white elastomeric (sewn into a tube) at rest (a) and stretched in Y-axis (b).

Figure 7.75 (Sample 21) shows an aesthetic variation on an earlier use of the TP4 structure (Sample 9) with a monofilament stripe. This combination of yarns creates an effect, when the fabric is stretched, of revealing more of the monofilament section. This creates a fabric that looks more open and allows more light or air to pass through it. The effect of this could be utilised for interior or filtration purposes (such as an artistic/visual installation, window blind, particle filter, etc.). I found the appearance of Sample 21 to be pleasing and the substitution of cream wool (in Sample 9) for grey polyester provides a different feel as both yarns are synthetic and lighter, finer and less fibrous than the wool used to knit this fabric in Stage 2.



(a)



(b)

Figure 7.75 Sample 21 (TP4) in stripes of grey polyester and transparent polyamide monofilament at rest (a) and stretched in Y-axis (b)[64].

The variation shown in **Figure 7.76** and **Figure 7.77** (Sample 22) enhances the aesthetic nature of the pattern by using stripes along the lines of the purl rib. In addition, the fabric is knitted with placement of the auxetic structure only in the central area, the rest of the fabric area is left as plain jersey fabric. This creates a strong contrast between the grey and the black elastic yarns and the areas of plain and auxetic fabric. A similar effect is given in the sample shown in **Figure 7.78** (Sample 23). Here, stripes are used again to enhance contrast in the auxetic structure, which in turn is contrasted against a conventional rib structure in sections. Both Sample 22 and 23 show movement and change in contrast when stretched. This is a striking way to draw attention to the auxetic behaviour visually, rather than through numerical data.

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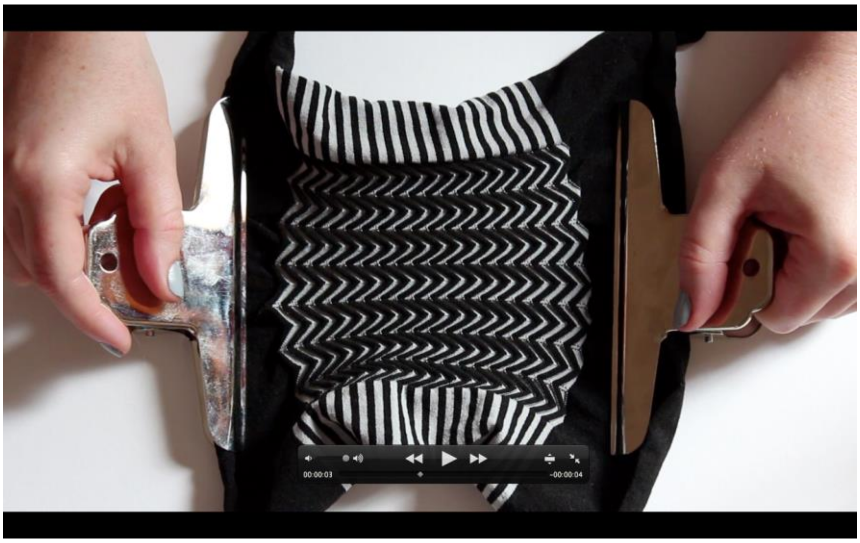
[64] N.B. the stretched fabric does increase in the transverse direction, but the image shows the fabric buckling when stretched and opening up. This is thought to be due to the size of the fabric sample or the constraints of the clamps. A similar effect is seen in **Figure 7.74**.

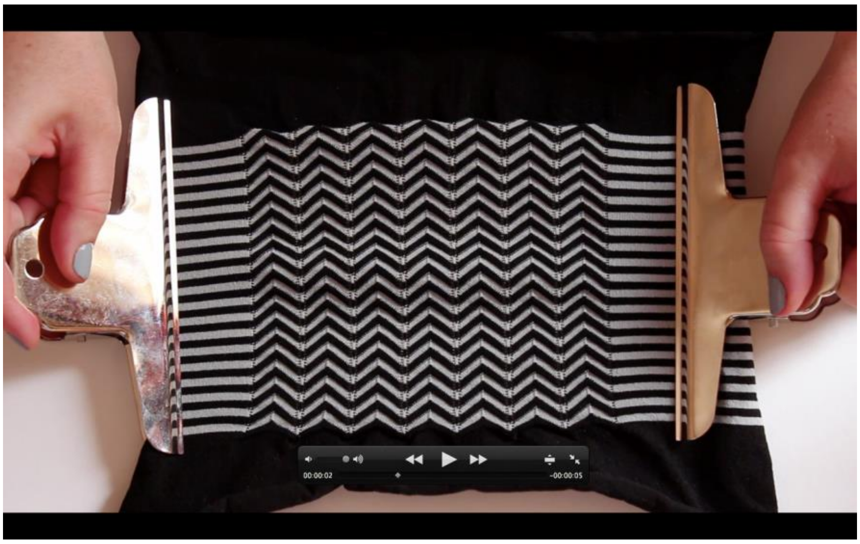


(a)

(b)

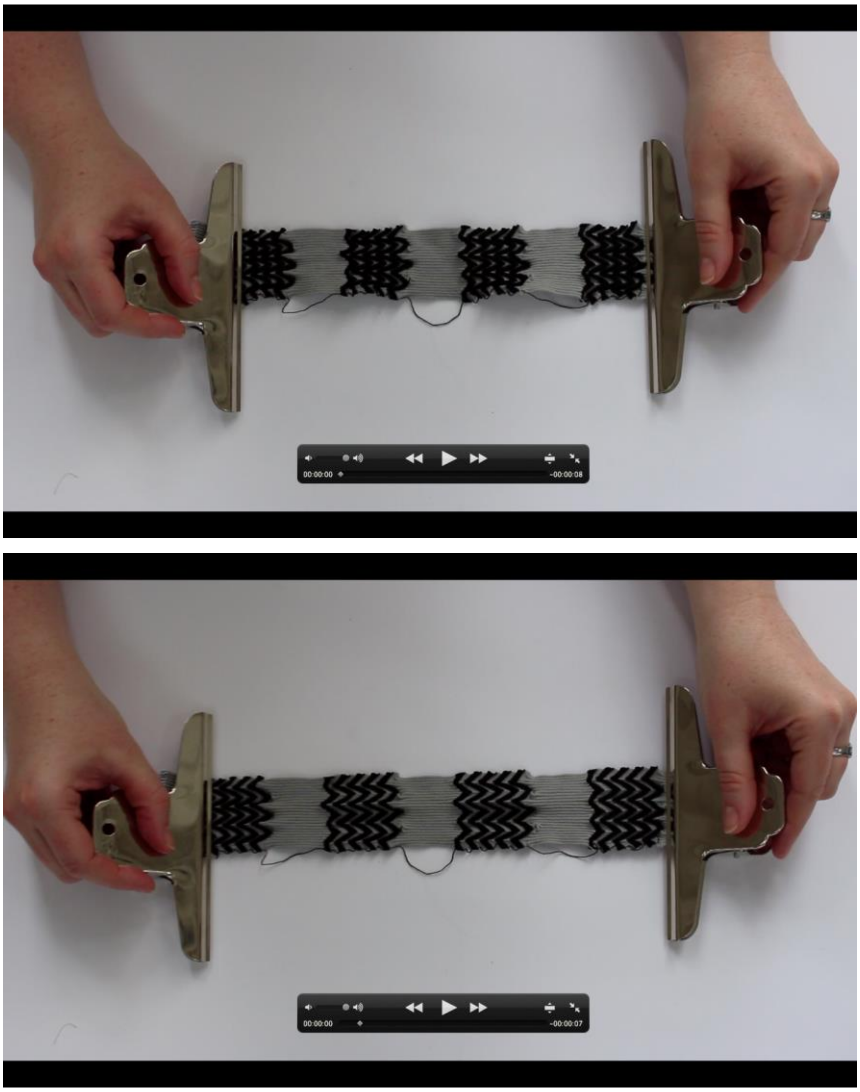
Figure 7.76 Sample 22 (TP4) knitted in grey and black covered elastic yarn at rest (a) and stretched in Y-axis (b). The pattern is positioned in the centre of a plain knitted ground.

(a)



(b)

Figure 7.77 Sample 22 (TP4) knitted in grey and black covered elastic yarn at rest (a) and stretched in X-axis (b).

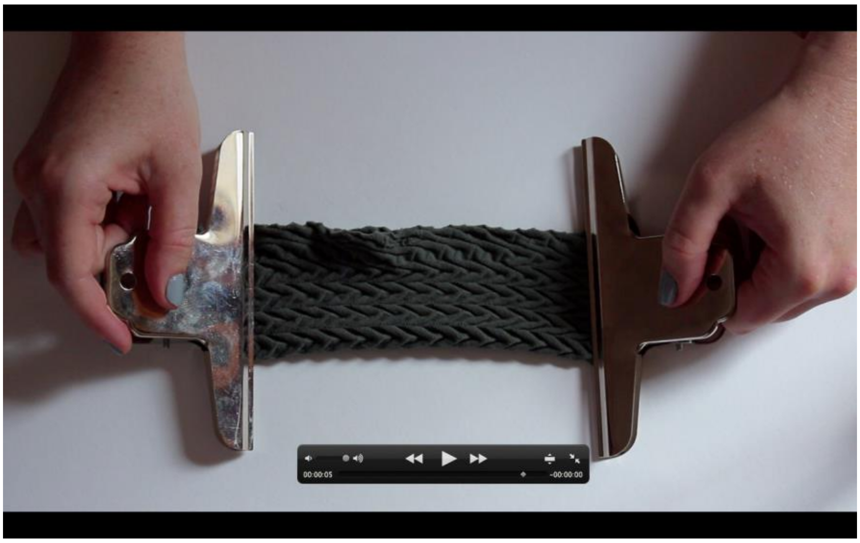


(a)

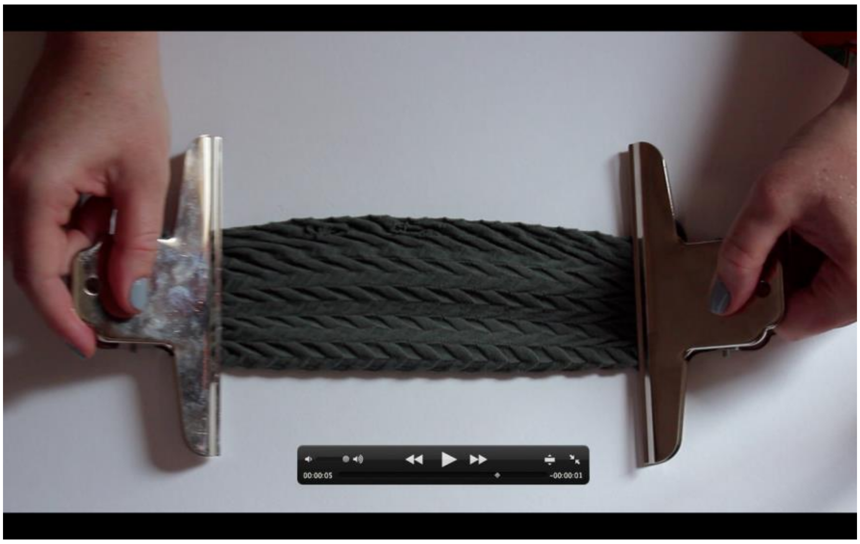
(b)

Figure 7.78 Sample 23 (TP4) structure in stripes of black and grey covered elastic at rest (a) and stretched in Y-axis (b). The structure is placed between sections of full-needle rib.

Figure 7.79 (Sample 24) and **Figure 7.80** (Sample 25) feature an increased thickness of the purl rib areas of contrast (the stripes of face and reverse stitch). In the original samples in Stage 2, the purl rib consisted of 6 courses of face stitch alternated with 6 courses of reverse stitch. In this version, the stripes are increased to 12 courses each; this is referred to as a 'larger scale' version of the TP4 structure. The increased thickness of the purl rib gives a softer zigzag than the thinner zigzags seen in the previous versions. The auxetic effect is still present but, as in other samples, how pronounced the effect is depends on the yarn and tension used for knitting.

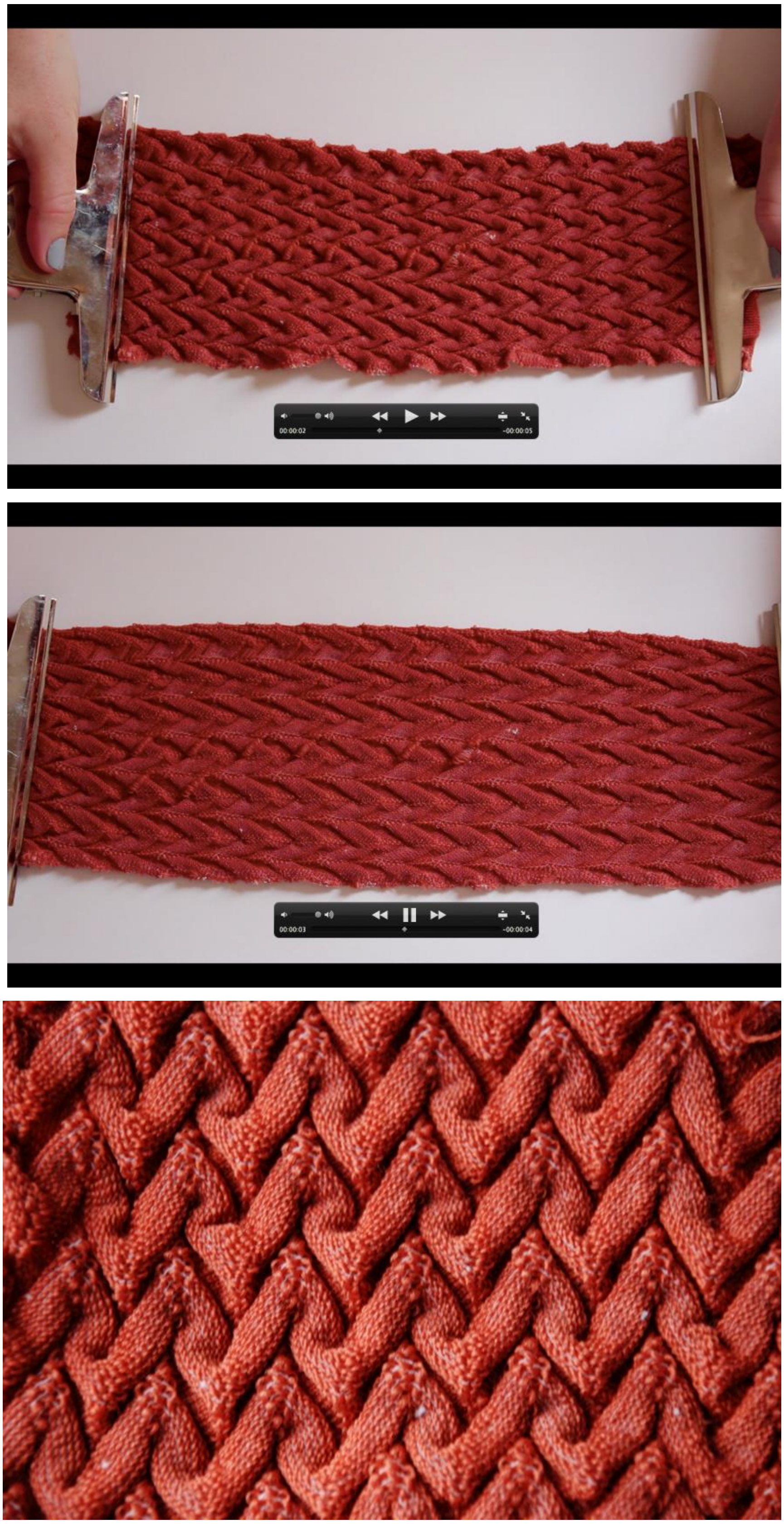


(a)



(b)

Figure 7.79 Sample 24 (TP4) with a wider purl rib thickness, knitted in grey covered elastic at rest (a) and stretched in Y-axis (b).



(a)

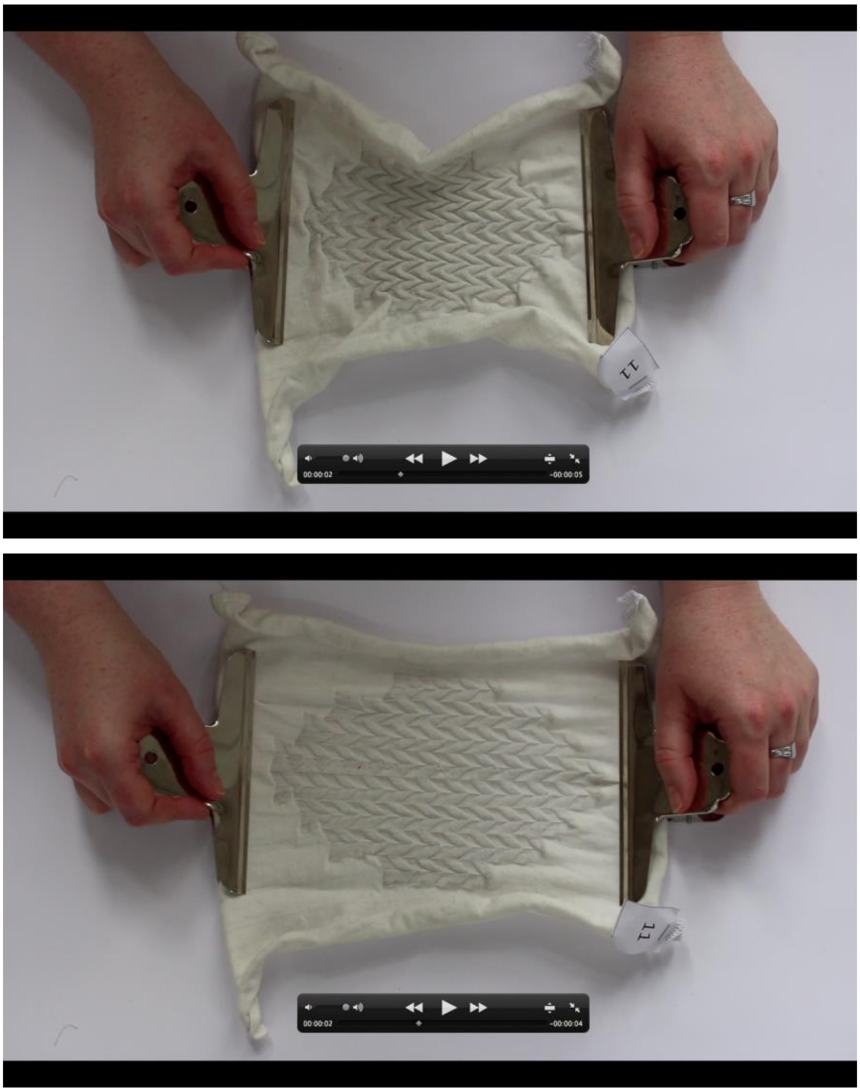
(b)

(c)

Figure 7.80 Sample 25 (TP4) (12 course purl rib) in orange polyester, plated with elastic at rest (a) and stretched in Y-axis (b). The close-up shows attractive twists (c).

In

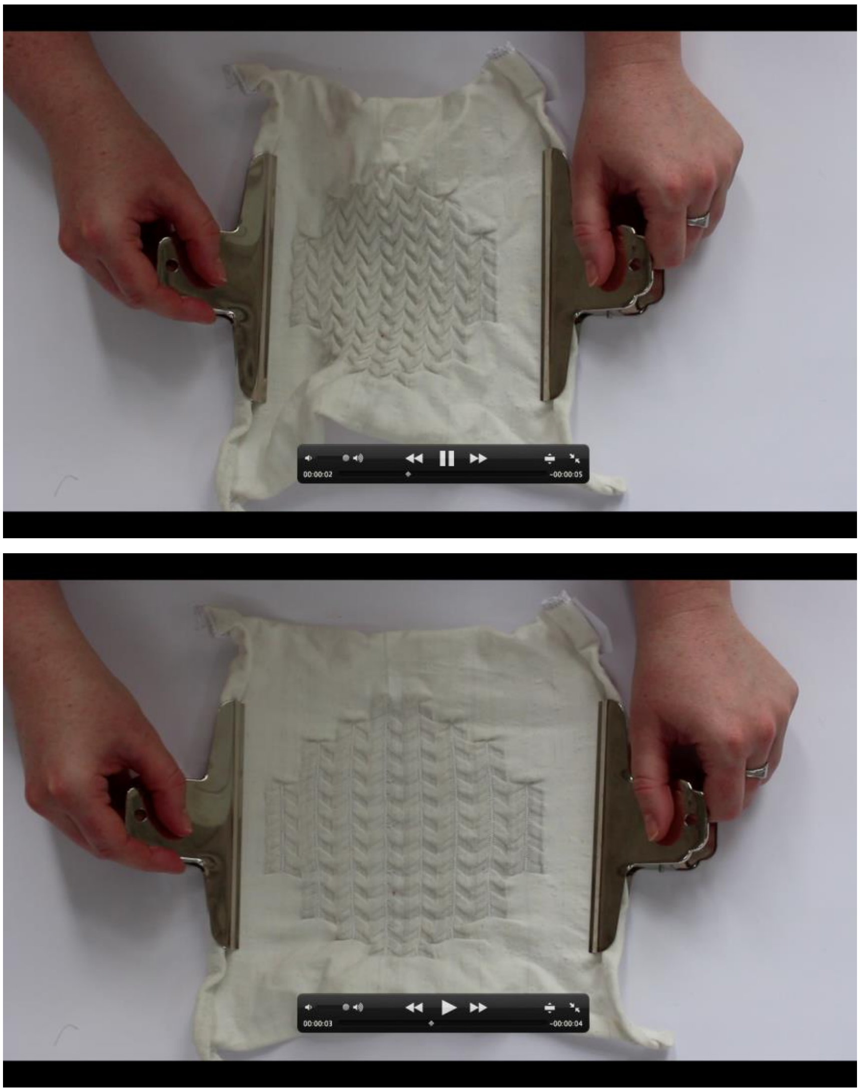
Figure 7.81 and **Figure 7.82** the wider purl rib is shown in the centre of a panel of plain fabric. The pattern is placed to give a circular area of auxetic structures as opposed to the rectangular section in Sample 22. This shows the possibility of the auxetic structures to be placed in sections on applications. For example, in a sportswear garment, there might be a need for auxetic structures in certain areas (such as at areas of stretch, like elbows, underarms, etc.) but not across relatively static areas (like forearms, stomach, etc.). Because the auxetic structure can be included in the same fabric as plain structures, it reduces the number of seams needed to create complex garments. Similarly, the double curvature provided in these structures can be exploited where needed (such as across curved or convex shapes), but does not need to be an all-over structure and can leave areas of garments plain.



(a)

(b)

Figure 7.81 Sample 26 (TP4) Larger scale in white elastomeric yarn with pattern placement at rest (a) and being stretched in Y-axis (b).



(a)

(b)

Figure 7.82 Sample 26 (TP4) Larger scale in white elastomeric yarn with pattern placement at rest (a) and being stretched in X-axis (b).

7.2.4. Samples 27-29 (TP5) – from Practical Stage 2

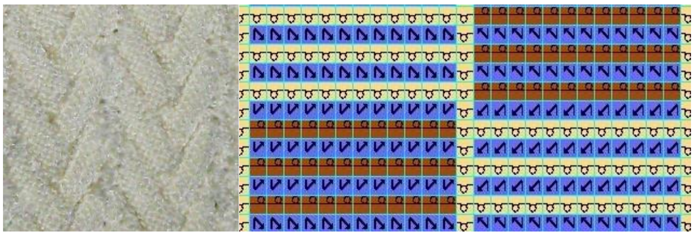
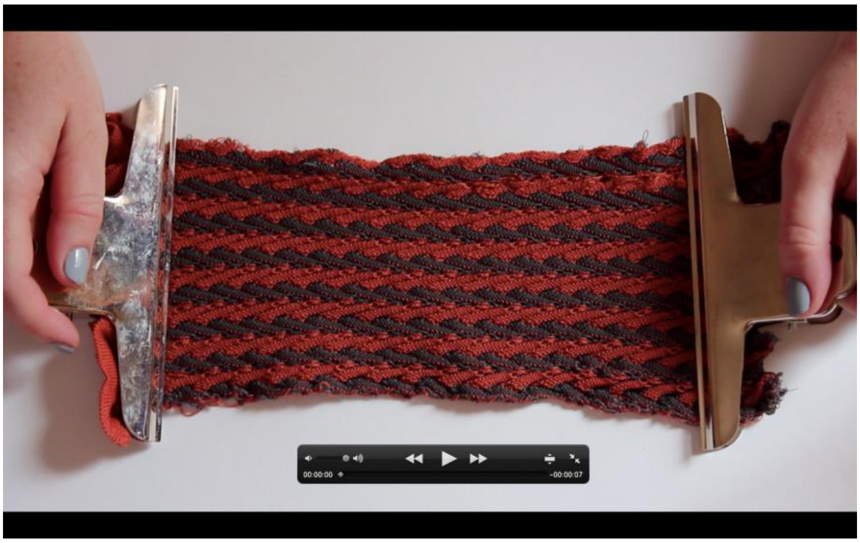


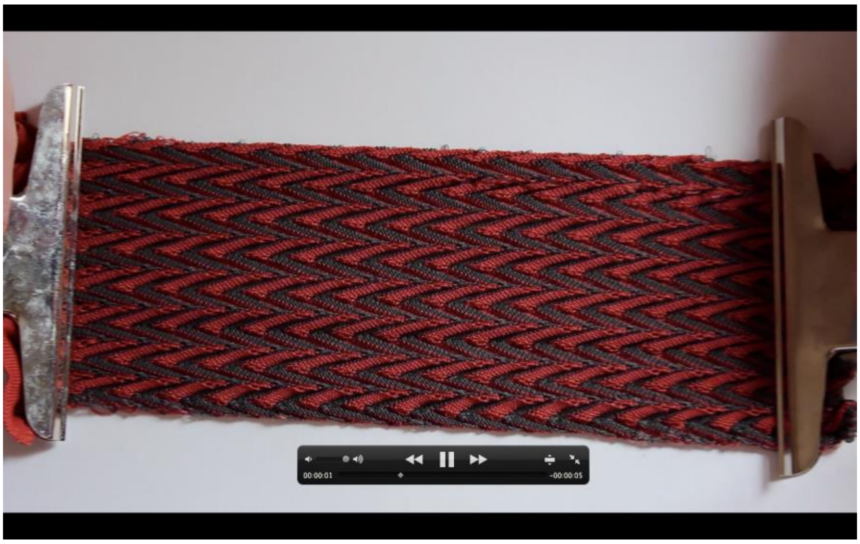
Figure 5.55 (Chapter 5)

The structure known as TP5 (Transfer Purl 5 – Samples 10-12 in Stage 2) has been trialled in variations similar to those for TP4. In **Figure 7.83** Sample 27 shows a striped version of TP5 (similar to Sample 12 in Stage 2) that displays how the stripes break up due to the stitch structure. This gives the impression of either disjointed stripes or a stripe running along the wale direction. The polyester yarn used in Sample 27 produces successful auxetic fabric, as the structure tends to fold in closely on itself, which is a useful property for these auxetic relief structures.

In **Figure 7.84** (Sample 28) and **Figure 7.85** (Sample 29) the stripes of the purl rib stripe are doubled from the original 6 courses to 12 courses. In TP4, the thicker purl rib limited the auxetic effect by making the zigzag less pronounced, but in TP5 this increased thickness made the auxetic effect more pronounced and visually interesting. The tendency of TP5's structure to interleave the alternating areas of face and reverse stitch to act like a herring-bone pattern is made more noticeable when the sections are wider. In the versions of this wider purl rib, the polyester worked very well when not plated with elastic yarn (as in **Figure 7.85**), because the fabric was less dense and could contract more. The version with elastic, however, made a sturdy fabric that had a more pronounced return when stretched.

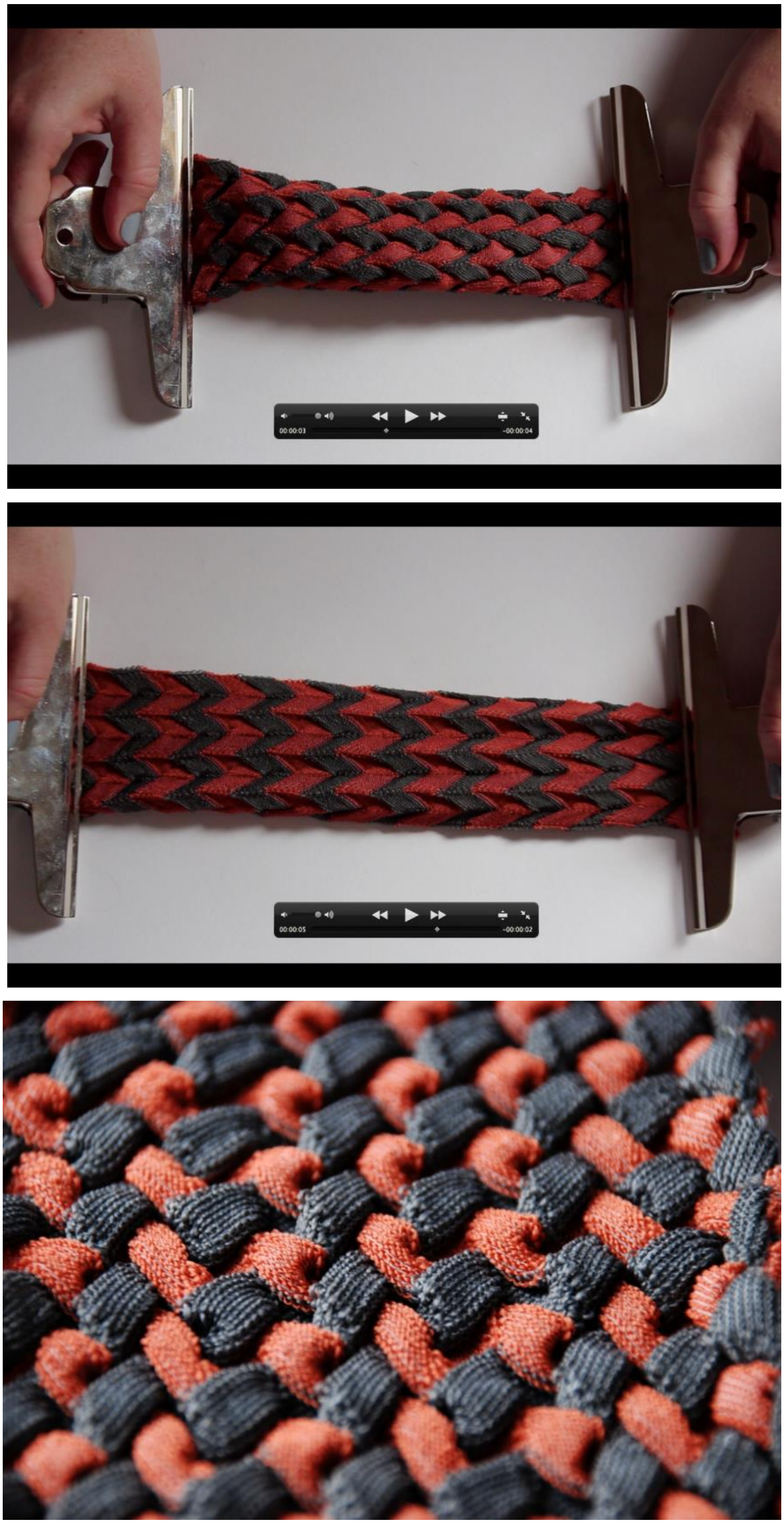


(a)



(b)

Figure 7.83 Sample 27 (TP5) in grey and orange polyester stripes at rest (a) and stretched in Y-axis (b).

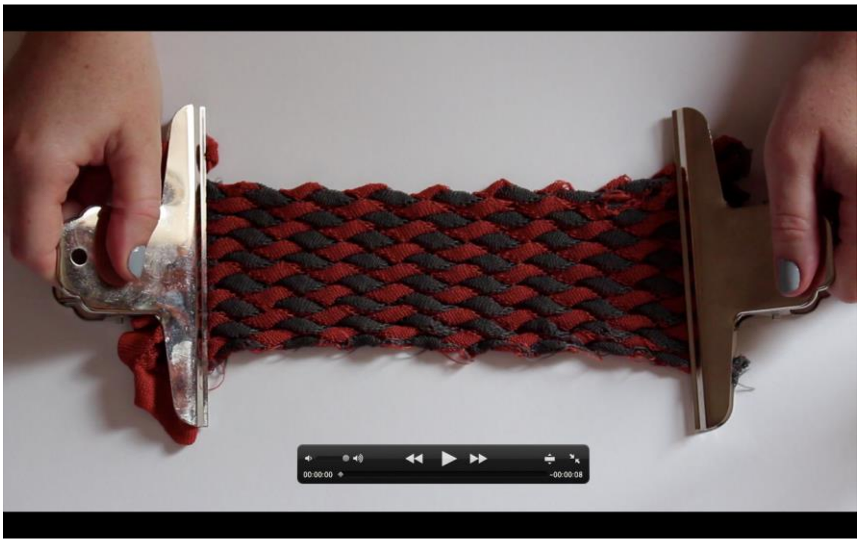


(a)

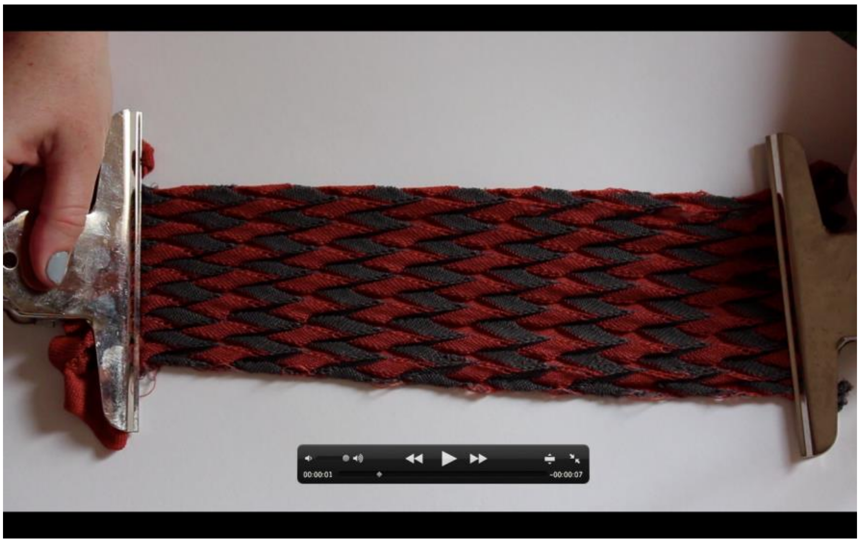
(b)

(c)

Figure 7.84 Sample 28 (TP5) with wider purl rib, striped in grey and orange polyester, with elastic. The fabric is sewn into a tube at rest (a) and stretched in Y-axis (b). (c) shows a close-up of the fabric aesthetic.



(a)



(b)

Figure 7.85 Sample 29 (TP5) with wider purl rib, knitted in grey and orange polyester without elastic at rest (a) and stretched in Y-axis (b).

7.2.5. Sample 30 (Bulk test) – from Practical Stage 3

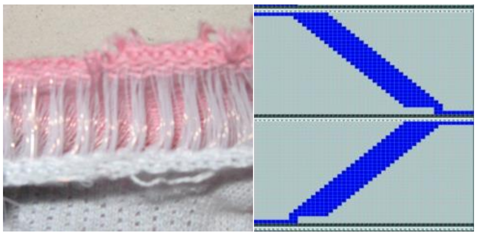


Figure 6.62 (Chapter 6)

The auxetic spacer fabric exploration in Stage 3 produced one notably auxetic fabric, which was chosen for further development in Stage 4. Developing from the initial fabrics produced in polyester and cotton with polyamide monofilaments in the centre, **Figure 7.86** shows the auxetic spacer fabric knitted in covered elastic yarns. The half-gauge structure within the wall fabrics is knitted in alternating stripes of white and orange (with white and grey on the opposite wall fabric). Using horizontal stripes of yarns causes narrow vertical stripes of one wale each to show on the outer surface due to the fabric's stitch structure. These stripes add visual interest to a fabric that is mainly noteworthy for its internal structure.

(a)

(b)

(c)

Figure 7.86 Sample 30 (Bulk test/Auxetic spacer fabric) knitted in orange, grey and white elastics at rest (a), stretched in the X-axis (b) and a view of the wall fabric (c).

7.2.6. Conclusion on fabric development

The samples developed in Stage 4 create a collection of fabrics with visual, tactile and auxetic variations to be shown in the final focus group and any relevant showcasing opportunities. These fabrics show evidence of design considerations, producing aesthetically interesting samples with a range of properties to be considered by others. The collection of fabrics developed from Stages 1-4 aim to provide viewers (from focus groups and conferences) and readers (of this thesis and related publications) with a variety of fabrics to appeal to different tastes and areas of interest/expertise.

7.3. Testing results for Stages 1- 4

After completion of the fabric development Stages 1- 4, the test frame as described section **3.10.** was used to test a selected range of the samples from across the four stages. Samples to be measured with this test frame were chosen as they had shown interesting results in preliminary testing (Stages 1- 3), and to provide representations of different stitch structures and yarn fibres used during this study.

The quantitative testing from using the test frame diversifies the information available about the samples in this thesis. It provides a quantitative alternative to the qualitative responses that I favour through my designer-maker approach. Inclusion of this information also aims to validate the auxetic effect in the conventions of the scientific community, who are one of the desired audiences for this thesis.

The graphs in this section show the quantitative information in a visual format, as described in section **3.12.** of this thesis. The use of lines to show the change in measurement of the fabrics is favoured in this study as it provides a direct correlation of the fabric movement to the graph – i.e. when the transverse measurement gets wider, the curve goes up, and when the transverse measurements get smaller, the curve goes down. It is thought that the combination of photographic, video, graphical, diagrammatic, numerical and percentile information will provide a range of data types to appeal to wide audiences in dissemination. Different data types might appeal to different readers, and it is hoped that the mix of data types will encourage understanding of the approaches of different subjects.

Using the wooden testing frame provided the opportunity to gather comparable and detailed testing information from the chosen samples. The information from this testing was used in Focus Group 4 (FG4) as one of a number of artefacts showing how technical information can be used in describing auxetic materials and the auxetic fabrics made in this study.

7.3.1. Graphs from testing and image analysis

7.3.1.1. Sample 2 (Purl zigzag stagger)

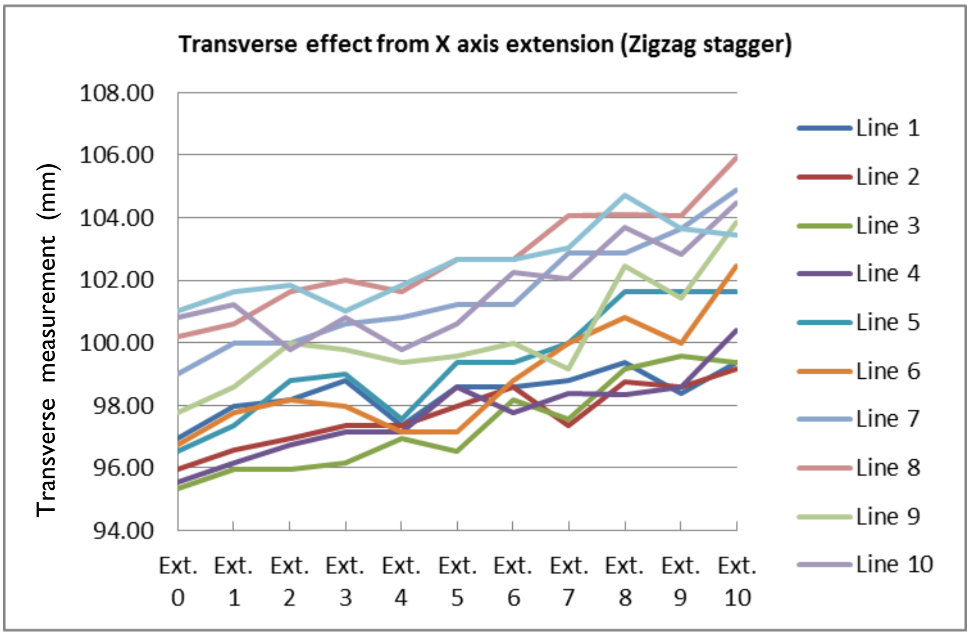


Figure 7.87 Graph of frame testing results from Sample 2 extending in the X-axis and measuring expansion in the Y-axis (Practical Stage 1).

Figure 7.87 shows results for the testing of 10 transverse measurements (Lines 1-10) on Sample 2 (Purl zigzag stagger) over an extension of 100mm. The curves on the graph show a general tendency to increase in measurement (mm) over the course of extension – thereby showing an auxetic effect in the fabric. This test shows the results of extending in the X-axis (course direction) and measuring the Y-axis (wale direction). Unlike the preliminary testing stage, the frame testing stage extends samples (using human force) until there is significant resistance to further stretching[65].

Figure 7.88 also shows results from measuring Sample 2, but this time extending in the X-axis (course direction) and measuring expansion in the Y-axis (wale direction). The results show a general trend for initial increase in the transverse measurement. It is worth noting that the sections measured to give information for lines 1, 2, 10 and 11 are constrained by the clamps and therefore may not give results comparable to the other, unrestrained sections. Five of the lines measured give a curve that increases initially and then decreases over the course of the extension. Of these five lines, none of the measurements after an extension of 70mm are smaller than the original measurement at rest. From this it can be said that in this case, Sample 2 showed a NPR initially and did not show a positive PR, as the transverse measurement did not decrease from the original measurement when at rest.

[65] This gives a number of measurements to provide a graph, rather than the preliminary testing that gave one measurement at what was judged to be the widest expansion.

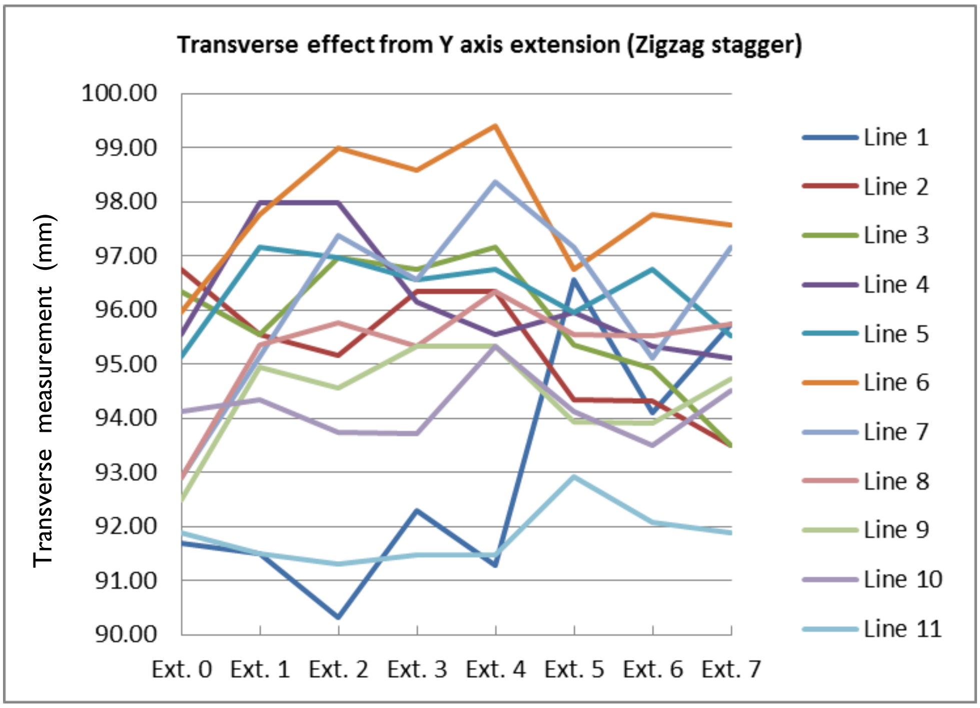


Figure 7.88 Graph of frame testing results from Sample 2 extending in the Y-axis and measuring expansion in the X-axis (Practical Stage 1).

7.3.1.2. Sample 4 (Purl rectangle)

The results of measuring Sample 4 (Purl rectangle) can be seen in **Figure 7.89**. The graph showing the measurements in the Y-axis appears erratic, but this can be explained by the marking of the samples. The 3-dimensional nature of the relief structures distorts the fabrics, making regular marking of the points used for measurement problematic. As the fabric moves and unfolds under extension, the marked points may move in an unpredictable manner, leading to irregular results. It is not expected that a smooth curve would be achieved in the measurement of these samples.

A notable observation from **Figure 7.89** is that all of the lines measured expand beyond their original measurements. Each line, after extension of 80mm, has a greater measurement than when at rest. The results at extensions 4 and 6 are likely to be caused by irregular unfolding of the fabric.

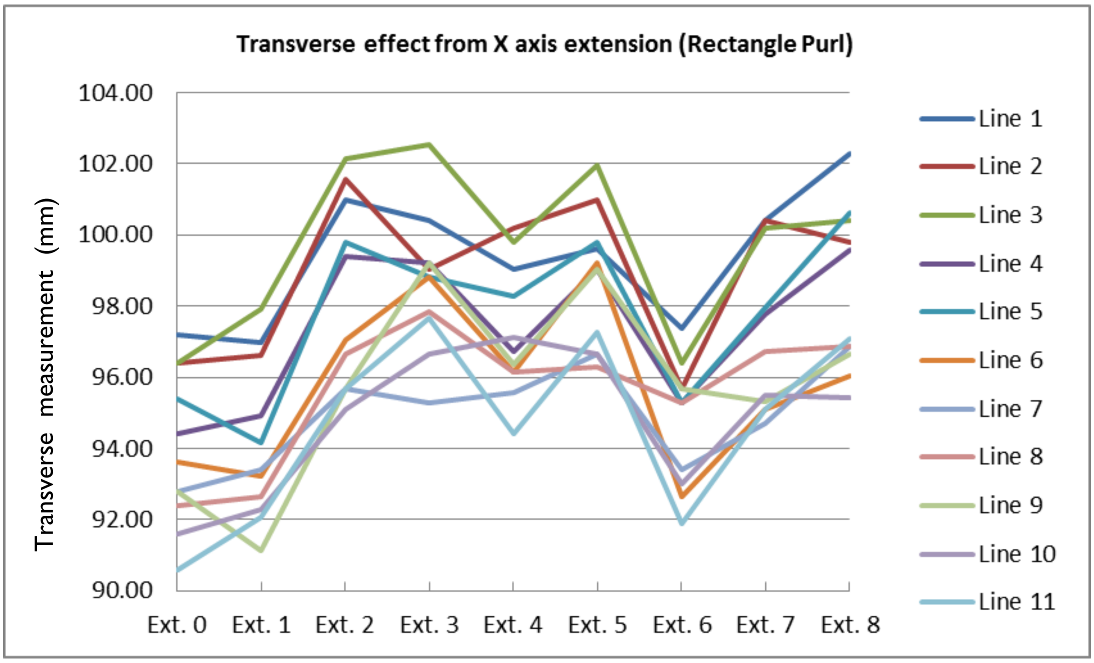


Figure 7.89 Graph of frame testing results from Sample 4 extending in the X-axis and measuring expansion in the Y-axis (Practical Stage 1).

7.3.1.3. Sample 12 (TP5 stripe)

The testing of Sample 12 (TP5 Stripe) shows a smoother curve than some of the previous graphs (as shown in **Figure 7.90**). As with previous tests, the results from the lines nearest to the clamps (1, 2, 10 and 11) show the least pronounced changes in measurement, whereas the more central lines, such as line 6, give free-moving, more pronounced curves. The general trend for this graph shows a curve that increases and then gradually decreases. That initial increase shows distinctive auxetic behaviour.

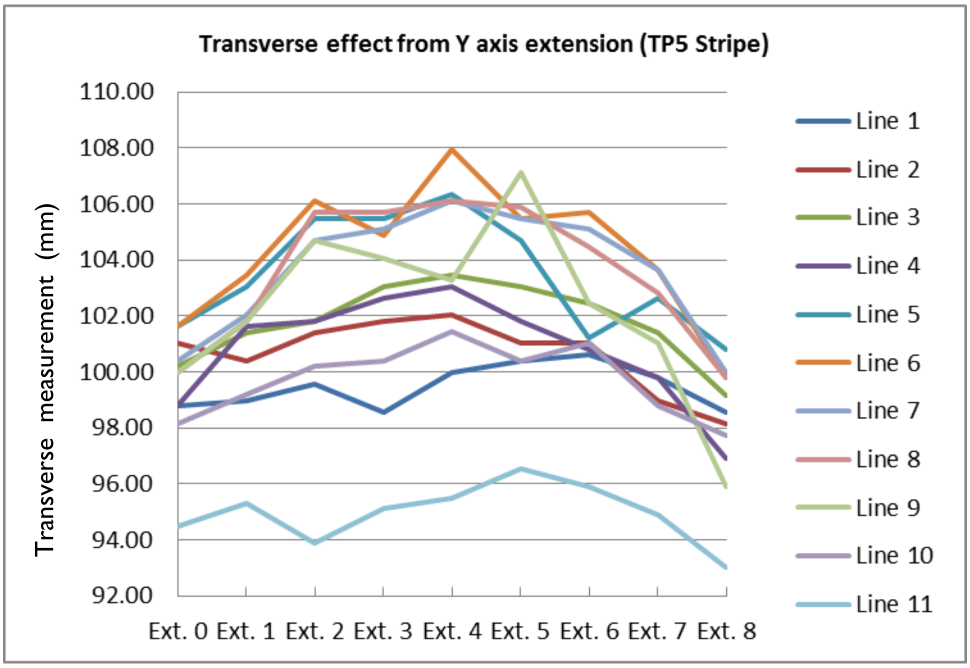


Figure 7.90 Graph of frame testing results from Sample 12 extending in the Y-axis and measuring expansion in the X-axis (Practical Stage 2).

7.3.1.4. Sample 20 (TP4)

The transverse measurements from extending Sample 20 in the X-axis can be seen in **Figure 7.91**. This graph gives a fairly smooth curve that initially increases and then decreases in transverse measurement. As with the other graphs, the outlying lines nearest to the clamps (lines 1, 2, 10 and 11) show less pronounced curves. Lines 3-9 have freer movement and give more pronounced curves, all of which have a larger measurement after extension of 110mm than they did at rest.

Figure 7.92 shows similar results when Sample 20 is stretched in the Y-axis. The comparable auxetic behaviour, when the fabric is stretched in both the X and Y-axes, makes this version of TP4 using 3 ends of fine, covered elastic among the most interesting of the auxetic, knitted samples. Because of the interesting result from this frame measuring, the testing was repeated 10 times to provide repeated results.

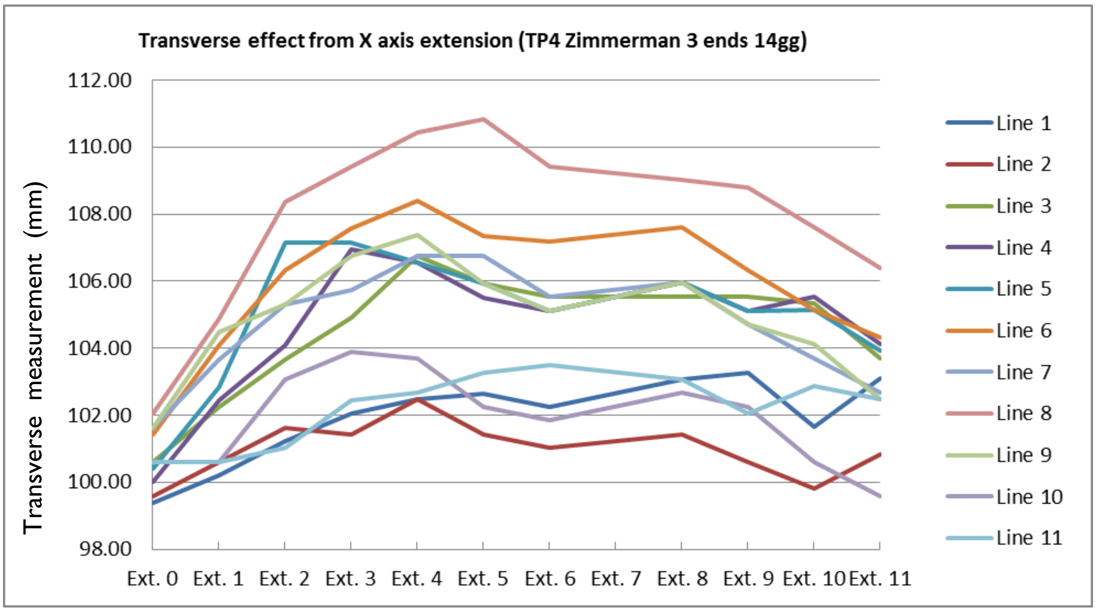


Figure 7.91 Graph of frame testing results from Sample 20 extending in the X-axis and measuring expansion in the Y-axis (Practical Stage 4).

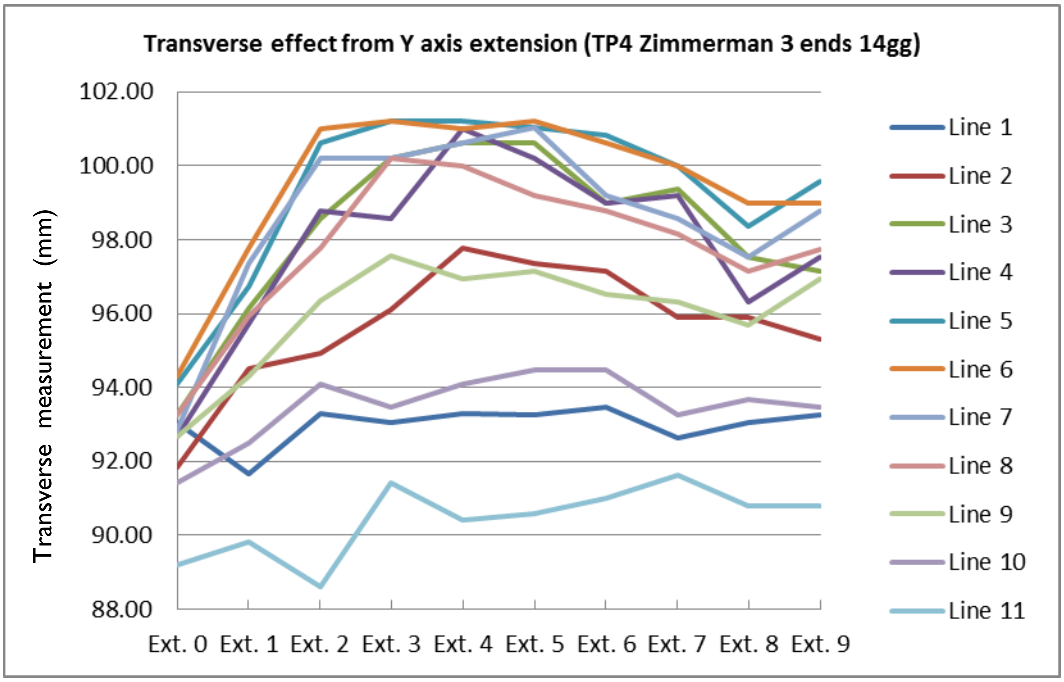


Figure 7.92 Graph of frame testing results from Sample 20 extending in the Y-axis and measuring expansion in the X-axis (Practical Stage 4).

7.3.2. Repeated tests of Sample 20

The repeated results of the testing of Sample 20 show curves with similar shapes to the individual tests. In **Figure 7.93** and **Figure 7.94**, each line shown is an average of combined results from the line it represents from the single tests. Lines 1,2,10 and 11 still show limited curves due to their proximity to the clamps in the test frame. The curves all increase initially and then begin to decrease, but they generally remain at a larger measurement than the measurement at rest (Ext. 0).

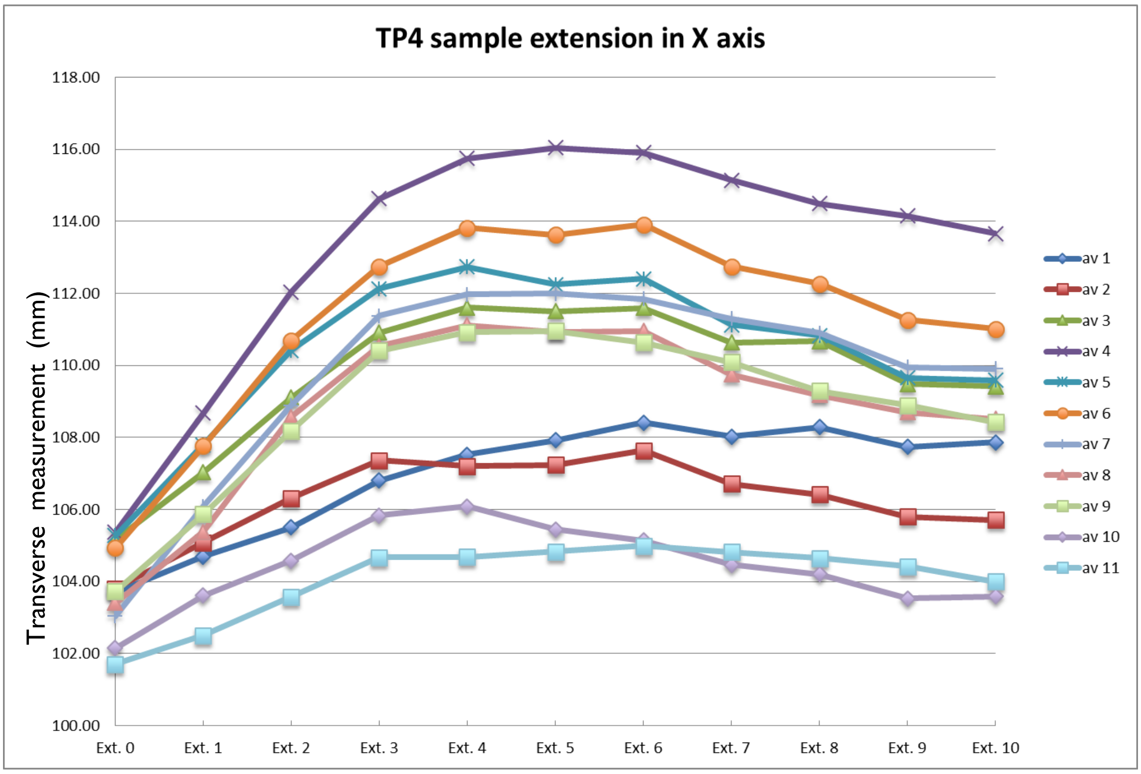


Figure 7.93 10 times repeated testing of Sample 20 – extended in the X-axis, expansion measured in the Y-axis (comparable to **Figure 7.91**).

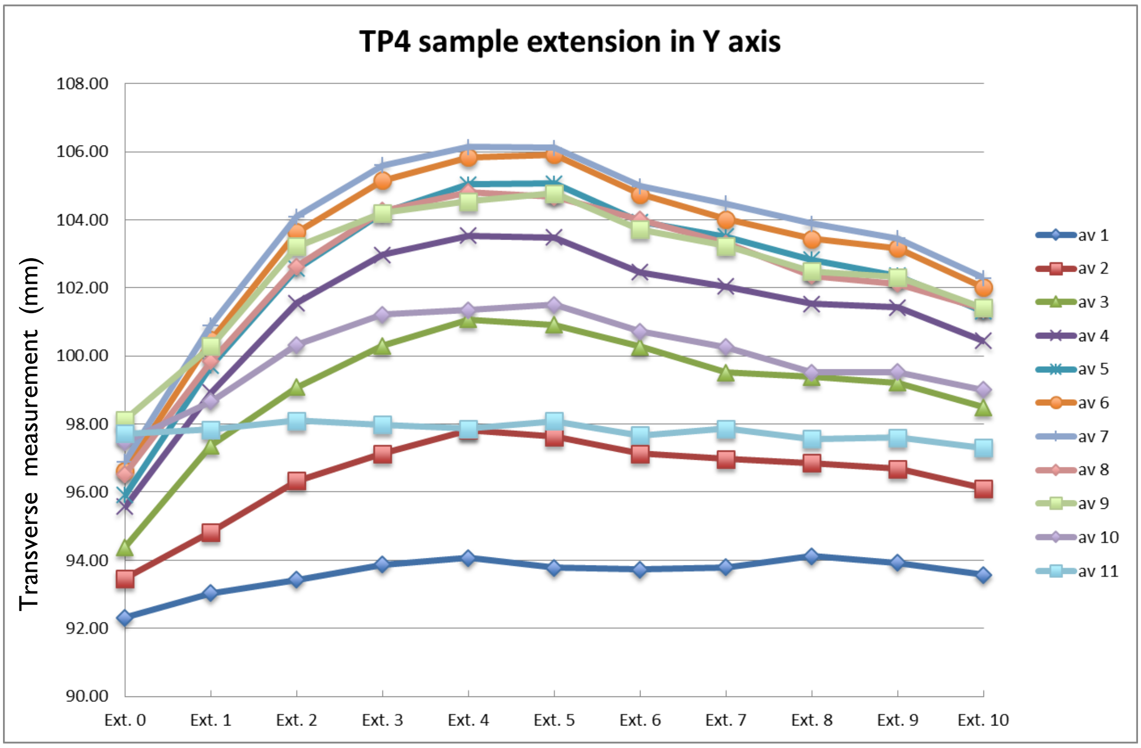


Figure 7.94 10 times repeated testing of Sample 20 – extended in the Y-axis, expansion measured in the X-axis (comparable to **Figure 7.92**)

7.3.3. Conclusions on frame testing

This repeated test shows the validity of the methods used for measuring the auxetic behaviour of the samples. Discussion of the test results and the creation of visual formats for representing the auxetic behaviour of the knitted fabrics from this study are also discussed in detail in the related paper: GLAZZARD, M. and BREEDON, P., 2014. Weft-knitted auxetic textile design. *Physica Status Solidi (b),* 251 (2), 267-272.

The benefit of graphing the results from the testing in the way shown in **Figure 7.87** to **Figure 7.94** is that the curve on the graph mimics the movement of the sample over extensions. The information is not translated into a negative value, but is a measurement that increases (or decreases) over the course of several extensions. This graph makes the information easily perceived visually. It is the opinion presented in this thesis that an auxetic effect has more relevance to users, designers or consumers, if ideas of *growth* or *expansion* correlate to something that increases (rather than a negative value at varying magnitudes).

The information from the testing has been disseminated at a conference on auxetic systems (Bolton, 2012) and is used as one of a number of artefacts in the final focus group.

7.4. Focus group stage and analysis

Focus group 4 (FG4): 15th January 2013 (duration: 1.5 hours)

The final focus group in this study brought together samples and artefacts from across the duration of the study. The format for the study considered the results of focus groups 1-3 and used successful elements of each of these discussions. The fabrics shown to these participants represented a range of samples from practical Stages 1-4.

7.4.1. Selection of participants

Participants for the final focus group were individually invited from practitioners in textile and design fields. The range of the participants' experience included knitwear design, knitwear technology, interactive architecture design, wellbeing, craft, textile design and interaction design,
The final group consisted of:

- The author/researcher
- Research assistant in digital textile design for functional use - background in craft and design
- Lecturer in Product Design - background in craft and jewellery
- Textile technologist – industrial knit and warp-knit background with expertise in auxetic textiles
- Lecturer in Decorative Arts
- Lecturer in Embroidered Textile Design
- Former lecturer in Knitwear Design – background in commercial knitwear design
- Researcher in Architecture and Smart Systems

7.4.2. Plan and format of focus group

The focus group began with an introduction to my background, the nature of auxetic materials and the aims of this study. Participants also introduced themselves and their work background. Discussion during the focus group was kept semi-structured with topics being introduced and developed as appropriate. Fabrics and artefacts from across the duration of this study were introduced to the participants after the initial disciplinary discussion. Participants were encouraged to interact and play with the fabrics and asked to respond to them – Questions included the following:

- Why did they choose to write about particular fabrics/artefacts?
- Could they use the fabric in their work?
- What changes would they like to see to the fabrics?
- Whether they like or dislike the types of information available (about auxetic material and the study)?

The written exercise was done as an introduction before the general spoken section. Participants were asked to choose two samples and one artefact (outlined below) to write their reactions about, before a general discussion of the results. The questions on the hand-outs are shown in **Table 7.12**.

Sample number: Reactions to sample - Look, touch, other… - Story or application for sample - How might you use this in your practice?
Image number: - Reactions to image - Clarity, descriptive properties, presentation, etc. - Why did this image appeal to you?

Table 7.12 Questions asked to participants in FG4 during a hand-out exercise.

This exercise allowed participants to react to the samples howsoever they felt appropriate, before the group discussion started. The aim was to get gut-reactions to samples (and the choice of samples) before talking about the research project.

As before, the focus group was recorded using a sound and video recorder. The information was then transcribed and coded. During coding, the information was analysed to reveal themes of conversation. The themes were determined from the data and used qualitative interpretations of the essence of each response (rather than using specific terms to categorise).

7.4.3. Samples and additional artefacts for focus group

Figure 7.95 Range of samples shown at focus group 4.

In addition to the fabrics and to the disciplinary exercise from focus group 3, there was a range of additional artefacts for participants to discuss in written and spoken tasks. These are made up of the following:

- Diagram of NPR effect (**Figure 2.21**)
- Diagrams of double arrowhead geometry (**Figure 2.26**)
- Diagram of re-entrant hexagon geometry (**Figure 2.23**)
- Diagram of chiral auxetic relief structure (**Figure 2.28**)
- Diagram of TP4 auxetic effect (**Figure 5.58**)
- Diagram of auxetic spacer effect (**Figure 6.61**)
- Spreadsheet of figures from repeat sample testing (**Figure F.124** and **Figure F.127**)
- Graphs from repeat sample testing (**Figure F.123** and **Figure F.128**)
- Magazine article on auxetic materials (Rodie, 2010)
- Conference proceedings article on auxetic material design (Glazzard & Breedon, 2012)
- Journal article on auxetic materials (Glazzard & Breedon, 2014)
- Working diagram of methodology (**Figure G.132**)

As with the previous focus groups, the analysis of the focus group starts with coding into themes of information (as shown in **Table 7.13**), which can be grouped into larger 'parent themes' for comparison with other focus groups in visual and graphical ways.

Parent theme	Sub themes	FG4: number of responses
Physical	Properties	5
	Material	20
	Scale	5
	Structure	10
Knowledge	Knowledge	3
	Knowledge transfer	7
	Understanding	9
	Experiential	0
	Tacit	0
Qualitative	Qualitative	8
	Tactile	25
	Aesthetic	28
	Emotional	11
Quantitative	Quantitative	0
	Results	0
Applications	Applications	31
	Industry	6
	Fashion	20
	Function	0
Communication	Communication	12
	Language	0
	Simile	4
	Collaboration	3
	Education	1
Discipline	Discipline	21
	Practice	8
	Methodology	8
	Process	9
	Design	3
	Engineering	0
	Craft	0
Change	Change	14
Positive	Positive	34

Table 7.13 Coding of responses from focus group 4.

7.4.4. Focus group themes

Nine themes will be discussed in this section featuring the most common or interesting discussions from FG4.

7.4.4.1. Applications

As with the other focus groups, applications were an important topic for conversation. Because of the practical and design methods used by each practitioner, end applications were an important area of interest. As with the other groups, questions were raised as to what the 'final' application would be. Applications were used as a method for describing the samples, for example, 'quite medical, or sporty'. Discussion on application was not always specific but sometimes referred to large areas such as 'fashion' or 'medical'. Applications were also mentioned in relation to how each practitioner would use the concept of devising an application in their individual practice.

Original application ideas from the discussion were:

- One size garments/second skin garments
- A window/roof blind
- Landscape or skate park/playground (using the geometric shape, but different scale and material to the sample)
- Light and air sensors
- Contemporary jewellery
- Emergency blanket

7.4.4.2. Aesthetic

Aesthetic considerations were, as with the other focus groups, a key area for comment and consideration. Initial reactions were usually strongly linked to appearance of fabrics. Colour and pattern were important factors in influencing the reactions. One participant commented on a 'purity' implied by some of the colour combinations. All respondents admitted a visual element in their reasons for choosing particular samples.

The aesthetic of Sample 17 (Rectangle Purl), which, when knitted in polyester and elastomeric, gives a fixed, but irregular 3-dimensional structure (caused more by the knitting machine than the structure as the structure is a regular pattern), was referred to as a 'picture rather than a pattern' (shown in **Figure 7.69**) and a 'landscape'. This sample uses the visual stimuli to imply a sense of artistry that the participant perceived, though the sample was a regularly programmed and manufactured fabric. This sample provoked the application of a 'skate park' because of the irregular peaks and curves on the surface.

One participant commented on the same structures having noticeably different appearances across the fabric sample range. Another suggested one fabric she chose looked 'crafty'. These responses suggest that the participants have creative, material-led practices, such as are important in my own knit methodology.

The knitwear practitioner commented on the combination of the function and the aesthetic by way of the structure and the material:

> *In a way it's kind of a given, because the whole auxetic effect creates the fabric, so it's a given, [the auxetic] is bound to be a secondary thing because straight away you look at something and you respond to it. This fabric, if it didn't stretch and recover it wouldn't look like that. So in a way [to deal with the auxetics] you're dealing with what it looks like anyway.*
>
> Knitwear design practitioner, 2013

This view of structure, fibres, aesthetic and function all working together is a pragmatic and arguably typical view from a practical knit perspective. There are so many factors in knit that affect the overall property of a fabric, that it is advisable to acknowledge that they are all interdependent. This point articulates that function *is* aesthetic, and aesthetic *is* function, as the two do not exist separately. This statement ties in with a belief at the centre of the methodology of this thesis – that function and aesthetics are not mutually exclusive.

7.4.4.3. Tactile

The feel of the particular fabrics had a large effect on how participants perceived them. This idea that technical fabrics are 'hard' and fashion fabrics are 'soft' was repeated by a number of people (as in previous focus groups). This was used as a reason for having trouble envisaging the fabrics in a particular usage. This is demonstrated in the quotes below.

> *…it's more like a technical textile, it's surprisingly hard (red elastic and monofilament TP4)…*
>
> Architecture practitioner, 2013

> *It feels man-made, but I think actually that could be explored further with harder yarns. I guess it influences my opinion of the application because you're using something I relate to fashion, but if it was harder, perhaps I'd see it in more varied applications.*
>
> Textile design practitioner, 2013

Tactile qualities, as with the other focus groups, were a way of describing the initial reaction to the textiles. It was also mentioned that the feel of some fabrics was different from how the participant had presumed from the appearance. Tactile responses were often indicative of either positive or negative feelings towards the samples. A knitwear practitioner mentioned the 'handle' not being very good, which comes from experiential fabric knowledge. In this case the feel was seen to be a problem, but an appreciation of the fabric outweighed this. As with the aesthetic elements, the yarn, tactile elements and quality were all part of what makes these fabrics auxetic, so they are not separable from the fabrics' properties.

7.4.4.4. Discipline

The tendency for participants to rationalise the work from this study through their own practices continued during this session. Towards the end, one engineering participant likened my experimental sample phase to create auxetic materials to his own 'problem solving' process and thought of it as an engineering method. By likening my practice to his own, he understood and accepted the methodology. Though the methodology in this study is specifically not an engineering one, there are many similarities between creative or practical disciplines which participants should be able to use in order to facilitate knowledge transfer. The following quote indicates an innate understanding of what a person's discipline can communicate to themselves and others.

> *That's why I automatically say, a bit flippantly, that oh, it's fashion. You know, it's fairly obvious, but that's the background we come from, but that's this thing about being a knitwear designer and spending your life feeling that you have to prove yourself, because people don't get it.*
>
> Knitwear design practitioner, 2013

This quote corresponds with the thinking throughout this project, that to make a fashion garment would be simple and obvious – with a fabric and the appropriate knowledge, the garment is the next logical step, but providing a garment would not allow practitioners from other disciplines to think about their own practice. It would encourage a detachment as quoted above 'oh, it's fashion', which would deter or inhibit interest from those outside fashion and textiles. One member of the group questioned why there was not a final garment on the table to show, but all members agreed that seeing a finished garment would distort their perceptions of what these fabrics could be used for. In the interest of knowledge transfer, it could be damaging to present final outcomes that are not of interest to all users.

7.4.4.5. Fashion and traditional textile applications

The idea of clothing or traditional textile applications framed several responses to the fabrics. This was expected, due to the nature of my background and the nature of knitted fabric use. A knitwear practitioner commented on how the fabrics would make a great sock – but also that this would be a 'waste' of a 'lovely' fabric. The instinctive application of a fabric into an apparel outcome is second nature to a knitwear designer, but the concept that a simple clothing application would be inappropriate for these fabrics is a new observation from this focus group. The knitwear practitioner here was suggesting that the research and methodological work would go un-noticed in an everyday item such as a sock, or in an item that was marketed for its appearance.

The section of the hand-out that requested 'stories' inspired fashion stories in some, as participants felt obliged to propose applications for the fabrics and chose fashion applications. A textile-engineering participant saw the fabrics as having a 'fashion lean rather than a technical lean'.

7.4.4.6. Material

Materials were of interest to all practitioners across the four focus groups. All practical practitioners, designers, makers and artists questioned were in some way involved in materials. The material used for knitting was mentioned in terms of its contribution to the overall structure of the fabrics and how the placement of fibres and structures will affect the overall properties of the fabric, either in engineered or design terms. In turn, the materials will influence the application. Material is also mentioned in relation to practice, methods and methodology.

7.4.4.7 Communication

Communication was a topic that crossed into several other themes, but held high importance. From the feeling of needing to 'prove oneself' (as a knitwear designer within research areas) to how the application of X, Y and Z planes to materials expresses information to individuals - communication was important to both practice and discussion.

7.4.4.8. Emotional

Emotional responses were given by some of the respondents, such as the idea of 'enjoying' the appearance of a fabric, or it being 'satisfying'. These responses demonstrate a connection between how participants react to materials and how they use them in their practices. These emotional responses tended to come from participants with material-led and craft practices.

7.4.4.9. Change

As with several comments from other focus groups, the participants suggested things that they would change about the fabrics. One suggestion was to change the material and the scale dramatically in order to make a 'skate/scooter park', while another suggested knitting seamlessly, or using warp knitting instead. These comments start to rationalise the objects on the table into other practices. Where respondents had difficulty imagining applications within their own areas, they were interested in small changes in order to help the fabrics become more useful for them, or perhaps, more familiar.

7.4.5. Individual responses relating to methodology

Some responses did not fit with the themes of the others, but were of interest because of the links to participants' methodologies.

7.4.5.1. Quantitative and engineering perspectives on methodology

The textile-engineering practitioner had experience with developing auxetic warp-knitted fabrics as well as experience in weft-knitting and underwear industries. He was positive about the development of the auxetic weft-knits to show a range of appearances and auxetic effects (as shown in the quote below):

> *[The auxetic fabrics have] amazing aesthetic values as well. It's the combination of the two… I'm currently very pleased to see that you have so many combinations. Knowing the auxetic and what it can do as well is really quite refreshing for me.*

Textile engineer, 2013

This participant had reservations about the 'academic' way in which he perceived that this study was conducted. In his opinion 'industry' always works from the end use backwards and academia works the other way round[66]. Despite these reservations, he accepted the fabrics as a significant contribution to the area of auxetic textiles.

Another participant, who considered himself to have a quantitative and engineering/scientific approach, offered visual and adaptable suggestions that included inspiration from materials and form into different materials and scales (as in his reaction to the purl rectangle fabric below).

> *I don't know how I got to that, but this one reminded me of a mini landscape. Like a set of mountains, but I was wondering if you had a massive version of this whether you could make a playground or a scooter park?*

Architecture practitioner, 2013

[66] These perceptions were contested by other participants.

He made the observation that architects do not make materials and the open material experimentation occurs in other areas. Though he likened and justified his methods through an engineering 'problem solving' methodology, through discussion with knitwear practitioners it was agreed that this architecture practice had clear comparisons with what they considered to be a 'creative practice'.

By framing discussion of the creative practices in the group in his own terms, it was easier for the architecture practitioner to comprehend the process. I would classify some of the processes he described as engineering problems as design problems, as he would classify some of my design problems as engineering problems.

7.4.5.2. Methodological responses from textile design backgrounds

Responses from textile design practitioners were commonly concerned with the aesthetic qualities and the method of making used. The communication of process was something of relevance to the textile design practitioners, who related their understanding of the fabrics in different ways from the non-design participants.

> *I suppose strangely enough I'm not necessarily intrigued, if I didn't know about the auxetic properties I might not have noticed by stretching it, that I was stretching it more in the opposite direction to the way I was pulling it. So I might not have noticed that if I hadn't been told.*
>
> Embroidery design practitioner, 2013

As shown in this quote, the function of the fabrics was a secondary concern over what would be usual considerations in design practice (e.g. the look, the feel, the potential for application, alteration, etc.). Even when the full range of properties was explained, participants tended to remain concerned with the primary interests of the individual. When questioned about the diagrammatic/written artefacts, and methods of knowledge transfer this reaction was given:

> *I think that's definitely your avenue because you've made plain that the algebraic information is already out there. For me the 'team' of people that you're batting for is the person who is not going to go straight to the algebraic info, it's somebody like me who's going to think – how do I do that, without having to learn another language, something that is easily translatable to everybody? Obviously you have to show that you're making it open to everybody, I don't know how much detail you have to go to in that specific area. It's more of a designer's approach than another discipline's.*
>
> Embroidery design practitioner, 2013

This comment shows a desire of the participant to be able to use information readily, without difficulty in understanding the language used. The addition of images was thought to be very helpful. Some of the design practitioners gave similar comments about being 'put off' by lots of algebraic information or by large amounts of numeric information.

It is possible through these comments to see that there are several problems inherent in the presentation of technical and research information.

- Views of my own disciplinary background produce perceptions of which disciplines I want to represent/work with (this was made more prominent by the fact that most of the participants had met me before the focus group and had their own ideas about my practice).
- Participants' own backgrounds produce perceptions of what my aims are/what this work is about.
- Technical and research information is often limiting in its dissemination.
- Language and imagery used can encourage or deter individuals from the content of projects or writing.

By publishing and presenting findings to mixed practitioners, it is hoped to find a balance where the knowledge transfer both enables understanding of more technical, functional aspects to those who do not work with these regularly, but also to promote design processes to those who do not practise or value them.

7.4.6. Role of artefacts/diagrams

The presentation of the fabrics alongside a range of paper artefacts for added information was welcomed by all participants. One found the images (**Figure 2.21**) to be the most helpful towards understanding the concept of auxetic materials:

I understand now, and I couldn't quite get it, because when you described it I thought it was magic! But it's not actually, it's taking from your Z-plane and going onto your X and Y-plane, in my language really.

Decorative arts design practitioner, 2013

One found that a diagram added further explanation that added to her understanding of the intricacy of a structure:

> *I'll start with the image, the one I chose is depicting this sample* ***(Figure 5.58)****. I chose it because for someone that's visual who might not understand the written text that is a really clear and concise image to explain exactly what happens when you create the structure.*

Embroidery design practitioner, 2013

Regarding the diagram of the auxetic spacer fabric (**Figure 6.61**), one participant found the diagram helpful in seeing potential and form that could encourage his use of such a form in further development. The diagram changed their view of the fabric into a more versatile, non-specific form:

> *I never really got a grip of what the potential for the change in form was and I think that's partly to do with the scale you've been working at. But that made it really exciting because suddenly you have a 3D form like a box on 2 planes, and it could be releasing things depending on the scale it could be releasing drugs for example, it could be acting as a switch for components, it could have components within it.*
>
> Architecture practitioner, 2013

Similarly, the diagram could be interpreted as an inspirational tool to promote idea generation. It is of interest that two different participants saw the diagrams as promoting either objectivity (removing the designer's inputs and aesthetic response) or subjectivity, as below:

> *I thought that the clarity of that and the difference in form made that creativity really easy. It triggered all sorts of ideas really quickly. As an apparently objective diagram it did all sorts of really interesting emotional, subjective things. Really exciting. That's it.*
>
> Craft and design practitioner, 2013

The diagrams allowed participants to relate the structure into their own practice or thought process without being influenced by scale, tactility, colour or other aesthetic choices of the designer. The idea that to represent in an image the geometry rather than necessarily a physical sample might be beneficial in getting rid of the assumptions around materials (as one participant suggested 'the yarn sends you messages').

The numerical information available received a mixed response from the group. Some of the designers mentioned being 'put off' by algebra and graphical information, one saying a 'graph doesn't say anything to me, as a designer'. A participant from a textile engineering perspective also found the algebra confusing in a paper, and felt that it is for mathematicians and not always suitable for other readers. He acknowledged a 'need' for algebra when publishing in scientific and engineering journals. It is worth noting that the paper: 'Weft-knitted auxetic textile design', derived from this study and published in specialist physics journal *Physica Status Solidi (b)* [Glazzard & Breedon, 2014] specifically addresses this idea by not using algebraic information in the description of auxetic materials in a scientific journal.

A consensus was reached among the group that the auxetic effect could be represented in percentages as 'everyone understands percentages' (as used in Glazzard & Breedon, 2012; Glazzard & Breedon, 2014). This would be sufficient information to understand the auxetic effect in numerical forms. The suggestion was made that a reader can be presented with several versions of the relevant information and be able to choose what elements they want to use from it. This is in line with the research objectives of this study.

7.4.7. Conclusion on analysis

Several comments were made that supported the objective of this thesis to allow a diversity of information when disseminating information, in order to communicate to the widest possible audience.

The conversation about how best to incorporate technical information into writing is something that I have already been tackling in published papers and by showcasing the practical research work to audiences form diverse backgrounds and in different settings (i.e. conferences based in design and engineering).

This study's main aim, to assess the value of a knit design methodology, was directly addressed in this focus group. Along with the comments from the previous focus groups, FG4 provided valuable insights into the methodology from both knit design and external perspectives. These insights contribute to the continuing building of theory.

7.4.8. Theory building

The theory, as drawn from the data in Focus Group 4 (FG4) and obtained through practical experimentation and reflection, is outlined below in **Table 7.14**.

Proposition	Evidence from data	Outcome
Design and experiential knowledge is appropriate to produce knitted auxetic materials.	Samples 15-30.	Make explicit the role of design knowledge to the production of fabrics.
Range of appearance and auxetic behaviour is achievable through variation in scale and yarn.	Design decisions to vary the fabrics in appearance produces a range of auxetic materials (in appearance, feel and auxetic behaviour).	Range of samples. Improved engagement and dissemination.
Producing a 'collection' of fabrics creates a more interesting outcome	The visual identity of the range of samples encouraged engagement from FG participants and from conference organisers	Improved engagement with project. Publications.
Visual information helps expand understanding for designers.	Design practitioners found that diagrams helped understanding of structures and aided idea formation.	Use of images, videos and diagrams at RTD conference (discussed in **Chapter 8**)
Algebraic information is not always required when describing functional textiles.	Some participants found algebra confusing and unnecessary. Some found diagrammatic and simple numerical information helpful.	Glazzard & Breedon, 2014. Paper on auxetic materials published in scientific journal without the use of algebra .
Algebraic information is not always required when describing auxetic behaviour. Simple numerical information can be more helpful.	All participants preferred simple numerical information (percentages) to algebraic information.	Glazzard & Breedon, 2014. Discussion with group at Auxetics conference (2012). See quote from Julian Wright (section **8.3.4.**) and Morris (2012).

A choice of information is more suitable to explain work that crosses disciplinary boundaries.	Agreement of participants that different information is helpful to different people. Ability to choose information to best suit.	Published work with different information styles. Published same work in different areas (see list of related publication (section **1.2.1.**) using information tailored to the publication style.
Range of visual, physical and numerical information encourages visualisation of further development.	Using artefacts with samples encouraged ideas for applications and development.	Publication of simple diagrams alongside physical samples (or photographs/ videos of – Such as for RTD conference).
Practitioners are not necessarily of a single discipline.	Hand-out exercises showed no evidence that any participants thought of themselves as singly disciplined.	Seek multi-disciplinary outcomes.
A range of textures and colours expands the scope for ideas and applications.	Feedback from each focus group and from assessment stages of research about colour and texture development. Limited scope led to pre-formed ideas.	Show samples in a range of fibre types, colours, patterns and scales to diversify responses.
Methodologies across creative subjects are comparable.	FG4 Agreement of participants that the working methodology diagram (**Figure G.4.**) resembled their process.	Frame a complex, individual methodology through a generic creative process. Provide options for comparison when discussing process.
Background of FG leader and preconceptions about fabric may result in more fashion-based applications/discussions than anything else.	Fashion applications were common among participants. Some acknowledged that this was what they thought the fabric was for.	3D-printed materials provide non-fashion application for structures.

Participants had trouble in visualising uses for fabric in their own areas. They may prefer a gradual move towards familiarity in order to envisage applications.	Changes to fabrics were suggested in order to alter the material/process/scale/embellishment etc.	In dissemination and future work a wide range of material and other variations can be discussed.

Table 7.14 Theory from data in FG4.

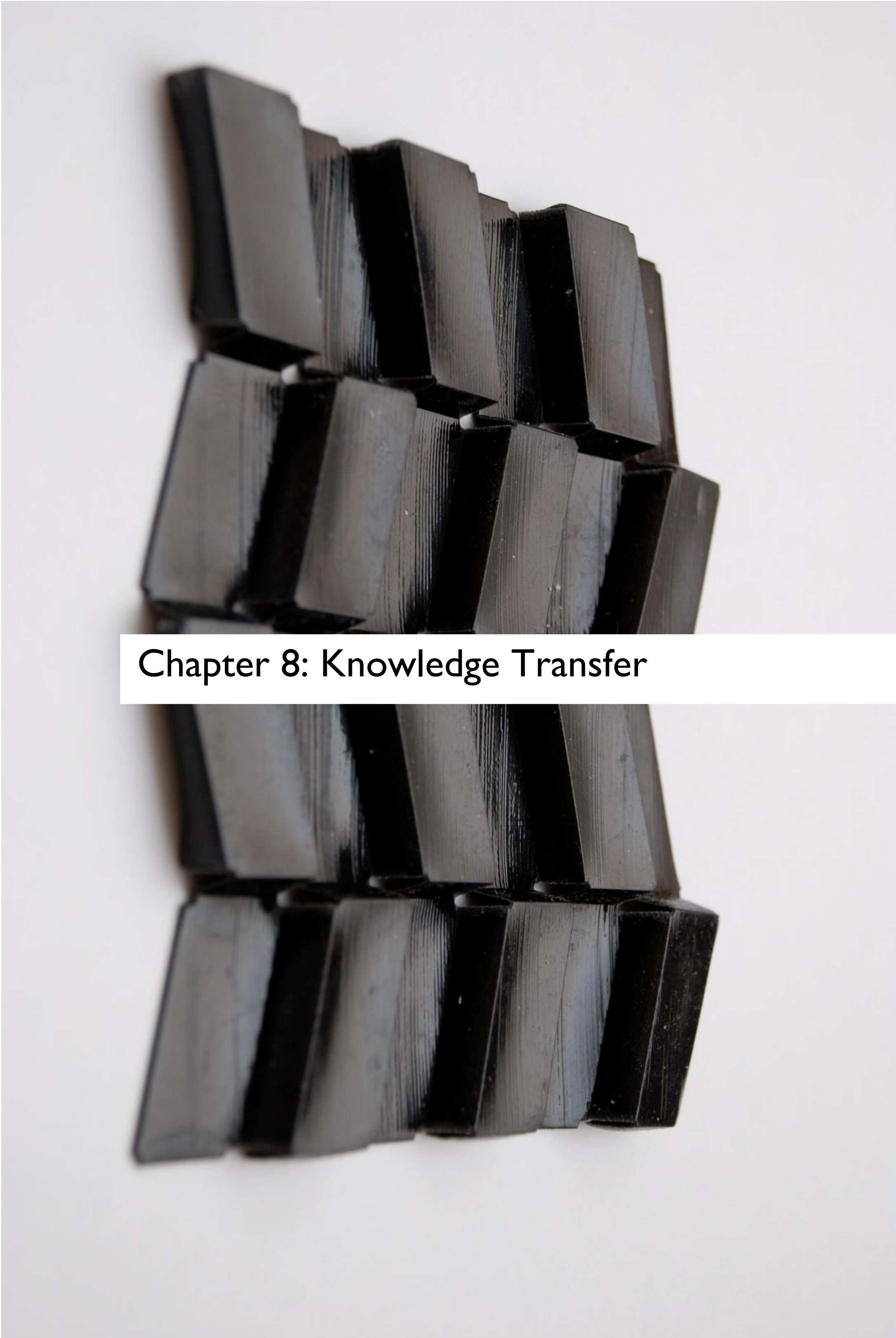
7.5. Chapter and practical stage conclusion

Stage 4 showed that a variety of fabric outcomes could be achieved by returning to the initial investigation of auxetic structures in Stages 1-3. The variations in colour, yarn, pattern and scale granted the set of fabrics new areas of interest and encouraged engagement from focus group participants. As a designer, I feel that this stage was particularly successful, as the results were developed both functionally and aesthetically. The experimentation stage was free and intuitive, allowing for experiential and personal decision-making. The considered use of colours in a limited range produced similarities to a 'collection' for fashion or textile design outcomes.

The fabrics from Stage 4 used mainly synthetic fibre yarns to respond to comments from earlier stages that the feel of natural fibre yarns suggested apparel applications. The use of polyester allowed the fabrics to retain their auxetic, relief structures, but provided a different tactile experience. Experimentation with covered elastomeric yarns incorporated more stretch and contraction into fabrics designed around principles of stretch and expansion. Though the yarns and structures varied the auxetic structures from Stages 1-3, the structures remained auxetic after the alterations were made. This combination of quantitative testing information and qualitative responses to fabrics made a case for the benefits of design decision-making in the production of auxetic fabrics.

The practical stages of this study have demonstrated that, by using design thinking and experiential knowledge, auxetic fabrics can be created. In addition to the creation of these fabrics, the information gathered from personal reflection and measuring, using focus groups, has provided a valuable range of results and outcomes that can be compared in order to establish their place within design research (or related research areas such as engineering).

The production of numerical, diagrammatic, graphical, percentage, photographic, video and spoken results provides a wide-ranging and important development as to how information from 'technical textiles', design research, knit design (to name a few) can be handled and disseminated.



Chapter 8: Knowledge Transfer

8. KNOWLEDGE TRANSFER

8.1. Summary of perception and intentions

This thesis so far has discussed the nature of knit design and the nature of knowledge transfer. For various reasons such as limited education resources and segregated communities of knit practice, there are difficulties in the movement and understanding of knit knowledge into related areas (e.g. textile subjects in design or engineering). This thesis came about in response to literature, which I felt had misunderstood and misrepresented a subject that I have experience and knowledge of, as well as a keen interest in. Some of the key reasons for this are the limited transfer of knowledge surrounding knit and common misconceptions of how knit designers work, how useful their work can be and what kind of outcomes they can produce. Each of these considerations has created or contributed to a public perception about the application, usefulness and subject area of knitted textiles.

With this in mind, the aim of this thesis in relation to the knowledge transfer discussion is to propose a better way of representing the contribution of knitted textile design to textile research, technical textile research & development and knowledge generation. This has been done through conducting a project using design and experience-based, practice-led knowledge to create functional, auxetic textiles of interest to practitioners outside knit design practice.

This chapter describes outcomes of this study specifically related to knowledge transfer and gives a summary of the knowledge produced and disseminated so far and how the act of disseminating the work has become part of the work and an outcome of the thesis.

Two projects explore further advancement of the work in this thesis. Firstly, a Master's student design project shows novel design applications of knitted, auxetic textiles. Secondly, the knitted structures from this study are translated into 3D-printed materials, which also show auxetic behaviour. The projects explore two research questions:

1. What information is needed for unfamiliar practitioners to understand and engage with auxetic knitted textiles?
2. How can tacit, experiential knowledge of knit structures be transferred into different processes and different materials?

Each major instance of dissemination of the work in this study is also discussed. Over the duration of this study, there have been several presentations to, and discussions of work with experts in design, making, science and engineering. These actions have strengthened the contribution of this thesis and provided feedback, reflection and validation.

8.2. Knowledge transfer through projects

There have been two projects conducted in addition to the main body of this study. The inclusion of projects outside the initial scope of the research design was welcomed to allow evolution and extra perspectives, in keeping with the exploratory nature of the design process.

8.2.1. Master's project

Part of the efforts to expand the knowledge transfer was in the form of a project set for Master's degree students at Nottingham Trent University. As part of a live project module, a brief[67] was written for students to experiment with and incorporate auxetic materials into design ideas, visualisations and a product prototype based on their research. This project addressed the lack of auxetic materials present in product design (after discussion at Auxetics 2012 [Morris, 2012]). The project consisted of a small group of students from postgraduate courses in 'Smart Design' and 'Advanced Product Design Engineering' being briefed on auxetic materials and provided with samples and some key examples of existing literature. Regardless of their backgrounds, the students were encouraged to be creative and to use visuals in their reports. For the initial brief (30% of the project mark), they were to think how the properties of auxetic materials could be used purposefully and then to generate potential applications and products. For the longer part (70% of project mark), one of the ideas generated from the first part was to be developed into a prototype. In the following quote from the first report, the students express their understanding of the project:

> *The outcome of the process is to ascertain products that could be improved were they to employ auxetic materials in their makeup, which would also serve the purpose of marketing auxetic materials to potential commercial partners and publicising auxetic effects to the general public through interaction with the technology.*
>
> Bruijnzeels, Fiati and Vrablecova, 2013: 1

The tone of the report was different from much of the current literature on auxetic materials, as its foremost concern was addressing applications for auxetics. The students developed their own testing rig as shown in **Figure 8.96**. They found that the force needed to stretch the knitted samples is not large and, in many cases, the weight of the clamp (220g) is enough to cause a noticeable extension and, as a result, they proposed an improvement to the rig for future work. From this testing, the students chose to represent their findings in conventional Poisson's ratio terms. As shown in **Figure 8.97**, the Poisson's ratio shows distinct negative values represented through the graph format.

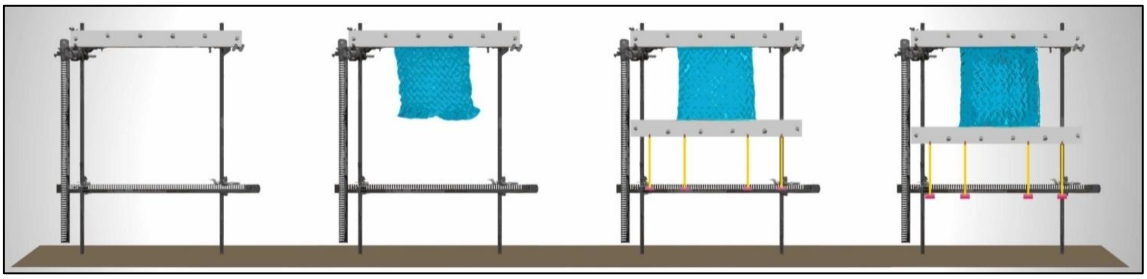


Figure 8.96 Photographs of testing rig from report (Source: Bruijnzeels, Fiati and Vrablecova, 2013: 2)

[67] The full brief can be found in **Appendix H**.

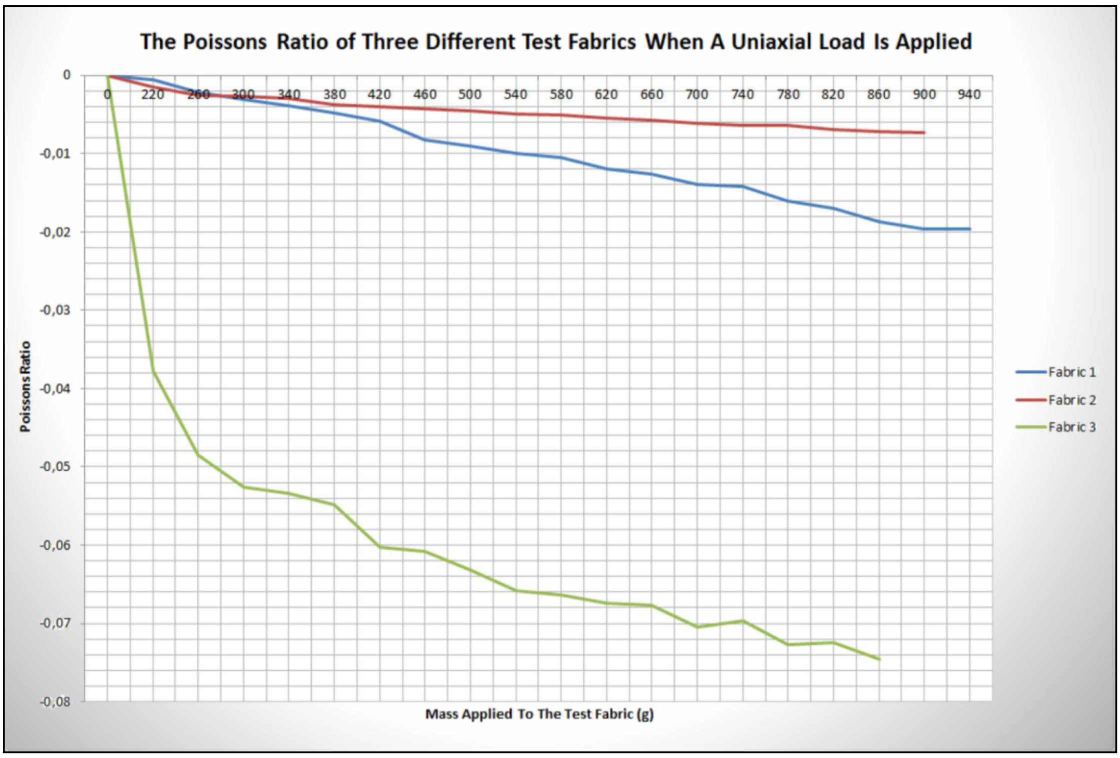


Figure 8.97 Graph showing test results of three auxetic knitted fabrics. (Source: Bruijnzeels, Fiati and Vrablecova, 2013: 2)

The data interpretation in the students' work is different from that in this thesis. They state that all seven knitted samples they measured showed auxetic behaviour, but that the Poisson's ratio varied and more research would be required to 'determine the controlling factors for this behaviour' (ibid.: 2). Because of these inconsistencies, only the results of three of the tests were plotted.

The first of the two products that the report eventually focused on was auxetic screens – for use over windows and roof lights to provide varying degrees of shade and insulation (**Figure 8.98**). The proposed screen uses the 'semi-transparency' of the fabric to allow some daylight in, while still providing shade. This acknowledges the inherent properties of a weft-knitted fabric in such an application.

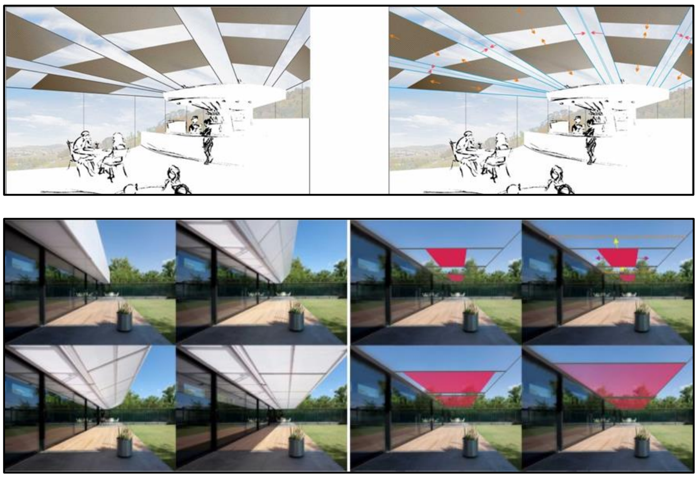


Figure 8.98 Auxetic screen design (Illustrations by Zuzana Vrablecova). (Source: Bruijnzeels, Fiati and Vrablecova, 2013: 5)

The second proposed application is for auxetic plasters and bandages. These would make use of the double curvature and the porosity of the materials. The students identified a gap in the market for plasters that tackled the problem of stiffness. The students identified a significant limitation caused by a conventional plaster when trying to bend a finger. This is shown by the tendency of the plaster to remain straight, while the finger bends as can be seen in **Figure 8.99**. They proposed that the same ability to bend easily can be used in applications such as bandages and areas on wetsuits that suffer from bending, for example, elbows and knees (ibid.: 5).

Figure 8.99 'Bent finger test'. (Source: Bruijnzeels and Luo, 2013: 3)

8.2.1.1. Personal response to the project

As a representative of both groups, Susanne Bruijnzeels commented on her experience with the project. She found working with textiles to be a new and enjoyable experience. The first method the group used was to play with the fabrics to learn their properties and to inform the design outcomes. They found that the information on auxetic materials was useful once they understood the terminology used in the texts. The students found the use of auxetic materials as a starting point different from the design process they were used to. In their experience, a 'problem' would usually be presented to work back from. Group members found it necessary to provide their own 'proof' of the auxetic behaviour –

through the testing of the fabrics – but also used visual and qualitative assessment of the fabrics' behaviour when developing their designs.

8.2.1.2. Conclusions on Master's project

The students in this project found the combination of existing literature and the use of hands-on experience suitable to their understanding of auxetic materials. The existing auxetics literature used terminology that needed to be made understandable before the information could be useful to the students. This supports the proposition in this study that scientific information alone is not always appropriate and that alternative information provides valuable insights to practitioners from different areas and backgrounds.

The student group found some gaps in the market where auxetic materials could be used beneficially. They used familiar methods (testing), instinctive methods (play) and enjoyed working with textiles for the first time. The applications of plasters and decorative blinds were new to the literature and reasoned arguments were given to the contribution of such products to the existing market.

The students' consideration of ergonomics, user experience and market position is important to expand the auxetics debate out of laboratory environments into viable products and realistic representations, when considering product design outcomes. The benefit of this to knitted textile design is the development of specific, technical, knitted products that use design approaches and acknowledge user experience, real-world problems and inherent fabric properties.

The groups use of 'play' as an acknowledged method was a surprise result of the project. The students considered their practices to be largely scientific and objective, with the information in the reports being mostly quantitative, but 'play' was cited as an important method for understanding the fabric – correlating with ideas from fashion and textile design – (Aldrich, 2007; Glazzard & Breedon, 2011: 105, Glazzard et al., 2014), which is not always an acknowledged method from more scientific disciplines.

8.2.2. 3D-printing project

During this study, I was given the opportunity to attend a network event in Aalto University, Helsinki (in association with the Arcintex network). As part of the network event, participants attended a workshop to programme and create 3D-printed materials of their own design. With the help of an industrial designer, my first task was to 3D-print the diagram of the TP4 structure (numbered **5.8.**) from Stage 2 (repeated here for reference).

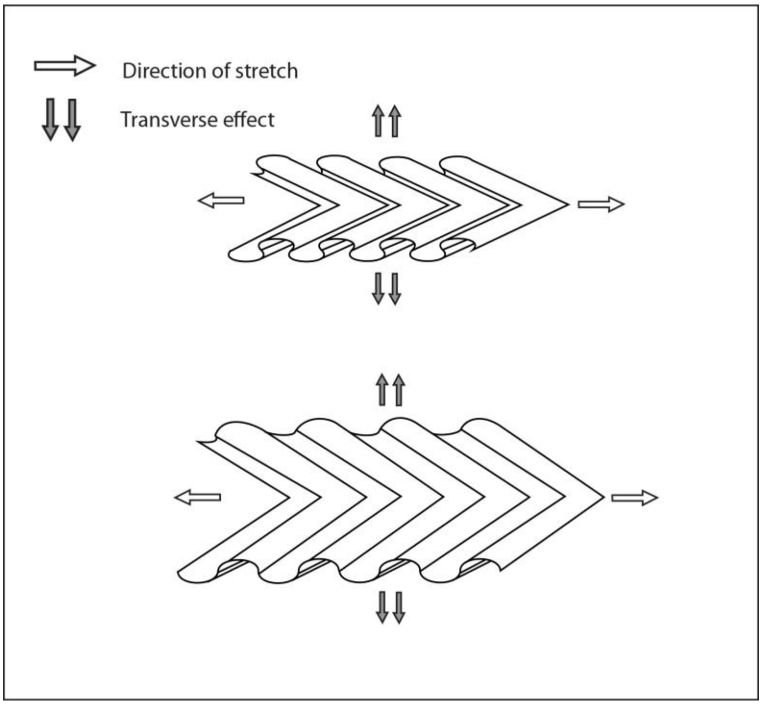


Figure 5.58 Available in section **5.2.8.**

The image in diagram **Figure 5.58** was developed into a 3D geometry in an interactive exchange between the industrial designer employed to facilitate the workshops and me. The result of the first print (3D-print 1) can be seen in **Figure 8.100**. The main material is a black, rubber-like material and the lighter-coloured sections are a hard plastic that were used to act as supporting ligaments, a design decision inspired by auxetic geometries from existing literature. The second version of this structure (3D-print 2, seen in **Figure 8.101**) did not use the hard plastic reinforcement and curves used to produce the shape were contracted further, as can be seen by comparing the side-view/cross-section of the two prints.

Figure 8.100 3D-print 1 made using the diagrammatic representation of TP4.

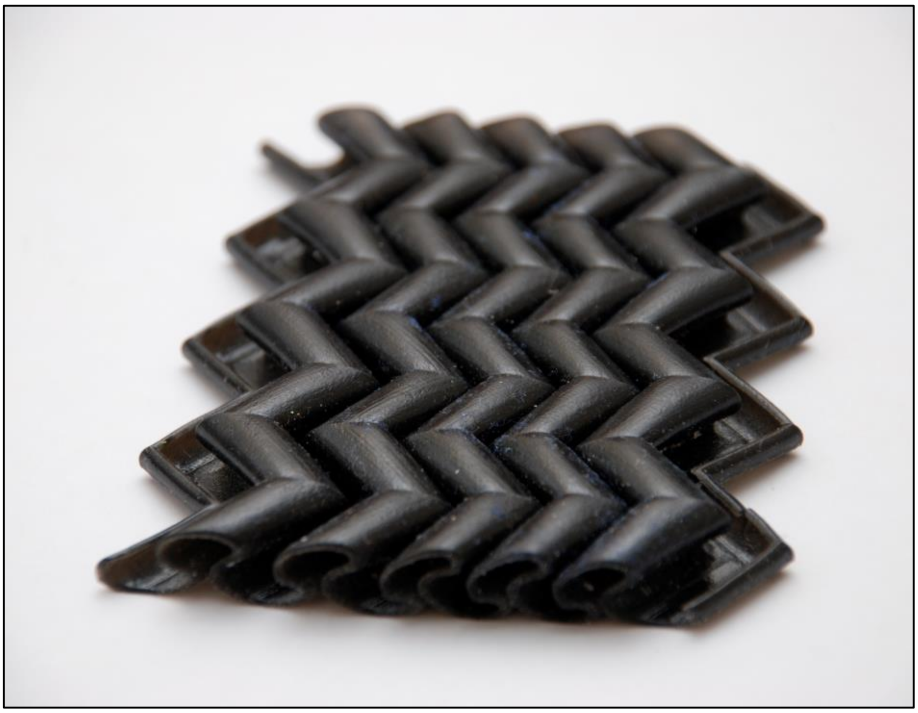


Figure 8.101 3D-print 2 made using the TP4 structure with only the rubber-like material and more contracted curves.

The notable outcome of making these 3D-prints was that the samples derived from the shape approximation of a knitted, auxetic structure also show auxetic properties. The images in **Figure 8.102** show 3D-print 1 based on the TP4 structure being stretched[68] and showing auxetic properties. When discussed using the axes attributed to the knitted fabrics in this study, 3D-print 1 shows expansion in the X-axis when stretched in the Y-axis. 3D-print 2 shows a less-pronounced auxetic reaction in the X-axis (**Figure 8.103**), but shows interesting auxetic behaviour in the Z-axis when stretched in the Y-axis, as shown in **Figure 8.104**.

Figure 8.102 3D-print 1 showing auxetic behaviour when stretched (stretch occurs in the Y-axis and expansion in the X-axis when given comparative axes to the knitted fabrics in this study).

[68] It is worth noting that the rubber used in the 3D-prints is brittle, which makes stretching difficult without damaging the samples.

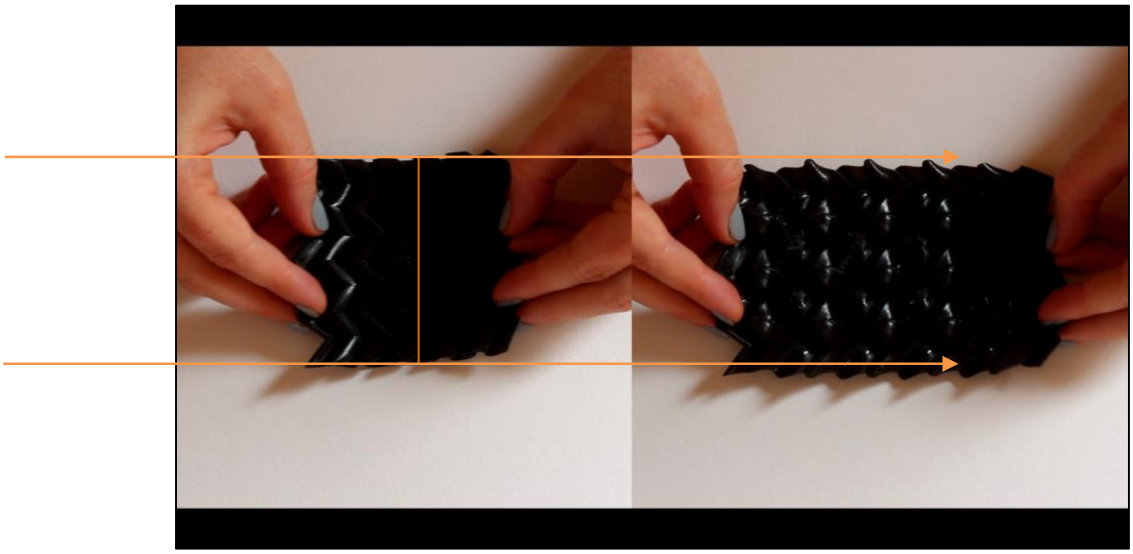


Figure 8.103 3D-print 2 showing some auxetic behaviour in the X-axis when stretched.

Figure 8.104 3D-print 2 showing expansion in the Z-axis when stretched.

The three most interesting results from this project were:

1) That knit can be used as a model for creating an auxetic geometry.
2) That the experiential knowledge of the discrepancy between essence and detail of a knitted fabric is key to this modelling. The 3D-prints are not stitch-specific and contain only the essence of the important elements of the fabric – this is enough to create the auxetic effect.
3) That the translation of knitting can produce a comparable material with different qualities – e.g. the rubber is not porous or absorbent for example.

To elaborate on the importance of the role of experiential knowledge stated in point 2 above, the programme for 3D-prints 1 and 2 was created from an existing diagram using experiential knowledge, but a third print (shown in **Figure 8.105**) was designed using more collaboration with the industrial designer, who was not from a knit background. 3D-print 3 used a very different interpretation of how the geometry could be conveyed. During conversations with the industrial designer, we both expressed difficulty in articulating our views on the essence of the fabric to each other. There were several ways that the fabric could be discussed, which made interpretation difficult. Some examples of how the fabric was viewed in discussions include:

- The fabric is the same on the front and the back.
- The sections of stitch curl towards connecting sections.
- The unit is repeated regularly.

It was difficult to agree on the best way to represent the TP5 fabric, as I was not able to programme the 3D file, and the industrial designer was not able to draw on experience of knitted structures. In my opinion as a knit design practitioner, 3D-print 3 does not capture the essence of the finished TP5 fabric and thus does not behave as the fabric does. The design of 3D-print 3 is more theoretical, more linear and based on the technical make-up of the fabric rather than the actual fabric's qualities.

Figure 8.105 3D-print 3 and the TP5 fabric it is based on (Sample 28)

A final print was produced (3D-print 4 in **Figure 8.106**) based on the auxetic spacer fabric from Stage 2 (Samples 13 and 14). Like 3D-prints 1 and 2, 3D-print 4 was based on a diagram made before the workshop (**Figure 6.1.** repeated here for reference). The production of the 3D-print from this diagram was found to be straightforward to translate into a 3D-printing programme and allowed for a successful reproduction of the essence of the fabric from Stage 3.

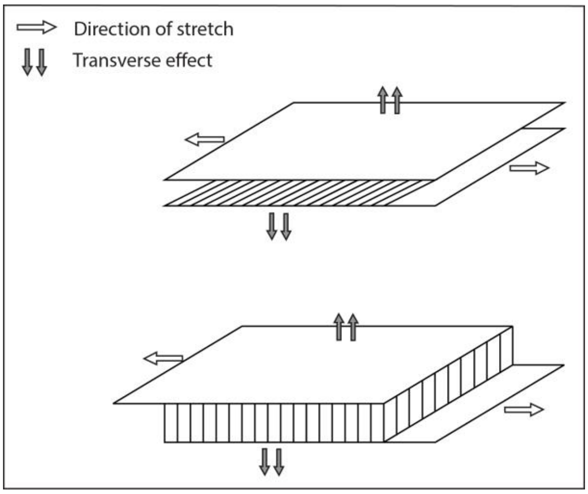


Figure 6.1 available in section **6.1.1.**

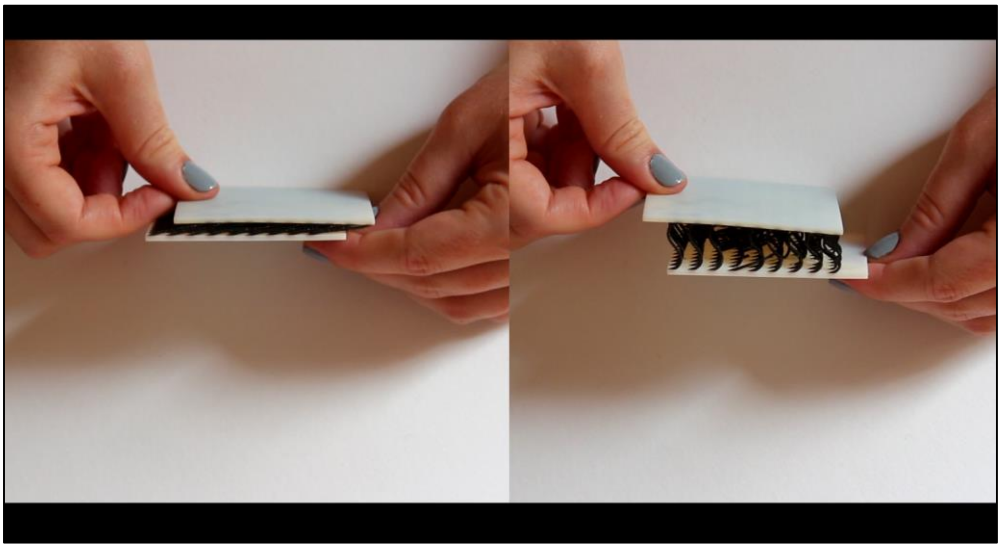


Figure 8.106 3D-print 4 being stretched in the X-axis and showing expansion in the Z-axis.

8.2.2.1. Conclusions on 3D-printing project

The tacit, experiential knowledge of producing knitted textiles is shown to be transferrable to 3D-printing in this project. The fabrics were translated into geometries and these were converted into 3D forms and artefacts.

The most successful translations of the knitted fabrics from this study predominantly used experiential knowledge of knitted structures to inform the geometries. The experientially-perceived essence of the fabric proved to be more useful than the technical or theoretical elements of the knitted structure. The production of 3D-printed material, using knitted auxetic fabric as geometries, can extend the use of these stitch structures to applications that preclude the use of knitted fabric because of their physical properties (such as variations on scale, material, porosity, shape, etc.).

8.3. Dissemination

Disseminating the outcomes of this study is an important measure of its success. Presentations and publications are seen as a method of showcasing and testing material from this thesis to external parties and different communities of practice. Through focus groups and presentation of work to different audiences and participants, it was possible to reflect on the language, imagery, artefacts and outcomes of the study for suitability and coherency. Six different cases of dissemination are discussed below for their contribution to knowledge transfer and the aims of this thesis. A full list of references of publications from this thesis can be found in section **1.2.1**.

8.3.1. Focus groups

The four focus groups used in this study provided opportunities to gather alternative opinions on the project development and outcomes of the research. Focus group participants had experience of a wide range of specialisms and provided varied opinions on the study and its outcomes. The inclusion of other people's opinions was vital to the continuing development of ideas that were not solely formed within the research design and not solely evaluated to an individual ideology. Detailed outcomes of the use of focus groups are discussed at the end of **Chapters 4-7** and in **Chapter 9**.

8.3.2. Smart Design Conference, Nottingham, November 2011.

Paper title: 'Designing a Knit Methodology for Technical Textiles' (Glazzard & Breedon, 2011)

The first presentation of initial design development work took place at a conference of delegates from mixed disciplinary backgrounds. The conference themes included: technical textiles/wearable devices; personal/home robotics; clinical and medical devices; smart packaging and intelligent environments.

Delivering a paper detailing the early stages of this thesis' development was the first opportunity to showcase the concept and results to an external audience. The paper and presentation were well-received and prompted audience discussion. This paper discussed the study as a whole and gave a good indication that the process and the outcomes had relevance in a function-led, design community.

8.3.3. Defining Contributions, Research Practice Course Conference, Nottingham, May 2012.

Paper title: 'Reclaiming a Knitter's Perspective' (Glazzard, 2012)

This conference gave a chance to disseminate to a mixed group of postgraduate research contemporaries. The paper concentrated on methodological issues and questioned the nature of disciplines. This was the first airing of the disciplinary comment of this study and received a positive reaction from the audience present.

8.3.4. Auxetics, Bolton, September 2012 and KTN workshop and PSSB journal paper.

Paper title: 'Weft-Knitted Auxetic Textile Design' (Glazzard & Breedon, 2014)

The conference on Auxetic materials comprised a mostly-scientific audience and allowed me to present the auxetic materials in this thesis to experts in the field. A KTN workshop also allowed for a group discussion on the effectiveness of knowledge transfer within the auxetic field (Morris, 2012). This gave the opportunity for me to promote design values and methods.

Presentation of my work at this conference exposed the project to auxetic research contemporaries including Hong Hu, who was a significant influence on the early stages of the work (Liu et al., 2010; Liu & Hu, 2010; Hu et al., 2011). This exposure provided a chance to receive feedback from auxetic researchers and helped to validate the focus on design methods within auxetic materials as a contribution to knowledge. Julian Wright, a delegate with experience in auxetic materials said about my presentation and contribution to how the auxetics field may develop and promote knowledge transfer:

> *You have made one important contribution, which I thank you for. That we, as a group get too bogged down in the technical side of things, but maybe that is not the right way. We are always using negative Poisson's ratio as the main definition of auxetics. But maybe we need something more accessible to people outside this room (community) , such as using the area or another method…something that doesn't require having a degree in physics to understand.*
>
> Julian Wright, 2013.

After participation in the conference, a journal paper was published in Physica Status Solidi B (PSSB). The paper gave me a chance to publish design and practice-led work in a scientific journal. I see this publication and the positive responses of the conference delegates as a validation of the objectives of this thesis to:

- Present this information in a style suitable for practitioners of different backgrounds through considered verbal and visual use and feedback through showcasing.
- Inform methods of design practice for textile and product with regard to function-focused knitted materials.

8.3.5. Arcintex, Helsinki, March 2013

The Arcintex networking event allowed for discussion of this study with academics from across Europe from areas of architecture, interaction design and textiles. This network also provided the opportunity to develop the fabrics from this study into 3D-prints, as discussed in section **8.2.2.**

8.3.6. Research Through Design, Gateshead, September 2013.
Paper title: Exploring 3D-Printed Structures Through Textile Design (Glazzard & Breedon, 2013)

Research Through Design provided a visual and academic outlet for the work in this thesis. The conference was curated to include an exhibition of made objects as well as round-table discussions about the design work. The attendees were made up of delegates from wide-ranging areas of design.

A number of fabric samples, 3D-printed materials, selected diagrams and videos showing fabrics being stretched and played with were exhibited. The conference had a hands-on approach and presenters' artefacts played a central role in presentations and discussions.

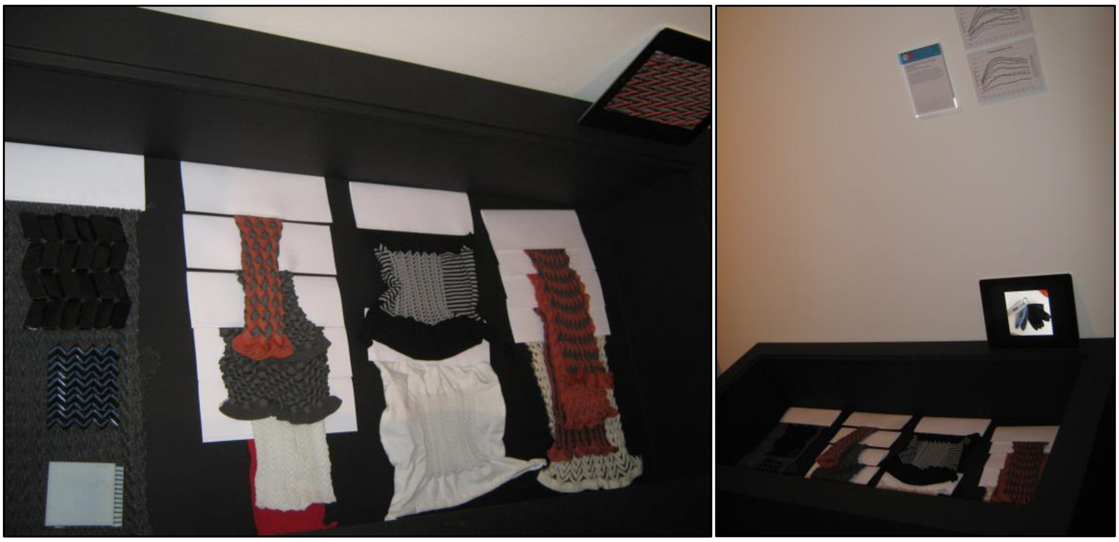


Figure 8.107 Images showing exhibition at the Baltic art gallery, Gateshead, UK as part of Research Through Design, September 2013.

The gallery context (shown in **Figure 8.107**) and the emphasis on methodological and aesthetic contributions granted validity to different aspects of this study from those at previous disseminations. Here the work was primarily categorised under the title of 'making' and highlighted the contribution of the designer-maker approach to this work.

8.3.7. Conclusion on dissemination

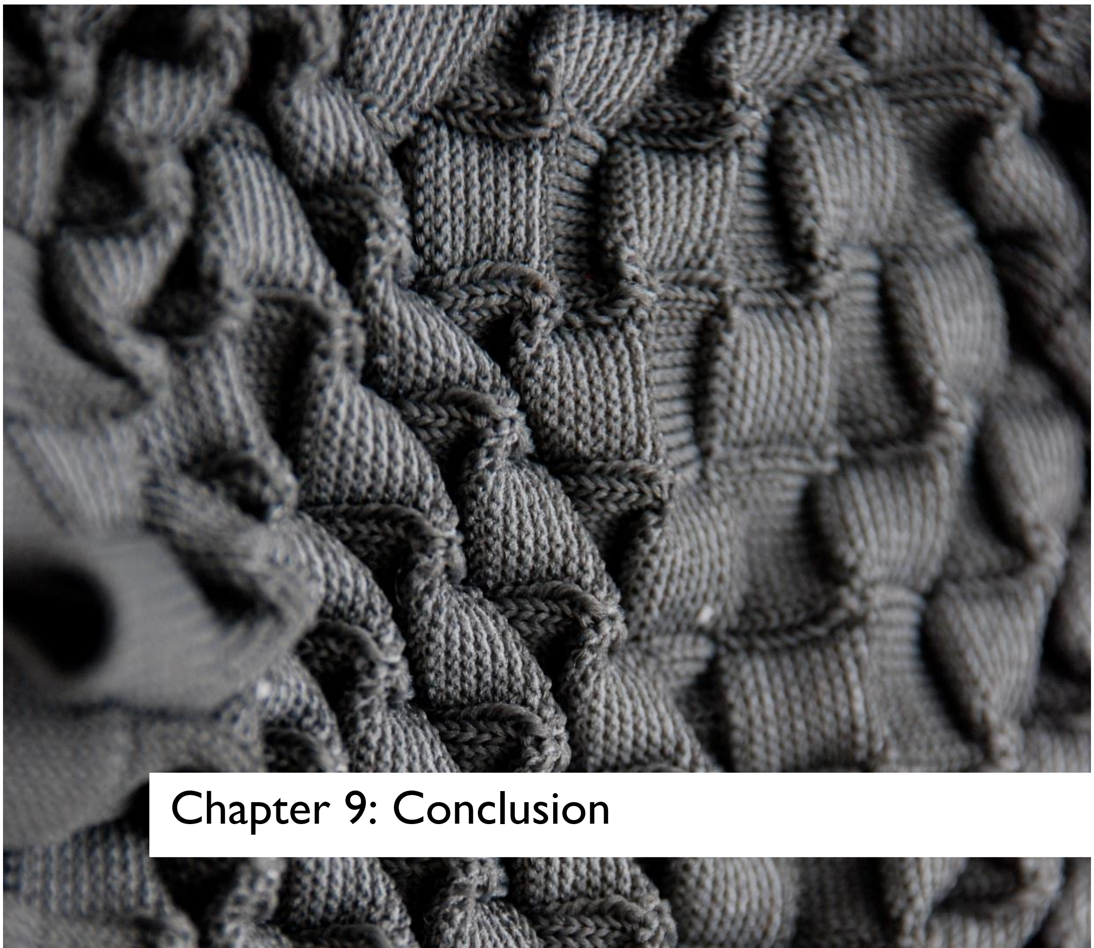
The range of dissemination of results of this study helps validate some of the key aims and objectives of this thesis. Fabrics and processes were discussed with practitioners, including architects, scientists, engineers, industrial designers, jewellers, artists, fashion designers and textile designers, among others. The reactions of these mixed audiences and participant groups stimulated reflection on the work being produced, the methodology used and the language and imagery chosen to express it.

8.4. Conclusions on knowledge transfer

Knowledge transfer has played a large part in the creation of this thesis. Early reflection acknowledged that the contributions from a practice-led, experiential thesis were at risk of being considered idiosyncratic or too subjective by certain communities of practitioners, who make up part of the intended audience for this thesis. Though the subjectivity of this work is essential to and recognised in the process, the voices of other practitioners help to triangulate, validate and diversify the contributions from this study.

To facilitate knowledge transfer over the course of this study, language and imagery used had to be easily understood by people with differing expertise. The success of the language and imagery choices has been trialled in the focus groups, conference presentations and publications, that all involved participants and audiences with different knowledge, experience and perspectives.

Chapter 9: Conclusion



9. CONCLUSION

This chapter summarises the contributions of this study to knowledge. It highlights how the aims and objectives of this thesis have been met and discusses how future work can be developed from the findings.

9.1. Main points of contribution to knowledge

The main contributions made by this study benefit methodological, knowledge transfer, knit design and auxetic material research.

The methodological contributions show a documentation of, and emphasis on knit design processes, considerations and values:

- A practice-led, designer-maker methodology has been described for the production of knitted textiles.
- A design-led approach has been applied to appraisal of auxetic materials through qualitative and quantitative feedback and my own reflection along with that of others.
- Conventions in research methodology that propose regimented repeatability of process have been challenged by presenting an amorphous, adaptive, generic knit methodology.

Knowledge transfer has been encouraged through the presentation of information in diverse formats to diverse audiences:

- Knowledge transfer has been facilitated and evaluated between different design and scientific disciplines using appropriate language, imagery and content.
- Design knowledge has been demonstrated to be sufficient and appropriate for use in non-design arenas.
- Alternative methods of presenting auxetic behaviour are presented using percentages, graphs, diagrams, photographs and videos. This approach also champions a plain English approach to conveying findings from functional textile/auxetic material research.

Contributions to knit design and auxetic materials were made by presenting and developing a knit design methodology and applying this to the production of weft-knitted auxetic materials. This provides new potential for development in both knit and auxetic fields:

- The overt use of experiential design knowledge successfully created 30 novel, function-focused, auxetic textiles.
- The complex and confusing position of knit design among other knit-related, textile or design disciplines has been highlighted.

My contributions as a designer in this study are shown in a diagrammatic form in **Figure 9.108**. This diagram shows the scales of contributions from individual contributions, areas of interest and the fields of knowledge that can find benefit from the transferrable knowledge in this thesis.

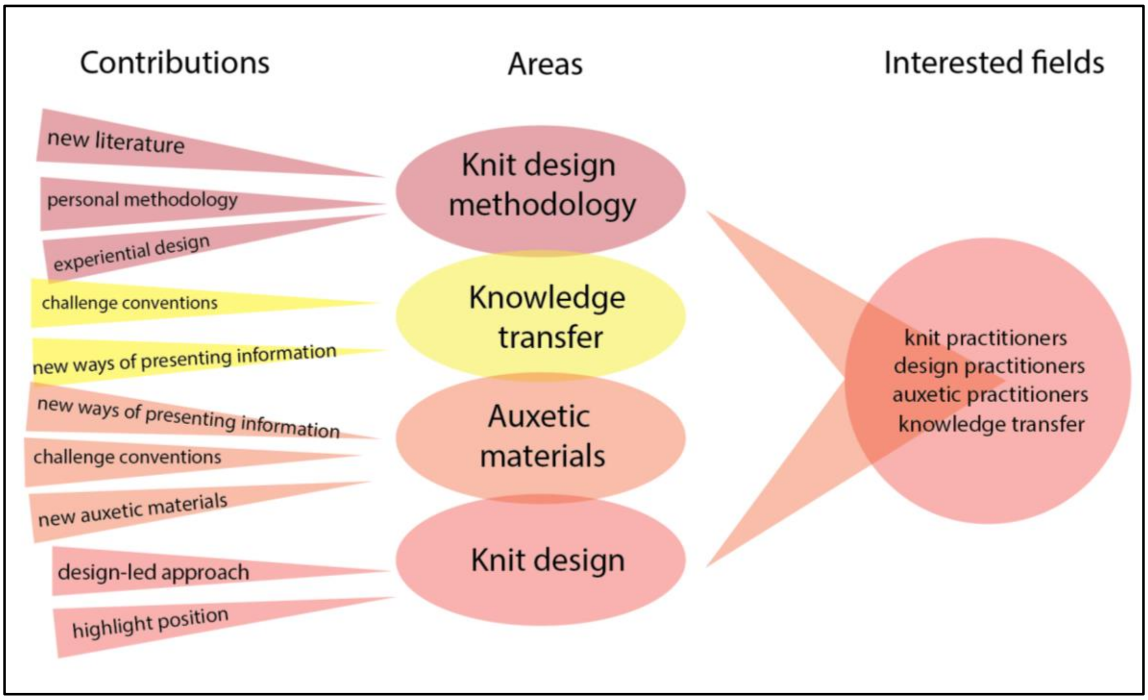


Figure 9.108 Visual representation of the contributions to knowledge of this study.

9.2. Other points of discussion

9.2.1. Disciplinary discussion

The difference between design and engineering, when it comes to knitting, is still a grey area. Since, in the case of many knitted outcomes, purpose is inseparable from form, it is not possible to determine a difference between a knit engineer and a knit designer by citing a lack of functionality in a designer (as El-Mogahzy [2000] might in his definition of 'function-focused fibrous products') or indeed a lack of aesthetic design consideration in an engineer (when speaking in 2012, Hu discussed pattern-based design for engineering outcomes [subsequently published paper - Wang & Hu, 2014]). Considering these crossovers, it might be more salient to propose that the major difference between those who consider themselves engineers and those who are designers (or other groups) is based in an individual or group ideology rather than in process, product or even methodology.

9.2.2. Methodological discussion

The methodology used in this thesis is a practice-led, designer-maker methodology. This is a methodology deeply linked to personal approaches, experiential knowledge, reflection, making and tacit knowledge. Because this was *my* practice-led, designer maker methodology in knit, it contained aspects which I consider to be important, including: subjective appraisal, objective note-taking, personal reflection, the views of others, and qualitative and quantitative information. This thesis promotes the fact that the methodology used in this project is not a rigid, linear process; it is amorphous, adaptive and reflective, depending on the factors that contribute to the process and the order they are considered in[69].

[69] This is discussed in detail in **Chapter 3** sections **3.5.** and **3.7.**

Through conducting the context review in **Chapter 2**, several gaps surrounding the practice-led, designer-maker approach were found in the fields of knit and auxetics, giving this thesis a novel contribution in those areas. A designer-maker approach focuses on the skills of the researcher/designer and allows autonomy of process based on experience and subjectivity. It does not exclude objectivity, rather, the two are used both together and at different times.

Focus groups and other audiences had strong tendencies to discuss the fabrics from this study in terms of their potential applications. This application-focus may be one of the problems affecting knowledge transfer in the design field. From a craft (or designer-maker and certain other art/design) perspective, the exploration of materials without an end product and the designing of an end product in reaction to a material is not an unusual practice. As craft is relevant to design processes and outcomes alike, it is difficult to see that its methodology is so unusual or questionable to non-craft practitioners. The methodological discussions throughout the dissemination of this project have provoked positive and empathetic responses from a wide range of practitioners. As with the focus group participants, it is hoped that readers of this thesis will find some of the methods and the considerations used in this thesis to bear some resemblance to their own design or making practice.

I hope through this thesis to have offered an alternative to the rigid frameworks of traditional, academic research. Such rigid research structures do not describe my methodology or allow it to contribute in reflective, explorative ways.

9.2.3. Knowledge discussion

From evidence found in existing literature, large differences are perceived in disciplinary methodologies, however, focus groups and audiences in this study gave feedback to the contrary. This thesis proposes that the role of educational establishments and academic literature in perpetuating definitions and divisions separating viewpoints on knit and textile production is increasingly prevalent. Concentration on the facilitation of sharing information, knowledge, methods and processes is more important than ever before.

The nature of knowledge in knit practice is increasingly both limited and diversified. This thesis states that the particular knowledge I have acquired through practice, making, design and experience has significant validity and usefulness across different disciplines. As with other practitioners, I have presented the intricacies of my practice to argue its worth, and to give it parity with more 'scientific' approaches.

9.2.4. Beneficiaries

This study contributes to disciplinary discussion, design discussion and knit discussion. It provides new ways of presenting information and facilitating knowledge transfer for those in the field of auxetic materials. These methods of presenting information may be applied to other engineering areas, as methods to increase audience engagement and encourage application of research information in design areas.

Knit practitioners are likely to benefit from this thesis as it provides a designer-maker methodology and, unlike much of the available literature, is not primarily concerned with knitwear or engineering practices. Documenting the pragmatic and transferrable nature of knit design can provide impetus for knit designers to use their knit practice in different areas, and for practitioners from different areas to use knit designers for their valuable skills.

9.3. Final conclusions on practical stages

The production of 30 fabric samples (based around seven stitch structures) that show auxetic behaviour has demonstrated the worth of design knowledge in the field of functional textiles and auxetic systems. Inclusion of reflective subjective and qualitative information and reflection has been found to enhance the outcomes, rather than making the practice alien to those who favour other methods. Evidence of this has been seen when making presentations at six conferences[70] and the use of four focus groups.

9.3.1. Theory Proposition from practical stages

The theory in this thesis is built directly from the responses of focus groups and reflection on the fabric development. The aim of this research has not been to create statistical theory to be used to illustrate 'fact' or 'proof'. The aim has been to communicate design and engineering knowledge that can

[70] List of conferences available in section **3.12.**

be transferred in different directions between practitioners. In **Table 9.15** is an overview of the most important, controversial and applicable theoretical propositions drawn from the focus groups and other data in this study. The darker the row on the table, the more times that proposition was evidenced in the research.

9.3.1.1. Summary of theoretical contribution

The theory collation is inspired by grounded theory principals and offers insights and interpretation rather than generalisable proof. Each proposition and outcome is based on an event in the research and has contributed to the fabric development, focus group design or dissemination. The outcomes have been fed back into the research design or propose considerations for future work.

9.3.1.2. Theory from focus group evidence

Proposition	Evidence from data	Outcome	Evidence featured in
Visual information can help expand understanding for designers.	Design practitioners found diagrams to help understanding of structures and aided idea formation.	Research Through Design conference.	FG4
Algebraic information is not always required when describing functional textiles.	Some participants found algebra confusing and unnecessary. Some found diagrammatic and simple numerical information helpful.	Glazzard & Breedon, 2013. Paper on auxetic materials published in scientific journal without the use of algebra.	FG4
Algebraic information is not always required when describing auxetic behaviour. Simple numerical information can be more helpful.	Participants preferred simple numerical information (percentages) to algebraic information.	Glazzard & Breedon, 2013. Discussion with group at Auxetics conference (Morris, 2012)[71].	FG4
A choice of information is more suitable to explain work that crosses disciplinary boundaries.	Agreement of participants that different information is helpful to different people. Ability to choose information to best suit.	Publish work with different information styles. Publish same work in different areas using information tailored to the publication style.	FG4 FG2

[71] See quote from Julian Wright (section **8.3.4.**) and Morris (2012).

Practitioners are not necessarily of a single discipline.	Hand-out exercises showed no evidence that any participants thought of themselves as singly disciplined.	Seek multi-disciplinary outcomes.	FG4 FG3 FG2
A range of textures and colours will expand the scope for ideas and applications.	Feedback from each focus group and from assessment stages of research about colour and texture development. Limited scope led to pre-formed ideas.	Prepare samples in a range of fibre types, colours, patterns and scales to diversify responses.	FG4 FG3
Methodologies across creative subjects are comparable.	FG4 Agreement of participants that the working methodology (**Figure G.4**) resembled their process.	Frame a complex, individual methodology through a generic creative process.	FG4
Background of FG leader and preconceptions about fabric may cause more fashion applications and discussions than other areas.	Fashion applications were common among participants. Some acknowledged that this was what they thought the fabric was for.	3D-printed materials provide non-fashion application for structures.	FG4 FG2 FG1
Illustrative descriptions help participants to communicate a shared understanding about complex ideas.	The use of similes and metaphors played a strong role in describing samples.	Link to Eckert & Stacey research (2000: 526).	FG3
Tactile information is important to the understanding of a textile. This is most important to design practitioners.	Tactile appraisal often changed responses based on aesthetic appraisal.	Aim to include physical samples where possible (e.g. Exhibitions, RTD conference).	FG3
Methodological background can affect all subsequent work, not only related work. Methodology and background is cumulative.	A knit design practitioner uses a scientific method in designing fabric. Another knit design practitioner uses artist and designer practices.	Multi-disciplinary information is useful even to specialised audiences.	FG3 FG2

Knitwear design process considers elements of designing simultaneously.	Knit design practitioner acknowledges the process of designing the fabric and the product simultaneously. The process is not linear.	Consider diagrammatic version of methodology to include parallel/iterative considerations.	FG3
Tacit appraisal is important, at least as an initial or developmental reaction.	Tacit appraisal is important to all participants	Include and value tacit responses.	FG3 FG2 FG1
Disciplinary allegiance may be overt (but does not exclude influences from other areas).	Individuals acknowledged the influence of their backgrounds on communication and appraisal.	Include and value perspectives of researcher and contributors.	FG3 FG2 FG1
Subject specific language can cause problems for multi-disciplinary groups.	Some communication problems between individuals stemmed from language use.	Avoid jargon where possible. Where not possible, include alternatives.	FG3
Tactile and aesthetic responses are important for all participants.	Tactile and aesthetic responses are common to all participants. Participants trusted 'gut' reactions.	Tactile and aesthetic discussion should be included where possible.	FG2
Physical and tactile resemblance is important to appraisal (as with simile/metaphor FG2).	Positive and negative responses were sometimes associated to resemblance to objects from the participant's experience.	Include important physical and tactile information to allow these responses.	FG1
Limited textile process understanding leads to negative connotations.	Textile processes were seen to be a making limitation.	RTD paper – 3D printing – Use of textile structures in different materials and via different processes. Encourage more comprehensive understanding of processes – illustrate range and potential.	FG1
A pragmatic comparison can be made from textile or fashion design to other making disciplines. KT	Dress-making was likened to engineering, using a substitution of materials and processes.	Generic comparison may help to inform understanding of processes. Use different	FG1

can be helped by relating understanding to others' specialisms.		ways of presenting information to encourage understanding.	
Aesthetic response can be an important contributor to reactions and value judgements.	Aesthetic properties were important to the participants – especially when taking a product through to market – in appraisal and reaction.	Include aesthetic comment where possible.	FG1

Table 9.15 Collection of theory derived from FGs 1-4.

9.3.1.3. Theory from physical artefact evidence

Table 9.16 shows evidence that develops or supports the claims made in this thesis from the practical development, representation and testing of fabrics. To complement the evidence from the focus groups, this data comes directly from the fabric development. Physical artefacts and the process of making them is a key method in this study and the information below demonstrates the achievement of the objectives of this thesis to: create auxetic textiles; use the perspective of a designer; design functionality; present this information in a style suitable for practitioners of different backgrounds; and to use parallel methods of practice-led design and reflection alongside development of fabrics.

Proposition	Evidence from physical data	Outcome
Auxetic, weft-knitted textiles can be produced using a design approach.	Samples (including variations). Purl Rectangle Purl zigzag S Purl zigzag stagger Purl diagonal TP4 TP5 Bulk test	Fabrics can now be developed in to prototypes, garments and products.
Measurement of auxetic effect can be visual and conducted simply.	Simple test frame and photography of extended samples provided quantitative data to prove auxetic effect.	Simple data can be easily shared with different communities. Documented in this thesis and related research papers.
Auxetic data can be represented visually.	Auxetic behaviour shown through graphical forms, diagrammatic forms and illustrative forms.	Visual representation of structural effect to work alongside any numerical data. Supported by focus group evidence and research papers.

Knowledge from knitting can be used to provide insight into other design areas.	Production of 3D-printed, auxetic materials using geometries derived from knitted fabric and the experiential analysis of it.	Documented in videos, photos and a research paper.

Table 9.16 Collection of theory derived from physical artefact evidence.

9.4. Further work and concluding remarks

The most obvious way to advance the work from this study, from a designer-maker perspective, would be to incorporate the auxetic stitch structures into items of knitwear or other knitted textile applications. The fabrics designed here would be easily adapted to use within knitwear applications as they are produced using conventional yarns and machinery. The stitch structures also provide auxetic behaviour, whether used as an all-over structure or used in placement with plain knit structures. The applications suggested in focus groups or by the Master's student project (section **8.2.1.**) provide a starting point from which to design a number of garments and products. In addition to a practical application development, the methodology used in this thesis could be used to produce other uses for knit design knowledge, or areas of application for practice-led, designer-maker knowledge.

The 3D-prints described in section **8.2.2.** could be developed to be printed using different materials or to develop complex shapes, such as tubes which would be difficult to produce in the original knitted structures.

The testing methods used in this thesis are considered sufficient proof of auxetic behaviour, but those from different disciplines may wish to reproduce the tests in line with their own norms and values.

The main contribution of this thesis promotes the value of knit design and practice-led, designer-maker perspectives. This ambition requires support from other practitioners, researchers and knitters. When I started this PhD research, someone advised me to 'do the PhD that only you can do'. That PhD is documented in this thesis. My experiences, preferences, beliefs and ideals have all shaped this project in its conception, development and dissemination. This thesis does not have the final word or close discussion on any of these subjects, but it does hope to open discussion.

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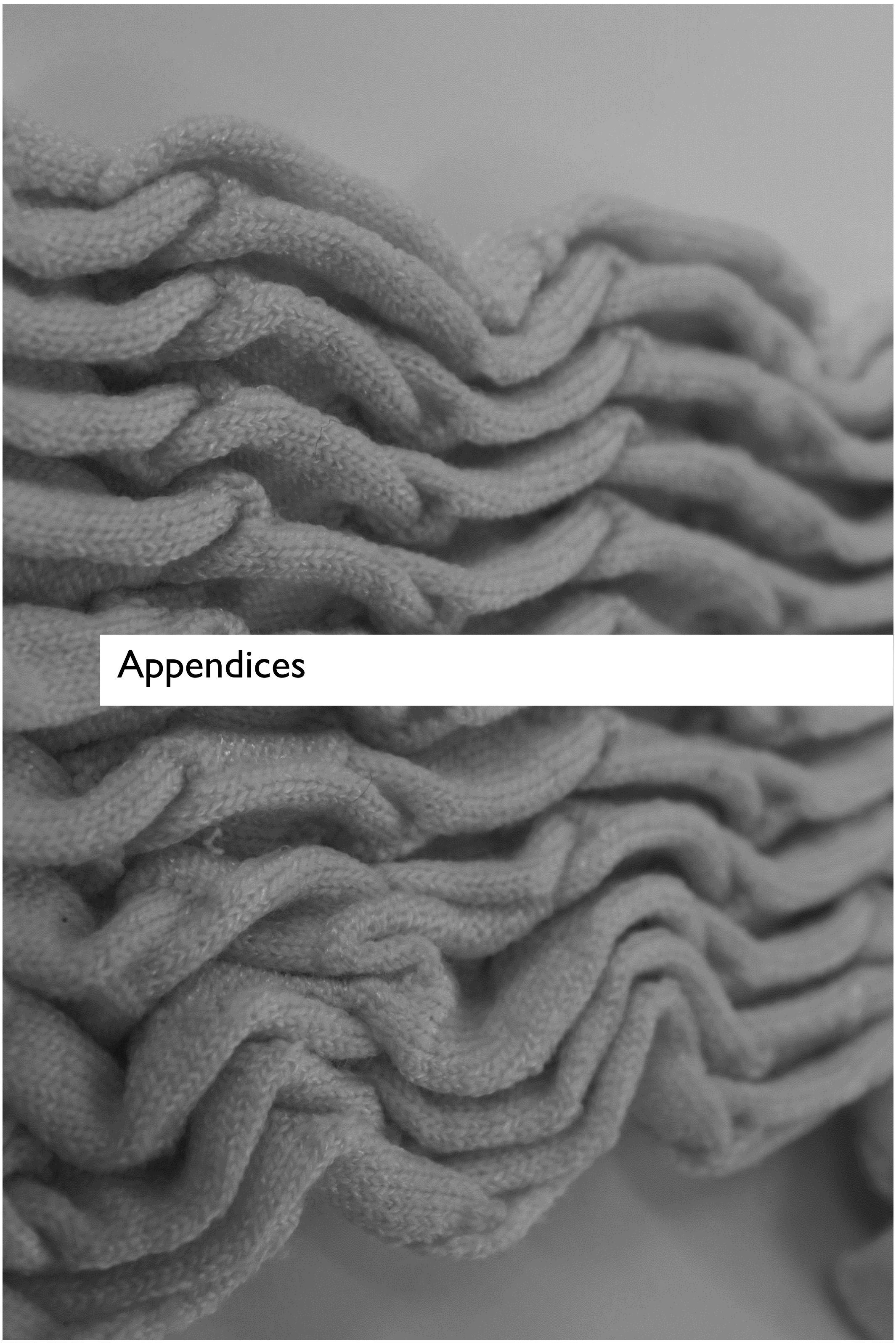
Appendices



Appendix A:Table of knitted structure/fabric properties

The table in this section describes the author's views on the comparable properties of different knitted structures primarily based on stitch structures created using knitting machines. The information comes from subjective and experiential knowledge. Plain fabric is used as a benchmark for all single-bed fabrics, and rib fabric is used as a benchmark for all double-bed fabrics to measure stretch against, i.e. a plain fabric is 0 and a single-bed fabric with more stretch shows a '+', and less stretch shows a '-'.

Structure	Beds/faces	Stretch X	Stretch Y	3 dimensionality	Machine limitations	Aesthetic potential	Curl	Other
Plain	SB	0	0	None		Stripe	Y	Curling edges
Full needle	DB	0	0	Slightly thicker		Stripe	N	Dense
Rib	DB	+	0	Proportional to needle selection	Racking, welt	Stripe, thickness	N	More stretch in X with less wales per rib
Mock Rib	DB	+	0	Proportional to needle selection		Stripe, needle selection, plating	N	Stretch in rib areas. Can vary needle selection at any time
Plating	SB/DB	n/a	n/a	Dependent	Plating feeder	Contrast yarn in plating feeder will show on relief	n/a	Lycra to add stretch or colour/contrast for patterning
Pleats	DB	+	0	Good	Bed width	Varied proportion of pleats	N	Gauge heavily influences effect
Relief	DB	0	0	Some – Good		Patterns, plating, 3D rack, tuck, hold	In SB	
Garter/Purl Rib	DB (whole rows)	0	+	Some – Good	Transfer ability	Horizontal rib,	N	
Pointelle	SB mainly	0	0	None	Transfer frequency/direction	Lace pattern, mesh	In SB	May warp fabric dimension
Shaping/ fashioning	SB mainly	0	0	None – Very good	Transfer frequency/direction	Fully fashioned, 3D shaped pieces, distorted stripe	Y	Integral transfer to create whole shape
Lateral transfer	DB	-	0	Some	Transfer frequency/direction	Aran, channels, lines, plating	N	Can incorporate cables
Cables	DB mainly	-	0	Some	Transfer frequency/direction	Patterns, compound patterns, plating	N	
Travelling Rib	DB	Variable	Variable	Some	Transfer frequency/direction	Channels, lines, plating	N	
Tuck	SB/DB	+	-	Some	No. tucks	Pattern, relief, elastic, distorted stripe	In SB	Basic tuck for patterning
Cardigan	DB	+	-	Some		Stripe	N	Shorter in length per row than plain
Miss stitch	SB	-	0	Some		Pattern, fairisle	Y	Shorter in length per row than plain
Ripple	DB	0	-	Some – Good	Take down, weight	Partial area, colour, elastic	N	Can be made very large as channels, can be asymmetric tubular sides
Milano	DB	0	-	Slightly thicker		Stripe	Slight	Stiff fabric
Float (across gap)	SB/DB	-	0	None	Feeder height & width of float	Width, hand manipulation	n/a	
Weaving	SB	-	0	Slight – Some	Dependent on m/c	Pattern, yarn choice	Y	
Lay-in	DB	-	0/-	Some	Feeders on m/c	Patterning, yarn choice	N	Can lay in horizontally, need machine adaptation to lay in vertically
Partial knit	SB	n/a	n/a	None – very good	m/c take down	3D, patterning, ruffles, bobbles, giant cables etc	Y	Can make socks, corners, circles, ruffles…endless
Half gauge	SB/DB	n/a	n/a	n/a	Bed width	Thick yarns, loose knit	n/a	Half gauge on X or Y axis or both
Ladder	SB/DB	-	0	None	Width of float, fashioning ratio	Patterning	n/a	
Pockets	DB	0	0/-	Some – good		Yarn choice, width, patterning, filling pockets	N	DB or SB background. Causes buckling on DB areas
Tubular	SB (round)	0	0	Very good	Cast on type., fashioning capability	Fashioning, intarsia, stripe, tuck etc. Hand manipulation with cord	Y	Knitted in a spiral
Intarsia	SB	0/+/-	0	None	Feeder set up, yarn ends	Colour, yarn choice, pattern, holes	Y	Dependent on crossover or not.
Channels	DB	0	-	Some – good		Width, length, filling channel	Y/N	Dependent on background fabric, will buckle against background
Yoke/integral transfer	SB/tubular	0	0	None – Very good	Transfer frequency/direction	3D tubular, distorted stripe	Y	
Drop stitch	SB	+	+	Some – good	Weight	Patterns, relief	Y	Uses two beds to create effect on SB
Plush	SB	-	-	Good	m/c capability	Patterns, relief	Y	Uses two beds to create effect on SB
Spacer	DB			Good	m/c capability, width b/w beds	Little	N	
Rack	DB	+	+	None	Racking distance	Relief, plating, ratio	N	
Tuck & Rack	DB	+	+	None – Very good		Zig-zag stripe, 3D peaks	N	
Jacquard – stripe back	DB	0	-	None	Number of yarns	Pattern on face, stripe on back	Slight	Thick milano fabric
Jacquard – bird's eye	DB	0	0	None	2 yarns per row?	Pattern on face, check on back	N	Can be dense fabric
Jacquard – ladder back	DB	-	0	None	Number of yarns	Pattern on face, half-gauge ladder on back	N	Can be messy at back, 2 SB fabrics interlocked in structure
Jacquard – tubular/blister	DB	-	-	None – good	2 yarns per row	Reversible pattern, lycra for blister	N	Using lycra will balloon out contrast yarn
Interlock	DB	-	0	None	m/c capability	Vertical stripe	N	Stable in dimension
Purl	DB (1 bed at a time)	0	+	Slight		Ridged fabric, can change width of 'purl ribs'	N	Edges do not curl

Table A.17 Table showing properties of various stitch structures.

Appendix B: Evaluation matrices Stages 1-3

This appendix shows the developmental records of Stages 1-3. The information was used in a side-by-side format, as can be seen in the example in **Figure B.109**, but for legibility the entry for each knitted sample is included in a separate table in this section. Sample numbers corresponding to the samples in the text of the thesis (Stages 1-3) are given where appropriate. Those entries that do not begin 'Sample. N' are not discussed in the main body of text. The notes in each table contain formal and informal observations from the time of fabric developments. The notes on attractiveness of samples comes from the importance within this study of my own subjective values, in acknowledgement of the strength of forms, contrast, colour and textures, singly and in combination (Ittens et al., 1975: 132-133) The notes were used to track the development and success of fabrics personally.

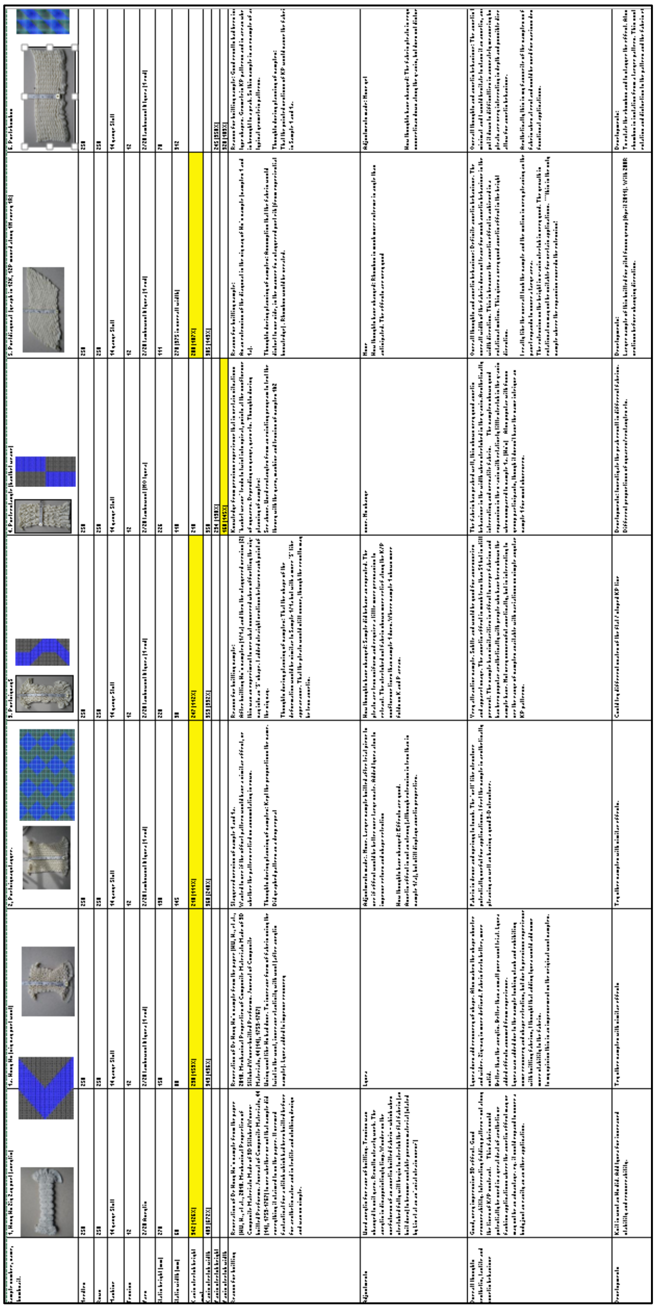
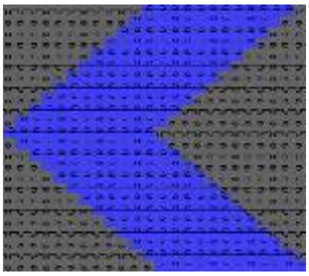
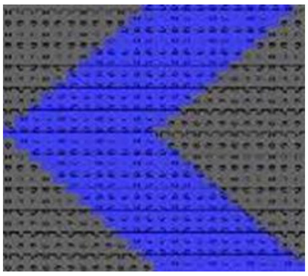


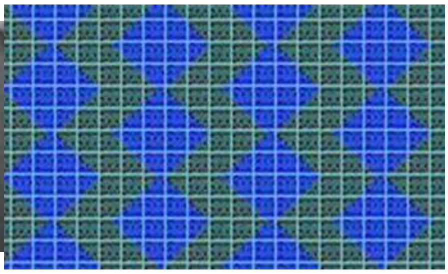
Figure B.109 Impression of the scale of evaluation matrix for Stage 1.

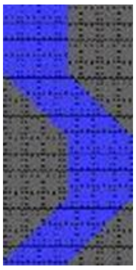
Chapter 4: Evaluation Matrix for Stage 1

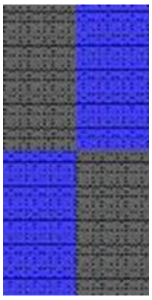
Sample number, name, thumbnail.	1, Hong Hu Zig Zag purl (acrylic)  
Needles	250
Courses	250
Machine	14 gauge Stoll
Tension	12
Yarn	2/28 Acrylic
Static height (mm)	270
Static width (mm)	60
X-axis stretch height (mm)	342 (126%)
X-axis stretch width (mm)	403 (672%)
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	Recreation of Dr Hong Hu's sample from the paper [Hu, H., et al., 2010. Mechanical Properties of Composite Materials Made of 3D Stitched Woven-knitted Preforms. Journal of Composite Materials, 44 (14), 1753-1767] to see whether or not that sample did everything it claimed to on the paper. It seemed fantastical for a stitch which had been knitted before for aesthetic value and in textile and clothing design and was so simple.
Adjustments	Used acrylic for ease of knitting. Tension was changed to suit yarn. Results clearly work. The acrylic is disappointingly limp. Wonder on the usefulness of an auxetic knitted fabric – which when stretched fully will begin to stretch the flat fabric (as knit does) to become unstable porous material (stated by Liu et al as an 'axial strain curve')
Overall thoughts aesthetic, tactile and auxetic behaviour	Good, very impressive 3D effect. Good recoverability. Interesting folding pattern – not along the lines of K/P contrast. This fabric could potentially be used in a great number of aesthetic or fashion applications where the auxetic effect may or may not be an advantage. e.g. it could expand to cover a body just as easily as another application.
Developments	Knit in wool as Hu did. Add lycra for increased stability and recoverability[72]

[72] Recoverability refers to the fabrics ability to return to its original size and shape.

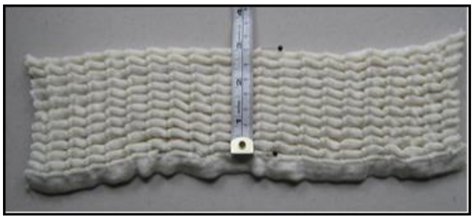
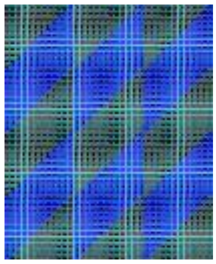
Sample number, name, thumbnail.	Sample 1a. Hong Hu (zig zag purl wool)  
Needles	250
Courses	250
Machine	14 gauge Stoll
Tension	12
Yarn	2/28 lambs wool & lycra (1 end)
Static height (mm)	150
Static width (mm)	80
X-axis stretch height (mm)	230 (153%)
X-axis stretch width (mm)	349 (436%)
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	Recreation of Dr Hong Hu's sample from the paper [Hu, H., et al., 2010. Mechanical Properties of Composite Materials Made of 3D Stitched Woven-knitted Preforms. Journal of Composite Materials, 44 (14), 1753-1767] Using wool like Hu had done. To increase form of fabric using the twist in the wool, increase elasticity with wool (after acrylic sample). Lycra added to improve recovery
Adjustments	Lycra
Overall thoughts aesthetic, tactile and auxetic behaviour	Lycra does add recovery of shape. Also makes the shape shorter and wider. Zig-zag is more defined. Fabric feels better, more solid. Better than the acrylic. Better than a small pure wool trial. Lycra added effects assumed from experience. Lycra was added due to the sample looking slack and exhibiting some recovery and shape retention, but due to previous experience with knitting fabrics, I thought that adding lycra would add some more stability to the fabric. In my opinion this is an improvement on the original wool samples.
Developments	Try other samples with similar effects

Sample number, name, thumbnail.	Sample 2. Purlzigzagstagger.  
Needles	250
Courses	250
Machine	14 gauge Stoll
Tension	12
Yarn	2/28 lambswool & lycra (1 end)
Static height (mm)	190
Static width (mm)	145
X-axis stretch height (mm)	210 (111%)
X-axis stretch width (mm)	360 (248%)
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	Staggered version of sample 1 and 1a. Wanted to see if the offset pattern would have a similar effect, or whether the pattern relied on accumulating in courses. Thoughts during planning of samples: Kept the proportions the same. Did graphed pattern as a drop repeat
Adjustments	Adjustments made:. None. Larger sample knitted after trial piece to see if effect would be better over large scale. Added lycra also to improve return and shape retention How thoughts have changed: Effects are good. Auxetic effect is not as strong (although extension is less than in sample 1a), but still displays auxetic properties.
Overall thoughts aesthetic, tactile and auxetic behaviour	Fabric is dense and springy to touch. The 'cell' like structure potentially useful for applications. I feel the sample is aesthetically pleasing as well as having a good 3-D structure.
Developments	Try other samples with similar effects.

Sample number, name, thumbnail.	Sample 3. PurlzigzagS  
Needles	250
Courses	250
Machine	14 gauge Stoll
Tension	12
Yarn	2/28 lambswool & lycra (1 end)
Static height (mm)	220
Static width (mm)	90
X-axis stretch height (mm)	247 (112%)
X-axis stretch width (mm)	353 (392%)
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	Reason for knitting sample: After knitting Hu's samples (1/1a) and then the staggered version (2) this was an experiment to see what occurred when offsetting the zig-zag into an 'S' shape. I added straight sections between each point of the zig zag. Thoughts during planning of samples: That the shape of the deformation would be similar to Sample 1/1a but with a more 'S' like appearance. That the pleats would still occur, though the results may be less auxetic.
Adjustments	How thoughts have changed: Sample did behave as expected. The pleats are less uniform and require a little more persuasion to retract. The stretched out fabric shows more relief along the K/P confluence lines than sample 1 does, whereas sample 1 shows more folds on K and P areas.
Overall thoughts aesthetic, tactile and auxetic behaviour	Very attractive sample. Subtle and would be good for accessories and apparel usage. The auxetic effect is much less than S1 but is still present. The sample has similarities in effect to crepe fabrics and has been popular aesthetically with people who have been shown the sample base. Not very successful auxetically, but is interesting to see the range of samples available with variations on simple angular KP patterns.
Developments	Could try different scales of the flat / sloped KP line

Sample number, name, thumbnail.	Sample 4. Purl rectangle (basket weave)  
Needles	250
Courses	250
Machine	14 gauge Stoll
Tension	12
Yarn	2/28 lambswool (NO lycra)
Static height (mm)	226
Static width (mm)	110
X-axis stretch height (mm)	210
X-axis stretch width (mm)	350
Y-axis stretch height (mm)	294 (130%)
Y-axis stretch width (mm)	160 (145%)
Reason for knitting	Knowledge from previous experience that in certain situations 'basket weave' tends to twist into spiral points at the confluence of squares. Depending on gauge, yarn etc. Thoughts during planning of samples: See above. Used rectangles from an existing program to test the theory with the yarn, machine and tension of samples 1&2
Adjustments	none. No change
Overall thoughts aesthetic, tactile and auxetic behaviour	The fabric has peaked well, this shows very good auxetic behaviour in the width when stretched in the y-axis. Aesthetically interesting and versatile fabric. The samples shows good expansion in the x - axis with relatively little stretch in the y-axis when compared to sample 1a. (Hu's) Also popular with focus group participants, though it doesn't have the same intrigue as sample 1 for most observers.
Developments	Developments: Investigate the peak result in different fabrics. Different proportions of squares/rectangles etc.

Sample number, name, thumbnail.	Sample 5. Purldiagonal (graph is 12K, 12P moved along 1N every 1R) 
Needles	250
Courses	250
Machine	14 gauge Stoll
Tension	12
Yarn	2/28 lambswool & lycra (1 end)
Static height (mm)	111
Static width (mm)	270 (375 in overall width)
X-axis stretch height (mm)	208 (187%)
X-axis stretch width (mm)	385 (143%)
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	Reason for knitting sample: As an extension of the diagonal in the zig zag of Hu's sample (samples 1 and 1a). Thoughts during planning of samples: Assumption that the fabric would distort to one side, in the manner of a staggered purl rib (from experiential knowledge) . Rhombus would be created.
Adjustments	None How thoughts have changed: Rhombus is much more extreme in angle than anticipated. The effects are very good
Overall thoughts aesthetic, tactile and auxetic behaviour	Overall thoughts and auxetic behaviour: Definite auxetic behaviour. The overall width of the fabric does not leave for much auxetic behaviour in the width direction. This is because the auxetic effect is achieved in a rotational motion. This gives a very good auxetic effect in the height direction. I really like the overall look of the sample and the motion is very pleasing as the panel expands to cover a large area. The extension on the height in x-axis stretch is very good. The growth is rotational so may not be suitable for certain applications. ***this is the only sample where the expansion exceeds the extension!
Developments	Developments: Larger sample of this knitted for pilot focus group (April 2011). With 200R sections before changing direction.

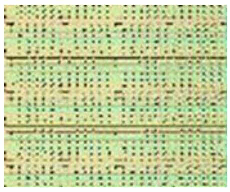
Sample number, name, thumbnail.	Purlrhombus  
Needles	250
Courses	250
Machine	14 gauge Stoll
Tension	12
Yarn	2/28 lambswool & lycra (1 end)
Static height (mm)	70
Static width (mm)	312
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	245 (350%)
Y-axis stretch width (mm)	320 (103%)
Reason for knitting	Reason for knitting sample: Good results had been indicated with rhombus type shapes. Geometric KP patterns and in areas where the K or P section is brought to a peak. So this sample is an example of another variation in typical geometric patterns. Thoughts during planning of samples: That the pointed sections of KP would cause the fabric to kick out as it did in Sample 1 and 1a.
Adjustments	Adjustments made: None yet How thoughts have changed: The fabric pleats in regular proportions, it concertinas down along the y-axis, but does not distort proportion.
Overall thoughts aesthetic, tactile and auxetic behaviour	Overall thoughts and auxetic behaviour: The auxetic behaviour is very minimal and I would hesitate to class it as auxetic, and I would be tempted to put it down to difficulties in accurately measuring knitted fabrics. The pleats are very interesting in depth and possible directional changes could allow for auxetic behaviour. Aesthetically this is my favourite of the samples so far. It is a very dense fabric when at rest and could be used for various decorative and functional applications.
Developments	Developments: To rotate the rhombus and to stagger the effect. Also perhaps to treat the rhombus in isolation from a larger pattern. This could add an element of rotation and distortion to the pattern and the fabric effect.

Chapter 5: Evaluation Matrix for Stage 2

Sample number, name, thumbnail.	Transfer Purl  
Needles	200
Courses	250
Machine	14g
Tension	12
Yarn	Wool 2/28
Static height (mm)	240
Static width (mm)	195
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	Replication of the 'arrowhead' pattern type of auxetic behaviour. After the success of the KP relief stitches in stage 1, I wanted to see if those could be incorporated into transferred lines to distort the direction of any effect that might be achieved. It uses a traditional lace transfer technique to create a zigzag effect.
Adjustments	The fabric has broken out into a lot of holes, due to the number of transfers in the programme.
Overall thoughts aesthetic, tactile and auxetic behaviour	No auxetic behaviour. Comes out detailed and intricate, likes scales. It is an attractive fabric, but the high number of transfers causes it to break out into holes. This makes it unsightly.
Developments	Edit the programme data to use fewer transfers.

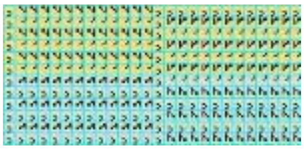
Sample number, name, thumbnail.	Transfer purl 1 
Needles	200
Courses	
Machine	14g
Tension	12
Yarn	wool 2/28
Static height (mm)	285
Static width (mm)	210
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	Attempt to simplify the number of transfers into a more tolerable programme.
Adjustments	This gives a rather flat and lifeless fabric, the particular attempt to stagger the transfers gives an uneven fabric.
Overall thoughts aesthetic, tactile and auxetic behaviour	Not auxetic. Not very interesting. Not attractive fabric due to uneven nature of the revised pattern.
Developments	Scrap this method of simplifying.

Sample number, name, thumbnail.	Transfer Purl 1b 
Needles	200
Courses	
Machine	14g
Tension	12
Yarn	wool 2/28
Static height (mm)	285
Static width (mm)	210
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	Attempt to do the same fabric structure at a 90 degree rotation to the original two attempts.
Adjustments	None
Overall thoughts aesthetic, tactile and auxetic behaviour	The fabric has a quite 3D effect, but there is a very slight auxetic effect. The fabric is quite attractive due to the pronounced 3D effect.
Developments	

Sample number, name, thumbnail.	Transfer Purl 2 (a&b)  
Needles	200
Courses	
Machine	14g
Tension	12
Yarn	wool 2/28
Static height (mm)	315
Static width (mm)	255
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	Two similar larger scale arrowhead patterns. Transfer done only when on knit or purl (depending on the sample).
Adjustments	None
Overall thoughts aesthetic, tactile and auxetic behaviour	This does not have any auxetic effect. The samples are flat and uninteresting. The pattern is aesthetically pleasing, but has no application outside aesthetic applications.
Developments	

Sample number, name, thumbnail.	Sample 6. Transfer Purl 4 (V2) 
Needles	200
Courses	250
Machine	14g
Tension	12.5
Yarn	wool 2/28 & Lycra
Static height (mm)	240
Static width (mm)	160
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	365 (151%)
Y-axis stretch width (mm)	180 (113%)
Reason for knitting	Continuous line (stripes of knit and purl) version of sample 3. Using the same lace transfer pattern as Transfer Purl 1 and 3. This is a mix between the 'arrowhead' pattern from samples 1 and 2 and an attempt to rotate the effects from Sample 1a.
Adjustments	Sample may benefit from having slightly wider stripes - this should give the fabric more space to expand.
Overall thoughts aesthetic, tactile and auxetic behaviour	Fabric is similar to Transfer Purl 3, but does not have the herringbone effect. In this way it looks like a horizontal version of Liu et al.'s sample.
Developments	Try with wider purl rib to give fabric more room to expand.

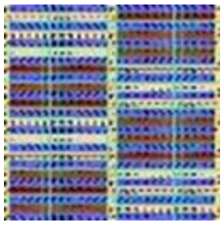
Sample number, name, thumbnail.	Sample 7. Transfer Purl 4 (V2) (plated wool/nylon) 
Needles	(cut sample)
Courses	250
Machine	14g
Tension	12.5
Yarn	wool 2/72 / Nylon (bulk)
Static height (mm)	310
Static width (mm)	115
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	490 (158%)
Y-axis stretch width (mm)	130 (113%)
Reason for knitting	In order to introduce colour and different materials into some of the more successful samples of the group. Possibility of using the nylon to try to fuse/bond to itself and create an interesting texture. Also the desire to try plating as it would create a pleasing pattern when the fabric is stretched to reveal the K/P differences.
Adjustments	Any number of possible combinations of yarn colour and material.
Overall thoughts aesthetic, tactile and auxetic behaviour	Fabric is very attractive when the contrast of the colours of the K and P are shown when stretched. The different materials - though giving a different feel to the sample, give the same results in auxetic behaviour.
Developments	Any number of possible combinations of yarn colour and material.

Sample number, name, thumbnail.	Sample 8. Transfer Purl 4 Version 3 (polyester stripes)  
Needles	200
Courses	250
Machine	14g
Tension	12.5
Yarn	wool 2/28 & Lycra / Polyester 2/32 (2 ends)
Static height (mm)	320
Static width (mm)	165
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	475 (148%)
Y-axis stretch width (mm)	190 (115%)
Reason for knitting	Trying sample 4, which was successful, but with different yarn for a change in colour and material. Hope that polyester will be able to be heat-treated to be stable and give structure to the stripe to levy against when stretch is applied in the auxetic fabric.
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	Fabric is attractive in its appearance with the zigzag stripes being hidden when relaxed and exposed when stretched. This shows the auxetic nature in aesthetics as well as in results. The fabric is still auxetic, the polyester is different in property from the wool. It does not retract as it does not have the lycra.
Developments	setting with heat?

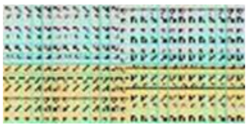
Sample number, name, thumbnail.	Sample 9. TP4 Version (Monofilament) 
Needles	200
Courses	250
Machine	14g
Tension	12.5
Yarn	wool 2/28 & Lycra / Transfil 90Den Polyamide
Static height (mm)	300
Static width (mm)	155
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	480 (160%)
Y-axis stretch width (mm)	190 (126%)
Reason for knitting	Use of the monofilament due to the hunch that using a stiffer material would give some leverage to the fabric when stretched and give a more auxetic effect. Also because it would be pleasing to see the 'transparent' sections moving against the opaque. Monofilament put in the knit section because the difference in type normally forces the other stripe out, against the purl, which does this anyway - this is an advantage visually.
Adjustments	The machine speed was slowed to 0.4 metres/second (not viable for mass production!)[73]
Overall thoughts aesthetic, tactile and auxetic behaviour	Fabric is the most auxetic of the group. (not as much as some in stage 1) It is obviously more auxetic even before measuring - the motion is very pleasing due to the high contrast in density of the two stripes.
Developments	Tension to be tighter on the monofilament. This would show less of it against the wool.

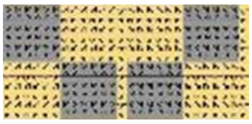
[73] The top speed of the Stoll machines used in this thesis is 1.2 metres per second (m/s). The machine knitting at 0.4 m/s is operating at a third of the possible speed. In mass-production the machine would ideally be operated at as fast a speed as possible to optimise production.

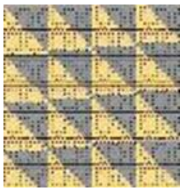
Sample number, name, thumbnail.	Sample 9a. TP4 Version Monofilament 2 
Needles	200
Courses	250
Machine	14g
Tension	Wool 12.5 Monofilament 11.5
Yarn	wool 2/28 & Lycra / Transfil 90Den Polyamide
Static height (mm)	280
Static width (mm)	145
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	430 (153%)
Y-axis stretch width (mm)	170 (117%)
Reason for knitting	Version of previous sample with tighter tension on the monofilament stripes
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	The fabric does not knit well like this. The monofilament is breaking out into many holes. Also the result is less auxetic…I assume this is due to the smaller area of the monofilament pushing against the wool.
Developments	Try 2 ends of the monofilament to thicken it up…..this may or may not work, seeing as my idea about the tension proved to be opposite to reality.

Sample number, name, thumbnail.	Sample 10. Transfer Purl 5 (version 2)  
Needles	200
Courses	250
Machine	14g
Tension	12.5
Yarn	wool 2/28 & Lycra
Static height (mm)	256
Static width (mm)	150
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	388 (152%)
Y-axis stretch width (mm)	167 (111%)
Reason for knitting	This sample tries a new approach to altering the direction of stitches with transfer. The zig zag structure, as used in Transfer Purl 1, is used, but with the knit and purl areas done in a basket weave style. The staggering of these stripes was predicted to cause purl ribs which alternate in zigzags across the width.
Adjustments	Try the fabric with the purl and knit in continuous stripes.
Overall thoughts aesthetic, tactile and auxetic behaviour	The fabric retracts into a pleasing herringbone pattern - where the contrast of the knit and purl interlock. It seems to show auxetic effect in both axes.
Developments	

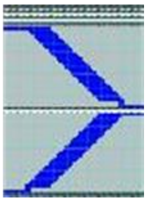
Sample number, name, thumbnail.	Sample 11. TP 5 V2 (Plated) 
Needles	(cut sample)
Courses	250
Machine	14g
Tension	12.5
Yarn	wool 2/72 / Nylon (bulk)
Static height (mm)	325
Static width (mm)	105
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	493 (152%)
Y-axis stretch width (mm)	118 (112%)
Reason for knitting	As with other plated sample.
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	Results same as with TP 5 in other materials. The same pleasing visual effect when stretched is there as with TP 4 plated, but not so well defined due to the stitch layout. As auxetic as the other versions of this sample.
Developments	

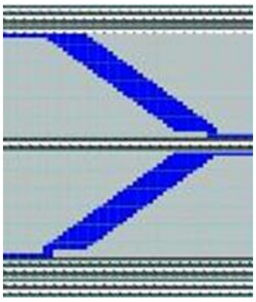
Sample number, name, thumbnail.	Sample 12. Transfer Purl 5 version Stripe  
Needles	200
Courses	250
Machine	14g
Tension	12.5
Yarn	wool 2/28 & Lycra / Polyester 2/32 (2 ends)
Static height (mm)	327
Static width (mm)	152
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	460 (141%)
Y-axis stretch width (mm)	170 (112%)
Reason for knitting	Trying sample 4, which was successful, but with different yarn for a change in colour and material. Hope that polyester will be able to be heat-treated to be stable and give structure to the stripe to levy against when stretch is applied in the auxetic fabric.
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	The fabric is pleasing in that the herringbone is now split into vertical stripes. This is a good effect when relaxed, and shows some contrast when stretched.
Developments	

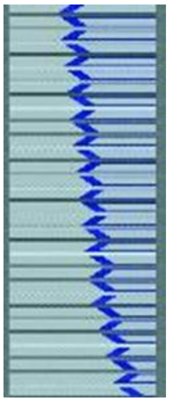
Sample number, name, thumbnail.	Transfer Purl 6 (prg)  
Needles	200
Courses	250
Machine	14g
Tension	12.5
Yarn	wool 2/28 & Lycra
Static height (mm)	298
Static width (mm)	168
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	395 (133%)
Y-axis stretch width (mm)	173 (103%)
Reason for knitting	Attempt to add elements of the basket weave and contrast into the format from this group of samples.
Adjustments	None
Overall thoughts aesthetic, tactile and auxetic behaviour	Barely auxetic and ill-defined in aesthetic structure.
Developments	

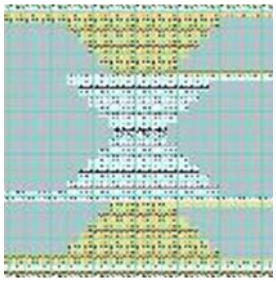
Sample number, name, thumbnail.	Purl Triangle  
Needles	200
Courses	250
Machine	14g
Tension	12.5
Yarn	wool 2/28 & Lycra
Static height (mm)	192
Static width (mm)	234
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	Attempt to encourage the rotating joins in auxetic work like Grima's. Unsuccessful. Consider removing from this group and attaching to group 1 as it is really a follow on from those samples, not these.
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	Nice effect in the pattern. Quite 3D and 'scale' like.
Developments	

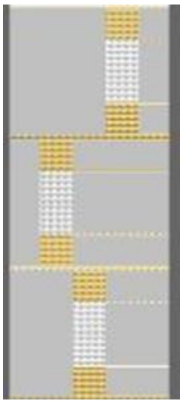
Chapter 6: Evaluation Matrix for Stage 3

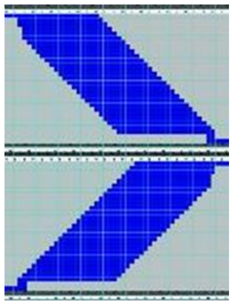
Sample number, name, thumbnail.	Sample 13. Bulk test 2 
Needles	50
Courses	
Machine	10gg Stoll
Tension	
Yarn	Nylon, polyamide monofilament - 90 D
Static height (mm)	
Static width (mm)	55.41
X-axis stretch height (mm)	1.57
X-axis stretch width (mm)	
Y-axis stretch height (mm)	73.96
Y-axis stretch width (mm)	13.79
Reason for knitting	Having initial idea of the cross-section appearance and how that when pulled at cross-purposes would rotate to expand the 'Z' axis (or depth)
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	Very good - worked first time! The fabric lies fairly flat, which I was not too sure if it would rotate itself out - is this because of the thin monofilament though? Would a thicker one also do this? The wall fabrics are not very sturdy and stretch a great deal when pulled before you start the aux effect. Also the nylon - though used for its strength, is distorting and not regaining its shape well.
Developments	Use a more stable yarn and structure for wall fabrics. Use a thicker monofilament **This takes a very long time to knit on MC - would be a problem for industrial manufacture.**

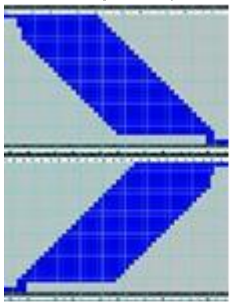
Sample number, name, thumbnail.	Sample 14. Bulk test 2b 
Needles	50
Courses	
Machine	10gg Stoll
Tension	
Yarn	Cotton, thick monofilament (240d?)
Static height (mm)	
Static width (mm)	103.76
X-axis stretch height (mm)	11.08
X-axis stretch width (mm)	
Y-axis stretch height (mm)	133.53
Y-axis stretch width (mm)	18.45
Reason for knitting	To try using interlock in the wall fabrics to give better stability when stretching. Also to attempt a thicker monofilament.
Adjustments	The current programme has excess fabric on all 4 corners, this is confusing when explaining how to pull the edges to get the aux effect - think about changing this so only the sides you pull have excess length/tabs.
Overall thoughts aesthetic, tactile and auxetic behaviour	Very good - the adjustments work well and the overall effect is more impressive. The thicker monofilament also lies flat and requires the force to be rotated vertically. The thicker MF also gives a very good spongey feel to the fabric when stretched. The recovery seems good.
Developments	try one with elastomeric yarns in the wall and the same thick MF in the spacer - this creates a very unpleasant fabric - very thick and tight - forces the MF into a very tight space and rips a lot of it in the process. The 'rotation' effect is still there, but it is less pronounced as the MF is forced to a less acute angle - the force required is also much greater.

Sample number, name, thumbnail.	Bulk partial Stoll 
Needles	100
Courses	
Machine	10gg Stoll
Tension	
Yarn	Cotton, 90D monofilament
Static height (mm)	
Static width (mm)	
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	Attempt to cause a rotation relationship between both wall fabrics. By using the monofilament in a central strip and changing the orientation of the filaments half way, it was hoped that when pulled, the two wall fabrics would rotate in opposite directions.
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	Does not work - the wall fabrics are too curly and the overall structure of the piece is too soft to have any effect. Could possibly be made to work with a wider section in the middle, but I feel it is unlikely to have any effect or will not be worth continuing.
Developments	

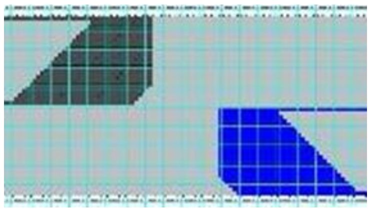
Sample number, name, thumbnail.	Spacer fabric 
Needles	
Courses	
Machine	10gg Stoll
Tension	
Yarn	Cotton/acrylic
Static height (mm)	
Static width (mm)	
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	Experiment into alternative ways of creating spacer fabrics - not designed to be auxetic, but to experiment with a technique which, if successful could be adjusted to an aux structure.
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	The structure works (in principle as 2 sock heels done from opposing beds and linked with a DB row at the base of the heel)
Developments	Try adjusting the size of the heel to a large scale thereby increasing the width between beds - also the shape so as to create an auxetic structure.

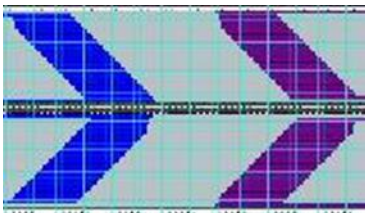
Sample number, name, thumbnail.	Spacer fabric 2 
Needles	
Courses	
Machine	10gg Stoll
Tension	
Yarn	acrylic
Static height (mm)	
Static width (mm)	
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	Attempt at trying to increase the partial knit scale from 'Spacer Fabric'. Done in a staggered pattern - to reflect several aux patterns, but kept in a straight-sided flap, to see what effect the hole caused by this would have.
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	Machine struggles with extended amounts of partial knit when knitting on both beds simultaneously (though I am told it has very good sinkers and is suitable for this kind of knitting).
Developments	Rethink plan entirely!

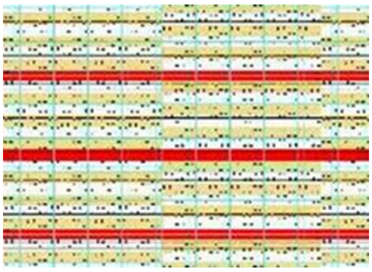
Sample number, name, thumbnail.	Bulk test 2b 20 space 
Needles	
Courses	
Machine	10gg Stoll
Tension	
Yarn	brushed cotton, monofilament
Static height (mm)	
Static width (mm)	
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	To test whether the floats from bulk test 2b could be knitted much longer. The size of the auxetic response should be directly related to the length of the floats. Also to test the method of making the floats right to the edge of the wall fabrics so that there are only excess tabs on the relevant wall edges (to be pulled for aux effect)
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	The fabric still lies flat - and the aux effect still is shown clearly. The spacer is not as sturdy as Bulk Test 2B - the longer floats make the monofilament less supportive. The tabs work well for the clarity of the purpose and operation of the structure. Doubling up on the MF tucks on subsequent courses does not cause a problem.
Developments	Using a much thicker MF would give a better resistance between beds when wider-spaced.

Sample number, name, thumbnail.	Bulk test 2b 20 space (1 Elastic wall) 
Needles	
Courses	
Machine	10gg Stoll
Tension	
Yarn	brushed cotton, covered elastic, monofilament
Static height (mm)	
Static width (mm)	
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	To test the results of knitting one wall fabric in elastomeric yarn and the other in a normal cotton yarn.
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	The fabric is a very strange one. It forms a curved shape with the elastic panel drawing in.
Developments	Try knitting the same materials but with the shorter-floated fabric

Sample number, name, thumbnail.	Spacer development 
Needles	
Courses	
Machine	10gg Stoll
Tension	
Yarn	
Static height (mm)	
Static width (mm)	
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	To attempt to subvert a 'knitter's block' and to go back to the base of the spacer development and see how different it is from the auxetic spacers.
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	Very different to the auxetic spacers. A colleague said I was pretty much pushing spacers as far as they will go, but I feel that there is much more that can be done. Though it may not be possible to experiment with all of these here. Not auxetic.
Developments	

Sample number, name, thumbnail.	Spacer circular 
Needles	
Courses	
Machine	10gg Stoll
Tension	
Yarn	
Static height (mm)	
Static width (mm)	
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	To test whether it is possible to encourage the filaments to distort into the central space in the circular fabric by doing a conventional spacer pattern in two parts.
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	This does not really work, or does not work well. But the gap between the spacers is interesting, as it causes a definite re-entrant section which rises up when stretched. I do not think it is auxetic in itself, but could be worth developing somehow.
Developments	There could be a way of 'quilting' or joining the walls into an interesting pattern, or of manipulating the pattern in the gaps of the spacer so that a rotation, or a more interesting effect is caused by the moving of the wall fabrics.

Sample number, name, thumbnail.	Shear spacer symmetrical 
Needles	
Courses	
Machine	10gg Stoll
Tension	
Yarn	
Static height (mm)	
Static width (mm)	
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	Similar to the previous sample, but with the hope that the two opposing shear spacers will open symmetrically and raise the wall of the fabric by using the stretch between them (in the form of elastic on that wall)
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	Works I think. Is not tested properly, or knitted in suitable yarns yet, but it seems to work - in theory. The spacer filaments could probably do to be shorter to show the effect more clearly. There is a bit of a problem with the gap being bigger at the bottom, but hopefully this is resolvable....
Developments	This is already the most complex fabric I have knitted, but there may be ways to encourage the stretch in only the top wall, by using a mock/lycra rib or an intarsia in the centre of the structure. Try with shorter filaments and see….

Sample number, name, thumbnail.	Circular interlock 
Needles	
Courses	
Machine	10gg Stoll
Tension	
Yarn	4 ends high bulk nylon and double-covered elastic
Static height (mm)	
Static width (mm)	
X-axis stretch height (mm)	
X-axis stretch width (mm)	
Y-axis stretch height (mm)	
Y-axis stretch width (mm)	
Reason for knitting	As suggested by Will. But with an elastic strand floated in - with hope that it would cause re-entrant structures - it did not….(and would not) Again not auxetic - but it is an interesting and new way of making those fabrics with a space and a 3D element.
Adjustments	
Overall thoughts aesthetic, tactile and auxetic behaviour	Could possibly be adapted into something auxetic
Developments	

Appendix C: Poisson's ratio calculations

The Poisson's ratio calculations for the samples in Stages 1 and 2 are shown below. The information from these tables is shown and discussed in **Chapters 4** and **5**.

			Applied stretch parallel to width of knitted material						
Material	width of knit	length of knit	width stretched to...	length measured ..	change in stretched	change in measured	change in stretched /original stretch	change in measured /original measured	Value (Poisson's Ratio)
STAGE 1							Longitudinal Strain	Transverse Strain	Poisson's Ratio = - transverse strain / longitudinal strain
Sample 1a	80	150	349	230	269	80	3.3625	0.5333333	-0.159
Sample 2	145	190	360	210	215	20	1.4827586	0.1052632	-0.071
Sample 3	90	220	353	247	263	27	2.9222222	0.1227273	-0.042
Sample4	110	226	350	210	240	-16	2.1818182	-0.0707965	0.032
Sample 5	270	111	385	208	115	97	0.4259259	0.8738739	-2.052
STAGE 2									
Sample 6	160	240							
Sample 7	115	310							
Sample 8	165	320							
Sample 9	155	300							
Sample 9a	145	280							
Sample 10	150	256							
Sample 11	105	325							
Sample 12	152	327							

Table C.18 Table showing Poisson's ratio calculations for Stage 1 and 2 when stretched in the X-axis.

			Applied stretch parallel to length of knitted material						
Material	width of knit	length of knit	length stretched to...	width measured ..	change in stretched	change in measured	change in stretched /original stretch	change in measured /original measured	Value (Poisson's Ratio)
STAGE 1							Longitudinal Strain	Transverse Strain	Poisson's Ratio = - transverse strain / longitudinal strain
Sample 1a	80	150	n	n	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Sample 2	145	190	n	n	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Sample 3	90	220	n	n	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
Sample4	110	226	249	160	23	50	0.1017699	0.4545455	-4.466
Sample 5	270	111	n	n	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
STAGE 2									
Sample 6	160	240	365	180	125	20	0.5208333	0.125	-0.240
Sample 7	115	310	490	130	180	15	0.5806452	0.1304348	-0.225
Sample 8	165	320	475	190	155	25	0.484375	0.1515152	-0.313
Sample 9	155	300	480	190	180	35	0.6	0.2258065	-0.376
Sample 9a	145	280	430	170	150	25	0.5357143	0.1724138	-0.322
Sample 10	150	256	388	167	132	17	0.515625	0.1133333	-0.220
Sample 11	105	325	493	118	168	13	0.5169231	0.1238095	-0.240
Sample 12	152	327	460	170	133	18	0.4067278	0.1184211	-0.291

Table C.19 Table showing Poisson's ratio calculations for Stage 1 and 2 when stretched in the Y-axis.

Appendix D: Practical Stage 4 yarn and pattern variants

The development of fabrics in Stage 4 is shown in the tables below. This stage did not require the evaluation matrix of Stages 1-3 as the experimentation was mainly in the yarn, with some slight structural variations in the scale of the patterns within the stitch structures. These fabrics are discussed in **Chapter 7**.

Stage 4 Samples

12/7/12.

Wool
Wool and Lycra
Cotton
Mohair
Cashmere/Angora

Nylon
Polyester
Viscose
Lycra (circled)
Covered Elastic (circled)

Zimmerman Ultralastic 3772X - 0010.

	Yarn and Spec	Sample	Reaction	Patterns	Developments	
	Zimmerman 2 ends. White ultralastic 3772x - 0010.	Transfer Pr14 V2 1 colour 250x200 10gg.	Works — Distorted around edges		Try convert to 14gg.	} smaller than 10cm.
	Zimmerman 2 ends. White.	Pr1 Rectangle 14gg	Does not form many peaks — Some... Yarn too bulky?		Use. 1 end? — does not work well.	" Still
WMC =5	Z " " 1 end.	TP 5 14gg	Quite flat.		Trying with 2 ends	
WMC =5	Purl Diagonal Zimmerman 2 ends.	14gg	Flat. Some relief at edges.		Replace starts.	
WMC = 0	TP4V2 1 col 400N x 500R. 14gg 3ends	14gg	Better aux effect Problems with take down and holes.	Tight ridges when steamed. Little stitch definition	WMC = 0 Tension?	[1]s & [2]s
WMC =5	Purl zig zag stagger. Large sample. 2ends	14gg				

Zimmerman yarn distorts through the rollers.

31/10/12.

Stage 4 Samples

Wool	Nylon
Wool and Lycra	Polyester
Cotton	Viscose
Mohair	Lycra
Cashmere/Angora	Covered Elastic

Yarn and Spec	Sample	Reaction	Patterns	Developments
Grey Linen Blend Fineman. Lycra. lend	TPS 12x12 300N x 250R 14gg Plated.	Stiff and not that 3D. Some aux.	Not very uniform Not as 3D as other yarn.	Try adding central N in between transfers. (eg.) [illegible]
" "	TPS 12x12 300N x 250R 14gg Plated Version 3	Better. more uniform. Bit aux		Scrunched up when steaming try this more
" "				

AMANN GROUP
Col.0416
5000m
No.100tex35
A5411
sabaTEX

– grey.

Stage 4 Samples

Amann
Saba Tex
Col 0416 5000m
No. 100 Tex 35
A4011

Wool	Nylon
Wool and Lycra	Polyester
Cotton	Viscose
Mohair	Lycra
Cashmere/Angora	Covered Elastic

Bulk.

	Yarn and Spec	Sample	Reaction	Patterns	Developments
14gg	Saba tex Grey & Zimmerman lycra.	TP4 V2 Col 400N x 500R 14g. Stripe	Not aux? elastic goes to nothing	Peaks in the nylon. Pleasing pattern Shiny & textured Diff front & Back	nylon & M/F Tighter nylon.
14gg	Saba tex grey & Transfil 110/1 Dtex 90x1 60,000M.	"	works, but needs re-knitting (		
14gg	" " 140 DTEX. AMAN. TRANSFIL	"	Re-knitted on 10/10/12. Works but holes in.	Seems a bit aux, not too much.	Lycra in one/both yarns?
14gg	Aman Saba tex grey (K) & Wykes Bilorex Black (P)	Zig Zag Stagger Plated 14gg	looks good in grey. Really defined lycra shows a bit	quite soft still	
14gg	" (K) " & White Zimmerman (P)	"	Much stiffer after steaming. White is subtle but looks good when stretched.		
14gg	Saba tex grey (K) & White Zimmerman (P)	Purl rectangle small scale 12×12 plated	looks really good, but is uneven in texture.	Aux effect is good	– Trying another sample
14gg	Purl zig zag plated " " Yarns as above.		Same as before not very remarkable Slow recovery attractive but uneven		

14gg. Aman, Saba tex grey (without lycra). T=10.5 | Rectangle small scale 12×12 | – Really good reaction. Comes out a distorted shape ↓ ↑ shrinks a lot! | – Stripes? | – May come out more uniform if knitted larger.

Purl zig zag stagger stripe 14gg. "Light Brown Donisthorpe' 'Grey Saba tex' T=10.5	good 3D and colour contrast. Not so tight as when plated with lycra.	Plate with lycra or leave at this stage.
"TPS 12x12 200N x 250R 14gg ~~stripe~~" Grey Saba Tex & ~~L Brown Donisthorpe~~. T = 11 (Adj on M/C)	Really good. reaction Stitch in pattern. Very auxetic.	Would look good in stripes.
"TPS 12x12 200N x 250R 14gg stripe ~~plated~~" Grey Sabu Tex & L Brown Donisthorpe T=11 (Adj on M/C)	Really good harlequin style. Good aux effect - Nice change of appearance when stretched	Try with plating elastic
"TPS 12x12 200N x 250R 14gg stripe plated" T = 12 White Zimmermann + Grey + LB (1 end each)	Good. Nice looking. Slightly irregular. nice return.	larger
"TP4 12x12 ~~400N x 500R 14gg~~ 300N 10gg" T=11 F=4. Orange bulk (Donisthorpe) Doubled pattern (12x12)	Aux - good. Nice visual effect. Didn't work on 14gg so move to 10g. (Bit loose) Some holes.	Try with lycra? plated.
" " 10gg F=4 Plating = 5. with Donisthorpe & Zimmermann lycra (1 end)	Not as auxetic. More stable and better tension. but looser fabric gives better aux effect.	

(NB) This probably detracts from their suitability for products, but makes better aux results

COLOUR SCHEME?? – Sketchbook

Knit stage 4: aesthetic checklist

Should I do this one as I didn't design it?

Sample 1. (Liu et al.)			
	Plain	x	
	Striped		
	Plated		
	Variations in sample scale	✗	
	Variation in pattern scale		
14g ✓	Variation in gauge		
	Intarsia		
	Variations in colour		

What are these? Does it mean they work?

Some statements/terminology need revising for thesis write up – explain

Pattern works and smaller so have only tried larger. Normal 13, 27

2 (purl zigzagstagger)			
	Plain	x	
12R	Striped		PR
	Plated		Original
	Variations in sample ~~scale~~ size.		350R x 350N PR
Larger = 27N	Variation in pattern scale		Double scale = PR
14g ✓ 10g	Variation in gauge		10g PR
	Intarsia		
	Variations in colour		

The angle remains the same as shown to be best angle of K/P (Liu et al. 20

3 (purl zigzagS)			
	Plain	✗	
4R	Striped		PR
	Plated		Or
	Variations in sample scale	✗	
Smaller – 6N Larger – 24N	Variation in pattern scale		PR
14g ✓	Variation in gauge		PR. 10gg
	Intarsia		
	Variations in colour		
4(purl			

4) Purl.

rectangle)			
	Plain	x	
	Striped	X	PR
	Plated	X	lycra.
	Variations in sample ~~scale~~ size	X	
15 x 30 ✓ 12 x 12 ✓	Variation in pattern scale	✓	Small scale 12 x 12 PR
14g	Variation in gauge		
	Intarsia		
	Variations in colour	X.	
5 (purl diagonal)			Variation in pattern layout X
	Plain	x	
12x12	Striped		PR
	Plated		
	Variations in sample ~~scale~~ size	x	
12x12 ✓ 6x6 ✓ 20x20 ✓	Variation in pattern scale		PR
14g	Variation in gauge		
	Intarsia		
	Variations in colour		
Transfer Purl 4 ~~(V2)~~ (Version wool stripe V2.)			
	Plain	x	
	Striped	x	
	Plated	x	
	Variations in sample scale	x	
Try 12R x 12R	Variation in pattern scale	x	
14g	Variation in gauge	x	
	Intarsia		
	Variations in colour	x	
Transfer purl 5 (version2)			
	Plain	x	
	Striped	x	

This is the better version

Files } TP4V ~~wool~~ Woolstripe V2 is the one with the FB/BB ~~##~~ central stitches aligned to the stripes.

	Plated	
	Variations in sample scale	X
	Variation in pattern scale	X
14g	Variation in gauge	X
	Intarsia	
	Variations in colour	
Bulk test 2b		
	Plain	x ← Horizontal OR vertical via interlock
	Striped	
	Plated	
	Variations in sample scale	
	Variation in pattern scale	x
10g	Variation in gauge	
	Intarsia	
	Variation in layers	x
	Variations in colour	
Spacer circular		
	Plain	x
	Striped	
	Plated	
	Variations in sample scale	
	Variation in pattern scale	
10g	Variation in gauge	
	Intarsia	
	Variation in layers	x
	Variations in colour	
Shear spacer symmetrical		
	Plain	
	Striped	
	Plated	

	Variations in sample scale	
	Variation in pattern scale	
10g	Variation in gauge	
	Intarsia	
	Variation in layers	x
	Variations in colour	

Thermoform/set yarn? – which.

Knitting Stage 4: Checklist

Sample 1. (Liu et al.)		
	Wool	
	Wool and Lycra	x
	Cotton	
	Mohair	
	Cashmere/angora	
	Nylon	
	Polyester	
	Viscose	
	Lycra	
	Covered Elastic	
	Acrylic	x
	Monofilament	
	Metal	
2 (purl zigzagstagger)		
F =	Wool	x ✓
	Wool and Lycra	x ✓
	Cotton	
	Mohair	
	Cashmere/angora	
	Nylon	
	Polyester	
	Viscose	
	Lycra	
	Covered Elastic	
	Acrylic	
	Monofilament	
	Metal	
3 (purl zigzagS)		
F =	Wool	
	Wool and Lycra	x ✓
	Cotton	
	Mohair	
	Cashmere/angora	
	Nylon	
	Polyester	
	Viscose	
	Lycra	
	Covered Elastic	
	Acrylic	
	Monofilament	
	Metal	
4(purl rectangle)		
F =	Wool	✓
	Wool and Lycra	x ✓
Linen ✓	Cotton	
	Mohair	
	Cashmere/angora	
	Nylon	
	Polyester	✓
	Viscose	
	Lycra	✓ 12/7/12
	Covered Elastic	✓ 12/7/12
	Acrylic	
	Monofilament	
	Metal	
5 (purl diagonal)		
F =	Wool	
	Wool and Lycra	x ✓
	Cotton	
	Mohair	
	Cashmere/angora	
	Nylon	
	Polyester	
	Viscose	
	Lycra	
	Covered Elastic	
	Acrylic	
	Monofilament	
	Metal	
Transfer Purl 4 (V2)		
F =	Wool	
	Wool and Lycra	x ✓
	Cotton	
	Mohair	
Linen ✓	Cashmere/angora	
	Nylon	✓
	Polyester	x ✓
	Viscose	
10g / 14gg.	Lycra	✓ 7/12/12
	Covered Elastic	x ✓
	Acrylic	
	Monofilament	x ✓
	Metal	
Transfer purl 5 (version2)		
F =	Wool	✓
	Wool and Lycra	x ✓
Linen ✓	Cotton	
	Mohair	

	Cashmere/angora	
	Nylon	x
	Polyester	x
	Viscose	
	Lycra	✓
	Covered Elastic	✓
	Acrylic	
	Monofilament	
	Metal	
Bulk test 2b		
F =	Wool	
F =	Wool and Lycra	
	Cotton	x ✓
	Mohair	
	Cashmere/angora	
	Nylon	x ✓
	Polyester	x ✓
	Viscose	
	Lycra	
	Covered Elastic	x ✓
	Acrylic	
	Monofilament	x ✓
	Metal	
Spacer circular		
F =	Wool	
F =	Wool and Lycra	
	Cotton	
	Mohair	
	Cashmere/angora	
	Nylon	
	Polyester	x ✓
	Viscose	
	Lycra	
	Covered Elastic	x ✓
	Acrylic	
	Monofilament	x ✓
	Metal	
Shear spacer symmetrical		
F =	Wool	
F =	Wool and Lycra	
	Cotton	
	Mohair	
	Cashmere/angora	
	Nylon	x ✓
	Polyester	
	Viscose	
	Lycra	
	Covered Elastic	x ✓
	Acrylic	

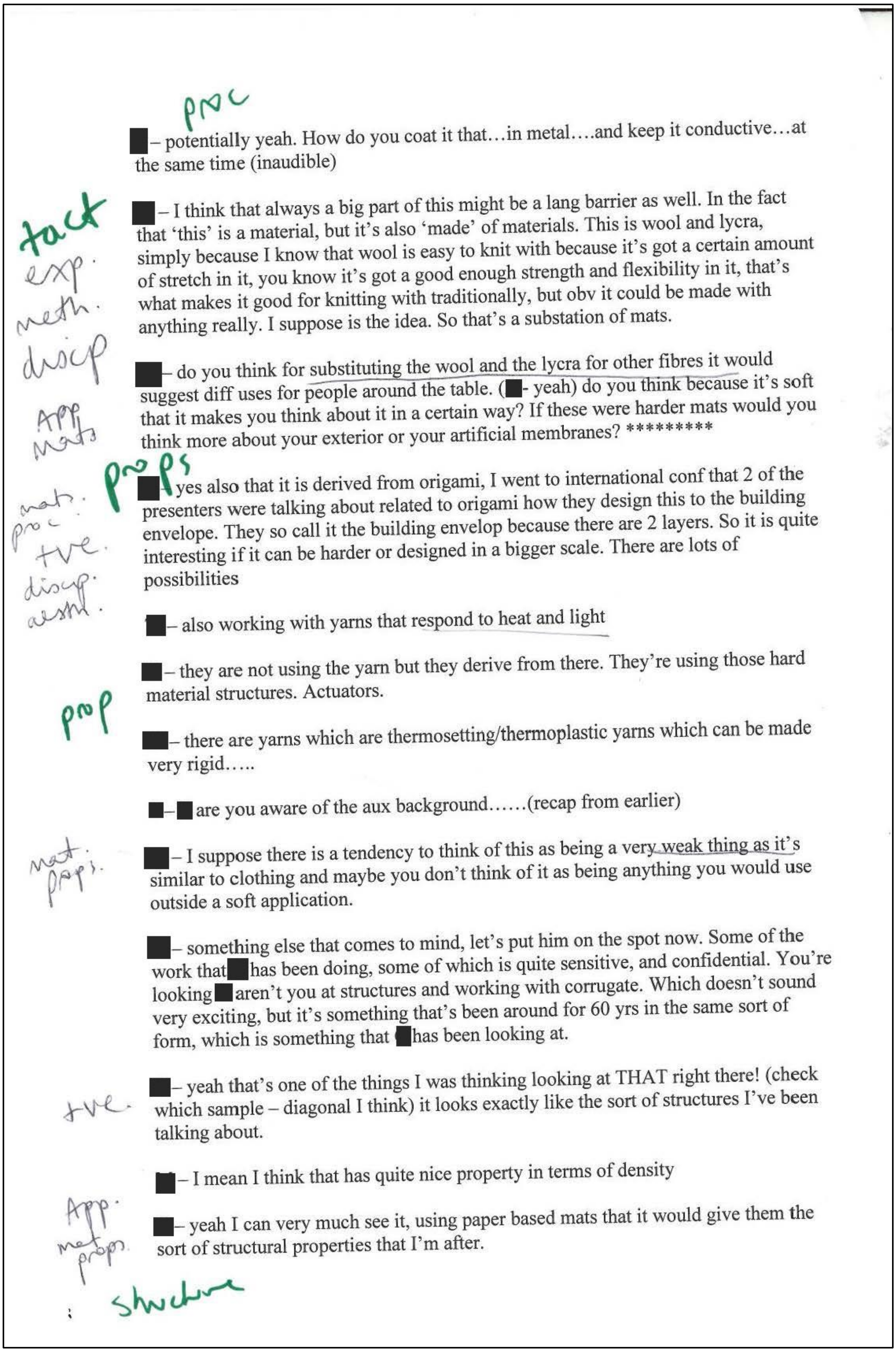
	Monofilament	x ✓
	Metal	

Diff yarns / textures on FB & BB. But M/F in centre. (or not?)

Appendix E: Focus group coding (examples)

This appendix shows extracts from the transcripts from the focus groups (FG) from **Chapters 4-7**. The annotation on the extracts shows how themes were attributed to statements. These were then added up to show which themes were common and which themes recurred through the four focus groups.

Chapter 4: Focus group 1



[redacted] – potentially yeah. How do you coat it that…in metal….and keep it conductive…at the same time (inaudible)

[redacted] – I think that always a big part of this might be a lang barrier as well. In the fact that 'this' is a material, but it's also 'made' of materials. This is wool and lycra, simply because I know that wool is easy to knit with because it's got a certain amount of stretch in it, you know it's got a good enough strength and flexibility in it, that's what makes it good for knitting with traditionally, but obv it could be made with anything really. I suppose is the idea. So that's a substation of mats.

[redacted] – do you think for substituting the wool and the lycra for other fibres it would suggest diff uses for people around the table. ([redacted] - yeah) do you think because it's soft that it makes you think about it in a certain way? If these were harder mats would you think more about your exterior or your artificial membranes? *********

[redacted] – yes also that it is derived from origami, I went to international conf that 2 of the presenters were talking about related to origami how they design this to the building envelope. They so call it the building envelop because there are 2 layers. So it is quite interesting if it can be harder or designed in a bigger scale. There are lots of possibilities

[redacted] – also working with yarns that respond to heat and light

[redacted] – they are not using the yarn but they derive from there. They're using those hard material structures. Actuators.

[redacted] – there are yarns which are thermosetting/thermoplastic yarns which can be made very rigid…..

[redacted] – [redacted] are you aware of the aux background……(recap from earlier)

[redacted] – I suppose there is a tendency to think of this as being a very weak thing as it's similar to clothing and maybe you don't think of it as being anything you would use outside a soft application.

[redacted] – something else that comes to mind, let's put him on the spot now. Some of the work that [redacted] has been doing, some of which is quite sensitive, and confidential. You're looking [redacted] aren't you at structures and working with corrugate. Which doesn't sound very exciting, but it's something that's been around for 60 yrs in the same sort of form, which is something that [redacted] has been looking at.

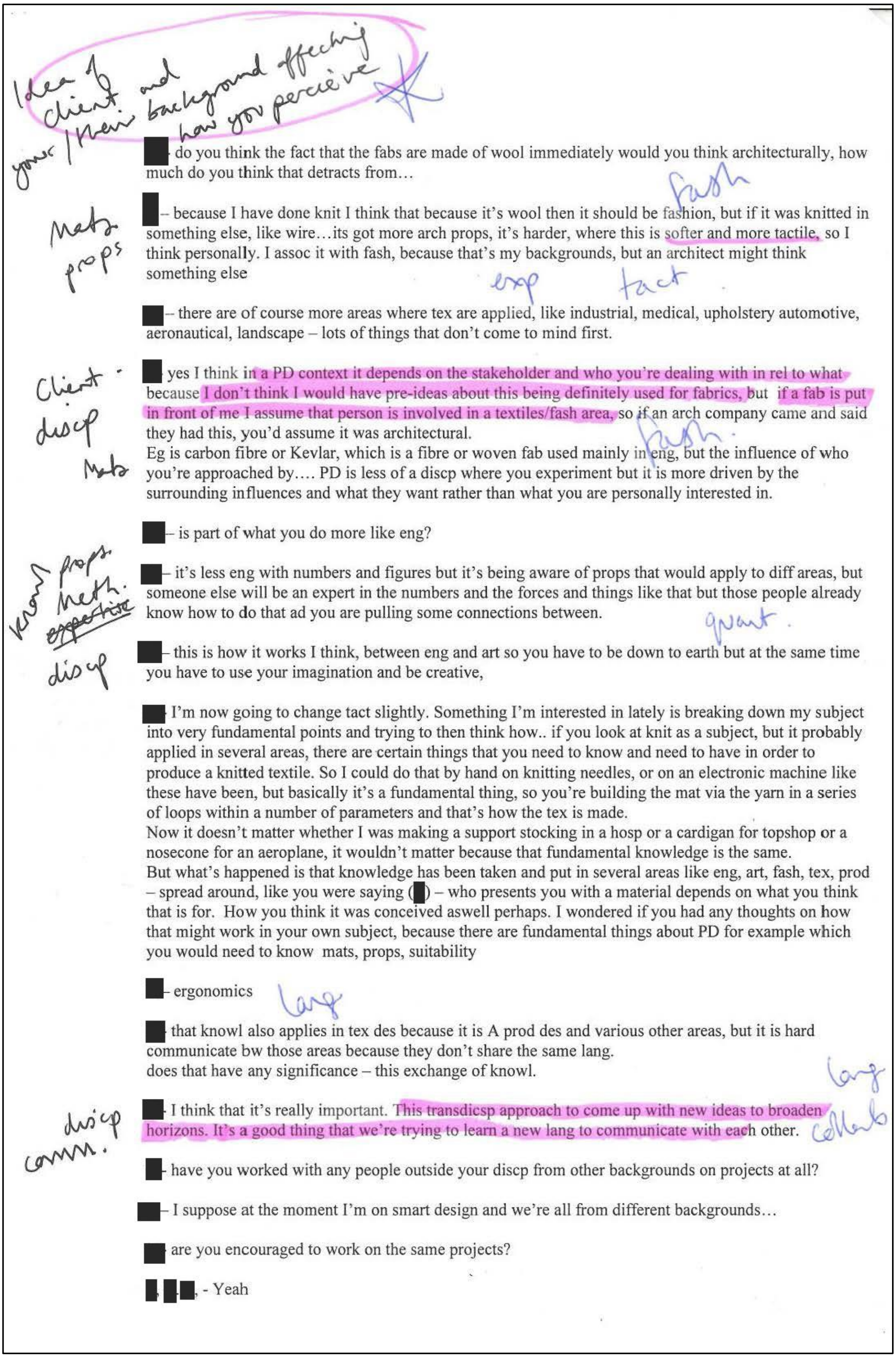
[redacted] – yeah that's one of the things I was thinking looking at THAT right there! (check which sample – diagonal I think) it looks exactly like the sort of structures I've been talking about.

[redacted] – I mean I think that has quite nice property in terms of density

[redacted] – yeah I can very much see it, using paper based mats that it would give them the sort of structural properties that I'm after.

Figure E.110 Example of annotated transcription for coding, from FG1.

Chapter 5: Focus group 2



[redacted] do you think the fact that the fabs are made of wool immediately would you think architecturally, how much do you think that detracts from…

[redacted] – because I have done knit I think that because it's wool then it should be fashion, but if it was knitted in something else, like wire…its got more arch props, it's harder, where this is softer and more tactile, so I think personally. I assoc it with fash, because that's my backgrounds, but an architect might think something else

[redacted] – there are of course more areas where tex are applied, like industrial, medical, upholstery automotive, aeronautical, landscape – lots of things that don't come to mind first.

[redacted] yes I think in a PD context it depends on the stakeholder and who you're dealing with in rel to what because I don't think I would have pre-ideas about this being definitely used for fabrics, but if a fab is put in front of me I assume that person is involved in a textiles/fash area, so if an arch company came and said they had this, you'd assume it was architectural.
Eg is carbon fibre or Kevlar, which is a fibre or woven fab used mainly in eng, but the influence of who you're approached by…. PD is less of a discp where you experiment but it is more driven by the surrounding influences and what they want rather than what you are personally interested in.

[redacted] – is part of what you do more like eng?

[redacted] – it's less eng with numbers and figures but it's being aware of props that would apply to diff areas, but someone else will be an expert in the numbers and the forces and things like that but those people already know how to do that ad you are pulling some connections between.

[redacted] – this is how it works I think, between eng and art so you have to be down to earth but at the same time you have to use your imagination and be creative,

[redacted] I'm now going to change tact slightly. Something I'm interested in lately is breaking down my subject into very fundamental points and trying to then think how.. if you look at knit as a subject, but it probably applied in several areas, there are certain things that you need to know and need to have in order to produce a knitted textile. So I could do that by hand on knitting needles, or on an electronic machine like these have been, but basically it's a fundamental thing, so you're building the mat via the yarn in a series of loops within a number of parameters and that's how the tex is made.
Now it doesn't matter whether I was making a support stocking in a hosp or a cardigan for topshop or a nosecone for an aeroplane, it wouldn't matter because that fundamental knowledge is the same.
But what's happened is that knowledge has been taken and put in several areas like eng, art, fash, tex, prod – spread around, like you were saying ([redacted]) – who presents you with a material depends on what you think that is for. How you think it was conceived aswell perhaps. I wondered if you had any thoughts on how that might work in your own subject, because there are fundamental things about PD for example which you would need to know mats, props, suitability

[redacted] – ergonomics

[redacted] that knowl also applies in tex des because it is A prod des and various other areas, but it is hard communicate bw those areas because they don't share the same lang.
does that have any significance – this exchange of knowl.

[redacted] I think that it's really important. This transdicsp approach to come up with new ideas to broaden horizons. It's a good thing that we're trying to learn a new lang to communicate with each other.

[redacted] – have you worked with any people outside your discp from other backgrounds on projects at all?

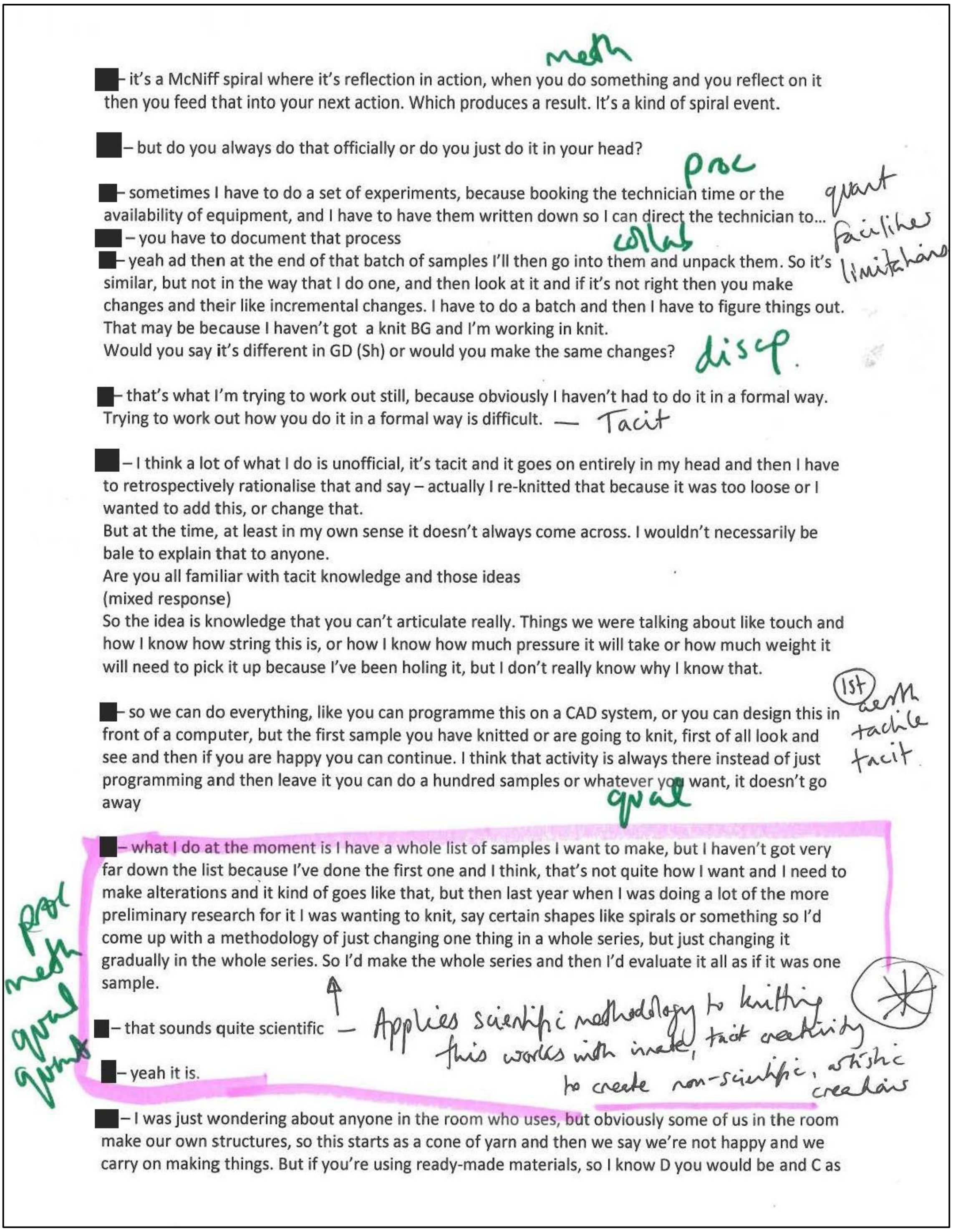
[redacted] – I suppose at the moment I'm on smart design and we're all from different backgrounds…

[redacted] are you encouraged to work on the same projects?

[redacted] - Yeah

Figure E.111 Example of annotated transcription for coding, from FG2.

Chapter 6: Focus group 3



[redacted]– it's a McNiff spiral where it's reflection in action, when you do something and you reflect on it then you feed that into your next action. Which produces a result. It's a kind of spiral event.

[redacted]– but do you always do that officially or do you just do it in your head?

[redacted]– sometimes I have to do a set of experiments, because booking the technician time or the availability of equipment, and I have to have them written down so I can direct the technician to...
[redacted]– you have to document that process
[redacted]– yeah ad then at the end of that batch of samples I'll then go into them and unpack them. So it's similar, but not in the way that I do one, and then look at it and if it's not right then you make changes and their like incremental changes. I have to do a batch and then I have to figure things out. That may be because I haven't got a knit BG and I'm working in knit.
Would you say it's different in GD (Sh) or would you make the same changes?

[redacted]– that's what I'm trying to work out still, because obviously I haven't had to do it in a formal way. Trying to work out how you do it in a formal way is difficult.

[redacted]– I think a lot of what I do is unofficial, it's tacit and it goes on entirely in my head and then I have to retrospectively rationalise that and say – actually I re-knitted that because it was too loose or I wanted to add this, or change that.
But at the time, at least in my own sense it doesn't always come across. I wouldn't necessarily be bale to explain that to anyone.
Are you all familiar with tacit knowledge and those ideas
(mixed response)
So the idea is knowledge that you can't articulate really. Things we were talking about like touch and how I know how string this is, or how I know how much pressure it will take or how much weight it will need to pick it up because I've been holing it, but I don't really know why I know that.

[redacted]– so we can do everything, like you can programme this on a CAD system, or you can design this in front of a computer, but the first sample you have knitted or are going to knit, first of all look and see and then if you are happy you can continue. I think that activity is always there instead of just programming and then leave it you can do a hundred samples or whatever you want, it doesn't go away

[redacted]– what I do at the moment is I have a whole list of samples I want to make, but I haven't got very far down the list because I've done the first one and I think, that's not quite how I want and I need to make alterations and it kind of goes like that, but then last year when I was doing a lot of the more preliminary research for it I was wanting to knit, say certain shapes like spirals or something so I'd come up with a methodology of just changing one thing in a whole series, but just changing it gradually in the whole series. So I'd make the whole series and then I'd evaluate it all as if it was one sample.

[redacted]– that sounds quite scientific

[redacted]– yeah it is.

[redacted]– I was just wondering about anyone in the room who uses, but obviously some of us in the room make our own structures, so this starts as a cone of yarn and then we say we're not happy and we carry on making things. But if you're using ready-made materials, so I know D you would be and C as

Figure E.112 Example of annotated transcription for coding, from FG3.

Name(s): [redacted]

Sample number: 9

aesth +ve – Experiential know

Attractive sample with a definite 'right side'
+ve prop
excellent elastic properties – particularly widthways.
looks very different when fully stretched – reveals the structure.
structure
Has a good 'handle', feels spongey – the structure
structure
gives it substance – feels quite thick but it still very light weight.
prop
tactile

Sample number: 20 (pair with [redacted])

mat

first impressions – reminds [redacted] of a section of intestines, me off shin pads.

looks at form – how could you re-create the shape?

–ve aesth
tactile

me – appraise the aesthetic = ugly! But handle next and it feels very interesting – very spongey, then the form
App
and use – [redacted] considers what fashion use? me – too ugly for fashion – potential for structured corsets type thing – but more likely to be for engineering or product use?
funct eng
The form is really interesting.
+ve

Figure E.113 Example of annotated hand-out for coding, from FG3.

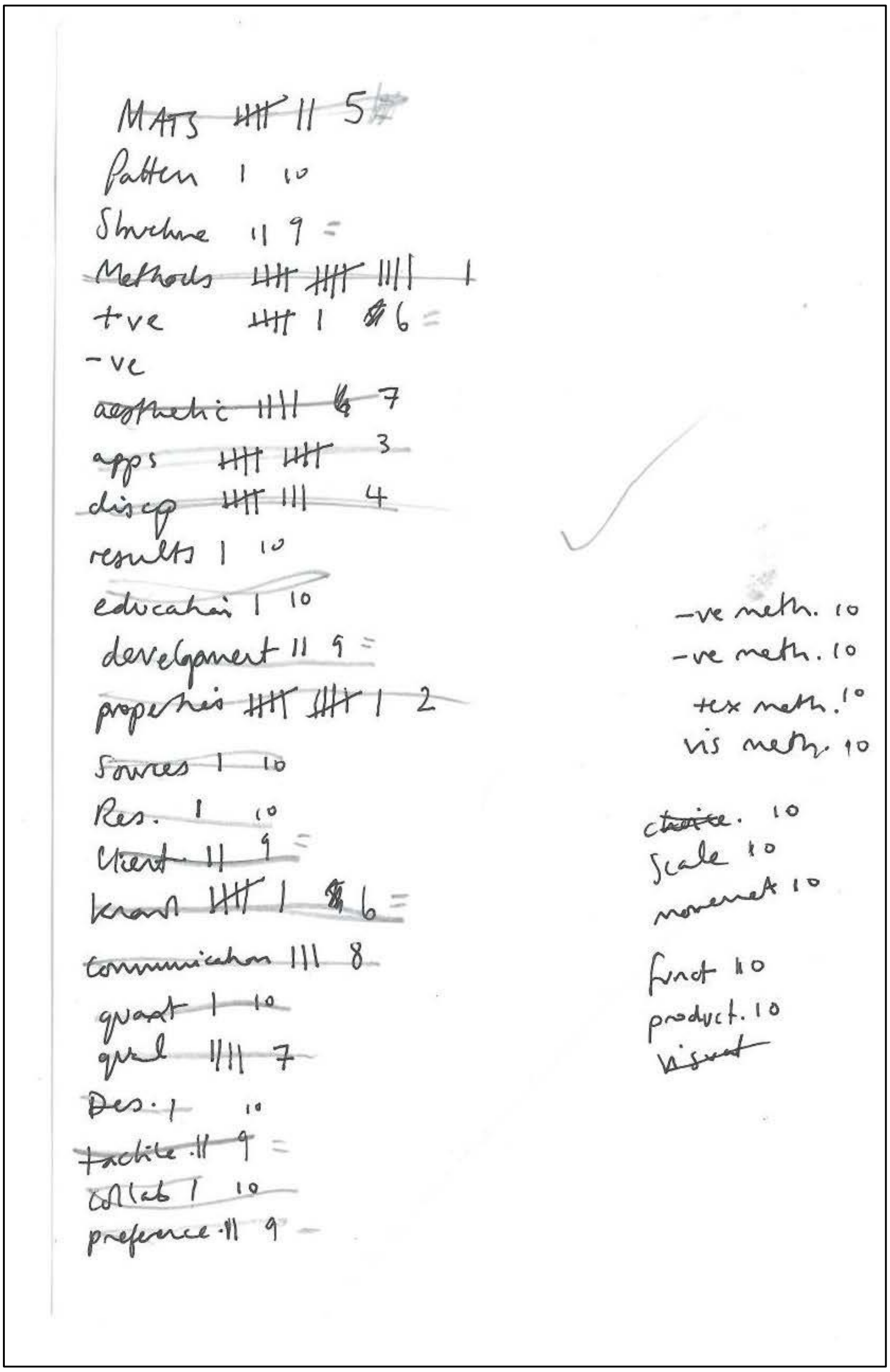
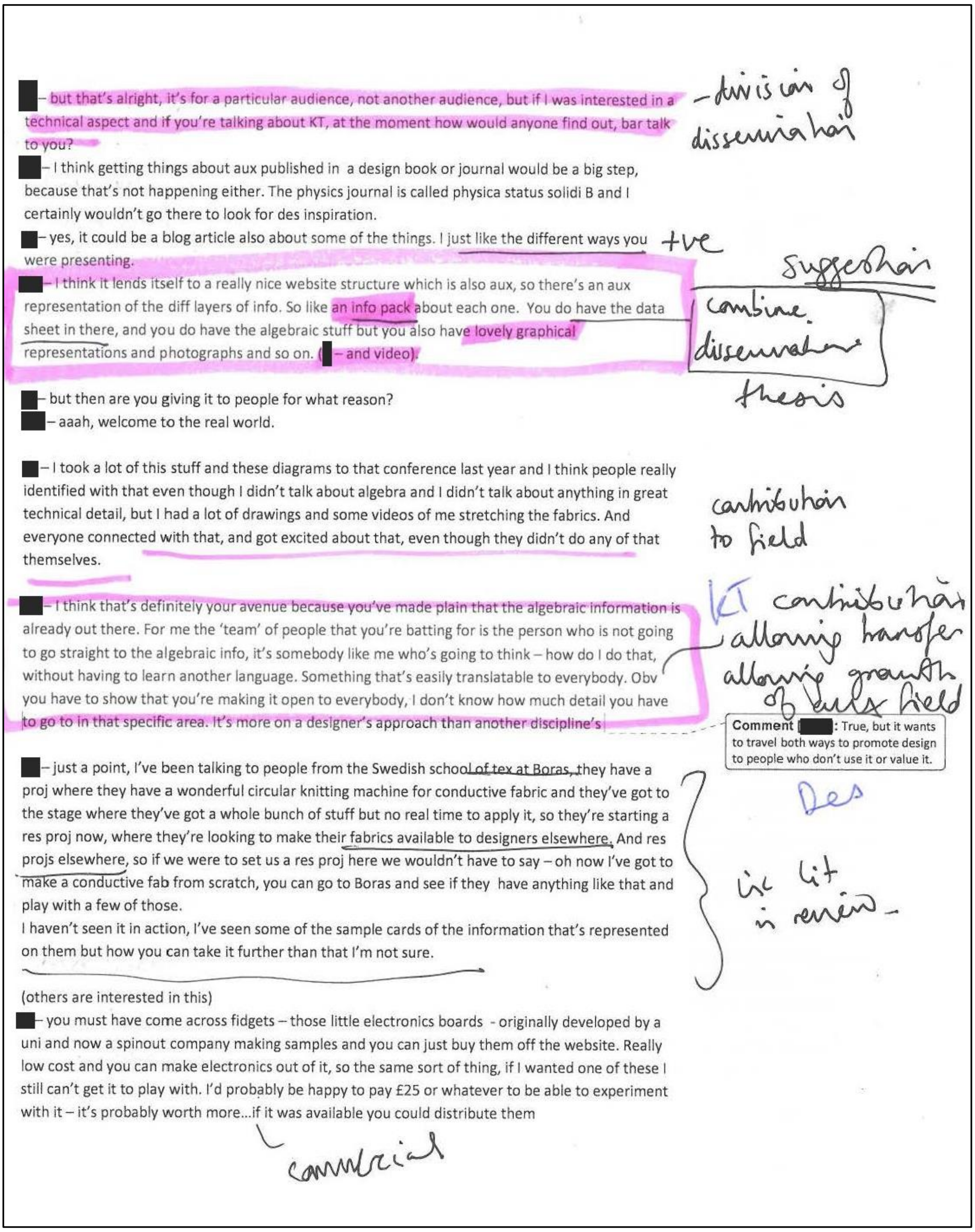


Figure E.114 Example of collation of coding results from FG3.

Chapter 7: Focus group 4



[redacted] – but that's alright, it's for a particular audience, not another audience, but if I was interested in a technical aspect and if you're talking about KT, at the moment how would anyone find out, bar talk to you?

[redacted] – I think getting things about aux published in a design book or journal would be a big step, because that's not happening either. The physics journal is called physica status solidi B and I certainly wouldn't go there to look for des inspiration.

[redacted] – yes, it could be a blog article also about some of the things. I just like the different ways you were presenting.

[redacted] – I think it lends itself to a really nice website structure which is also aux, so there's an aux representation of the diff layers of info. So like an info pack about each one. You do have the data sheet in there, and you do have the algebraic stuff but you also have lovely graphical representations and photographs and so on. ([redacted] – and video).

[redacted] – but then are you giving it to people for what reason?

[redacted] – aaah, welcome to the real world.

[redacted] – I took a lot of this stuff and these diagrams to that conference last year and I think people really identified with that even though I didn't talk about algebra and I didn't talk about anything in great technical detail, but I had a lot of drawings and some videos of me stretching the fabrics. And everyone connected with that, and got excited about that, even though they didn't do any of that themselves.

[redacted] – I think that's definitely your avenue because you've made plain that the algebraic information is already out there. For me the 'team' of people that you're batting for is the person who is not going to go straight to the algebraic info, it's somebody like me who's going to think – how do I do that, without having to learn another language. Something that's easily translatable to everybody. Obv you have to show that you're making it open to everybody, I don't know how much detail you have to go to in that specific area. It's more on a designer's approach than another discipline's

Comment [redacted]: True, but it wants to travel both ways to promote design to people who don't use it or value it.

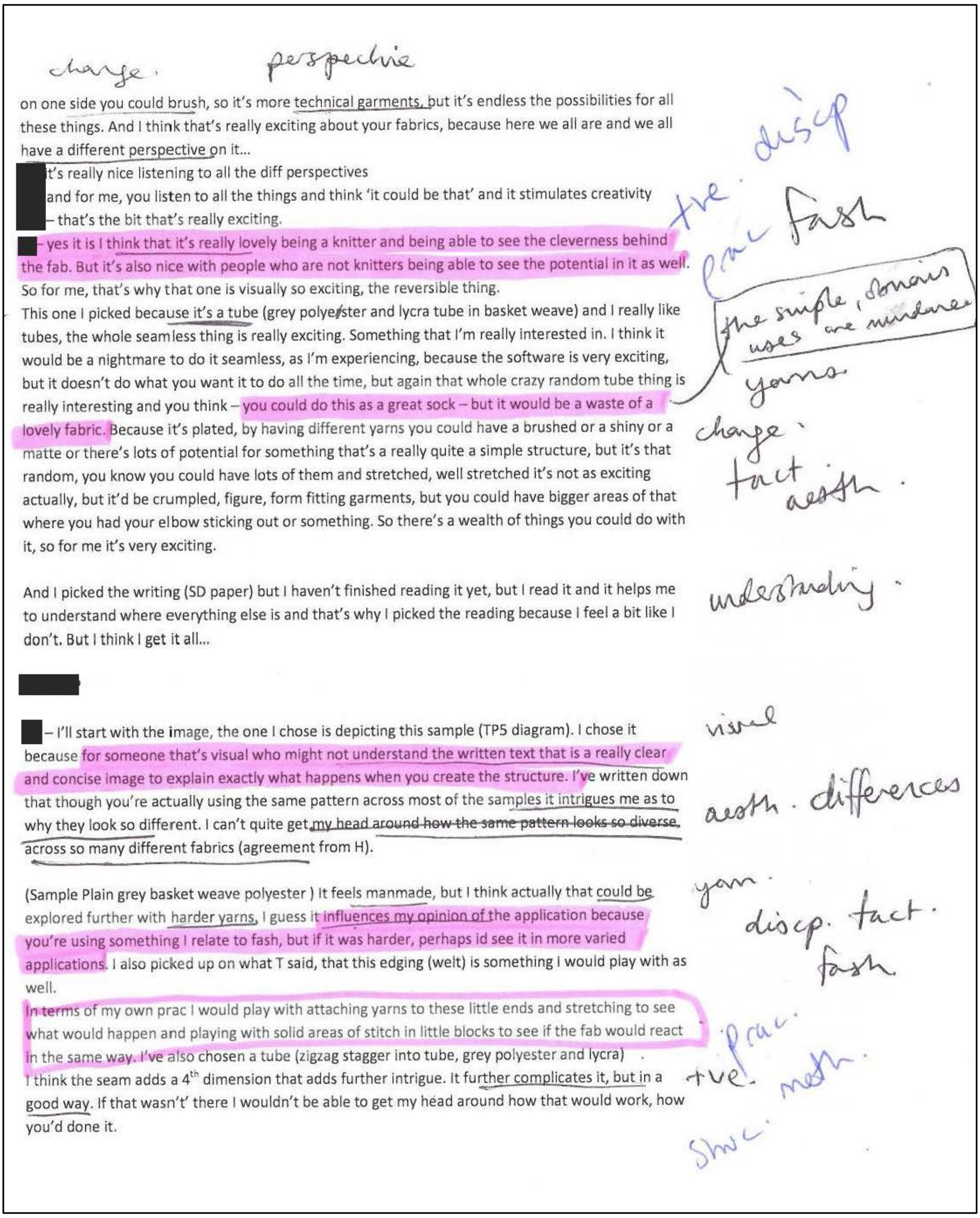
[redacted] – just a point, I've been talking to people from the Swedish school of tex at Boras, they have a proj where they have a wonderful circular knitting machine for conductive fabric and they've got to the stage where they've got a whole bunch of stuff but no real time to apply it, so they're starting a res proj now, where they're looking to make their fabrics available to designers elsewhere. And res projs elsewhere, so if we were to set us a res proj here we wouldn't have to say – oh now I've got to make a conductive fab from scratch, you can go to Boras and see if they have anything like that and play with a few of those.

I haven't seen it in action, I've seen some of the sample cards of the information that's represented on them but how you can take it further than that I'm not sure.

(others are interested in this)

[redacted] – you must have come across fidgets – those little electronics boards – originally developed by a uni and now a spinout company making samples and you can just buy them off the website. Really low cost and you can make electronics out of it, so the same sort of thing, if I wanted one of these I still can't get it to play with. I'd probably be happy to pay £25 or whatever to be able to experiment with it – it's probably worth more...if it was available you could distribute them

Figure E.115 Example of annotated transcription for coding, from FG4.



on one side you could brush, so it's more technical garments, but it's endless the possibilities for all these things. And I think that's really exciting about your fabrics, because here we all are and we all have a different perspective on it...

[redacted] it's really nice listening to all the diff perspectives and for me, you listen to all the things and think 'it could be that' and it stimulates creativity – that's the bit that's really exciting.

[redacted] – yes it is I think that it's really lovely being a knitter and being able to see the cleverness behind the fab. But it's also nice with people who are not knitters being able to see the potential in it as well. So for me, that's why that one is visually so exciting, the reversible thing.

This one I picked because it's a tube (grey polyester and lycra tube in basket weave) and I really like tubes, the whole seamless thing is really exciting. Something that I'm really interested in. I think it would be a nightmare to do it seamless, as I'm experiencing, because the software is very exciting, but it doesn't do what you want it to do all the time, but again that whole crazy random tube thing is really interesting and you think – you could do this as a great sock – but it would be a waste of a lovely fabric. Because it's plated, by having different yarns you could have a brushed or a shiny or a matte or there's lots of potential for something that's a really quite a simple structure, but it's that random, you know you could have lots of them and stretched, well stretched it's not as exciting actually, but it'd be crumpled, figure, form fitting garments, but you could have bigger areas of that where you had your elbow sticking out or something. So there's a wealth of things you could do with it, so for me it's very exciting.

And I picked the writing (SD paper) but I haven't finished reading it yet, but I read it and it helps me to understand where everything else is and that's why I picked the reading because I feel a bit like I don't. But I think I get it all...

[redacted]

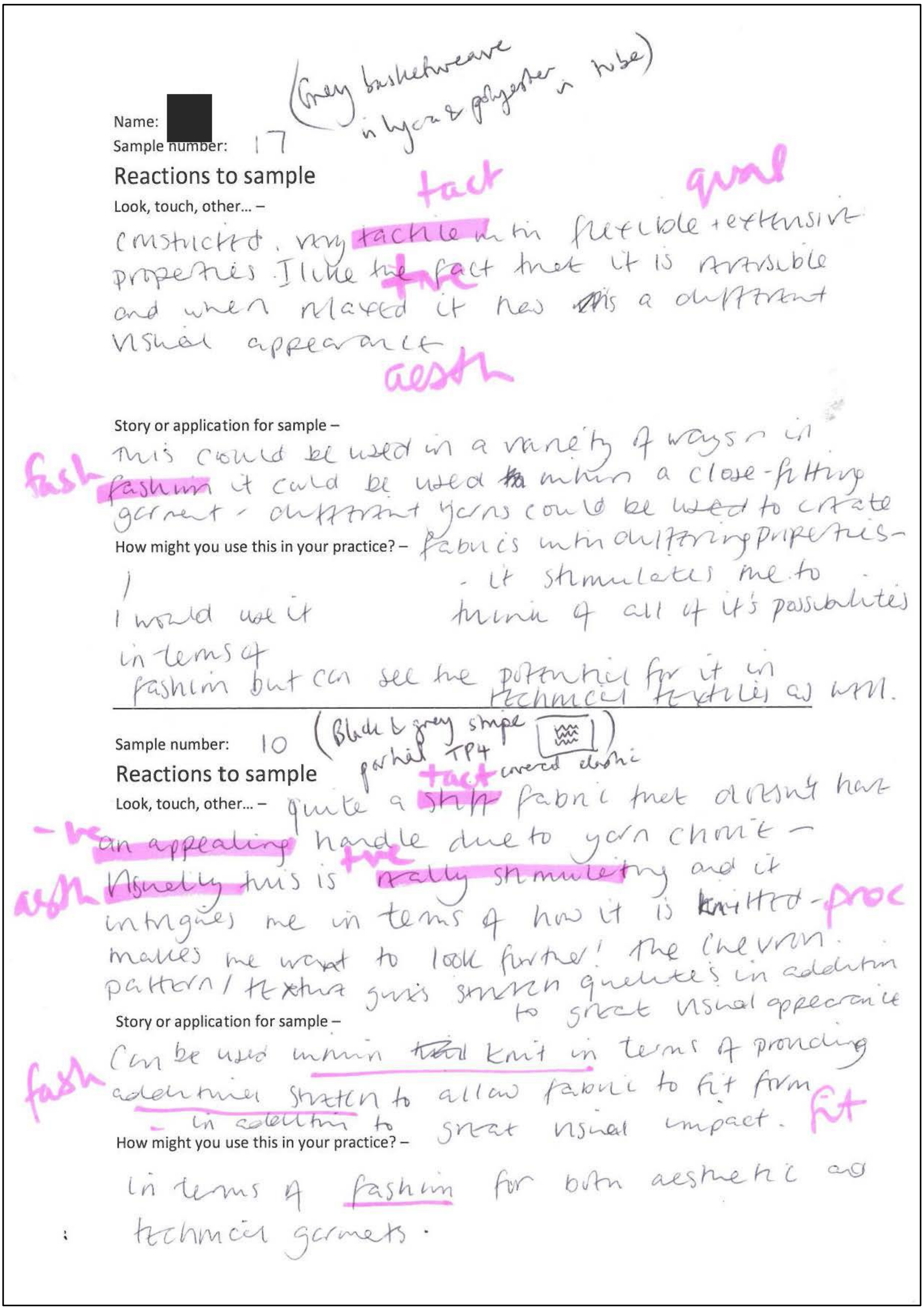
[redacted] – I'll start with the image, the one I chose is depicting this sample (TP5 diagram). I chose it because for someone that's visual who might not understand the written text that is a really clear and concise image to explain exactly what happens when you create the structure. I've written down that though you're actually using the same pattern across most of the samples it intrigues me as to why they look so different. I can't quite get my head around how the same pattern looks so diverse across so many different fabrics (agreement from H).

(Sample Plain grey basket weave polyester) It feels manmade, but I think actually that could be explored further with harder yarns, I guess it influences my opinion of the application because you're using something I relate to fash, but if it was harder, perhaps id see it in more varied applications. I also picked up on what T said, that this edging (welt) is something I would play with as well.

In terms of my own prac I would play with attaching yarns to these little ends and stretching to see what would happen and playing with solid areas of stitch in little blocks to see if the fab would react in the same way. I've also chosen a tube (zigzag stagger into tube, grey polyester and lycra)

I think the seam adds a 4th dimension that adds further intrigue. It further complicates it, but in a good way. If that wasn't't' there I wouldn't be able to get my head around how that would work, how you'd done it.

Figure E.116 Example of annotated transcription for coding, from FG4.


Name: [redacted]
(Grey basketweave in lycra & polyester in tube)
Sample number: 17

Reactions to sample

Look, touch, other… – constructed, very tactile with flexible + extensive properties. I like the fact that it is reversible and when relaxed it has is a different visual appearance

tact qual +ve aesth

Story or application for sample – This could be used in a variety of ways in fashion it could be used within a close-fitting garment - different yarns could be used to create

fash

How might you use this in your practice? – fabric is with differing properties - it stimulates me to think of all of it's possibilities

I would use it in terms of fashion but can see the potential for it in technical textiles as well.

Sample number: 10 (Black & grey stripe partial TP4 covered elastic)

Reactions to sample

Look, touch, other… – quite a stiff fabric that doesn't have an appealing handle due to yarn choice - visually this is really stimulating and it intrigues me in terms of how it is knitted - the chevron makes me want to look further! The chevron pattern / texture gives stretch qualities in addition to great visual appearance

tact -ve +ve aesth proc

Story or application for sample – Can be used within knit in terms of providing additional stretch to allow fabric to fit form - in addition to great visual impact.

fash fit

How might you use this in your practice? – in terms of fashion for both aesthetic and technical garments.

Figure E.117 Example of annotated hand-out for coding, from FG4.

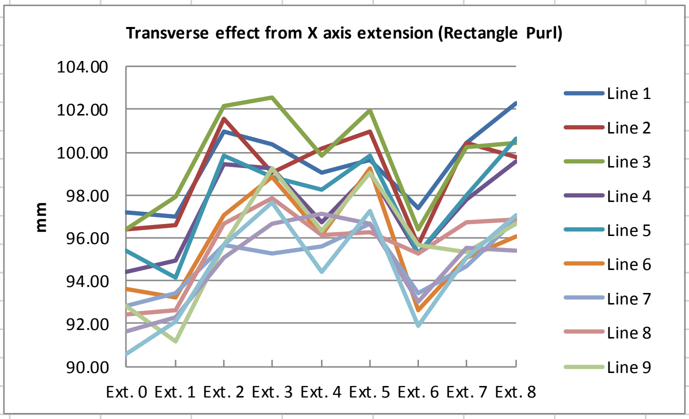
Appendix F: Testing results of selected samples Stages 1-4

This appendix shows the information from the frame testing of a selected range of samples from across Stages 1-4. The numerical results are generated through image analysis of photographs taken of the test frame during each extension of the fabric. For a detailed description of the testing method, see **Chapter 3**.

Pages F-2 to F-6 show testing results for these samples with relevant graphed information, generated from the data in the spreadsheets. Pages F-6 to F-16 show an example of repeating the test results for Sample 20 10 times by stretching both in the X and Y-axes. The graphs are presented as an averaged full set, as individual test results and averages for each line measured.

Sample 4 (Rectangle Purl) Stage 1

	Vertical distances X axis (Rectangle Purl)										
	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8	Line 9	Line 10	Line 11
Ext. 0	97.20	96.40	96.40	94.40	95.40	93.60	92.80	92.40	92.80	91.60	90.60
Ext. 1	96.98	96.60	97.92	94.91	94.15	93.21	93.40	92.64	91.13	92.26	92.08
Ext. 2	100.98	101.57	102.16	99.41	99.80	97.06	95.69	96.67	95.69	95.10	95.69
Ext. 3	100.39	99.02	102.55	99.22	98.82	98.82	95.29	97.84	99.22	96.67	97.65
Ext. 4	99.04	100.19	99.81	96.73	98.27	96.15	95.58	96.15	96.35	97.12	94.42
Ext. 5	99.61	100.98	101.96	99.02	99.80	99.22	96.67	96.27	99.02	96.67	97.25
Ext. 6	97.36	95.66	96.42	95.28	95.28	92.64	93.40	95.28	95.66	93.02	91.89
Ext. 7	100.41	100.41	100.20	97.76	97.96	95.10	94.69	96.73	95.31	95.51	95.10
Ext. 8	102.29	99.79	100.42	99.58	100.63	96.04	96.88	96.88	96.67	95.42	97.08
Ext. 9											
Ext. 10											
Ext. 11											



	Vertical distances Y axis (Rectangle Purl)										
	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8	Line 9	Line 10	Line 11
Ext. 0	88.78	87.96	88.98	92.86	90.61	92.45	91.22	92.65	90.61	86.94	88.16
Ext. 1	83.33	81.57	85.88	87.45	88.04	88.04	88.43	86.67	84.51	82.55	84.31
Ext. 2	86.70	85.89	89.75	91.17	92.99	92.79	91.17	90.76	88.12	85.48	85.48
Ext. 3	86.38	86.18	89.02	90.24	92.28	91.06	90.45	92.68	90.04	86.18	87.20
Ext. 4	84.73	85.54	89.41	89.21	92.26	90.22	89.61	92.46	90.43	85.74	87.98
Ext. 5	83.67	87.14	88.16	90.20	90.82	90.82	90.41	91.63	87.96	87.76	88.57
Ext. 6											
Ext. 7											
Ext. 8											
Ext. 9											
Ext. 10											
Ext. 11											

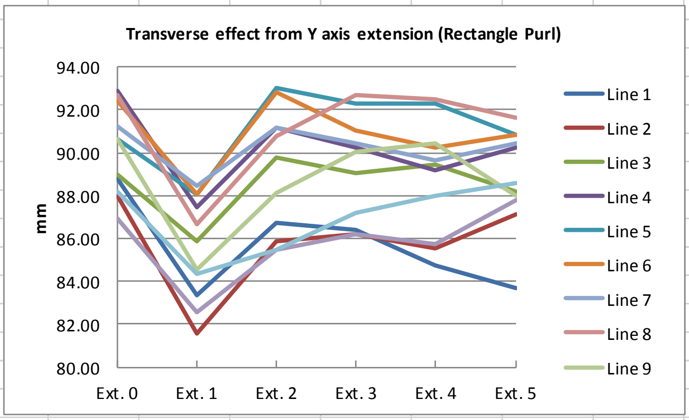
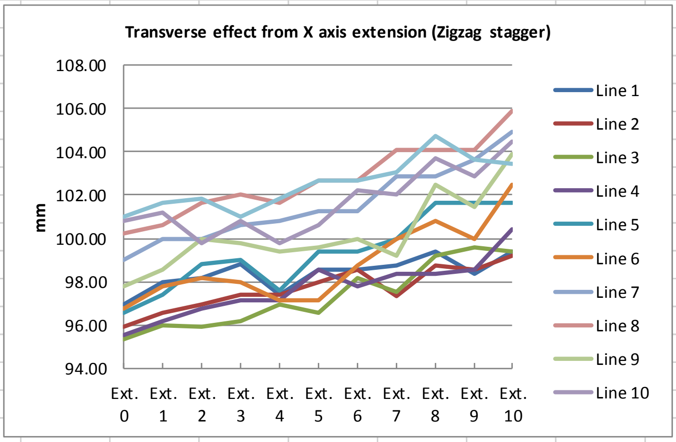


Figure F.118 Testing results and graphs for Sample 4, Stage 1.

Sample 2 (Zigzag stagger) Stage 1

	Vertical distances X axis Zigzag stagger										
	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8	Line 9	Line 10	Line 11
Ext. 0	96.96	95.94	95.33	95.54	96.55	96.75	98.99	100.20	97.77	100.81	101.01
Ext. 1	97.98	96.56	95.95	96.15	97.37	97.77	100.00	100.61	98.58	101.21	101.62
Ext. 2	98.17	96.96	95.94	96.75	98.78	98.17	100.00	101.62	100.00	99.80	101.83
Ext. 3	98.79	97.37	96.15	97.17	98.99	97.98	100.61	102.02	99.80	100.81	101.01
Ext. 4	97.37	97.37	96.96	97.17	97.57	97.17	100.81	101.62	99.39	99.80	101.82
Ext. 5	98.57	97.96	96.54	98.57	99.39	97.15	101.22	102.65	99.59	100.61	102.65
Ext. 6	98.57	98.57	98.17	97.76	99.39	98.78	101.22	102.65	100.00	102.24	102.65
Ext. 7	98.78	97.35	97.56	98.37	100.00	100.00	102.85	104.07	99.19	102.04	103.05
Ext. 8	99.39	98.77	99.18	98.36	101.64	100.82	102.86	104.09	102.45	103.68	104.70
Ext. 9	98.37	98.58	99.59	98.58	101.63	100.00	103.66	104.07	101.42	102.85	103.66
Ext. 10	99.39	99.19	99.39	100.41	101.63	102.44	104.89	105.91	103.87	104.48	103.46
Ext. 11											



	Vertical distances Y axis Zigzag stagger										
	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8	Line 9	Line 10	Line 11
Ext. 0	91.68	96.75	96.35	95.54	95.13	95.94	92.90	92.90	92.49	94.12	91.89
Ext. 1	91.50	95.55	95.55	97.98	97.17	97.77	95.14	95.34	94.94	94.33	91.50
Ext. 2	90.30	95.15	96.97	97.98	96.97	98.99	97.37	95.76	94.55	93.74	91.31
Ext. 3	92.29	96.35	96.75	96.15	96.55	98.58	96.55	95.33	95.33	93.71	91.48
Ext. 4	91.28	96.35	97.16	95.54	96.75	99.39	98.38	96.35	95.33	95.33	91.48
Ext. 5	96.56	94.33	95.34	95.95	95.95	96.76	97.17	95.55	93.93	94.13	92.91
Ext. 6	94.11	94.31	94.92	95.33	96.75	97.76	95.12	95.53	93.90	93.50	92.07
Ext. 7	95.73	93.50	93.50	95.12	95.53	97.56	97.15	95.73	94.72	94.51	91.87
Ext. 8											
Ext. 9											
Ext. 10											
Ext. 11											

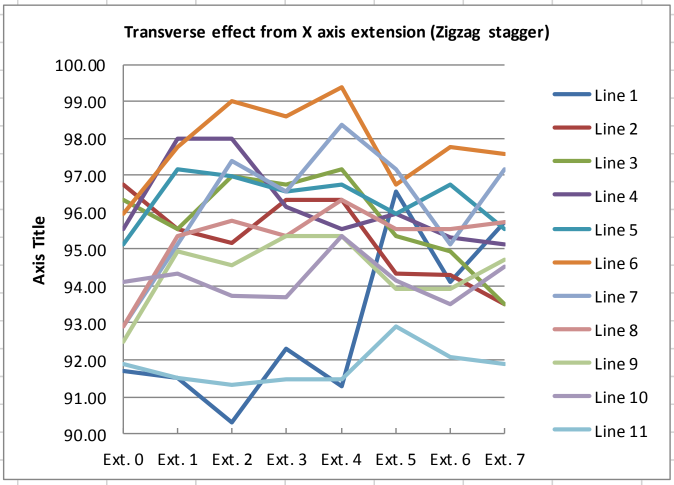
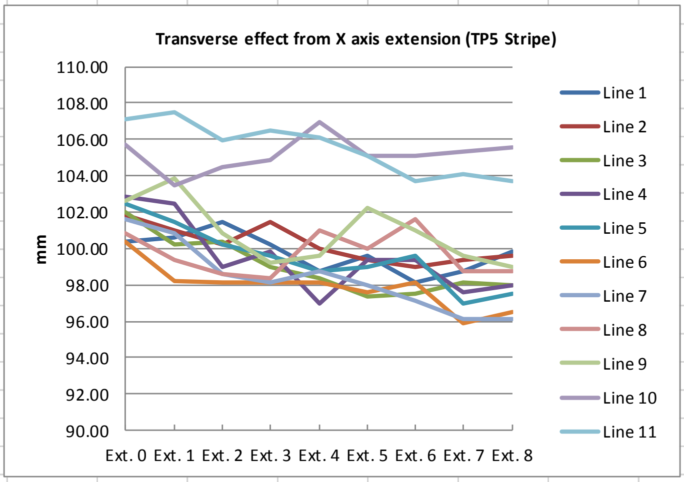


Figure F.119 Testing results and graphs for Sample 2, Stage 1.

Sample 12 (TP5 Stripe) Stage 2

	Vertical distances X axis TP5 (Stripe)									
	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8	Line 9	Line 10	Line 11
Ext. 0	100.41	101.83	102.04	102.85	102.44	100.41	101.63	100.81	102.65	105.70	107.13
Ext. 1	100.61	101.02	100.20	102.44	101.42	98.17	100.81	99.39	103.86	103.46	107.52
Ext. 2	101.43	100.20	100.41	98.98	100.20	98.16	98.57	98.57	100.82	104.49	105.92
Ext. 3	100.20	101.43	98.98	99.80	99.59	98.17	98.17	98.37	99.19	104.89	106.52
Ext. 4	98.78	100.00	98.37	96.94	98.78	98.16	98.78	101.02	99.59	106.94	106.12
Ext. 5	99.59	99.39	97.35	99.39	98.98	97.56	97.96	100.00	102.24	105.09	105.09
Ext. 6	98.16	98.98	97.55	99.39	99.59	98.16	97.14	101.64	101.02	105.11	103.68
Ext. 7	98.78	99.39	98.16	97.55	96.94	95.92	96.12	98.78	99.59	105.31	104.08
Ext. 8	99.80	99.59	97.96	97.96	97.55	96.52	96.11	98.77	98.98	105.52	103.68
Ext. 9											
Ext. 10											
Ext. 11											



	Vertical distances Y axis TP5 (Stripe)									
	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8	Line 9	Line 10	Line 11
Ext. 0	98.78	101.02	100.20	98.78	101.63	101.63	100.41	100.00	100.00	98.17	94.50
Ext. 1	98.98	100.41	101.42	101.63	103.05	103.46	102.03	101.83	101.83	99.19	95.33
Ext. 2	99.59	101.43	101.83	101.83	105.50	106.11	104.68	105.70	104.68	100.20	93.89
Ext. 3	98.57	101.83	103.05	102.65	105.50	104.89	105.09	105.70	104.07	100.41	95.11
Ext. 4	100.00	102.04	103.48	103.07	106.34	107.98	106.13	106.13	103.27	101.43	95.50
Ext. 5	100.41	101.02	103.05	101.83	104.68	105.50	105.50	105.91	107.13	100.41	96.54
Ext. 6	100.61	101.02	102.45	100.82	101.22	105.71	105.10	104.49	102.45	101.02	95.92
Ext. 7	99.80	98.98	101.42	99.80	102.64	103.66	103.66	102.85	101.02	98.78	94.92
Ext. 8	98.57	98.16	99.18	96.93	100.82	99.80	100.00	99.80	95.90	97.75	93.03
Ext. 9											
Ext. 10											
Ext. 11											

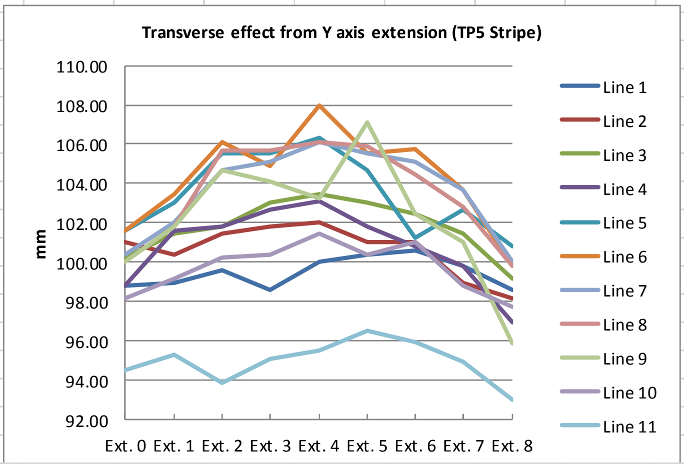
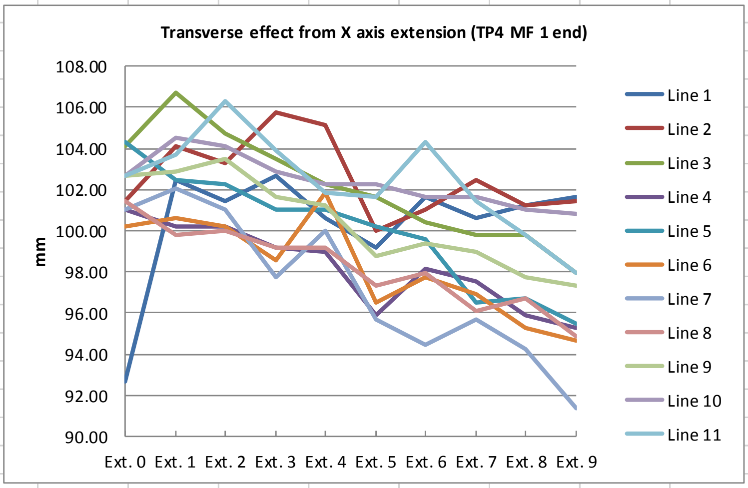


Figure F.120 Testing results and graphs for Sample 12, Stage 2.

Sample 9 (TP4 MF 1 end) Stage 2

	Vertical distances X axis TP4 MF (1 end)										
	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8	Line 9	Line 10	Line 11
Ext. 0	92.65	101.43	104.08	101.02	104.29	100.20	101.02	101.43	102.65	102.65	102.65
Ext. 1	102.45	104.08	106.73	100.20	102.45	100.61	102.04	99.80	102.86	104.49	103.67
Ext. 2	101.43	103.27	104.69	100.20	102.24	100.20	101.02	100.00	103.47	104.08	106.33
Ext. 3	102.66	105.73	103.48	99.18	101.02	98.57	97.75	99.18	101.64	102.86	103.89
Ext. 4	100.61	105.11	102.25	98.98	101.02	101.84	100.00	99.18	101.23	102.25	101.84
Ext. 5	99.18	100.00	101.64	95.91	100.20	96.52	95.71	97.34	98.77	102.25	101.64
Ext. 6	101.64	101.02	100.41	98.16	99.59	97.75	94.47	97.95	99.39	101.64	104.30
Ext. 7	100.61	102.45	99.80	97.55	96.52	96.93	95.71	96.11	98.98	101.64	101.43
Ext. 8	101.23	101.23	99.80	95.90	96.72	95.29	94.26	96.72	97.75	101.02	99.80
Ext. 9	101.64	101.44	97.95	95.28	95.48	94.66	91.38	94.87	97.33	100.82	97.95
Ext. 10											
Ext. 11											



	Vertical distances Y axis TP4 MF (1 end)										
	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8	Line 9	Line 10	Line 11
Ext. 0	94.11	100.00	100.81	100.81	100.81	100.00	101.63	101.63	96.54	91.67	89.43
Ext. 1	93.88	95.10	97.55	100.41	96.94	95.71	96.53	96.12	92.45	91.22	88.78
Ext. 2	93.27	95.10	97.76	98.57	97.55	96.94	97.35	96.53	93.47	91.22	89.39
Ext. 3	93.66	95.50	97.96	100.82	97.55	96.52	97.14	95.50	93.25	89.98	89.16
Ext. 4	93.25	94.89	96.73	100.20	96.73	97.14	97.55	96.52	92.84	89.57	88.14
Ext. 5	94.05	97.33	95.28	97.13	98.36	96.71	97.13	96.30	92.40	90.76	88.30
Ext. 6	92.64	96.11	93.87	97.14	97.55	96.52	96.52	95.91	94.48	93.46	90.80
Ext. 7	94.07	94.89	98.98	100.00	98.77	100.82	100.00	99.39	95.30	92.64	90.80
Ext. 8	94.24	95.27	98.15	98.56	98.15	98.97	97.53	97.33	95.47	91.15	87.24
Ext. 9	93.43	94.25	95.48	95.69	96.30	96.10	96.30	95.28	91.79	90.35	85.83
Ext. 10											
Ext. 11											

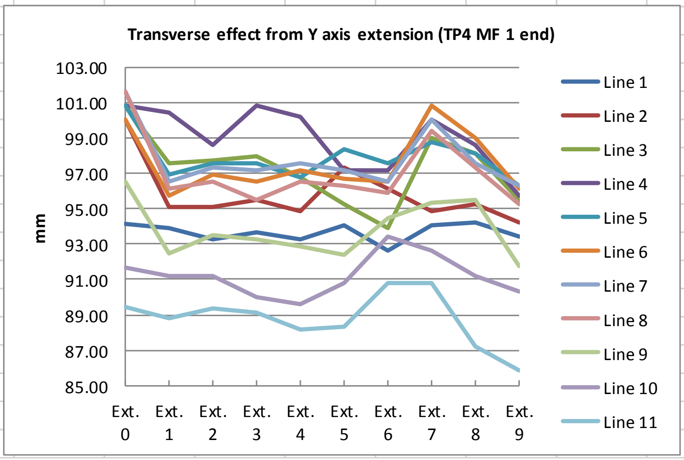
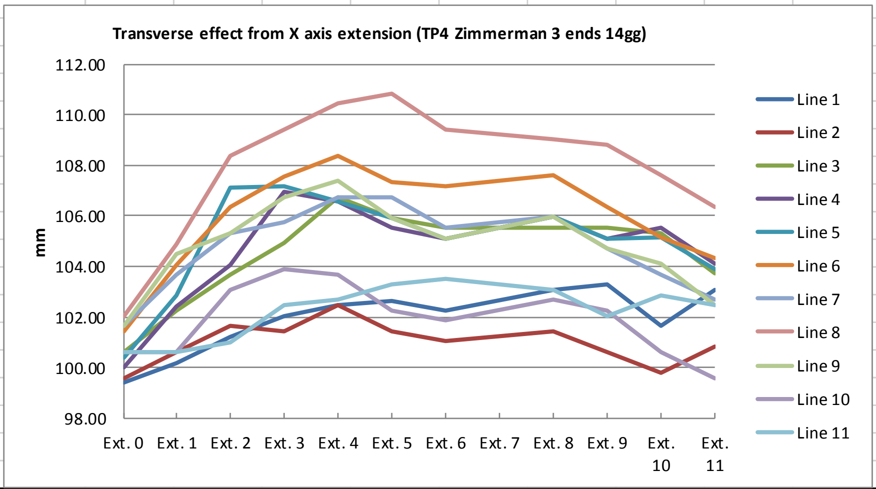


Figure F.121 Testing results and graphs for Sample 9, Stage 2.

Sample 20 (TP4 Zimmerman) Stage 4

	Vertical distances X axis TP4 Zimmerman (3 ends 14gg)										
	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8	Line 9	Line 10	Line 11
Ext. 0	99.39	99.59	100.61	100.00	100.41	101.43	101.63	102.04	101.63	100.61	100.61
Ext. 1	100.20	100.61	102.24	102.44	102.85	104.07	103.67	104.89	104.48	100.61	100.61
Ext. 2	101.22	101.63	103.67	104.08	107.14	106.33	105.31	108.37	105.31	103.06	101.02
Ext. 3	102.04	101.43	104.91	106.95	107.16	107.57	105.73	109.41	106.75	103.89	102.45
Ext. 4	102.46	102.46	106.76	106.56	106.56	108.40	106.76	110.45	107.38	103.69	102.66
Ext. 5	102.65	101.43	105.92	105.51	105.92	107.35	106.73	110.82	105.92	102.24	103.27
Ext. 6	102.25	101.02	105.53	105.12	105.12	107.17	105.53	109.43	105.12	101.84	103.48
Ext. 7											
Ext. 8	103.08	101.44	105.54	105.95	105.95	107.60	105.95	109.03	105.95	102.67	103.08
Ext. 9	103.27	100.61	105.52	105.11	105.11	106.34	104.70	108.79	104.70	102.25	102.04
Ext. 10	101.64	99.79	105.34	105.54	105.13	105.13	103.70	107.60	104.11	100.62	102.87
Ext. 11	103.09	100.82	103.70	104.12	103.91	104.32	102.67	106.38	102.47	99.59	102.47



	Vertical distances Y axis TP4 Zimmerman (3 ends 14gg)										
	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8	Line 9	Line 10	Line 11
Ext. 0	93.06	91.84	93.27	92.65	94.08	94.29	92.86	93.27	92.65	91.43	89.18
Ext. 1	91.67	94.51	96.14	95.73	96.75	97.76	97.36	95.93	94.31	92.48	89.84
Ext. 2	93.28	94.91	98.57	98.78	100.61	101.02	100.20	97.76	96.33	94.09	88.59
Ext. 3	93.06	96.12	100.20	98.57	101.22	101.22	100.20	100.20	97.55	93.47	91.43
Ext. 4	93.28	97.76	100.61	101.02	101.22	101.02	100.61	100.00	96.95	94.09	90.43
Ext. 5	93.25	97.34	100.61	100.20	101.02	101.23	101.02	99.18	97.14	94.48	90.59
Ext. 6	93.46	97.14	98.98	98.98	100.82	100.61	99.18	98.77	96.52	94.48	91.00
Ext. 7	92.64	95.91	99.39	99.18	100.00	100.00	98.57	98.16	96.32	93.25	91.62
Ext. 8	93.05	95.91	97.55	96.32	98.36	98.98	97.55	97.14	95.71	93.66	90.80
Ext. 9	93.25	95.30	97.14	97.55	99.59	98.98	98.77	97.75	96.93	93.46	90.80
Ext. 10											
Ext. 11											

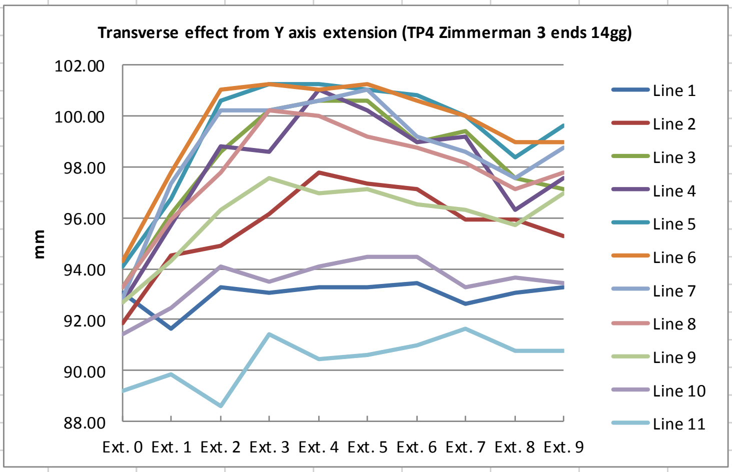
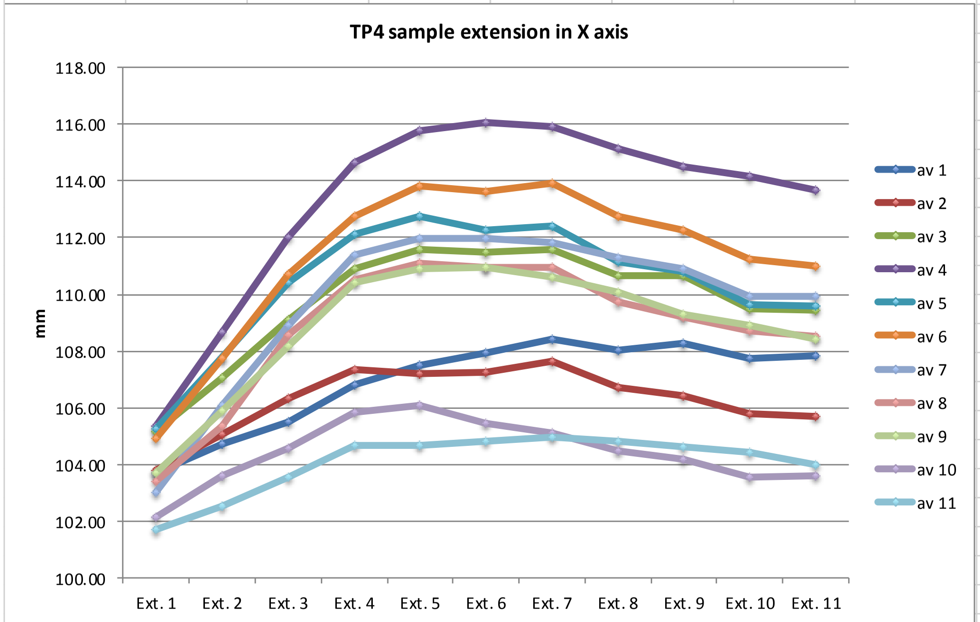


Figure F.122 Testing results and graphs for Sample 20, Stage 4.

10 repeat testing of TP4 Zimmerman – Extended in X-axis

Overall averages of 10 data sets for one sample testing (extension in X axis, measuring expansion in Y axis)

	Ext. 1	Ext. 2	Ext. 3	Ext. 4	Ext. 5	Ext. 6	Ext. 7	Ext. 8	Ext. 9	Ext. 10	Ext. 11	Highest % increase
av 1	103.71	104.70	105.51	106.81	107.52	107.92	108.41	108.03	108.28	107.74	107.86	104.540335
av 2	103.81	105.08	106.32	107.37	107.21	107.24	107.64	106.71	106.42	105.80	105.71	103.689162
av 3	105.15	107.04	109.10	110.91	111.60	111.50	111.59	110.64	110.67	109.49	109.42	106.138683
av 4	105.36	108.67	112.03	114.63	115.75	116.04	115.90	115.14	114.49	114.15	113.66	110.135431
av 5	105.28	107.80	110.42	112.13	112.73	112.24	112.40	111.13	110.83	109.66	109.59	107.078968
av 6	104.94	107.76	110.70	112.74	113.81	113.62	113.91	112.74	112.27	111.27	111.01	108.54715
av 7	103.05	106.08	108.89	111.38	111.97	111.99	111.85	111.30	110.90	109.95	109.91	108.679975
av 8	103.41	105.38	108.57	110.53	111.12	110.93	110.95	109.75	109.18	108.70	108.51	107.455601
av 9	103.73	105.87	108.19	110.40	110.93	110.95	110.64	110.09	109.30	108.89	108.42	106.964669
av 10	102.15	103.62	104.58	105.84	106.08	105.45	105.14	104.46	104.20	103.54	103.60	103.847966
av 11	101.71	102.51	103.58	104.67	104.68	104.84	104.99	104.83	104.65	104.42	104.00	103.224687



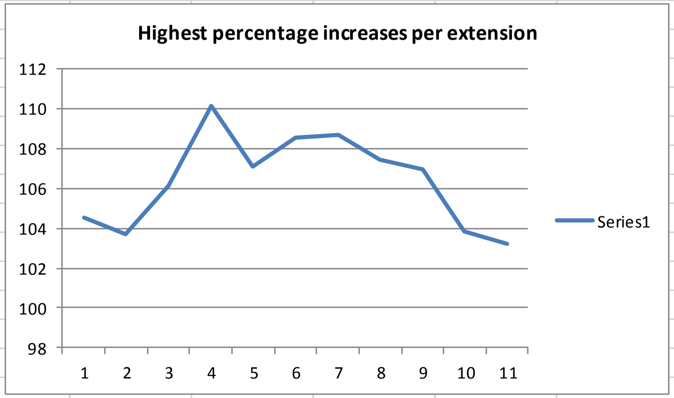
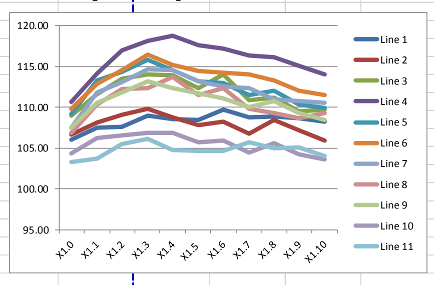


Figure F.123 Average of repeated testing results and graphs for Sample 20 extended in X-axis, Stage 4.

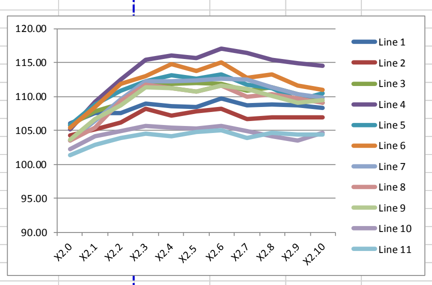
X axis extension Zimmerman TP4 10x testing

Verticals	X1.0	X1.1	X1.2	X1.3	X1.4	X1.5	X1.6	X1.7	X1.8	X1.9	X1.10
Line 1	106.00	107.53	107.57	108.94	108.57	108.48	109.75	108.72	108.83	108.67	108.26
Line 2	106.63	108.17	109.06	109.79	108.78	107.84	108.26	106.81	108.41	107.18	105.92
Line 3	108.96	111.57	113.51	114.05	113.86	112.28	113.99	110.84	111.18	109.51	109.74
Line 4	110.66	114.12	116.91	118.09	118.73	117.57	117.18	116.36	116.08	115.02	113.99
Line 5	109.18	113.27	114.36	115.75	114.49	113.13	112.93	111.48	112.03	110.36	109.95
Line 6	109.81	112.84	114.58	116.39	115.13	114.40	114.21	114.03	113.31	112.06	111.44
Line 7	107.48	111.78	113.09	114.69	114.49	113.13	112.51	112.33	110.96	110.78	110.59
Line 8	106.84	110.29	112.24	112.35	113.65	111.44	112.29	109.78	109.26	108.67	109.32
Line 9	107.48	110.51	111.82	113.20	112.38	111.65	111.02	109.99	110.75	109.30	108.47
Line 10	104.30	106.26	106.51	106.81	106.88	105.73	105.93	104.47	105.64	104.22	103.59
Line 11	103.24	103.71	105.45	106.18	104.76	104.67	104.65	105.75	105.00	105.07	104.01
Area	15481.69	17311.46	18976.73	20729.14	22026.35	23221.58	24933.11	26001.17	27470.31	28439.77	29830.23
Perimeter	508.55	540.65	564.67	595.89	616.06	632.20	657.23	678.33	697.78	716.94	731.51
Horizontal	110.66	121.13	130.49	140.65	150.26	159.23	170.88	179.64	189.98	199.54	209.51

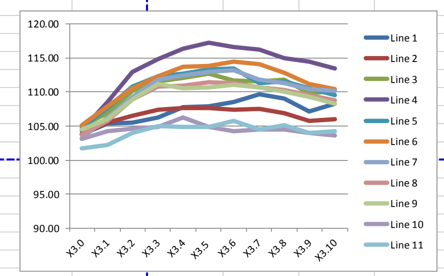
Average for each stage



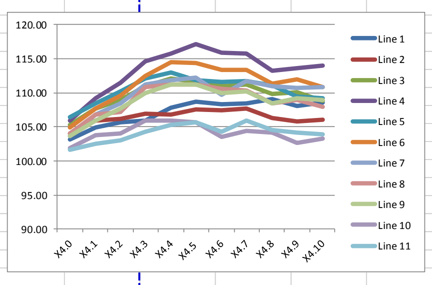
Verticals	X2.0	X2.1	X2.2	X2.3	X2.4	X2.5	X2.6	X2.7	X2.8	X2.9	X2.10
Line 1	106.00	107.53	107.57	108.94	108.57	108.48	109.75	108.72	108.83	108.67	108.26
Line 2	104.29	105.19	106.14	108.17	107.15	107.76	108.18	106.62	106.92	106.90	106.91
Line 3	105.77	107.74	108.90	111.98	111.81	111.99	111.79	110.85	111.38	110.29	109.03
Line 4	105.14	109.22	112.50	115.36	116.04	115.59	117.09	116.35	115.42	114.95	114.54
Line 5	105.77	108.80	110.81	112.19	113.08	112.63	113.27	111.70	111.17	109.45	110.51
Line 6	105.35	108.37	111.86	113.03	114.77	113.69	114.97	112.76	113.29	111.56	110.94
Line 7	103.44	106.47	109.53	112.19	112.23	112.42	112.64	112.55	111.38	110.29	109.88
Line 8	103.44	105.41	109.32	111.76	111.17	110.72	111.58	110.01	110.32	109.66	109.03
Line 9	103.65	106.68	108.69	111.34	111.17	110.72	111.58	111.07	110.11	109.02	109.45
Line 10	102.17	104.13	104.87	105.63	105.46	105.22	105.64	104.93	104.15	103.52	104.58
Line 11	101.32	102.86	103.81	104.57	104.18	104.80	105.00	103.87	104.58	104.36	104.37
Area	15027.36	16614.15	18350.24	20165.69	21660.74	23137.58	24675.06	25891.53	27404.64	28504.74	29636.23
Perimeter	512.62	535.39	554.08	580.34	607.17	631.26	652.20	673.35	693.14	716.82	732.79
Horizontal	111.28	120.04	130.51	139.92	149.92	160.05	170.55	180.03	190.45	200.05	208.96



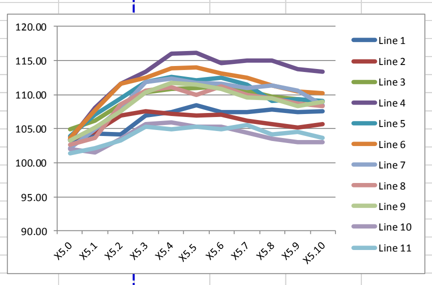
Verticals	X3.0	X3.1	X3.2	X3.3	X3.4	X3.5	X3.6	X3.7	X3.8	X3.9	X3.10
Line 1	103.68	105.35	105.45	106.32	107.79	107.86	108.51	109.62	109.01	107.20	108.29
Line 2	103.89	105.56	106.52	107.37	107.58	107.64	107.45	107.49	106.87	105.71	105.95
Line 3	104.96	106.83	110.13	111.61	112.04	112.74	111.70	111.54	111.78	109.75	110.20
Line 4	104.32	108.53	112.90	114.79	116.28	117.20	116.59	116.23	114.98	114.42	113.39
Line 5	104.74	107.68	110.77	112.25	112.67	113.38	113.40	111.32	111.57	110.60	109.56
Line 6	105.17	107.89	110.56	112.25	113.73	113.80	114.47	114.10	112.85	111.23	110.41
Line 7	103.25	106.20	109.28	111.82	112.46	112.95	113.19	111.75	111.35	110.38	110.20
Line 8	103.68	105.77	108.86	110.76	110.98	111.46	111.28	110.69	110.29	109.53	108.71
Line 9	104.53	105.98	108.86	111.19	110.55	110.62	111.06	110.69	110.07	109.32	108.29
Line 10	103.04	104.29	104.60	104.83	106.31	104.88	104.25	104.50	104.53	104.01	103.62
Line 11	101.76	102.17	103.97	105.04	104.82	104.88	105.74	104.50	105.17	104.01	104.26
Area	15093.16	16631.44	18450.76	20124.56	21691.33	23289.28	24847.31	26282.40	27609.73	28588.44	29916.10
Perimeter	511.17	533.56	554.91	582.86	606.03	630.98	656.49	678.92	696.75	712.79	732.48
Horizontal	111.34	120.61	130.54	140.62	150.02	160.51	171.28	181.70	191.14	200.81	209.79



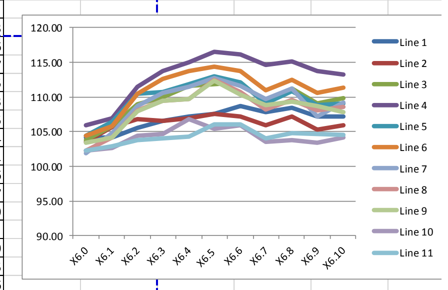
Verticals	X4.0	X4.1	X4.2	X4.3	X4.4	X4.5	X4.6	X4.7	X4.8	X4.9	X4.10
Line 1	103.18	104.86	105.73	105.92	107.85	108.63	108.25	108.47	109.02	108.12	108.55
Line 2	104.03	105.93	106.15	106.98	106.79	107.57	107.40	107.62	106.27	105.80	106.01
Line 3	105.31	107.64	108.91	111.01	112.11	111.60	111.01	111.24	109.87	110.03	108.76
Line 4	105.95	109.13	111.46	114.61	115.72	117.12	115.89	115.71	113.26	113.62	114.05
Line 5	106.38	108.49	110.18	112.07	112.96	111.82	111.65	111.66	111.14	109.39	109.18
Line 6	104.88	107.64	109.55	112.49	114.45	114.36	113.34	113.37	111.35	111.93	110.87
Line 7	103.60	106.78	108.49	111.22	111.89	112.24	109.74	111.66	110.93	110.66	110.87
Line 8	104.03	106.78	107.21	110.80	111.26	111.18	110.59	110.39	108.39	108.97	107.91
Line 9	103.60	105.93	107.64	109.95	111.26	111.18	109.95	110.18	108.39	109.18	108.97
Line 10	101.90	103.79	104.03	105.92	105.94	105.66	103.58	104.43	104.15	102.62	103.26
Line 11	101.69	102.51	102.97	104.23	105.30	105.66	104.22	105.92	104.58	104.10	103.89
Area	15098.39	16811.01	18366.45	20054.44	21878.94	23212.35	24664.31	26077.09	27092.86	28391.21	29648.77
Perimeter	509.30	530.45	550.94	579.93	602.27	624.96	653.46	668.78	690.35	707.76	722.26
Horizontal	110.85	121.31	130.57	140.24	150.82	159.98	170.65	180.36	189.47	199.53	209.48



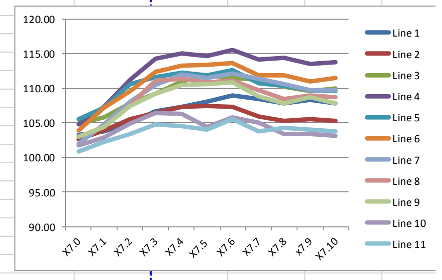
Verticals	X5.0	X5.1	X5.2	X5.3	X5.4	X5.5	X5.6	X5.7	X5.8	X5.9	X5.10
Line 1	103.23	104.28	104.13	106.96	107.43	108.47	107.42	107.40	107.79	107.44	107.62
Line 2	103.44	104.50	106.89	107.60	107.22	106.98	106.99	106.13	105.67	105.11	105.71
Line 3	104.92	106.19	108.59	110.36	110.84	111.02	111.23	110.59	109.70	109.34	108.89
Line 4	103.44	108.10	111.57	113.34	115.94	116.13	114.62	115.04	114.99	113.78	113.33
Line 5	103.86	107.04	109.44	111.85	112.54	112.08	112.50	111.43	109.06	109.34	109.10
Line 6	103.65	107.68	111.57	112.49	113.82	114.00	113.14	112.50	111.39	110.40	110.16
Line 7	102.17	104.92	107.96	111.85	112.33	111.66	111.65	111.01	111.39	110.61	108.46
Line 8	102.59	103.65	108.59	110.57	111.05	109.96	111.23	109.95	109.49	108.71	108.25
Line 9	103.23	105.13	107.53	110.36	111.69	111.45	110.81	109.52	109.49	108.28	108.89
Line 10	101.95	101.53	103.49	105.68	105.95	105.28	105.30	104.43	103.56	103.00	102.95
Line 11	101.32	102.17	103.28	105.26	104.88	105.28	104.87	105.49	104.19	104.48	103.59
Area	14765.95	16498.49	18325.92	20129.77	21770.41	23363.25	24563.16	25912.36	27122.88	28407.42	29541.23
Perimeter	505.05	529.85	547.84	578.72	604.63	623.98	644.53	664.14	690.91	705.42	726.87
Horizontal	110.86	120.39	130.91	140.56	151.05	161.00	170.34	180.63	189.54	200.28	209.30



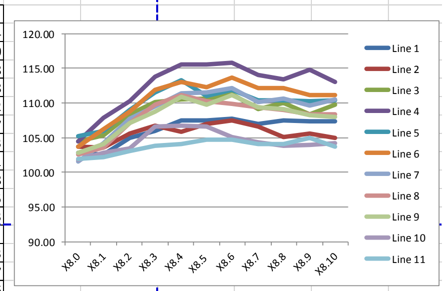
Verticals	X6.0	X6.1	X6.2	X6.3	X6.4	X6.5	X6.6	X6.7	X6.8	X6.9	X6.10
Line 1	104.19	104.13	105.53	106.52	107.19	107.59	108.63	107.82	108.46	107.16	107.13
Line 2	103.55	105.62	106.81	106.52	106.98	107.59	107.14	105.91	107.18	105.26	105.86
Line 3	103.77	105.83	108.94	109.91	111.65	111.86	112.04	109.09	111.23	109.07	109.87
Line 4	105.90	106.89	111.50	113.72	115.05	116.56	116.09	114.60	115.06	113.73	113.25
Line 5	104.41	106.47	110.44	110.76	111.86	112.93	112.04	109.09	110.80	108.86	109.03
Line 6	104.41	105.83	110.44	112.66	113.77	114.43	113.75	111.00	112.51	110.55	111.35
Line 7	101.84	104.77	108.73	110.54	111.44	112.72	111.62	109.73	111.23	107.16	109.24
Line 8	102.27	104.13	108.09	109.49	109.74	112.50	110.76	108.24	109.52	108.01	108.61
Line 9	103.34	104.13	107.88	109.49	109.74	112.29	110.34	108.88	109.31	108.65	107.76
Line 10	102.27	102.64	104.47	104.62	106.77	105.46	105.86	103.58	103.77	103.35	104.17
Line 11	102.27	102.86	103.83	103.98	104.22	106.10	106.08	104.01	104.84	104.62	104.59
Area	14985.57	16480.54	18414.53	19842.59	21581.10	23321.92	24629.63	25635.47	27368.17	28333.10	29493.49
Perimeter	510.25	529.34	552.00	573.38	603.12	621.53	645.08	660.41	685.92	704.73	730.65
Horizontal	111.02	120.49	131.33	139.98	150.28	160.96	170.62	179.63	190.71	199.92	208.76



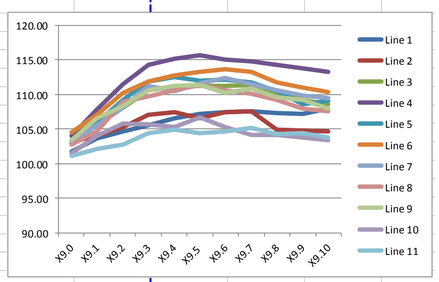
Verticals	X7.0	X7.1	X7.2	X7.3	X7.4	X7.5	X7.6	X7.7	X7.8	x7.9	X7.10
Line 1	103.23	103.71	105.06	106.65	107.30	108.05	108.94	108.42	107.83	108.24	107.84
Line 2	102.60	103.92	105.48	106.44	107.30	107.41	107.24	105.88	105.28	105.49	105.29
Line 3	104.93	105.83	107.82	109.20	110.92	111.87	111.50	111.17	110.17	109.51	109.96
Line 4	104.72	107.32	111.22	114.30	114.97	114.63	115.54	114.14	114.41	113.54	113.78
Line 5	105.57	107.11	110.58	111.54	112.20	111.87	112.56	110.75	110.38	109.73	109.53
Line 6	103.87	107.11	109.52	112.39	113.26	113.35	113.62	111.81	111.86	111.00	111.44
Line 7	101.96	104.77	108.03	110.47	111.98	111.44	112.13	111.38	110.59	109.73	109.75
Line 8	103.02	104.34	107.61	111.11	111.35	110.81	111.07	109.69	108.47	108.88	108.68
Line 9	103.02	104.34	107.39	109.20	110.49	110.59	110.86	108.84	107.83	108.67	107.84
Line 10	101.75	102.86	104.84	106.44	106.24	104.44	105.75	105.03	103.37	103.37	103.17
Line 11	100.90	102.22	103.35	104.74	104.53	104.01	105.54	103.76	104.22	104.01	103.80
Area	14963.07	16491.56	18294.91	20071.31	21722.16	23073.22	24690.98	25698.60	26995.19	28373.32	29740.68
Perimeter	505.18	528.46	553.27	580.27	603.29	627.76	645.09	667.52	673.25	699.69	728.84
Horizontal	111.31	120.71	130.79	141.07	151.16	160.48	170.86	179.57	190.19	199.75	209.73



Verticals	X8.0	X8.1	X8.2	X8.3	X8.4	X8.5	X8.6	X8.7	X8.8	X8.9	X8.10
Line 1	102.80	102.54	104.96	105.92	107.51	107.42	107.68	107.01	107.45	107.33	107.34
Line 2	103.65	103.60	105.60	106.77	105.81	107.00	107.47	106.59	105.12	105.63	105.00
Line 3	104.50	105.30	108.37	110.18	110.48	110.61	111.29	109.12	110.00	108.39	109.68
Line 4	104.50	107.85	110.28	113.79	115.58	115.49	115.75	113.98	113.39	114.75	113.08
Line 5	105.14	105.94	109.00	111.45	113.24	111.03	111.93	110.39	110.42	110.30	110.32
Line 6	103.65	106.15	108.79	111.88	113.03	112.31	113.63	112.08	112.12	111.15	111.17
Line 7	101.52	104.24	107.73	109.54	111.33	111.46	112.14	110.18	110.63	109.66	110.53
Line 8	102.59	103.60	107.09	109.75	111.12	110.18	109.81	109.34	108.94	108.39	108.41
Line 9	102.80	104.03	107.09	108.69	110.91	109.76	111.08	109.34	109.15	108.18	107.98
Line 10	101.74	102.76	103.47	106.56	106.66	106.58	105.13	104.27	103.85	103.93	104.15
Line 11	101.95	102.12	103.04	103.80	104.11	104.67	104.71	104.06	104.06	105.00	103.73
Area	14897.01	16398.78	18264.11	20032.98	21589.03	23071.40	24601.28	25601.94	27192.72	28450.77	29930.83
Perimeter	507.11	525.77	550.00	583.57	603.36	624.73	644.50	664.21	688.95	707.79	733.97
Horizontal	111.10	120.38	131.36	140.81	150.21	160.29	170.34	179.62	190.53	200.45	210.86



Verticals	X9.0	X9.1	X9.2	X9.3	X9.4	X9.5	X9.6	X9.7	X9.8	X9.9	X9.10
Line 1	101.73	103.64	104.71	105.53	106.62	107.18	107.48	107.53	107.28	107.18	108.01
Line 2	103.22	104.06	105.35	107.02	107.47	106.55	107.48	107.53	104.96	104.85	104.63
Line 3	104.07	106.61	108.12	110.64	111.09	111.22	111.30	111.36	110.24	109.29	108.65
Line 4	104.07	107.88	111.53	114.27	115.14	115.67	115.12	114.76	114.25	113.73	113.30
Line 5	103.43	105.97	109.18	111.92	112.58	112.07	112.15	111.78	110.45	108.66	109.07
Line 6	104.49	107.03	110.25	111.92	112.79	113.34	113.63	113.27	111.72	110.98	110.34
Line 7	103.00	105.55	108.12	111.28	110.45	111.64	112.36	111.57	110.66	109.92	109.49
Line 8	102.79	104.70	108.97	109.79	110.67	111.43	110.66	110.08	109.18	108.02	107.59
Line 9	103.43	106.61	108.33	110.64	111.30	111.43	110.24	110.93	109.61	109.29	108.01
Line 10	101.52	104.06	105.78	105.74	105.35	106.76	105.36	104.13	104.12	103.79	103.36
Line 11	101.09	102.15	102.80	104.46	104.92	104.42	104.73	105.19	104.33	104.43	103.79
Area	14946.19	16509.37	18297.71	20182.98	21701.45	23193.85	24360.54	25985.89	26977.47	28395.37	29520.66
Perimeter	509.66	528.69	556.65	578.74	608.09	622.43	642.22	667.68	680.44	701.29	722.74
Horizontal	110.88	120.84	130.47	140.92	150.68	160.24	169.81	180.85	189.44	200.19	209.05



Verticals	X10.0	X10.1	X10.2	X10.3	X10.4	X10.5	X10.6	X10.7	X10.8	X10.9	X10.10
Line 1	103.03	103.43	104.35	106.38	106.37	107.07	107.73	106.56	107.82	107.35	107.32
Line 2	102.81	104.28	105.19	107.02	107.01	106.01	108.79	106.56	106.76	106.08	105.84
Line 3	104.30	106.83	107.73	110.21	111.25	109.82	110.07	110.60	110.15	109.69	109.43
Line 4	104.94	107.68	110.48	114.04	114.01	114.47	115.17	114.22	113.54	113.93	113.87
Line 5	104.30	107.26	109.43	111.48	111.68	111.51	111.56	111.66	109.51	109.90	109.65
Line 6	104.09	107.05	109.85	111.91	113.37	112.57	114.32	112.51	111.42	111.81	111.97
Line 7	102.18	105.34	107.94	110.21	111.04	110.24	110.49	110.81	110.36	110.32	110.07
Line 8	102.81	105.13	107.73	108.93	110.19	109.60	110.28	109.32	108.24	108.20	108.59
Line 9	102.18	105.34	106.67	109.99	109.77	109.82	109.43	111.45	108.45	109.05	108.59
Line 10	100.90	103.85	103.71	106.16	105.31	104.53	104.54	104.86	104.22	103.53	103.10
Line 11	101.54	102.36	103.29	104.46	105.09	103.89	104.33	105.71	105.07	104.17	103.94
Area	14971.77	16575.98	18077.95	20148.83	21548.47	22991.90	24625.33	26004.52	27116.86	28538.16	29669.45
Perimeter	509.17	528.92	550.79	578.10	606.20	628.96	649.40	667.33	687.50	709.30	725.53
Horizontal	111.12	120.67	129.53	141.27	150.10	160.60	170.42	180.36	189.37	200.70	209.36

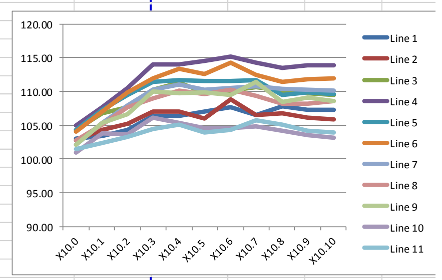
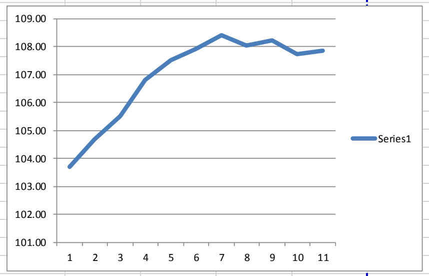
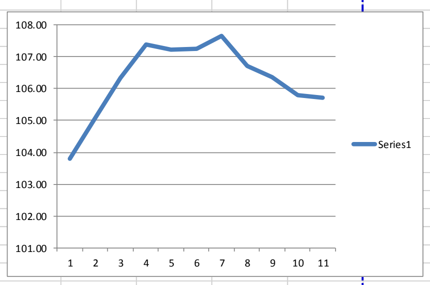


Figure F.124 Repeated testing results and graphs for Sample 20 extended in X-axis, Stage 4.

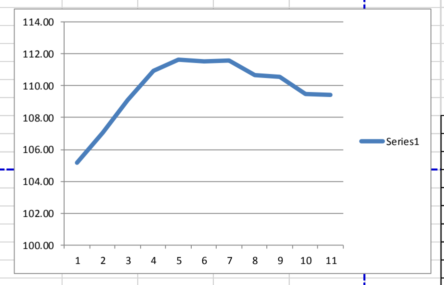
Line 1	106.00	107.53	107.57	108.94	108.57	108.48	109.75	108.72	108.83	108.67	108.26
Line 1	106.00	107.53	107.57	108.94	108.57	108.48	109.75	108.72	108.83	108.67	108.26
Line 1	103.68	105.35	105.45	106.32	107.79	107.86	108.51	109.62	109.01	107.20	108.29
Line 1	103.18	104.86	105.73	105.92	107.85	108.63	108.25	108.47	109.02	108.12	108.55
Line 1	103.23	104.28	104.13	106.96	107.43	108.47	107.42	107.40	107.79	107.44	107.62
Line 1	104.19	104.13	105.53	106.52	107.19	107.59	108.63	107.82	108.46	107.16	107.13
Line 1	103.23	103.71	105.06	106.65	107.30	108.05	108.94	108.42	107.83	108.24	107.84
Line 1	102.80	102.54	104.96	105.92	107.51	107.42	107.68	107.01	107.45	107.33	107.34
Line 1	101.73	103.64	104.71	105.53	106.62	107.18	107.48	107.53	107.28	107.18	108.01
Line 1	103.03	103.43	104.35	106.38	106.37	107.07	107.73	106.56	107.82	107.35	107.32
	103.71	104.70	105.51	106.81	107.52	107.92	108.41	108.03	108.23	107.74	107.86



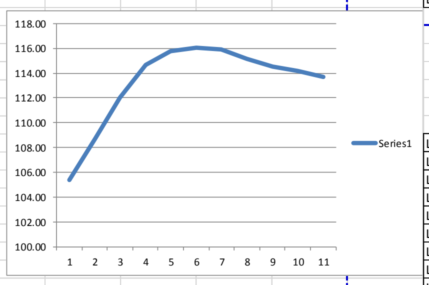
Line 2	106.63	108.17	109.06	109.79	108.78	107.84	108.26	106.81	108.41	107.18	105.92
Line 2	104.29	105.19	106.14	108.17	107.15	107.76	108.18	106.62	106.92	106.90	106.91
Line 2	103.89	105.56	106.52	107.37	107.58	107.64	107.45	107.49	106.87	105.71	105.95
Line 2	104.03	105.93	106.15	106.98	106.79	107.57	107.40	107.62	106.27	105.80	106.01
Line 2	103.44	104.50	106.89	107.60	107.22	106.98	106.99	106.13	105.67	105.11	105.71
Line 2	103.55	105.62	106.81	106.52	106.98	107.59	107.14	105.91	107.18	105.26	105.86
Line 2	102.60	103.92	105.48	106.44	107.30	107.41	107.24	105.88	105.28	105.49	105.29
Line 2	103.65	103.60	105.60	106.77	105.81	107.00	107.47	106.59	105.12	105.63	105.00
Line 2	103.22	104.06	105.35	107.02	107.47	106.55	107.48	107.53	104.96	104.85	104.63
Line 2	102.81	104.28	105.19	107.02	107.01	106.01	108.79	106.56	106.76	106.08	105.84
	103.81	105.08	106.32	107.37	107.21	107.24	107.64	106.71	106.35	105.80	105.71



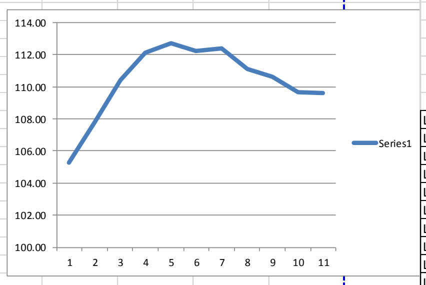
Line 3	108.96	111.57	113.51	114.05	113.86	112.28	113.99	110.84	111.18	109.51	109.74
Line 3	105.77	107.74	108.90	111.98	111.81	111.99	111.79	110.85	111.38	110.29	109.03
Line 3	104.96	106.83	110.13	111.61	112.04	112.74	111.70	111.54	111.78	109.75	110.20
Line 3	105.31	107.64	108.91	111.01	112.11	111.60	111.01	111.24	109.87	110.03	108.76
Line 3	104.92	106.19	108.59	110.36	110.84	111.02	111.23	110.59	109.70	109.34	108.89
Line 3	104.93	105.83	107.82	109.20	110.92	111.87	111.50	111.17	110.17	109.51	109.96
Line 3	103.77	105.83	108.94	109.91	111.65	111.86	112.04	109.09	111.23	109.07	109.87
Line 3	104.50	105.30	108.37	110.18	110.48	110.61	111.29	109.12	110.00	108.39	109.68
Line 3	104.07	106.61	108.12	110.64	111.09	111.22	111.30	111.36	110.24	109.29	108.65
Line 3	104.30	106.83	107.73	110.21	111.25	109.82	110.07	110.60	110.15	109.69	109.43
	105.15	107.04	109.10	110.91	111.60	111.50	111.59	110.64	110.57	109.49	109.42



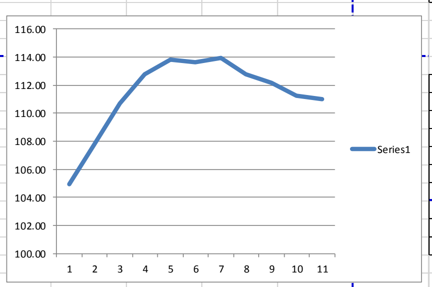
Line 4	110.66	114.12	116.91	118.09	118.73	117.57	117.18	116.36	116.08	115.02	113.99
Line 4	105.14	109.22	112.50	115.36	116.04	115.59	117.09	116.35	115.42	114.95	114.54
Line 4	104.32	108.53	112.90	114.79	116.28	117.20	116.59	116.23	114.98	114.42	113.39
Line 4	105.95	109.13	111.46	114.61	115.72	117.12	115.89	115.71	113.26	113.62	114.05
Line 4	103.44	108.10	111.57	113.34	115.94	116.13	114.62	115.04	114.99	113.78	113.33
Line 4	105.90	106.89	111.50	113.72	115.05	116.56	116.09	114.60	115.06	113.73	113.25
Line 4	104.72	107.32	111.22	114.30	114.97	114.63	115.54	114.14	114.41	113.54	113.78
Line 4	104.50	107.85	110.28	113.79	115.58	115.49	115.75	113.98	113.39	114.75	113.08
Line 4	104.07	107.88	111.53	114.27	115.14	115.67	115.12	114.76	114.25	113.73	113.30
Line 4	104.94	107.68	110.48	114.04	114.01	114.47	115.17	114.22	113.54	113.93	113.87
	105.36	108.67	112.03	114.63	115.75	116.04	115.90	115.14	114.54	114.15	113.66



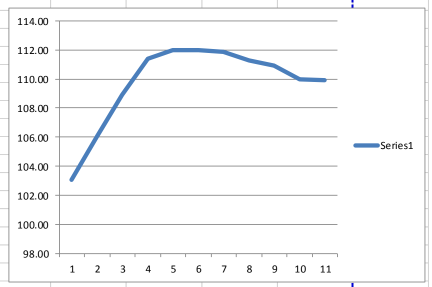
Line 5	109.18	113.27	114.36	115.75	114.49	113.13	112.93	111.48	112.03	110.36	109.95
Line 5	105.77	108.80	110.81	112.19	113.08	112.63	113.27	111.70	111.17	109.45	110.51
Line 5	104.74	107.68	110.77	112.25	112.67	113.38	113.40	111.32	111.57	110.60	109.56
Line 5	106.38	108.49	110.18	112.07	112.96	111.82	111.65	111.66	111.14	109.39	109.18
Line 5	103.86	107.04	109.44	111.85	112.54	112.08	112.50	111.43	109.06	109.34	109.10
Line 5	104.41	106.47	110.44	110.76	111.86	112.93	112.04	109.09	110.80	108.86	109.03
Line 5	105.57	107.11	110.58	111.54	112.20	111.87	112.56	110.75	110.38	109.73	109.53
Line 5	105.14	105.94	109.00	111.45	113.24	111.03	111.93	110.39	110.42	110.30	110.32
Line 5	103.43	105.97	109.18	111.92	112.58	112.07	112.15	111.78	110.45	108.66	109.07
Line 5	104.30	107.26	109.43	111.48	111.68	111.51	111.56	111.66	109.51	109.90	109.65
	105.28	107.80	110.42	112.13	112.73	112.24	112.40	111.13	110.65	109.66	109.59



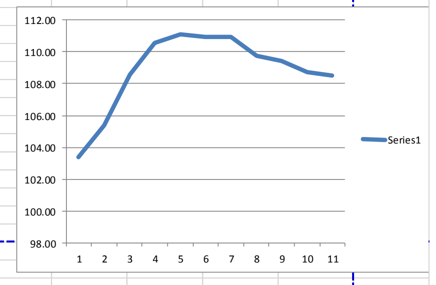
Line 6	109.81	112.84	114.58	116.39	115.13	114.40	114.21	114.03	113.31	112.06	111.44
Line 6	105.35	108.37	111.86	113.03	114.77	113.69	114.97	112.76	113.29	111.56	110.94
Line 6	105.17	107.89	110.56	112.25	113.73	113.80	114.47	114.10	112.85	111.23	110.41
Line 6	104.88	107.64	109.55	112.49	114.45	114.36	113.34	113.37	111.35	111.93	110.87
Line 6	103.65	107.68	111.57	112.49	113.82	114.00	113.14	112.50	111.39	110.40	110.16
Line 6	104.41	105.83	110.44	112.66	113.77	114.43	113.75	111.00	112.51	110.55	111.35
Line 6	103.87	107.11	109.52	112.39	113.26	113.35	113.62	111.81	111.86	111.00	111.44
Line 6	103.65	106.15	108.79	111.88	113.03	112.31	113.63	112.08	112.12	111.15	111.17
Line 6	104.49	107.03	110.25	111.92	112.79	113.34	113.63	113.27	111.72	110.98	110.34
Line 6	104.09	107.05	109.85	111.91	113.37	112.57	114.32	112.51	111.42	111.81	111.97
	104.94	107.76	110.70	112.74	113.81	113.62	113.91	112.74	112.18	111.27	111.01



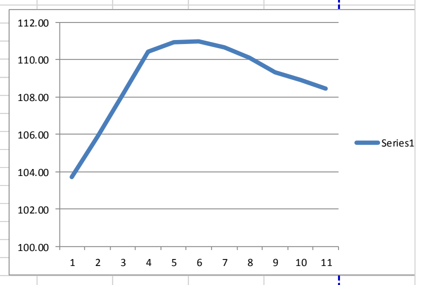
Line 7	107.48	111.78	113.09	114.69	114.49	113.13	112.51	112.33	110.96	110.78	110.59
Line 7	103.44	106.47	109.53	112.19	112.23	112.42	112.64	112.55	111.38	110.29	109.88
Line 7	103.25	106.20	109.28	111.82	112.46	112.95	113.19	111.75	111.35	110.38	110.20
Line 7	103.60	106.78	108.49	111.22	111.89	112.24	109.74	111.66	110.93	110.66	110.87
Line 7	102.17	104.92	107.96	111.85	112.33	111.66	111.65	111.01	111.39	110.61	108.46
Line 7	101.84	104.77	108.73	110.54	111.44	112.72	111.62	109.73	111.23	107.16	109.24
Line 7	101.96	104.77	108.03	110.47	111.98	111.44	112.13	111.38	110.59	109.73	109.75
Line 7	101.52	104.24	107.73	109.54	111.33	111.46	112.14	110.18	110.63	109.66	110.53
Line 7	103.00	105.55	108.12	111.28	110.45	111.64	112.36	111.57	110.66	109.92	109.49
Line 7	102.18	105.34	107.94	110.21	111.04	110.24	110.49	110.81	110.36	110.32	110.07
	103.05	106.08	108.89	111.38	111.97	111.99	111.85	111.30	110.95	109.95	109.91



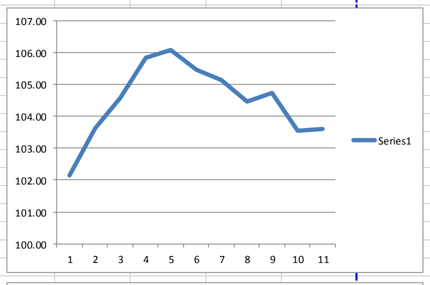
Line 8	106.84	110.29	112.24	112.35	113.65	111.44	112.29	109.78	109.26	108.67	109.32
Line 8	103.44	105.41	109.32	111.76	111.17	110.72	111.58	110.01	110.32	109.66	109.03
Line 8	103.68	105.77	108.86	110.76	110.98	111.46	111.28	110.69	110.29	109.53	108.71
Line 8	104.03	106.78	107.21	110.80	111.26	111.18	110.59	110.39	108.39	108.97	107.91
Line 8	102.59	103.65	108.59	110.57	111.05	109.96	111.23	109.95	111.39	108.71	108.25
Line 8	102.27	104.13	108.09	109.49	109.74	112.50	110.76	108.24	109.52	108.01	108.61
Line 8	103.02	104.34	107.61	111.11	111.35	110.81	111.07	109.69	108.47	108.88	108.68
Line 8	102.59	103.60	107.09	109.75	111.12	110.18	109.81	109.34	108.94	108.39	108.41
Line 8	102.79	104.70	108.97	109.79	110.67	111.43	110.66	110.08	109.18	108.02	107.59
Line 8	102.81	105.13	107.73	108.93	110.19	109.60	110.28	109.32	108.24	108.20	108.59
	103.41	105.38	108.57	110.53	111.12	110.93	110.95	109.75	109.40	108.70	108.51



Line 9	107.48	110.51	111.82	113.20	112.38	111.65	111.02	109.99	110.75	109.30	108.47
Line 9	103.65	106.68	108.69	111.34	111.17	110.72	111.58	111.07	110.11	109.02	109.45
Line 9	104.53	105.98	108.86	111.19	110.55	110.62	111.06	110.69	110.07	109.32	108.29
Line 9	103.60	105.93	107.64	109.95	111.26	111.18	109.95	110.18	108.39	109.18	108.97
Line 9	103.23	105.13	107.53	110.36	111.69	111.45	110.81	109.52	109.49	108.28	108.89
Line 9	103.34	104.13	107.88	109.49	109.74	112.29	110.34	108.88	109.31	108.65	107.76
Line 9	103.02	104.34	107.39	109.20	110.49	110.59	110.86	108.84	107.83	108.67	107.84
Line 9	102.80	104.03	107.09	108.69	110.91	109.76	111.08	109.34	109.15	108.18	107.98
Line 9	103.43	106.61	108.33	110.64	111.30	111.43	110.24	110.93	109.61	109.29	108.01
Line 9	102.18	105.34	106.67	109.99	109.77	109.82	109.43	111.45	108.45	109.05	108.59
	103.73	105.87	108.19	110.40	110.93	110.95	110.64	110.09	109.32	108.89	108.42



Line 10	104.30	106.26	106.51	106.81	106.88	105.73	105.93	104.47	105.64	104.22	103.59
Line 10	102.17	104.13	104.87	105.63	105.46	105.22	105.64	104.93	104.15	103.52	104.58
Line 10	103.04	104.29	104.60	104.83	106.31	104.88	104.25	104.50	104.53	104.01	103.62
Line 10	101.90	103.79	104.03	105.92	105.94	105.66	103.58	104.43	104.15	102.62	103.26
Line 10	101.95	101.53	103.49	105.68	105.95	105.28	105.30	104.43	109.49	103.00	102.95
Line 10	102.27	102.64	104.47	104.62	106.77	105.46	105.86	103.58	103.77	103.35	104.17
Line 10	101.75	102.86	104.84	106.44	106.24	104.44	105.75	105.03	103.37	103.37	103.17
Line 10	101.74	102.76	103.47	106.56	106.66	106.58	105.13	104.27	103.85	103.93	104.15
Line 10	101.52	104.06	105.78	105.74	105.35	106.76	105.36	104.13	104.12	103.79	103.36
Line 10	100.90	103.85	103.71	106.16	105.31	104.53	104.54	104.86	104.22	103.53	103.10
	102.15	103.62	104.58	105.84	106.08	105.45	105.14	104.46	104.73	103.54	103.60



Line 11	103.24	103.71	105.45	106.18	104.76	104.67	104.65	105.75	105.00	105.07	104.01
Line 11	101.32	102.86	103.81	104.57	104.18	104.80	105.00	103.87	104.58	104.36	104.37
Line 11	101.76	102.17	103.97	105.04	104.82	104.88	105.74	104.50	105.17	104.01	104.26
Line 11	101.69	102.51	102.97	104.23	105.30	105.66	104.22	105.92	104.58	104.10	103.89
Line 11	101.32	102.17	103.28	105.26	104.88	105.28	104.87	105.49	103.56	104.48	103.59
Line 11	102.27	102.86	103.83	103.98	104.22	106.10	106.08	104.01	104.84	104.62	104.59
Line 11	100.90	102.22	103.35	104.74	104.53	104.01	105.54	103.76	104.22	104.01	103.80
Line 11	101.95	102.12	103.04	103.80	104.11	104.67	104.71	104.06	104.06	105.00	103.73
Line 11	101.09	102.15	102.80	104.46	104.92	104.42	104.73	105.19	104.33	104.43	103.79
Line 11	101.54	102.36	103.29	104.46	105.09	103.89	104.33	105.71	105.07	104.17	103.94
	101.71	102.51	103.58	104.67	104.68	104.84	104.99	104.83	104.54	104.42	104.00

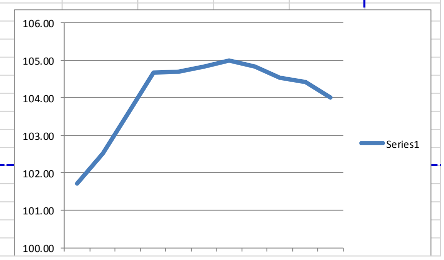


Figure F.125 Average of each line from repeated testing results, with graphs for Sample 20 extended in X-axis, Stage 4.

10 repeat testing of TP4 Zimmerman – Extended in Y-axis

Overall averages of 10 data sets for one sample testing (extension in Y axis, measuring expansion in X axis)

	Ext. 0	Ext. 1	Ext. 2	Ext. 3	Ext. 4	Ext. 5	Ext. 6	Ext. 7	Ext. 8	Ext. 9	Ext. 10	Highest percentage increase
av 1	92.32	93.04	93.42	93.87	94.07	93.78	93.72	93.79	94.13	93.93	93.57	101.957989
av 2	93.47	94.82	96.34	97.14	97.82	97.62	97.14	96.97	96.86	96.69	96.11	104.659695
av 3	94.38	97.37	99.08	100.30	101.07	100.91	100.28	99.52	99.39	99.21	98.49	107.084919
av 4	95.57	98.93	101.56	102.97	103.53	103.48	102.46	102.04	101.53	101.42	100.44	108.324421
av 5	95.92	99.71	102.56	104.21	105.04	105.07	103.95	103.51	102.83	102.36	101.31	109.548693
av 6	96.62	100.48	103.65	105.16	105.84	105.92	104.75	104.02	103.44	103.16	102.01	109.631191
av 7	96.89	100.90	104.09	105.61	106.14	106.11	104.99	104.48	103.89	103.46	102.29	109.541939
av 8	96.53	99.84	102.63	104.27	104.83	104.67	104.01	103.32	102.36	102.12	101.38	108.590253
av 9	98.13	100.29	103.22	104.21	104.55	104.78	103.71	103.23	102.49	102.31	101.42	106.774859
av 10	97.47	98.67	100.33	101.21	101.35	101.51	100.72	100.26	99.52	99.53	99.00	104.143639
av 11	97.72	97.84	98.10	97.99	97.87	98.09	97.67	97.86	97.56	97.60	97.30	100.374547

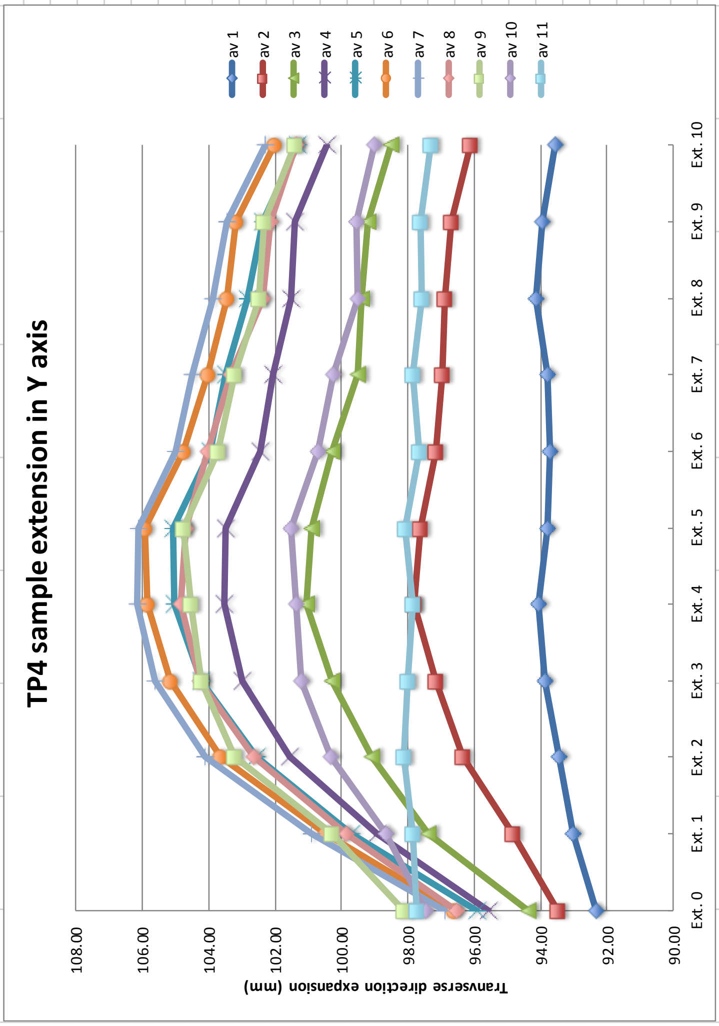
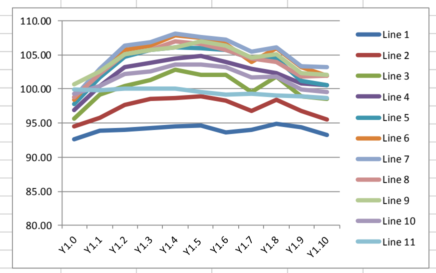


Figure F.126 Average of repeated testing results and graphs for Sample 20 extended in Y-axis, Stage 4.

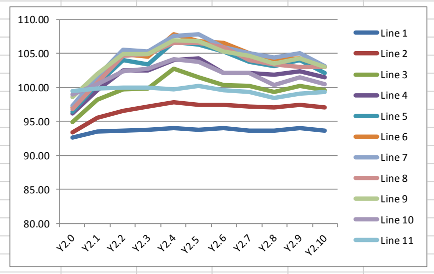
Y axis extension Zimmerman TP4 10x testing

Verticals	Y1.0	Y1.1	Y1.2	Y1.3	Y1.4	Y1.5	Y1.6	Y1.7	Y1.8	Y1.9	Y1.10
Line 1	92.63	93.85	94.03	94.26	94.48	94.66	93.59	94.01	94.84	94.42	93.20
Line 2	94.55	95.77	97.65	98.51	98.72	98.92	98.26	96.77	98.46	96.76	95.53
Line 3	95.61	99.17	100.43	101.27	102.76	102.11	102.08	99.53	101.87	98.89	98.49
Line 4	96.89	100.45	103.20	103.81	104.45	104.87	103.99	102.93	102.30	100.80	100.61
Line 5	97.74	101.72	104.69	105.72	106.15	105.94	105.69	104.41	104.43	101.23	100.61
Line 6	98.38	102.58	105.76	106.36	107.85	107.43	106.54	103.99	105.92	103.14	101.88
Line 7	98.80	103.00	106.40	106.79	108.06	107.64	107.18	105.47	106.14	103.35	103.15
Line 8	98.80	102.15	105.12	105.72	107.00	106.58	105.69	104.41	104.00	101.86	101.88
Line 9	100.72	102.58	105.12	105.72	106.15	107.00	106.33	104.62	105.07	102.29	102.10
Line 10	99.23	100.45	102.13	102.54	103.61	103.60	103.15	101.65	101.87	99.95	99.55
Line 11	99.87	99.81	100.00	99.99	100.00	99.56	99.11	99.32	99.10	98.89	98.71
Area	14110.10	15728.30	17698.97	19078.32	20689.59	22165.44	23335.53	24541.81	25997.95	26913.06	27887.91
Perimeter	487.93	503.28	528.09	547.64	570.48	590.65	608.21	629.09	653.26	668.13	686.20
Horizontal	111.16	120.88	131.34	140.33	150.95	160.61	170.21	180.81	191.17	200.54	209.91

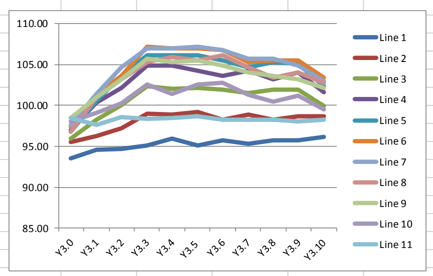
Average for each stage



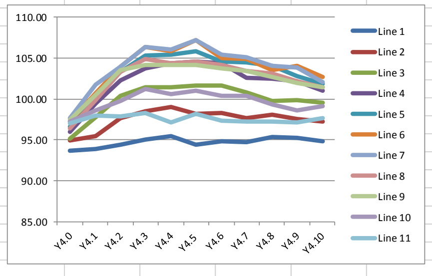
Verticals	Y2.0	Y2.1	Y2.2	Y2.3	Y2.4	Y2.5	Y2.6	Y2.7	Y2.8	Y2.9	Y2.10
Line 1	92.60	93.47	93.62	93.82	93.99	93.81	94.02	93.60	93.62	94.04	93.62
Line 2	93.45	95.60	96.59	97.23	97.81	97.42	97.42	97.20	97.00	97.44	97.02
Line 3	94.94	98.15	99.77	99.78	102.69	101.45	100.39	100.17	99.32	100.20	99.56
Line 4	96.21	99.63	102.53	102.55	103.96	104.21	102.09	102.07	101.86	102.32	101.47
Line 5	96.42	100.48	104.02	103.40	106.72	106.33	105.27	103.77	103.13	104.02	102.11
Line 6	97.06	101.55	104.87	104.46	107.78	106.76	106.55	105.04	104.18	104.23	102.96
Line 7	97.27	101.55	105.50	105.31	107.56	107.82	105.91	105.04	104.39	105.08	103.17
Line 8	96.85	100.70	104.66	104.89	106.50	106.55	105.91	103.98	103.34	102.96	102.96
Line 9	98.55	101.97	104.87	104.89	106.93	106.76	105.27	104.62	103.55	104.23	102.96
Line 10	98.97	100.48	102.32	102.76	104.17	103.79	102.09	102.07	100.38	101.47	100.41
Line 11	99.40	99.85	99.99	99.99	99.71	100.18	99.54	99.32	98.48	99.14	99.35
Area	13936.05	15679.90	17455.13	18971.19	20615.58	21939.23	23244.77	24414.75	25517.78	26965.34	28132.54
Perimeter	484.47	505.33	525.35	549.70	570.92	591.09	609.97	630.56	647.42	669.44	685.34
Horizontal	110.65	120.88	130.55	140.42	150.21	160.25	169.80	179.58	189.13	199.77	209.74



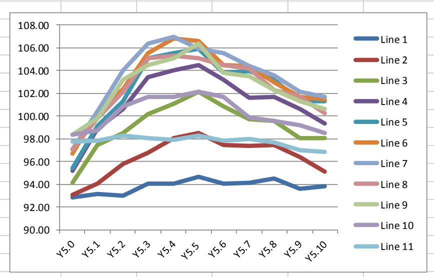
Verticals	Y3.0	Y3.1	Y3.2	Y3.3	Y3.4	Y3.5	Y3.6	Y3.7	Y3.8	Y3.9	Y3.10
Line 1	93.56	94.59	94.69	95.11	95.91	95.10	95.74	95.32	95.75	95.71	96.12
Line 2	95.47	96.29	97.24	98.93	98.88	99.14	98.29	98.92	98.29	98.68	98.67
Line 3	95.90	98.20	100.00	102.33	102.05	102.11	101.90	101.46	101.89	101.87	99.95
Line 4	96.96	100.33	102.12	104.88	104.80	104.23	103.59	104.21	103.16	103.99	101.65
Line 5	96.75	100.54	103.61	106.15	106.08	106.14	105.50	104.64	105.28	105.05	102.29
Line 6	97.38	101.39	103.61	107.21	106.92	106.99	106.78	105.27	105.49	105.47	103.35
Line 7	97.60	101.39	104.67	107.00	106.92	107.20	106.78	105.70	105.70	104.84	102.93
Line 8	96.75	100.97	103.18	105.30	105.86	105.50	106.14	104.64	103.37	103.99	102.71
Line 9	98.45	100.97	103.18	105.73	105.23	105.50	104.87	104.00	103.58	103.14	102.08
Line 10	98.02	99.05	100.21	102.54	101.42	102.53	102.75	101.25	100.41	101.23	99.52
Line 11	98.45	97.56	98.51	98.30	98.45	98.71	98.29	98.28	98.29	98.05	98.25
Area	13920.91	15680.03	17375.79	19091.44	20524.58	22016.54	23387.62	24480.45	25680.52	27067.07	28086.83
Perimeter	485.11	502.60	526.22	548.39	569.19	592.36	611.87	628.79	647.43	667.10	688.04
Horizontal	110.78	120.73	130.36	140.33	149.69	160.70	170.46	179.62	189.16	199.70	209.89



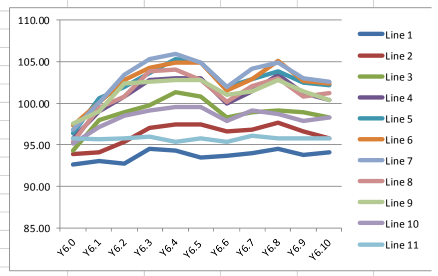
Verticals	Y4.0	Y4.1	Y4.2	Y4.3	Y4.4	Y4.5	Y4.6	Y4.7	Y4.8	Y4.9	Y4.10
Line 1	93.61	93.91	94.42	95.06	95.45	94.40	94.84	94.70	95.30	95.20	94.86
Line 2	94.89	95.40	97.61	98.46	99.05	98.23	98.23	97.67	98.06	97.53	97.19
Line 3	95.10	97.73	100.37	101.44	101.39	101.63	101.62	100.84	99.76	99.86	99.53
Line 4	95.95	99.42	102.29	103.78	104.35	104.60	104.38	102.54	102.51	102.19	101.01
Line 5	96.59	100.70	103.35	105.27	105.42	105.88	104.59	104.45	104.00	102.83	101.86
Line 6	97.23	100.70	103.99	106.33	105.84	107.16	105.02	104.87	103.58	104.10	102.71
Line 7	97.65	101.76	103.99	106.33	106.05	107.16	105.44	105.08	104.00	103.89	102.07
Line 8	96.38	99.85	103.35	104.84	104.35	104.60	104.17	103.39	103.15	102.19	101.44
Line 9	97.44	100.48	103.56	104.20	104.14	104.18	103.75	103.39	102.73	101.98	101.44
Line 10	97.23	98.58	99.74	101.23	100.54	100.99	100.35	100.42	99.33	98.59	99.10
Line 11	97.02	97.94	97.82	98.25	97.14	98.23	97.38	97.24	97.21	97.10	97.62
Area	13951.08	15559.53	17443.44	19030.05	20449.61	21971.89	23114.13	24310.50	25610.78	26771.82	27918.72
Perimeter	486.31	504.21	526.78	550.55	567.88	589.80	607.80	628.42	649.64	667.27	687.55
Horizontal	110.85	120.41	130.36	140.78	150.17	160.52	169.94	179.65	190.17	199.51	209.45



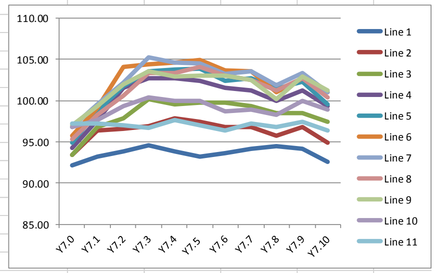
Verticals	Y5.0	Y5.1	Y5.2	Y5.3	Y5.4	Y5.5	Y5.6	Y5.7	Y5.8	Y5.9	Y5.10
Line 1	92.82	93.17	92.99	94.04	94.05	94.66	94.03	94.14	94.46	93.63	93.84
Line 2	93.03	94.02	95.75	96.80	98.08	98.49	97.43	97.33	97.43	96.39	95.11
Line 3	94.10	97.42	98.51	100.20	101.06	102.10	100.83	99.68	99.56	98.09	98.09
Line 4	95.16	98.91	100.63	103.38	104.03	104.44	103.16	101.59	101.68	100.63	99.36
Line 5	95.38	99.12	101.27	105.08	105.51	105.93	103.80	103.94	103.17	101.27	101.27
Line 6	96.66	100.39	102.33	105.50	106.79	106.57	104.44	104.36	102.95	101.69	101.48
Line 7	97.08	100.39	104.03	106.35	107.00	105.93	105.50	104.36	103.59	102.12	101.70
Line 8	97.08	99.75	102.12	105.08	105.30	105.08	104.44	104.15	102.32	101.69	100.21
Line 9	98.36	99.75	103.18	104.44	105.09	106.36	103.80	103.51	102.32	101.27	100.63
Line 10	98.36	98.69	100.85	101.68	101.69	102.10	101.68	99.89	99.56	99.15	98.51
Line 11	97.72	97.84	98.30	98.08	97.87	98.28	97.85	97.97	97.65	97.02	96.81
Area	13924.44	15490.14	17158.03	18898.54	20412.68	21963.35	23097.04	24413.07	25564.16	26647.16	27840.97
Perimeter	485.09	502.51	523.35	546.99	566.62	590.80	607.12	629.75	649.00	666.88	687.68
Horizontal	111.17	120.34	130.57	140.32	150.10	161.03	170.45	180.61	190.20	200.21	209.97



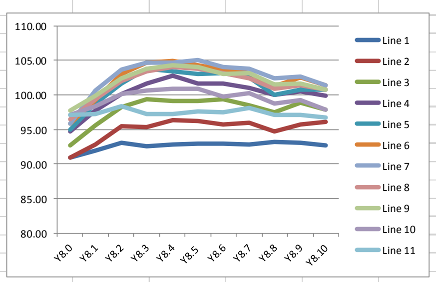
Verticals	Y6.0	Y6.1	Y6.2	Y6.3	Y6.4	Y6.5	Y6.6	Y6.7	Y6.8	Y6.9	Y6.10
Line 1	92.59	93.07	92.76	94.48	94.26	93.42	93.63	94.00	94.46	93.80	94.03
Line 2	93.87	94.13	95.31	97.03	97.45	97.45	96.60	96.76	97.65	96.57	95.74
Line 3	94.30	97.98	98.93	99.79	101.27	100.84	98.30	98.88	99.14	98.91	98.29
Line 4	95.79	99.04	100.84	102.76	102.97	102.95	100.00	101.43	103.40	101.25	100.42
Line 5	96.43	100.54	101.91	103.61	105.30	104.86	101.91	102.91	103.82	102.53	102.12
Line 6	97.29	100.11	102.76	104.25	104.88	104.86	101.48	102.91	105.10	102.74	102.33
Line 7	96.86	100.11	103.40	105.31	105.94	104.86	101.91	104.19	104.89	102.95	102.54
Line 8	95.37	99.47	100.84	103.82	104.03	102.74	100.21	102.06	102.97	100.82	101.27
Line 9	97.50	99.04	102.33	102.55	102.76	102.74	101.06	101.43	102.76	101.46	100.42
Line 10	95.15	97.12	98.50	99.15	99.57	99.57	97.87	99.09	98.72	97.85	98.29
Line 11	95.79	95.63	95.74	95.97	95.33	95.75	95.33	96.12	95.74	95.72	95.74
Area	13888.85	15574.97	17122.15	18723.91	20239.52	21537.16	22620.79	24049.18	25570.76	26645.43	27803.93
Perimeter	482.06	503.58	520.33	543.84	564.54	583.73	604.87	625.31	646.44	664.56	683.84
Horizontal	111.15	121.24	130.63	140.55	150.10	159.94	170.06	180.15	190.20	200.37	209.77



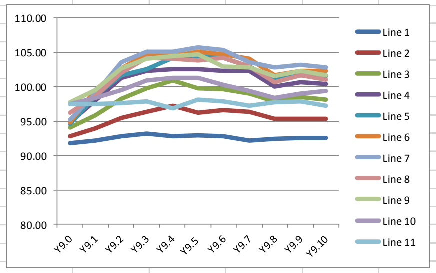
Verticals	Y7.0	Y7.1	Y7.2	Y7.3	Y7.4	Y7.5	Y7.6	Y7.7	Y7.8	Y7.9	Y7.10
Line 1	92.14	93.18	93.83	94.60	93.80	93.22	93.64	94.21	94.43	94.19	92.54
Line 2	93.42	96.38	96.59	96.94	97.82	97.46	96.82	96.76	95.71	96.74	94.87
Line 3	93.42	96.81	97.87	100.13	99.51	99.79	99.79	99.31	98.47	98.44	97.42
Line 4	94.28	97.66	101.49	102.68	102.69	102.33	101.48	101.23	99.96	101.20	99.33
Line 5	94.92	98.73	101.70	103.53	103.75	103.81	102.33	102.71	101.45	102.27	99.54
Line 6	95.77	99.16	104.04	104.38	104.59	104.87	103.60	103.56	101.03	102.69	101.03
Line 7	96.84	99.58	102.12	105.23	104.59	104.45	103.18	103.56	101.88	103.33	101.03
Line 8	95.34	98.30	100.63	103.32	103.32	104.03	102.97	102.50	101.24	102.69	100.39
Line 9	97.05	99.37	101.91	103.53	102.90	102.97	102.97	102.50	100.17	102.90	101.24
Line 10	96.84	97.66	99.36	100.34	99.94	100.00	98.73	98.89	98.26	99.93	98.91
Line 11	97.26	97.24	97.02	96.73	97.61	97.03	96.40	97.18	96.77	97.38	96.36
Area	13841.99	15556.74	17138.32	18781.35	20066.97	21588.31	22769.31	24231.09	25288.76	26733.45	27592.49
Perimeter	490.48	508.79	524.96	550.66	563.95	586.65	604.94	627.30	646.40	665.78	682.83
Horizontal	110.91	121.33	130.63	140.52	149.90	160.17	169.49	179.91	189.93	200.07	209.49



Verticals	Y8.0	Y8.1	Y8.2	Y8.3	Y8.4	Y8.5	Y8.6	Y8.7	Y8.8	Y8.9	Y8.10
Line 1	90.95	91.98	93.07	92.58	92.78	92.99	92.99	92.79	93.24	93.14	92.74
Line 2	90.95	92.83	95.41	95.34	96.39	96.18	95.75	95.97	94.73	95.68	96.13
Line 3	92.65	95.59	98.18	99.36	99.15	99.15	99.36	98.52	97.49	98.87	97.83
Line 4	94.77	97.71	100.10	101.69	102.76	101.70	101.70	101.07	100.04	100.56	99.94
Line 5	94.98	98.77	101.59	103.81	103.39	102.97	103.18	102.56	100.04	100.78	100.79
Line 6	95.83	99.20	103.08	104.66	104.88	104.25	103.61	103.19	101.31	102.47	101.42
Line 7	95.83	100.69	103.72	104.66	104.67	105.10	104.03	103.83	102.37	102.69	101.42
Line 8	96.47	99.41	102.01	103.39	104.03	103.82	103.18	102.34	100.88	101.41	100.79
Line 9	97.74	99.84	102.44	103.81	104.24	104.03	102.97	103.19	101.52	101.62	100.79
Line 10	97.11	98.35	100.10	100.63	100.85	100.85	99.79	100.22	98.76	99.29	97.83
Line 11	97.11	97.29	98.39	97.24	97.24	97.66	97.45	98.10	97.06	97.17	96.77
Area	13656.65	15354.62	17193.61	18677.74	20214.33	21599.65	22834.22	24153.70	25171.91	26508.36	27566.80
Perimeter	485.73	504.10	528.16	547.38	564.91	589.91	607.01	625.87	644.33	664.84	680.59
Horizontal	110.28	120.65	130.77	140.25	150.32	160.51	169.85	180.27	189.88	199.85	209.20



Verticals	Y9.0	Y9.1	Y9.2	Y9.3	Y9.4	Y9.5	Y9.6	Y9.7	Y9.8	Y9.9	Y9.10
Line 1	91.77	92.22	92.74	93.20	92.77	92.99	92.79	92.17	92.38	92.57	92.57
Line 2	92.84	93.92	95.50	96.38	97.23	96.16	96.60	96.40	95.34	95.33	95.33
Line 3	94.12	95.83	98.25	99.77	100.83	99.77	99.57	98.94	97.88	98.51	98.09
Line 4	94.76	97.96	101.21	102.31	102.53	102.52	102.32	102.32	99.99	100.64	100.42
Line 5	94.55	98.59	101.64	102.52	104.23	104.43	104.23	102.96	101.05	101.70	101.49
Line 6	94.76	99.44	102.70	104.64	104.44	105.06	104.65	104.01	101.69	102.34	102.34
Line 7	95.19	99.02	103.54	105.07	105.08	105.70	105.29	103.59	102.74	103.18	102.76
Line 8	96.26	98.59	102.06	104.22	104.02	103.79	104.23	102.96	100.63	101.70	101.06
Line 9	97.75	99.44	102.70	104.01	104.44	104.64	102.96	102.74	101.47	102.34	101.70
Line 10	97.54	98.38	99.52	100.83	101.26	101.25	100.20	99.36	98.30	98.94	99.36
Line 11	97.54	97.53	97.61	97.86	96.80	98.07	97.87	97.25	97.67	97.88	97.24
Area	13837.42	15400.77	17018.20	18678.71	20252.54	21563.06	22879.32	24029.72	25033.97	26610.92	27737.48
Perimeter	485.78	501.08	521.93	548.33	566.46	588.43	608.04	624.34	643.50	667.85	684.73
Horizontal	111.20	120.91	130.43	140.44	150.51	160.13	169.90	179.27	189.42	200.00	209.98



Verticals	Y10.0	Y10.1	Y10.2	Y10.3	Y10.4	Y10.5	Y10.6	Y10.7	Y10.8	Y10.9	Y10.10
Line 1	90.52	90.91	92.10	91.54	93.21	92.55	91.95	92.97	92.79	92.56	92.15
Line 2	92.22	93.89	95.71	95.77	96.82	96.80	95.97	95.94	95.96	95.75	95.54
Line 3	93.70	96.86	98.46	98.94	100.00	100.19	98.94	97.85	98.51	98.51	97.66
Line 4	94.97	98.14	101.22	101.90	102.76	102.95	101.90	101.04	100.41	100.63	100.20
Line 5	95.40	97.92	101.86	102.96	103.82	104.44	102.96	102.74	101.90	101.91	101.05
Line 6	95.82	100.26	103.34	103.80	104.46	105.29	104.87	102.95	103.17	102.75	100.63
Line 7	95.82	101.53	103.56	104.01	105.52	105.29	104.66	104.01	103.17	103.18	102.11
Line 8	96.03	99.20	102.28	102.11	103.82	104.01	103.17	102.74	101.68	101.91	101.05
Line 9	97.73	99.41	102.92	103.17	103.61	103.59	103.17	102.31	101.68	101.91	100.84
Line 10	96.24	97.92	100.59	100.42	100.42	100.41	100.63	99.77	99.57	98.93	98.51
Line 11	97.09	97.71	97.62	97.46	98.51	97.43	97.45	97.85	97.66	97.66	96.18
Area	13741.33	15468.28	17091.41	18617.31	20299.76	21678.97	22870.69	24167.73	25383.58	26557.34	27607.53
Perimeter	481.41	501.79	519.83	543.07	567.12	587.59	607.72	626.04	644.80	663.96	682.88
Horizontal	110.45	120.86	130.51	139.95	150.96	160.69	169.91	180.43	189.81	199.99	209.52

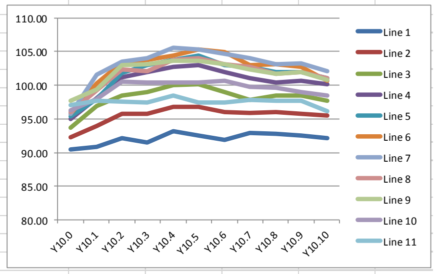
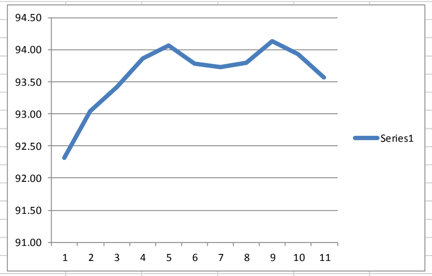
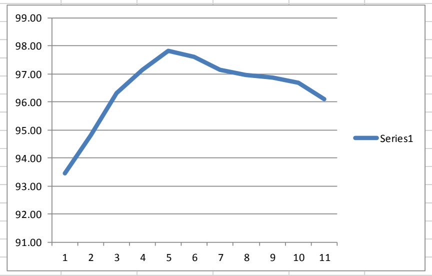


Figure F.127 Repeated testing results and graphs for Sample 20 extended in Y-axis, Stage 4.

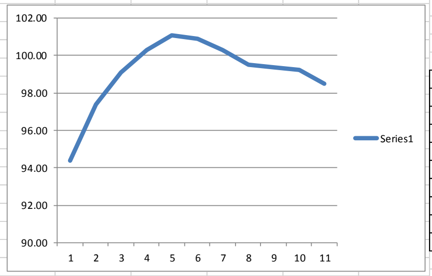
Line 1	92.63	93.85	94.03	94.26	94.48	94.66	93.59	94.01	94.84	94.42	93.20
Line 1	92.60	93.47	93.62	93.82	93.99	93.81	94.02	93.60	93.62	94.04	93.62
Line 1	93.56	94.59	94.69	95.11	95.91	95.10	95.74	95.32	95.75	95.71	96.12
Line 1	93.61	93.91	94.42	95.06	95.45	94.40	94.84	94.70	95.30	95.20	94.86
Line 1	92.82	93.17	92.99	94.04	94.05	94.66	94.03	94.14	94.46	93.63	93.84
Line 1	92.59	93.07	92.76	94.48	94.26	93.42	93.63	94.00	94.46	93.80	94.03
Line 1	92.14	93.18	93.83	94.60	93.80	93.22	93.64	94.21	94.43	94.19	92.54
Line 1	90.95	91.98	93.07	92.58	92.78	92.99	92.99	92.79	93.24	93.14	92.74
Line 1	91.77	92.22	92.74	93.20	92.77	92.99	92.79	92.17	92.38	92.57	92.57
Line 1	90.52	90.91	92.10	91.54	93.21	92.55	91.95	92.97	92.79	92.56	92.15
	92.32	93.04	93.42	93.87	94.07	93.78	93.72	93.79	94.13	93.93	93.57



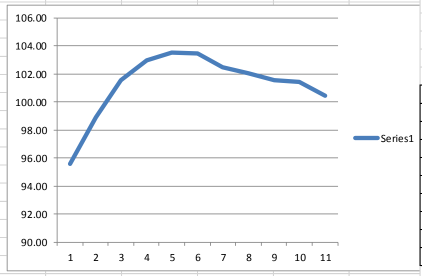
Line 2	94.55	95.77	97.65	98.51	98.72	98.92	98.26	96.77	98.46	96.76	95.53
Line 2	93.45	95.60	96.59	97.23	97.81	97.42	97.42	97.20	97.00	97.44	97.02
Line 2	95.47	96.29	97.24	98.93	98.88	99.14	98.29	98.92	98.29	98.68	98.67
Line 2	94.89	95.40	97.61	98.46	99.05	98.23	98.23	97.67	98.06	97.53	97.19
Line 2	93.03	94.02	95.75	96.80	98.08	98.49	97.43	97.33	97.43	96.39	95.11
Line 2	93.87	94.13	95.31	97.03	97.45	97.45	96.60	96.76	97.65	96.57	95.74
Line 2	93.42	96.38	96.59	96.94	97.82	97.46	96.82	96.76	95.71	96.74	94.87
Line 2	90.95	92.83	95.41	95.34	96.39	96.18	95.75	95.97	94.73	95.68	96.13
Line 2	92.84	93.92	95.50	96.38	97.23	96.16	96.60	96.40	95.34	95.33	95.33
Line 2	92.22	93.89	95.71	95.77	96.82	96.80	95.97	95.94	95.96	95.75	95.54
	93.47	94.82	96.34	97.14	97.82	97.62	97.14	96.97	96.86	96.69	96.11



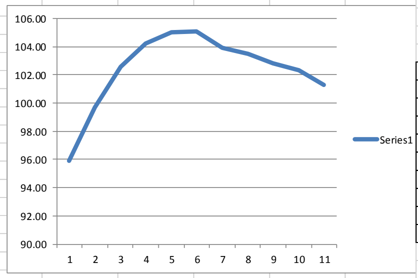
Line 3	95.61	99.17	100.43	101.27	102.76	102.11	102.08	99.53	101.87	98.89	98.49
Line 3	94.94	98.15	99.77	99.78	102.69	101.45	100.39	100.17	99.32	100.20	99.56
Line 3	95.90	98.20	100.00	102.33	102.05	102.11	101.90	101.46	101.89	101.87	99.95
Line 3	95.10	97.73	100.37	101.44	101.39	101.63	101.62	100.84	99.76	99.86	99.53
Line 3	94.10	97.42	98.51	100.20	101.06	102.10	100.83	99.68	99.56	98.09	98.09
Line 3	94.30	97.98	98.93	99.79	101.27	100.84	98.30	98.88	99.14	98.91	98.29
Line 3	93.42	96.81	97.87	100.13	99.51	99.79	99.79	99.31	98.47	98.44	97.42
Line 3	92.65	95.59	98.18	99.36	99.15	99.15	99.36	98.52	97.49	98.87	97.83
Line 3	94.12	95.83	98.25	99.77	100.83	99.77	99.57	98.94	97.88	98.51	98.09
Line 3	93.70	96.86	98.46	98.94	100.00	100.19	98.94	97.85	98.51	98.51	97.66
	94.38	97.37	99.08	100.30	101.07	100.91	100.28	99.52	99.39	99.21	98.49



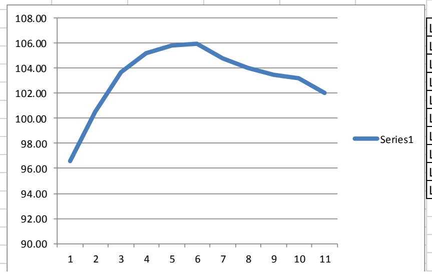
Line 4	96.89	100.45	103.20	103.81	104.45	104.87	103.99	102.93	102.30	100.80	100.61
Line 4	96.21	99.63	102.53	102.55	103.96	104.21	102.09	102.07	101.86	102.32	101.47
Line 4	96.96	100.33	102.12	104.88	104.80	104.23	103.59	104.21	103.16	103.99	101.65
Line 4	95.95	99.42	102.29	103.78	104.35	104.60	104.38	102.54	102.51	102.19	101.01
Line 4	95.16	98.91	100.63	103.38	104.03	104.44	103.16	101.59	101.68	100.63	99.36
Line 4	95.79	99.04	100.84	102.76	102.97	102.95	100.00	101.43	103.40	101.25	100.42
Line 4	94.28	97.66	101.49	102.68	102.69	102.33	101.48	101.23	99.96	101.20	99.33
Line 4	94.77	97.71	100.10	101.69	102.76	101.70	101.70	101.07	100.04	100.56	99.94
Line 4	94.76	97.96	101.21	102.31	102.53	102.52	102.32	102.32	99.99	100.64	100.42
Line 4	94.97	98.14	101.22	101.90	102.76	102.95	101.90	101.04	100.41	100.63	100.20
	95.57	98.93	101.56	102.97	103.53	103.48	102.46	102.04	101.53	101.42	100.44



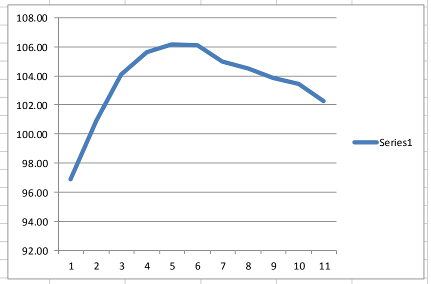
Line 5	97.74	101.72	104.69	105.72	106.15	105.94	105.69	104.41	104.43	101.23	100.61
Line 5	96.42	100.48	104.02	103.40	106.72	106.33	105.27	103.77	103.13	104.02	102.11
Line 5	96.75	100.54	103.61	106.15	106.08	106.14	105.50	104.64	105.28	105.05	102.29
Line 5	96.59	100.70	103.35	105.27	105.42	105.88	104.59	104.45	104.00	102.83	101.86
Line 5	95.38	99.12	101.27	105.08	105.51	105.93	103.80	103.94	103.17	101.27	101.27
Line 5	96.43	100.54	101.91	103.61	105.30	104.86	101.91	102.91	103.82	102.53	102.12
Line 5	94.92	98.73	101.70	103.53	103.75	103.81	102.33	102.71	101.45	102.27	99.54
Line 5	94.98	98.77	101.59	103.81	103.39	102.97	103.18	102.56	100.04	100.78	100.79
Line 5	94.55	98.59	101.64	102.52	104.23	104.43	104.23	102.96	101.05	101.70	101.49
Line 5	95.40	97.92	101.86	102.96	103.82	104.44	102.96	102.74	101.90	101.91	101.05
	95.92	99.71	102.56	104.21	105.04	105.07	103.95	103.51	102.83	102.36	101.31



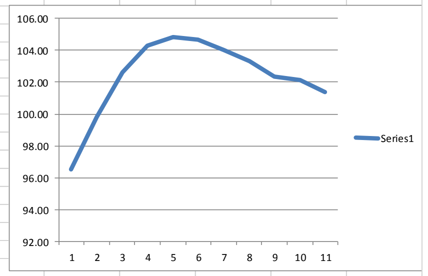
Line 6	98.38	102.58	105.76	106.36	107.85	107.43	106.54	103.99	105.92	103.14	101.88
Line 6	97.06	101.55	104.87	104.46	107.78	106.76	106.55	105.04	104.18	104.23	102.96
Line 6	97.38	101.39	103.61	107.21	106.92	106.99	106.78	105.27	105.49	105.47	103.35
Line 6	97.23	100.70	103.99	106.33	105.84	107.16	105.02	104.87	103.58	104.10	102.71
Line 6	96.66	100.39	102.33	105.50	106.79	106.57	104.44	104.36	102.95	101.69	101.48
Line 6	97.29	100.11	102.76	104.25	104.88	104.86	101.48	102.91	105.10	102.74	102.33
Line 6	95.77	99.16	104.04	104.38	104.59	104.87	103.60	103.56	101.03	102.69	101.03
Line 6	95.83	99.20	103.08	104.66	104.88	104.25	103.61	103.19	101.31	102.47	101.42
Line 6	94.76	99.44	102.70	104.64	104.44	105.06	104.65	104.01	101.69	102.34	102.34
Line 6	95.82	100.26	103.34	103.80	104.46	105.29	104.87	102.95	103.17	102.75	100.63
	96.62	100.48	103.65	105.16	105.84	105.92	104.75	104.02	103.44	103.16	102.01



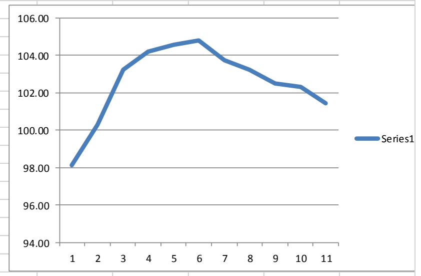
Line 7	98.80	103.00	106.40	106.79	108.06	107.64	107.18	105.47	106.14	103.35	103.15
Line 7	97.27	101.55	105.50	105.31	107.56	107.82	105.91	105.04	104.39	105.08	103.17
Line 7	97.60	101.39	104.67	107.00	106.92	107.20	106.78	105.70	105.70	104.84	102.93
Line 7	97.65	101.76	103.99	106.33	106.05	107.16	105.44	105.08	104.00	103.89	102.07
Line 7	97.08	100.39	104.03	106.35	107.00	105.93	105.50	104.36	103.59	102.12	101.70
Line 7	96.86	100.11	103.40	105.31	105.94	104.86	101.91	104.19	104.89	102.95	102.54
Line 7	96.84	99.58	102.12	105.23	104.59	104.45	103.18	103.56	101.88	103.33	101.03
Line 7	95.83	100.69	103.72	104.66	104.67	105.10	104.03	103.83	102.37	102.69	101.42
Line 7	95.19	99.02	103.54	105.07	105.08	105.70	105.29	103.59	102.74	103.18	102.76
Line 7	95.82	101.53	103.56	104.01	105.52	105.29	104.66	104.01	103.17	103.18	102.11
	96.89	100.90	104.09	105.61	106.14	106.11	104.99	104.48	103.89	103.46	102.29



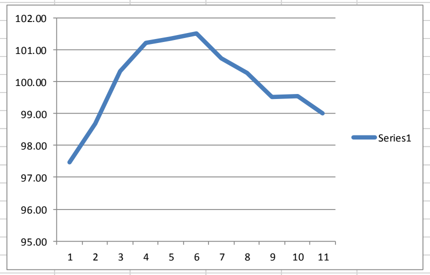
Line 8	98.80	102.15	105.12	105.72	107.00	106.58	105.69	104.41	104.00	101.86	101.88
Line 8	96.85	100.70	104.66	104.89	106.50	106.55	105.91	103.98	103.34	102.96	102.96
Line 8	96.75	100.97	103.18	105.30	105.86	105.50	106.14	104.64	103.37	103.99	102.71
Line 8	96.38	99.85	103.35	104.84	104.35	104.60	104.17	103.39	103.15	102.19	101.44
Line 8	97.08	99.75	102.12	105.08	105.30	105.08	104.44	104.15	102.32	101.69	100.21
Line 8	95.37	99.47	100.84	103.82	104.03	102.74	100.21	102.06	102.97	100.82	101.27
Line 8	95.34	98.30	100.63	103.32	103.32	104.03	102.97	102.50	101.24	102.69	100.39
Line 8	96.47	99.41	102.01	103.39	104.03	103.82	103.18	102.34	100.88	101.41	100.79
Line 8	96.26	98.59	102.06	104.22	104.02	103.79	104.23	102.96	100.63	101.70	101.06
Line 8	96.03	99.20	102.28	102.11	103.82	104.01	103.17	102.74	101.68	101.91	101.05
	96.53	99.84	102.63	104.27	104.83	104.67	104.01	103.32	102.36	102.12	101.38



Line 9	100.72	102.58	105.12	105.72	106.15	107.00	106.33	104.62	105.07	102.29	102.10
Line 9	98.55	101.97	104.87	104.89	106.93	106.76	105.27	104.62	103.55	104.23	102.96
Line 9	98.45	100.97	103.18	105.73	105.23	105.50	104.87	104.00	103.58	103.14	102.08
Line 9	97.44	100.48	103.56	104.20	104.14	104.18	103.75	103.39	102.73	101.98	101.44
Line 9	98.36	99.75	103.18	104.44	105.09	106.36	103.80	103.51	102.32	101.27	100.63
Line 9	97.50	99.04	102.33	102.55	102.76	102.74	101.06	101.43	102.76	101.46	100.42
Line 9	97.05	99.37	101.91	103.53	102.90	102.97	102.97	102.50	100.17	102.90	101.24
Line 9	97.74	99.84	102.44	103.81	104.24	104.03	102.97	103.19	101.52	101.62	100.79
Line 9	97.75	99.44	102.70	104.01	104.44	104.64	102.96	102.74	101.47	102.34	101.70
Line 9	97.73	99.41	102.92	103.17	103.61	103.59	103.17	102.31	101.68	101.91	100.84
	98.13	100.29	103.22	104.21	104.55	104.78	103.71	103.23	102.49	102.31	101.42



Line 10	99.23	100.45	102.13	102.54	103.61	103.60	103.15	101.65	101.87	99.95	99.55
Line 10	98.97	100.48	102.32	102.76	104.17	103.79	102.09	102.07	100.38	101.47	100.41
Line 10	98.02	99.05	100.21	102.54	101.42	102.53	102.75	101.25	100.41	101.23	99.52
Line 10	97.23	98.58	99.74	101.23	100.54	100.99	100.35	100.42	99.33	98.59	99.10
Line 10	98.36	98.69	100.85	101.68	101.69	102.10	101.68	99.89	99.56	99.15	98.51
Line 10	95.15	97.12	98.50	99.15	99.57	99.57	97.87	99.09	98.72	97.85	98.29
Line 10	96.84	97.66	99.36	100.34	99.94	100.00	98.73	98.89	98.26	99.93	98.91
Line 10	97.11	98.35	100.10	100.63	100.85	100.85	99.79	100.22	98.76	99.29	97.83
Line 10	97.54	98.38	99.52	100.83	101.26	101.25	100.20	99.36	98.30	98.94	99.36
Line 10	96.24	97.92	100.59	100.42	100.42	100.41	100.63	99.77	99.57	98.93	98.51
	97.47	98.67	100.33	101.21	101.35	101.51	100.72	100.26	99.52	99.53	99.00



Line 11	99.87	99.81	100.00	99.99	100.00	99.56	99.11	99.32	99.10	98.89	98.71
Line 11	99.40	99.85	99.99	99.99	99.71	100.18	99.54	99.32	98.48	99.14	99.35
Line 11	98.45	97.56	98.51	98.30	98.45	98.71	98.29	98.28	98.29	98.05	98.25
Line 11	97.02	97.94	97.82	98.25	97.14	98.23	97.38	97.24	97.21	97.10	97.62
Line 11	97.72	97.84	98.30	98.08	97.87	98.28	97.85	97.97	97.65	97.02	96.81
Line 11	95.79	95.63	95.74	95.97	95.33	95.75	95.33	96.12	95.74	95.72	95.74
Line 11	97.26	97.24	97.02	96.73	97.61	97.03	96.40	97.18	96.77	97.38	96.36
Line 11	97.11	97.29	98.39	97.24	97.24	97.66	97.45	98.10	97.06	97.17	96.77
Line 11	97.54	97.53	97.61	97.86	96.80	98.07	97.87	97.25	97.67	97.88	97.24
Line 11	97.09	97.71	97.62	97.46	98.51	97.43	97.45	97.85	97.66	97.66	96.18
	97.72	97.84	98.10	97.99	97.87	98.09	97.67	97.86	97.56	97.60	97.30

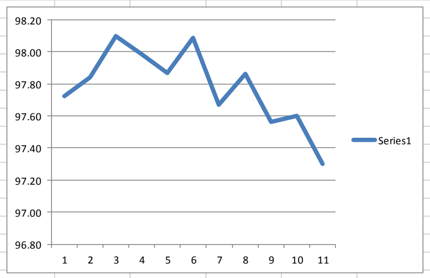


Figure F.128 Average of each line from repeated testing results, with graphs for Sample 20 extended in Y-axis, Stage 4.

Appendix G: Visual development of methodology

Since the beginning of this study, several attempts have been made to visualise the methodological process. Initially used as a tool to visualise my own process to myself and then to communicate this process to others. However, visualising a methodology has proved to be highly problematic due to the non-linear, cyclical, variable, busy and adaptive nature of the process and motives. The motivation behind designing a methodology diagram or visualisation is to provide both written and visual forms of information where possible, to enable different interactions from different readers.

The nature of the methodology diagram in this case is fundamentally flawed. Simple diagrams imply a sequence of events, when in reality there may be any number of simultaneous events, and they imply an order, which is highly negotiable or non-existent. Another major problem with the visualisation of a knitted textile process, is that there are a large number of variables which, when changed, alter the process in unpredictable and inexpressible ways.

The attempts made below attempt to interpret the complexity of a design thought process alongside its inseparable practical considerations (such as in **Figure G.129** which attempts to illustrate the considerations as many intertwined elements). The following diagrams were devised over the course of the project and are listed here in chronological order.

Figure G.129 is in some ways a successful representation, but also implies too linear a route through the thinking and doing processes. The busy, crossing and interlinking lines of consideration comes close to representing the chaos that can surround a design process. The idea that the elements begin as separate concerns and converge towards a combined end is also not representative. It is difficult to express 'weighting' of each element in terms of either importance or chronology and as such, this diagram is unsuccessful in its approach.

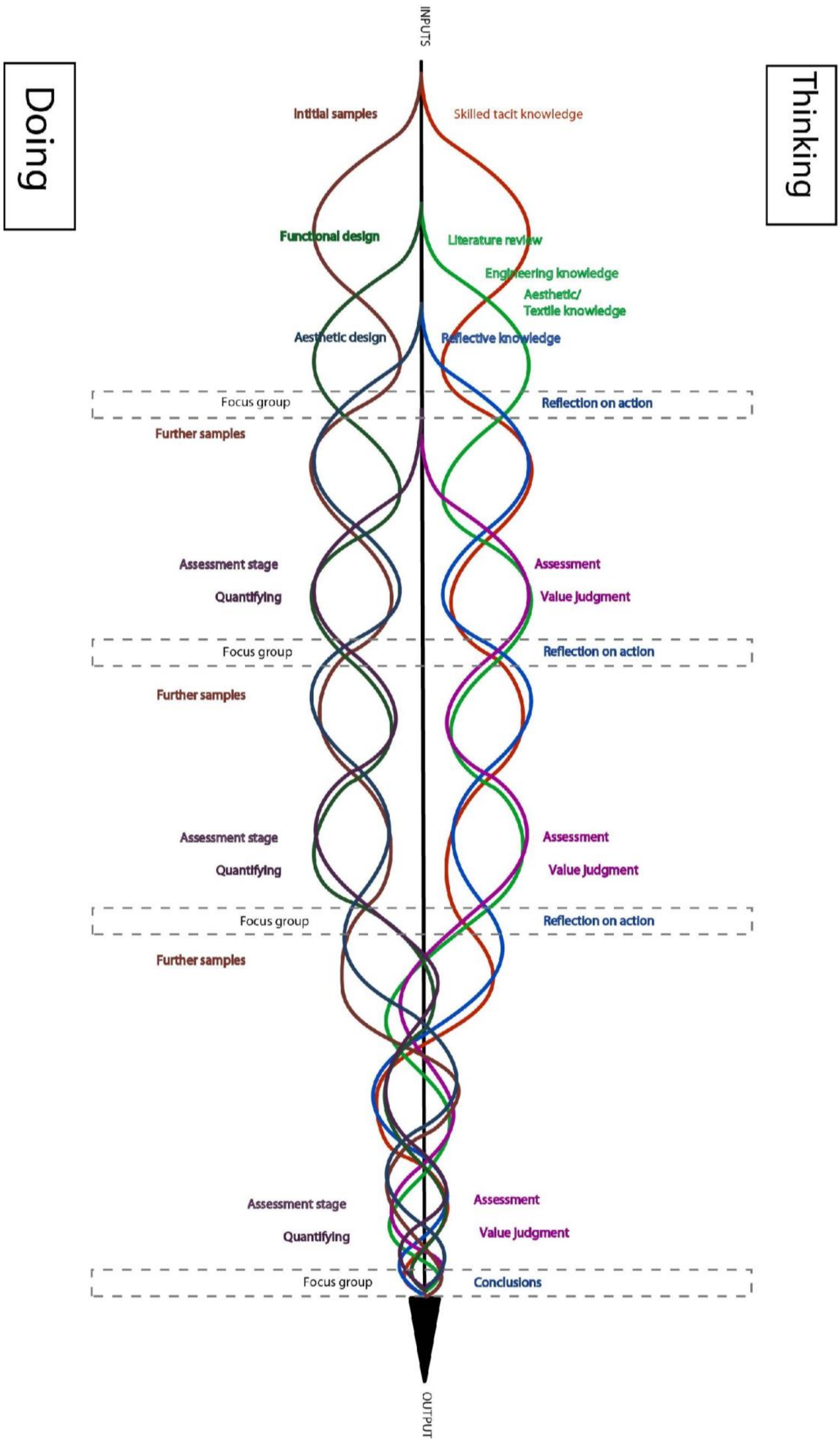


Figure G.129 Diagrammatic methodology representation 1.

Figure G.130 shows a more traditional approach to representation through a flow chart format that incorporates feedback loops. On either side of the central core there are inputs from the researcher and 'others' (participants in focus groups 1-3) and how they affect the various stages at the centre of the research. This diagram over simplifies the considerations of the study. It is true that outside perspectives have an important place, alongside the input from the practitioner, but the linear and equally-weighted aspect of this is not representative of the process.

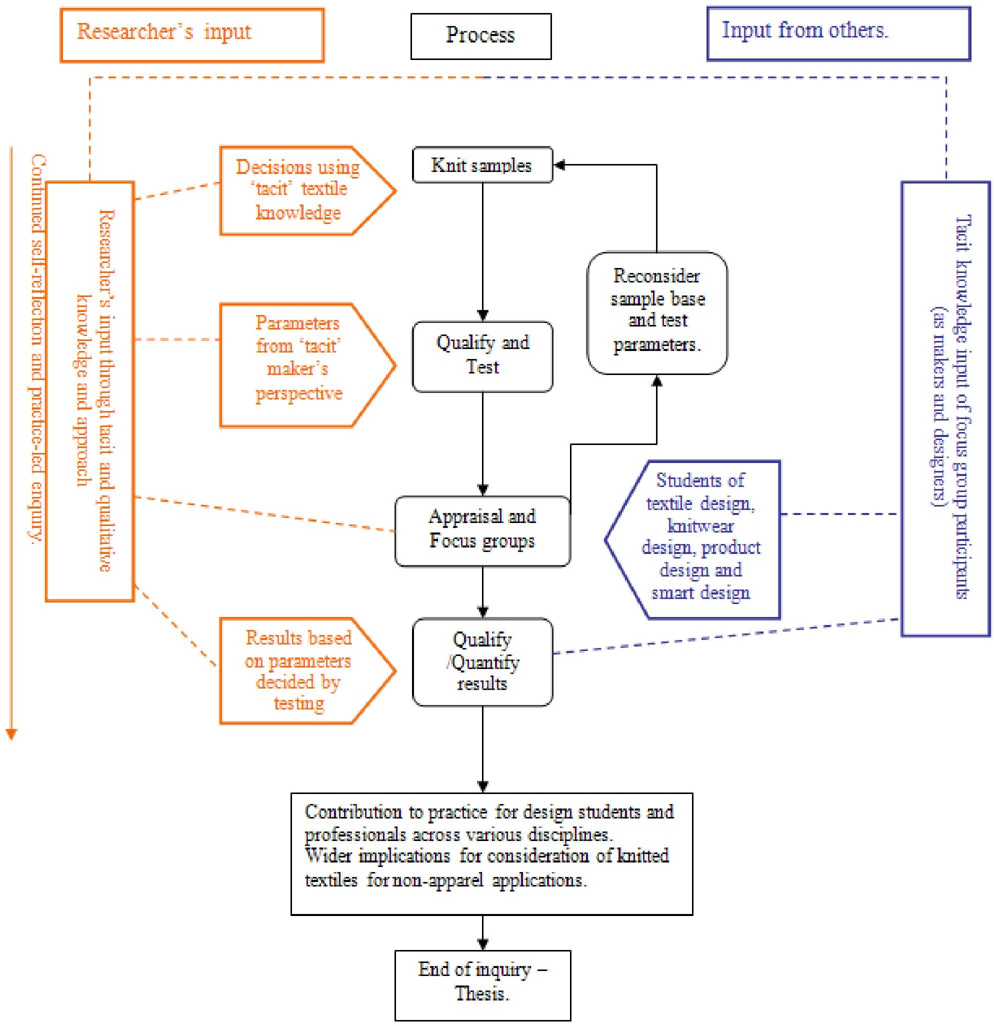


Figure G.130 Diagrammatic methodology representation 2.
Process with parallel considerations and feedback loops

Then the focus turns to defining disciplinary areas (as a way of understanding the complexity of the various methods and methodologies that might crossover to create the complex, true picture of what it means to have a knit or a design methodology. **Figure G.131** is focused more on knit practices and the idea of fundamental knowledge. It argues that there is a central core of fundamental knowledge - mainly practical and experiential - that all knit practices have in common. Other sub-disciplines (under the knit 'umbrella') have their own specialist knowledge – including agenda, testing, dissemination, etc. – which determines their specialist interests.

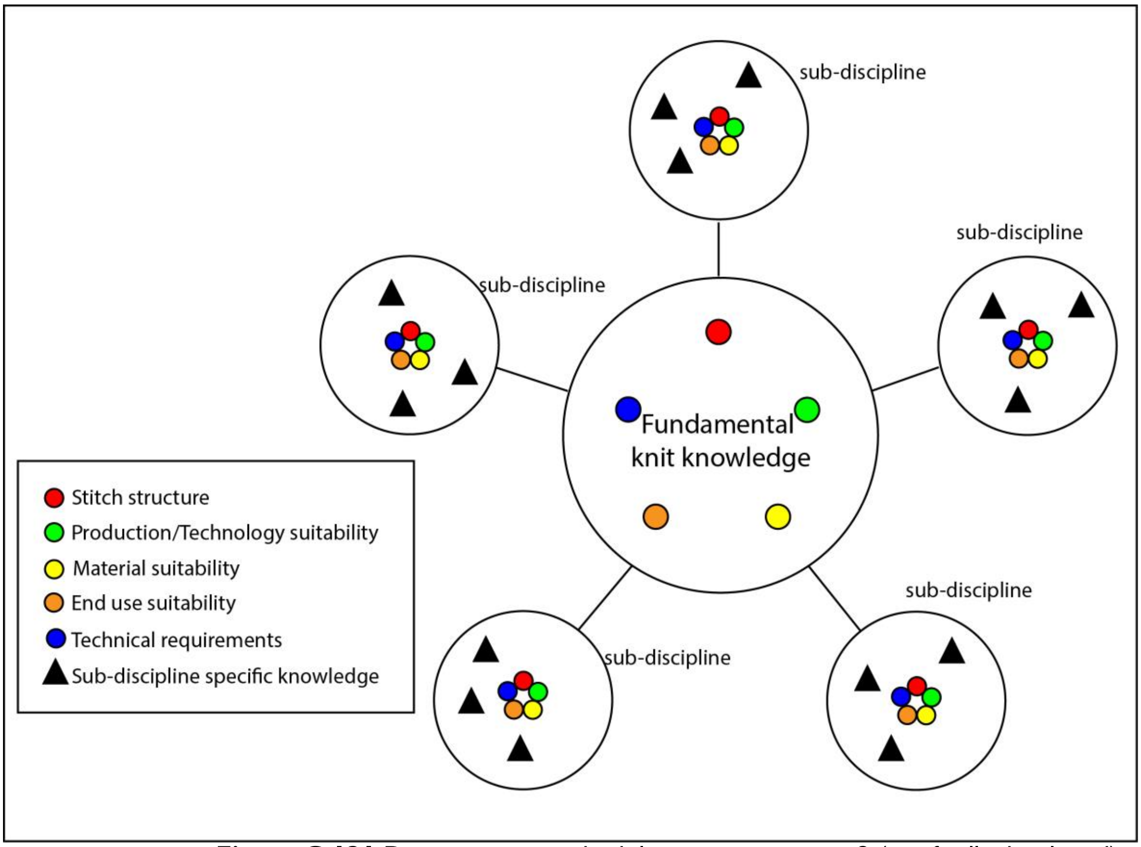


Figure G.131 Diagrammatic methodology representation 3 (not finally developed). Attempt at a representation of knowledge for knit practice

Figure G.132 shows a working diagram of the methodology used in this study (as presented to **Focus Group 4)**. It is similar to, but not the same as a generic knit methodology. The representation shows several possible feedback loops and indicates which sections were relevant for each stage of the research (**Practical Stages 1-4**). The core of the methodology (in black text, down the centre) is one possibility for a knit project. The starting point might be different in different types of project (e.g. might start with a stitch structure/colour/yarn/function as in Glazzard & Breedon, 2012: 105). This representation shows clarity and a methodical approach, however, as with **Figure G.129** and **Figure G.130** the general impression is too linear and does not convey the possibilities of busy, simultaneous and sometimes chaotic processes involved in a design project and its thought processes.

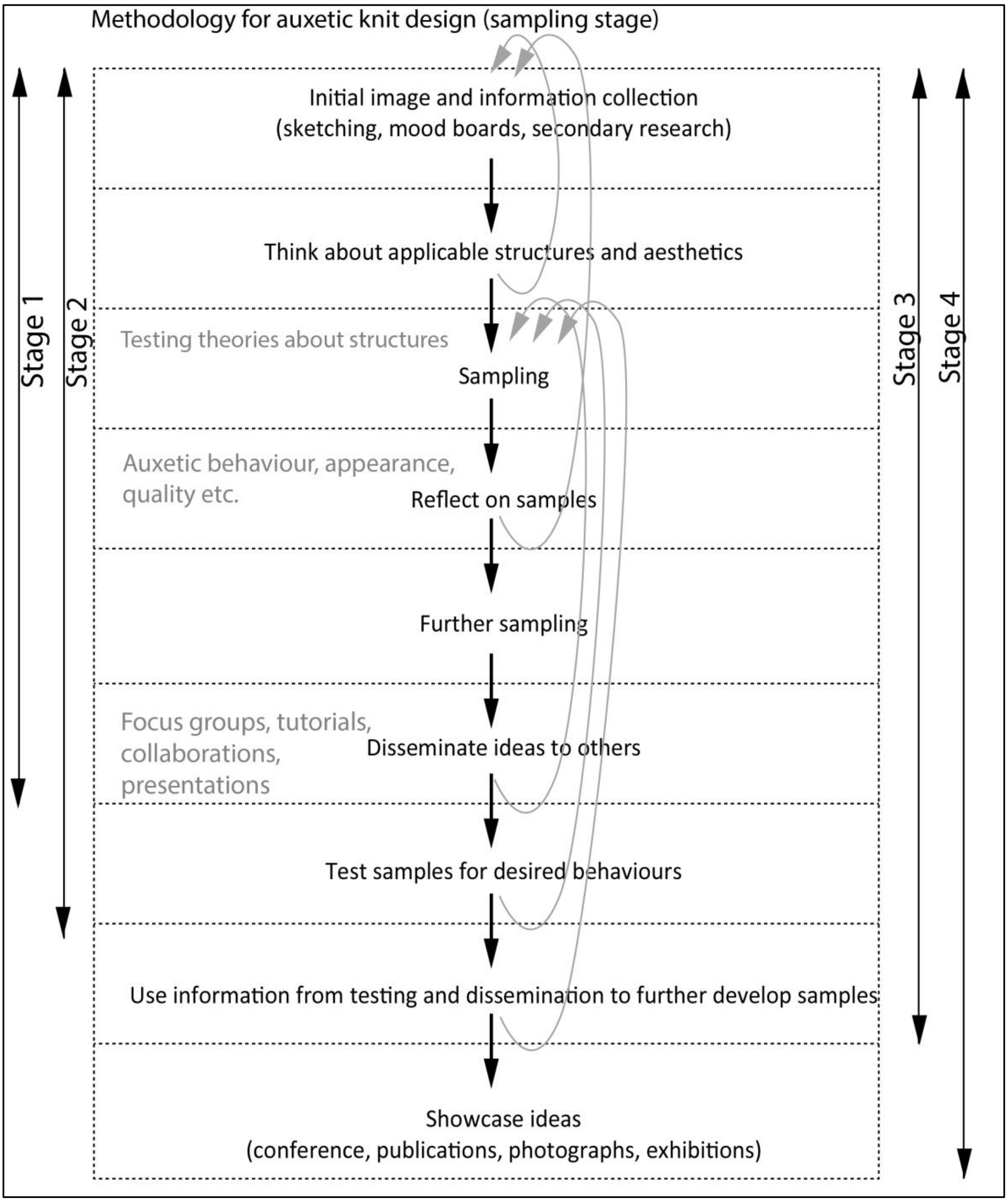


Figure G.132 Diagrammatic methodology representation 5. Approximate methodology for this research, presented at focus group 4. Similar to a generic knit methodology.

During these attempts, the methodology is not representing the amorphous nature of the design process used. All attempts have involved lineation of the process and not properly conveyed the chaos that a single design decision can bring with it.

In reality, the design process (in my experience and opinion) is more like a collision of information with unimaginable variations of output. **Figure G.129** is closest to giving this impression, but the straight arrow through the centre implies a direct route to the end, without deviation, tangents, side-stepping or dead ends of enquiry.

Appendix H: Briefs for Master's student project

The briefs in this appendix were given to students on the Smart Design Master's course at Nottingham Trent University in February 2013. The work they undertook is described in **Chapter 8**.

Auxetic Materials Brief (30%)

AIM

Design a product utilising auxetic knitted textiles or auxetic foams.

You must produce:

Part 1. (40% of coursework)

- A CAD, hand-drawn or animated visualisation of the product
- 3 A2 design boards (context, proposed concept, experiential timeline, product description)

Part 2. (40 % of coursework)

- Supporting developmental work (sketchbooks, references, ideation session, etc.)
- Personal reflection on working in a team (500 words)

Part 3. (20% of coursework)

- A 10 minute presentation demonstrating the work from 1&2 above. This will focus on the research, concepts and proposed product/s

Working in a team you will:

- Develop a proposal for a product/group of related products for a commercially viable market that uses the auxetic behaviour of the foams and/or knitted fabrics. This product may be situated in any product design field and may involve automated or manual actuation.
- You will consider the materials needed and how the auxetic behaviour contributes to the end use.
- Consider the properties of the materials you are using and how those might be used to best effect in a product.
- Consider the marketing/description of this product.

DEADLINE AND PRESENTATION:

CONTEXT OF THE PROJECT

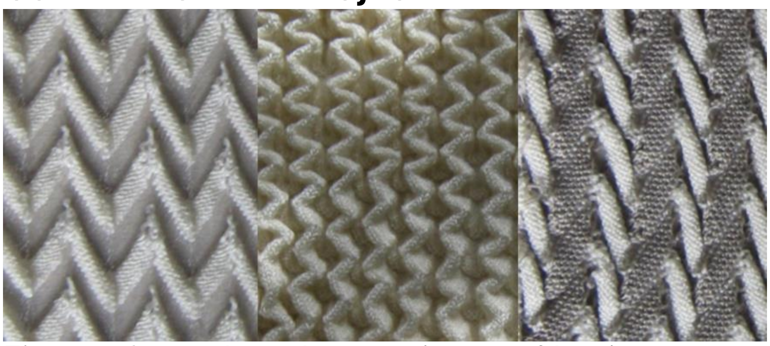
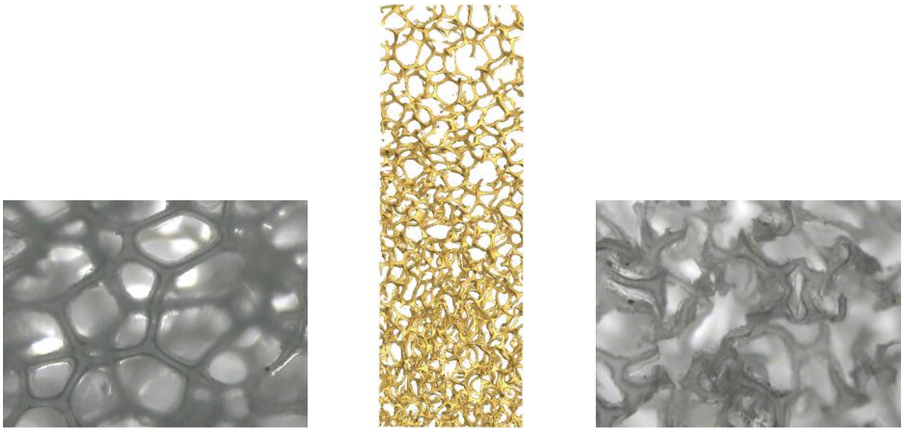


Figure 1. Auxetic knitted samples (example fabrics)



(a) Normal foam (b) Gradient foam (c) Auxetic foam
Figure 2. Auxetic polymer foams

Auxetic materials are those which expand when stretched transverse to the direction of the stretch (exhibiting a negative Poisson's ratio) (Alderson & Alderson, 2007).In addition auxetic materials narrow in the transverse direction when compressed. They may also exhibit a double curvature when bent and enhanced energy and sound absorption among other properties.

These materials are under investigation in several research projects around the world, but there are currently no commercially available products that purposefully exploit auxetic behaviour. Several areas for commercial product development have been proposed including health and medical, personal protection, sportswear, composites, sensors etc. (Liu & Hu, 2010; Auxetix 2006). The design of a product would aim to lift the research field out of a theoretical position into a tangible one with the possibility of publicity.

In order to achieve the desired effects, groups will have to liaise with Martha Glazzard (weft-knits) and Kim Alderson (foams) about the materials and their tailoring possibilities. There will be an initial ideation session and possibilities for further contact.

Working with two researchers in auxetics the task is to propose a suitable product that demonstrates the material properties of weft-knitted auxetic textiles and/or auxetic polymer foams. Examples of these materials will be made available and limited quantities available for groups creating prototypes.
The weft-knitted textiles are produced on standard textile manufacturing machinery. They can be altered in several ways within a range of functionalities and aesthetics (figure 1).
Auxetic foams are produced by a simple compression and heat setting technique and can be in the form of small blocks (up to car seat size have been reported), thin flat sheets, curved sheets and can have regions of normal and auxetic behaviour i.e. show gradient behaviour (figure 2).

In response to interesting developments from researchers this project aims to demonstrate commercially viable and appealing auxetic products. There is currently a communication gap between the researchers and the public markets, this can be counteracted by communicating to fields including designers and users through materials rather than academic writing (Glazzard & Breedon , 2011).

ASSESSMENT CRITERIA

Part 1 is marked based on the following criteria:

- Teamwork skills and professionalism
- An engaging and detailed description of concepts
- Use of relevant reading and accurate references
- Balanced structure
- Coherent, persuasive and demonstrating deep understanding and analysis
- The use of images, tables and graphs to demonstrate concepts and analysis

Part 2 is marked based on the following criteria:

- Creative exploration of design options and product development.
- Critical reflection on project
- Teamwork skills and professionalism

Part 3 (presentation) is marked based on the following criteria:

- Teamwork skills and professionalism
- Background research
- Structure of the presentation
- Use of Audio-Visual aids
- Clarity of the presentation
- Critical awareness of the design process

REFERENCES AND SUGGESTED READING

ALDERSON, A. and ALDERSON, K.L., 2007. Auxetic materials. *Proceedings of the Institution of Mechanical Engineers – Part G – Journal of Aerospace Engineering,* 221 (4), 565-575.

AUXETIX LTD, 2010. *Auxetix: Expanding Technology* [online]. Available at: http://www.auxetix.com/index.htm [Accessed September 19 2011].

GLAZZARD, M. and BREEDON, P., 2012. Designing a Knit Methodology for Technical Textiles. *In: Smart Design: First International Conference Proceedings, 22-24 November 2011.* Springer, pp. 103-108.

LIU, Y. and HU, H., 2010. A review on auxetic structures and polymeric materials. *Scientific Research and Essays,* 5 (10), 1052-1063.

Group D: AUXETIC MATERIALS 70% Brief
Investigating the use of auxetic knitted textiles or auxetic foams.

Introduction:

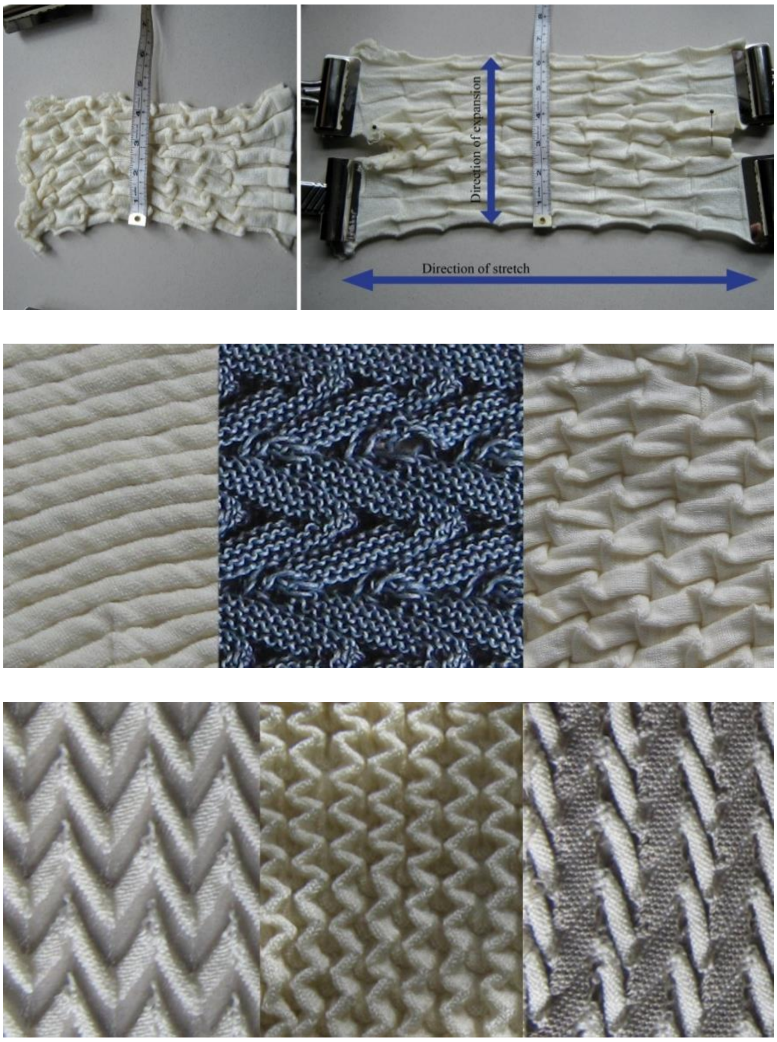
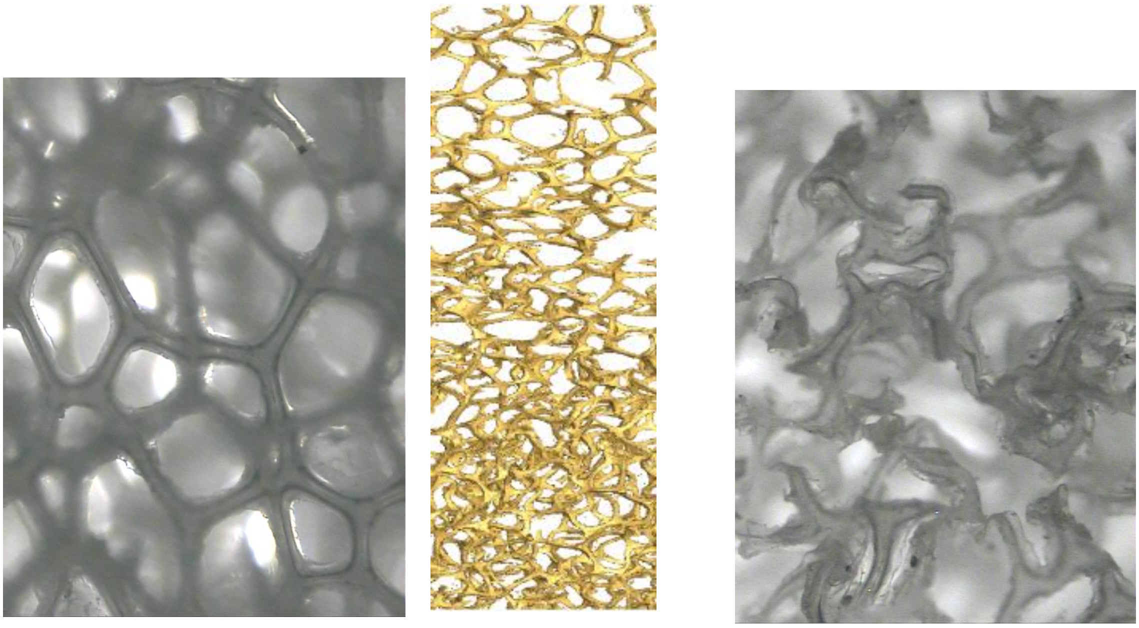


Figure D1. Auxetic knitted samples (example fabrics)



(a) Normal foam (b) Gradient foam (c) Auxetic foam

Figure D2. Auxetic polymer foams

Auxetic materials are those which expand when stretched transverse to the direction of the stretch (exhibiting a negative Poisson's ratio) (Alderson & Alderson, 2007). In addition auxetic materials narrow in the transverse direction when compressed. They may also exhibit a double curvature when bent and enhanced energy and sound absorption among other properties. These materials are under investigation in several research projects around the world, but there are currently no commercially available products that purposefully exploit auxetic behaviour. Several areas for commercial product development have been proposed including health and medical, personal protection, sportswear, composites, sensors etc. (Liu & Hu, 2010; Auxetix 2006). The design of a product would aim to lift the research field out of a theoretical position into a tangible one with the possibility of publicity.
In order to achieve the desired effects, groups will have to liaise with Martha Glazzard (weft-knits) and Kim Alderson (foams) about the materials and their tailoring possibilities. There will be an initial ideation session and possibilities for further contact.

The Project
Working with the two researchers in auxetics, the task is to propose a suitable product that demonstrates the material properties of weft-knitted auxetic textiles and/or auxetic polymer foams. Examples of these materials will be made available for testing and experimentation. Alternatively, negotiations to make bespoke materials can be negotiated with the group.

The weft-knitted textiles are produced on standard textile manufacturing machinery.
They can be altered in several ways within a range of functionalities and aesthetics (see Figure D1).
Auxetic foams are produced by a simple compression and heat setting technique and can be in the form of small blocks (up to car seat size have been reported), thin flat sheets, curved sheets and can have regions of normal and auxetic behaviour i.e. show gradient behaviour (see Figure D2). Instructions will be provided in order to manufacture foams to desired dimensions.

In response to developments from researchers this project aims to demonstrate commercially viable and appealing auxetic products. There is currently a communication gap between the researchers and the public markets, this can be counteracted by communicating to fields including designers and users through materials rather than academic writing (Glazzard & Breedon, 2011). Due to practical research by Alderson and Glazzard, there is a real possibility for prototype development of auxetic foam and fabric products.

Following from the initial research during the literature review and ideation segment (30% module weighting), the market of plasters, tapes and bandages for either medical or sport markets has been suggested. In the literature there are some references to bandages that may provide drug-release and mentions made of support bandages. Existing literature only explores theoretical applications and uses and a physical prototype along with supporting testing information would be a huge contribution to auxetics research.

You are expected to develop a proposal for a product/group of related products around the area of fabric or foam plasters, support bandages and medical tapes. Methods of adhesive and sterile padding will need to be explored.
Various modelling and testing will be expected in which the body's physicality and movement will be explored. Various scales of product should be trialled, e.g. finger joint plaster, heel plaster, knee bandage, etc.
Textile support can be negotiated in good time, with or through Martha Glazzard. Materials will be able to be cut, seamed and edges secured as needed.

The outcomes will indicate understanding and consideration of the following:

- testing methods
- fitness for purpose
- scale of product
- ergonomics/body movement
- comparison to existing products
- adhesives, sterilisation and fabric/foam material
- user instructions
- unique selling point that an auxetic material has in this application over conventional products.

Due to the emergent nature of this type of research, possibilities for development remain flexible and the findings will be of significant interest to academic researchers from a global auxetic materials network. Kim Alderson and Martha Glazzard are interested in the development work shown along the way and any novel insights provided from practitioners in the Smart Design/Advanced Product Engineering specialist area. The 10th annual conference on Auxetic Materials takes place summer 2013 in Poznan, Poland and would welcome applications from researchers and practitioners in design fields.

You will consider the materials needed and how the auxetic behaviour contributes to the end use. Consider the properties of the materials you are using and how those might be used to best effect in a product.

REFERENCES AND SUGGESTED READING

ALDERSON, A. and ALDERSON, K.L., 2007. Auxetic materials. *Proceedings of the Institution of Mechanical Engineers – Part G – Journal of Aerospace Engineering,* 221 (4), 565-575.

AUXETIX LTD, 2010. *Auxetix: Expanding Technology* [online]. Available at: http://www.auxetix.com/index.htm [Accessed September 19 2011].

GLAZZARD, M. and BREEDON, P., 2012. Designing a Knit Methodology for Technical Textiles. *In: Smart Design: First International Conference Proceedings, 22-24 November 2011*. Springer, pp. 103-108.

LIU, Y. and HU, H., 2010. A review on auxetic structures and polymeric materials. *Scientific Research and Essays,* 5 (10), 1052-1063.

The Requirements:

Part D1 (40 % of coursework)

1. A prototype using auxetic foams and/or knitted fabrics (this must not be more than 50cm^3)
2. Description of product for discussion

Part D2 (40 % of coursework)

Based on the findings,

1. Supporting developmental work (sketchbooks, references, ideation session, samples, evidence of discussion with researchers etc.)
2. Evidence of testing methods and justification of choices regarding testing.
3. Results from testing and development presented in ways suitable to a varied audience.
4. Personal reflection on working in a team (500 words)

Part D3 (20% of coursework)

1. A 10 minute presentation demonstrating the work from 1&2 above. This will focus on the research, concepts and proposed product/s
2. A poster showing visualisations and product information

Assessment:

Parts D1 and D2 are marked based on the following criteria:

- Coherent, persuasive and demonstrating deep understanding and analysis.
- Teamwork skills.

- An engaging and detailed description of concepts.
- Use of relevant case studies and references.
- Balanced structure.
- Accurate referencing.
- The use of figures, tables and graphs to demonstrate concepts and analysis.
- Quality and analysis of the design work.

Presentation, Part D3 is marked based on the following criteria:

- Teamwork skills.
- Background research.
- Structure of the presentation.
- Use of Audio-Visual aids.
- Clarity of the presentation.
- Analysis of the design.
- Time management.