An investigation of made-to-measure compression garments and their utility during running

Jack Ashby

A thesis submitted in partial fulfilment of the requirements of Nottingham Trent University for the degree of Doctor of Philosophy.

October 2021

Abstract

The effects of wearing made-to-measure compression garments on exercise performance and recovery has not been extensively examined. Most of the published research literature has opted to use 'off the shelf' standard sized compression garments (i.e., small, medium and large), which may not provide optimal fitting and consequently may not elicit the expected pressures. The research presented within this thesis was undertaken to examine the effect of wearing made-to-measure compression garments, developed using 3D scanning, on running biomechanics and thermal responses. The research within the thesis also presents novel methodologies for measuring compression garment pressures and examines the reliability and validity of 3D scanning.

The purpose of the first study was to develop a novel method to examine compression garment pressures and to determine the pressure profile (peak pressure and pressure gradient) on different aspects of the leg. Fifteen males volunteered to participate (age 24.6 ± 2.0 years, stature 178.9 ± 4.5 cm, body mass 77.4 ± 6.5 kg, mean ± standard deviation). Garment pressures were assessed from the malleolus to the gluteal fold using a Kikuhime pressure monitoring device which consists of a pressure transducer attached to a sensor that transmits pressure readings to the transducer with a typical error of measurement of ±1 mmHg. The sensor was pulled up the leg in 5 cm increments. Three-dimensional motion capture was used simultaneously with pressure measurements to quantify the measurement locations. Pressure assessment was performed on the anterior, posterior, lateral and medial aspects of the right leg. Pressure assessment was also performed at the anatomical locations used in previous research, defined as the established method (three medial lower leg, and three anterior upper leg locations; Brophy-Williams et al., 2014; Brophy-Williams et al., 2015). The main findings from the study were that peak pressure at the ankle was typically higher when measurements were made on the posterior (18.3 to 27.5 mmHg) and anterior (16.6 to 27.6 mmHg) compared to the lateral (12.4 to 21.2 mmHg) and medial (12.2 to 23.0 mmHg) aspects of the upper, lower and whole leg. The pressure gradient was steeper when measurements were made on the posterior (-21.7 to -26.9 mmHg) and anterior (-22.1 to -23.2 mmHg) compared to the lateral (-11.0 to -15.3 mmHg) and medial (-13.9 to -19.3 mmHg) aspects of the upper, lower and whole leg. The root mean squared difference was smaller for pressure measurements made on the posterior (1.8 ± 0.4 mmHg) compared to the lateral (2.7 ± 0.5 mmHg), anterior (3.1 ± 1.1 mmHg) and medial (3.2 ± 1.1 mmHg) aspects of the whole leg, when pressure measurements were made using the novel method. When comparing the novel method to the established method, the peak pressure at the ankle was higher when using the novel method (27.5 ± 2.2 mmHg) compared to the established method (19.8 ± 3.0 mmHg), when pressures were measured over the whole leg. The pressure gradient was also steeper using the novel method (-21.7 ± 2.9 mmHg) compared with the established method (-11.2 ± 4.5 mmHg). The measured pressure profile (peak pressure and pressure gradient) of a compression garment is significantly influenced by the aspect of the leg, and the posterior aspect showed the smallest variation of pressure. Therefore, pressure

measurements should be made using the posterior aspect of the whole leg using the novel method which provides more pressure measurements compared to the established method which allows a more informative reflection of the elicited pressure across the whole leg.

The purpose of the second study was to make made-to-measure compression garments that elicit pressures within and below clinical standards and establish whether pressures and gradients could be replicated between participants in different garment conditions. Ten males volunteered to participate (age 24.3 ± 4.6 years, stature 181.5 ± 1.8 cm, body mass 75.7 ± 3.8 kg, mean ± standard deviation). Based on three-dimensional scans of the participants' lower body, three different made-to-measure garments were manufactured: control, high gradient and asymmetrical. The control garment was designed to elicit pressure below clinical standards (< 14 mmHg) with no pressure gradient. The high gradient garment was designed to elicit pressure within clinical standards (14 – 35 mmHg) and to include a linear pressure gradient from distal to proximal (graduated compression). The asymmetrical garment was designed to elicit control conditions in the left leg and high gradient garment conditions in the right leg. Garment pressures were assessed using the method developed in study one (posterior). A root mean squared difference analysis was used to calculate the in-vivo linear graduation parameters. Linear regression showed that peak pressure at the ankle in the left and right leg were: control garment, 13.5 ± 2.3 and 12.9 ± 2.6; asymmetrical garment, 12.7 ± 2.5 and 26.3 ± 3.4; high gradient garment, 27.7 ± 2.2 and 27.5 ± 1.6 (all mmHg, mean ± standard deviation). The pressure reduction from the ankle to the gluteal fold in the left and right leg were: control garment, 8.9 ± 3.5 and 7.4 ± 3.0; asymmetrical garment, 7.8 ± 3.9 and 21.9 ± 3.2; high gradient garment, 25.0 ± 4.1 and 22.3 ± 3.6 (all mmHg, mean ± standard deviation). The results demonstrated that made-to-measure compression garments can be made to elicit pressures within and below clinical standards, and to elicit equivalent pressures and gradients in different participants and between participants' legs.

The purpose of the third study was to examine the reliability (test-retest, intra- and inter-day) and validity of 3D scanning to measure leg volume. Fifteen males volunteered to participate (age 24.6 ± 2.0 years, stature 178.9 ± 4.5 cm, body mass 77.4 ± 6.5 kg, mean ± standard deviation). The volume of the lower and upper legs was examined using two consecutive 3D scans and water displacement (criterion) at baseline, 1 hour post baseline (intra-day) and 24 hours post baseline (inter-day). Reliability (test-retest, intra- and inter-day) and validity of the 3D scanner were compared to the water displacement criterion method, using Bland and Altman limits of agreement, Pearson's product moment correlations, and paired samples t-tests. The 3D scanner method provided better test-retest reliability than the water displacement method as the 3D scanner had smaller systematic bias and limits of agreement (±1-1%, and 3-5% respectively) compared to the water displacement method (1-2% and 4-7% respectively), for lower leg and upper leg volume measurements. The intra- and inter-day reliability was also better for the 3D scanner evidenced by narrower limits of agreement for intra-day reliability (3D scanner: 4-7%, and water displacement: 8-20%) and inter-day reliability (3D scanner: 5-6%, and water displacement: 9-16%). The 3D scanner was also found to be a valid method for measuring upper leg volume as the systematic bias and limits of agreement were within 10% of volume measurements made using the criterion water displacement method. The results suggest that the use of 3D scanning may be a reliable and valid method to measure leg volume.

The purpose of the fourth study was to examine the effect of border removal and region of interest size on skin temperature outputs of thermal images (thermograms) using a sensitivity analysis, before and after exercise. Ten males volunteered to participate (age 23.5 ± 2.8 years, stature 181.9 ± 4.8 cm, body mass 76.2 ± 5.3 kg, mean ± standard deviation). Participants performed a 30-minute submaximal run on a treadmill and thermograms were captured of the upper and lower, anterior and posterior legs, before and after exercise using an infrared thermal imaging camera. Temperature data was extracted from the thermograms using a custom MATLAB® program which performed 2% increments of border removal from the unadjusted border, and 5% reductions of the region of interest size (length reduction) from the unadjusted length. A sensitivty analysis was performed to examine the influence of border removal and region of interest size on skin temperature. The sensitivity analysis showed that overall, the mean and maximum skin temperature had no to small sensitivity to the removal of the border and region of interest size on the thermograms. However, it was found that the inclusion of the region of interest border reduced skin temperature outputs between 0.14-0.24°C, at baseline and post exercise. The results suggest that the border of a thermogram should be removed when selecting a region of interest for analysis. Furthermore, regions of interest should be carefully selected over the specific area under investigation to reduce the influence of hot and cold areas within the thermogram caused by underlying tissues (muscle and bone).

The purpose of the fifth study was to examine the effect of wearing made-to-measure compression garments, with different pressure profiles, on thermal responses and comfort perception before and after exercise. Ten males volunteered to participate (age 23.5 ± 2.8 years, stature 181.9 ± 4.8 cm, body mass 76.2 ± 5.3 kg, mean ± standard deviation). Participants performed a 30-minute submaximal run on a treadmill whilst wearing four made-to-measure compression garments that differed in pressure and pressure gradient. The garment conditions were: 1) control garment which was designed to elicit pressure below clinical standards (< 14 mmHg) with no pressure gradient; 2) high gradient garment which was designed to elicit pressure within clinical standards (14–35 mmHg) and to include a steep pressure gradient from distal to proximal (graduated compression), 3) medium gradient garment which was designed to elicit pressure within clinical standards (14–35 mmHg) and to include a shallower pressure gradient from distal to proximal than the high gradient garment, and 4) asymmetrical garment which was designed to elicit control conditions in the left leg and high gradient in the right. Thermograms were captured of the upper and lower, anterior and posterior legs, at baseline, after a warm-up and after exercise, using an infrared thermal imaging camera. Participants completed a comfort questionnaire, comprised of multiple visual analogue scales, before and after exercise.

Temperature data was extracted from the thermograms using a custom MATLAB® program which standardised the regions of interest which were determined using the results from study four. The results revealed no differences of mean skin temperature between garment conditions at any time point ($P > 0.05$) and mean skin temperature change from baseline to post run ranged between 1.4 – 2.0°C, 1.1 – 1.5°C, 1.6 – 1.8°C and 1.2 – 1.7°C for the lower anterior and posterior, and the upper anterior and posterior leg segments respectively, in all four compression garment conditions. General comfort was lower for the left leg and right leg in the medium gradient garment (left: 7.9 ± 2.7, and right: 8.0 ± 2.7) compared to the control (left: 12.7 ± 1.8, and right: 12.8 ± 1.6), and asymmetrical (left: 12.1 ± 1.9, and right: 11.6 ± 2.2) garment conditions ($P < 0.05$). The pressure profile elicited by made-to-measure compression garments had no effect on thermal responses, and skin temperatures were not elevated to levels which would be associated with reductions in exercise performance (i.e., > 35°C). However, compression garments with higher pressures may provide greater discomfort, thus, there must be an optimal balance between wearer comfort and elicited pressures.

The purpose of the sixth study was to examine the effect of wearing made-to-measure compression garments, with different pressure profiles, on running biomechanics. Nine males volunteered to participate (age 22.9 ± 2.1 years, stature 182.0 ± 5.1 cm, body mass 76.4 ± 5.6 kg, mean ± standard deviation). Participants performed a 30-minute submaximal run on an instrumented treadmill whilst wearing made-to-measure compression garments that differed in pressure and pressure gradient. The garment conditions were identical to those of study five which were: control, high gradient, medium gradient and asymmetrical garments. Kinematics, kinetics and heart rate were measured during the run. Principal component analysis (PCA) was conducted to compare running kinematic and the kinetic variables of ground reaction force, joint powers, joint moments, joint angles and joint angular velocities, between compression garment conditions. The PCA results showed no differences between compression garment conditions for kinematic and kinetic variables, evidenced by a lack of data clustering. Heart rate was lower in the high gradient (128 ± 32 bpm) and medium gradient (127 ± 32 bpm) garments compared to the control (133 ± 33 bpm) garment condition ($P = 0.039$ and $P = 0.011$ respectively). The lower heart rate suggests that made-to-measure compression garments do not effect running kinematics and kinetics but may provide a cardiovascular benefit during submaximal running.

Overall, made-to-measure compression garments can be developed to elicit the same prescribed pressure profiles between participants. Moreover, the application of 3D scanning used to support the manufacture of the made-to-measure garments may also be used to reliably measure leg volume. Furthermore, when worn during submaximal running at 20.5 ± 0.8°C, made-to-measure compression garments with different pressure profiles do not elevate skin temperature to temperatures associated with performance decrements (i.e., > 35°C), and do not influence running biomechanics but may provide cardiovascular benefits as evidenced by reduced heart rate.

Dissemination of Research

Journal Articles

Ashby, J., Lewis, M., Sanchis-Sanchis, R., Sunderland, C., Barrett, L. A., & Morris, J. G. (2021). Customised pressure profiles of made-to-measure sports compression garments. *Sports Engineering*, *24*(1), 12. https://doi.org/10.1007/s12283-021-00350-5

Poster Presentations

Ashby, J., Lewis, M., Sanchis-Sanchis, R., Sunderland, C., & Morris, J. G. (2019). The assessment of pressure profiles in made to measure compression garments. British Association of Sport & Exercise Sciences, King Power Stadium.

Oral Presentations

Ashby, J. (2019). The effect of made-to-measure compression garments on performance and recovery. University of Valencia, Spain.

Acknowledgements

Firstly, I would like to thank my amazing supervisory team, Dr John Morris, Dr Martin Lewis, Dr Caroline Sunderland, and Dr Laura Barrett. It has been a privilege to work under your supervision and words cannot express how grateful I am for the opportunities you have all provided to allow me to develop as a researcher. You are all geniuses in your own right, and I will forever be in your debt for the outstanding supervision you have provided. I have been very lucky to have you as supervisors and I am hopeful that we can continue our work together in the future.

I would like to thank all the participants who took the time to participate in my research, without you, the research would not have been possible. I would like to thank the Sport Science technician team, Terry, Beverly, Jodie and Tom. You have all provided unwavering support and assistance throughout my research. No matter what issues arose during my data collections you were all able to assist in some way. Thank you to Nottingham Trent University as an institution. The facilities and professional development opportunities that have been provided during my PhD have been excellent and have no doubt progressed my abilities as an academic.

I would like to give a special thanks to Dr Maria Bisele, Dr Roberto Sanchis-Sanchis and Paul Bromley. Maria, you have given up many hours helping me throughout my PhD journey and I am forever grateful for your support. No amount of coffee could repay the debt I owe you! Roberto, No puedo agradecerle lo suficiente por la ayuda que brindó durante mi recopilación de datos. Incluso cuando estás a 1349 millas de distancia, siempre has estado ahí para ayudarme. Eres un verdadero amigo. Paul, thank you for providing the compression garments to perform this PhD, and thank you for providing the opportunities to gain invaluable industry experience.

To my mum and dad, you have provided me with every opportunity to grow and develop as a person. I know the past few years have been the most difficult of our lives but the love and support you have given me during this time has been invaluable and has motivated me to complete this PhD.

Finally, thank you to my partner Chella. You have always been there through the good and bad days and supported me to finish this PhD. Although you do not fully understand my work, thank you for your enthusiasm and listening to my thoughts, ideas, descriptions, and explanations. There have been moments when getting to this point seemed light years away, but you always provided the love, support and encouragement to progress. I hope that the completion of this PhD will allow me to provide you with the future that you truly deserve. Thank you for everything.

Table of Contents

List of Figures

List of Tables

Key Abbreviations and Glossary

Abbreviations

3D	Three-dimensional
VO_{2max}	Maximum oxygen uptake
PCA	Principal component analysis
ANOVA	Analysis of variance
RMSD	Root mean squared difference
SD	Standard deviation
LOA	Limits of agreement
ln	Logarithmic transformation
WD	Water displacement
mmHg	Millimetres of mercury
GRF	Ground reaction force
RPE	Ratings of perceived exertion

Glossary

Pressure Profile	The peak pressure and pressure gradient from the distal to the proximal end of the leg.
Emissivity	How much infrared radiation an object emits compared to a theoretical maximum amount using a reference 'black body'.
Reflected Temperature	This is used for compensating for the radiation from the surrounding area reflected by the object into the thermal imaging camera.
Atmospheric Temperature	The temperature of the air.
Relative Humidity	The amount of water vapor present in the air.
Object Distance	The distance between the thermal imaging camera and the object being examined.
Region of Interest	An area on a thermogram which is selected to extract temperature data.
Region of Interest Border	Defined as the cooler temperature which surrounds an imaged object.
Principle Component Analysis	A technique used for identification of a smaller number of uncorrelated variables known as principal components from a larger set of data.
Compression Garments	Specialised clothing which consists of elastomeric fibres and yarns used to apply an external, mechanical pressure on the surface of the body for stabilizing, compressing, and supporting underlying tissues.
Leg Length	The shortest distance between the ankle malleolus and the greater trochanter.

Chapter 1: General Introduction

1.1 Origin of Compression Garments

Compression garments are defined as specialised clothing which consist of elastomeric fibres and yarns used to apply an external, mechanical pressure on the surface of the body for stabilizing, compressing, and supporting underlying tissues (MacRae et al., 2011). Evidence of using compression garments dates back centuries and is recorded in the *Corpus Hippocraticum* (450 – 350 BC). The ancient Greek physicians believed that "all wounds, especially those of the lower limbs, contradict standing, sitting or walking" (Felty & Rooke, 2005). Therefore, they used forms of compression to counteract the effect of gravity and upright posture. Over time the understanding of the physiological mechanisms behind compression garments were identified, and by the 19th century adhesive compressive bandages were developed by Thomas Baynton, where they became commercially available to treat venous insufficiencies. As material and clothing technology improved, the first compression socks were developed by an inventor and engineer named Conrad Jobst. Jobst suffered from varicose veins, chronic venous insufficiency, and venous ulcers. However, whilst standing in a swimming pool he noticed that his pain was suppressed. He believed that the graduated compression, where highest pressures are applied at the ankle and reduce vertically, would replicate the experience of standing in the swimming pool. Through this experience he developed the commercially available 'Jobst Venous Pressure Gradient Stocking' (Burgdorf et al., 2015). From these compression stockings beginnings, numerous forms of compression garments have now been designed (and in many cases become commercially available) to target different areas of the body such as: bandaging, wraps, ankle length socks, knee high socks, tights, full body garments, arm sleeves, tops and shorts.

1.2 Compression Garments in Clinical Practice

Compression garments were first used as a clinical treatment to manage deep vein thrombosis (Scurr et al., 2001), chronic-venous insufficiency (Ibegbuna et al., 2003), oedema (Mosti et al., 2015), and burns and scars (Staley & Richard, 1997). Chronic venous disorder is a common condition of the lower limbs in humans and can affect approximately 5-30% of the adult population (Eberhardt &

Raffetto, 2014). Chronic venous disorder includes multiple venous-related conditions. Typical conditions that manifest from chronic venous disorder are reticular veins, varicose veins, oedema and venous ulcers (Meissner et al., 2007). It is widely believed that the pathophysiology of venous insufficiency is caused by primary valvular incompetence and congenital vein wall weakness (Xiong & Tao, 2018). Compression garments have been widely used to treat and manage venous insufficiency. The proposed mechanisms for their efficacy are: increased venous flow, reduced wall distension, improved haemodynamics, improved valvular function (to reduce venous hypertension) and decreased space available for oedema (Xiong & Tao, 2018). In clinical practice there are various compression garment pressure standards depending on the country where the garments are used. British compression standards are applied at three distinct classifications, measured in millimetres of mercury (mmHg). Class 1 (14 – 17 mmHg) garments are applied for varicose veins and mild oedema. Class 2 (18 – 24 mmHg) garments are applied for severe varicose veins, mild oedema, and the prevention of venous ulcer recurrence. Class 3 (25 – 35 mmHg) garments are applied for severe varicose veins, post-phlebitic limbs, ulcer prevention/recurrence and chronic venous insufficiency (Johnson, 2002). Medical-grade compression garments incorporate graduated compression which implies that the garment elicits high pressures at the distal end, with the pressure gradually reducing towards the proximal end of the garment. It has been proposed that applying a pressure gradient improves venous blood flow and venous return (Agu et al., 1999). It has been demonstrated that individuals with symptoms of venous insufficiency benefitted from wearing compression garments which elicited pressure between 10 - 20 mmHg (Amsler & Blättler, 2008). It has also been found that a 4 week application of compression bandaging significantly reduced arm lymphoedema by 38% from baseline values (McNeely et al., 2004). Although there is evidence to support the use of compression garments to treat venous disorders, consistent evidence of a pressure threshold which allows improvements in venous haemodynamic responses is not known within the medical literature (Beliard et al., 2014). Furthermore, this matter is further complicated by the fact that different pressure classifications are used by different countries; for example, in the United Kingdom (UK), France and Germany, specific compression garment pressures correspond to different classifications (Todd, 2015), which increases the difficulty of comparing beneficial pressures within the clinical compression garment research (**Table 1.1**).

Table 1.1. Clinical compression classifications used in the UK, United States of America (USA), France and Germany.

Classification	UK	USA	France	Germany
I	14–17 mmHg	15-20 mmHg	10–15 mmHg	18–21 mmHg
II	18–24 mmHg	20-30 mmHg	15–20 mmHg	23–32 mmHg
III	25–35 mmHg	30-40 mmHg	20–36 mmHg	34–46 mmHg
IV	N/A	>40 mmHg	>36 mmHg	>49 mmHg

1.3 Compression Garments in Sport

The use of compression garments within sport began to increase during the 1980s as the knowledge of their clinical efficacy gained interest within sport and such apparel became more easily available. Compression garments are now used during sports performance as well as during recovery from exercise by a variety of athletes. A recent study by Franke and colleagues (2021) investigated the use of compression garments by athletes and their results demonstrated that out of the 512 participating athletes, 88.1% and 11.9% were endurance athletes and non-endurance athletes respectively. Furthermore, 84.7% of the endurance athletes were runners. The rationale for wearing compression garments also differed between athletes. In total, 47.5% of athletes used compression garments to prevent re-injury, 14.5% used compression garments to reduce symptoms of an existing injury. Other rationales for wearing compression garments included injury prevention (13.6%), post-exercise recovery (14.3%), sports performance enhancement (8.8%) and to improve appearance (0.2%). Although many athletes wear compression garments to prevent injury or re-injury during exercise, there is currently no published research literature that definitively indicates that compression garments have these sorts of prophylactic effects. The published research literature typically examines the efficacy of wearing compression garments on exercise performance and recovery. However, the results of the published studies in this research area are very unclear, as some have demonstrated beneficial effects of wearing compression garments on exercise performance and recovery (Brown et al., 2017; Marqués-Jiménez et al., 2016) whereas others have not (da Silva et al., 2018).

Despite the limited evidence to support the use of compression garments in sport, world records have been achieved whilst wearing compression garments (Ali et al., 2011). For example, 20 km run performance (Lornah Kiplagat, 1:02:57, Udine, Italy, 2007), treadmill marathon performance (Michael Wardian, 2:23:58, Texas, USA, 2004) and outdoor marathon performance (Paula Radcliffe, 2:15:25, London, UK, 2003) world records have all been achieved whilst wearing such garments. Multiple factors contribute to these great achievements, rather than these being solely due to wearing compression garments obviously. However, the athletes' decision to wear a compression garment highlights the belief and confidence in the utility of such garments. In an article series titled "Five Questions With…" January (2021) Paula Radcliffe, one of the Britain's most decorated long-distance runners, was asked: "What running product under £100 has most impacted your running?".

> Paula Ratcliffe responded: "Compression socks. They help with blood circulation over longer races". She also added that wearing compression socks ensures that she "rarely suffers from calf pain".

There are many mechanisms that have been suggested to explain the efficacy of wearing compression garments during exercise. These include: reduced muscle oscillation, which may subsequently reduce muscle fibre recruitment and improve economy (Bringard et al., 2006; Broatch et al., 2020; Hsu et al., 2016), enhanced haemodynamics, as compression garments compress superficial veins, which reduces their diameter (vasoconstriction), which in turn increases the velocity of blood flow and reduces venous pooling (MacRae et al., 2011; Born et al., 2013). Furthermore, increased velocity of muscle blood flow may assist the removal of metabolites (i.e., lactate), both during exercise and during recovery from exercise (Berry & McMurray, 1987; Rimaud et al., 2010). Greater muscle oxygenation has also been suggested as a mechanism which may provide performance enhancements (Coza et al., 2012; Ménétrier et al., 2011). Finally, the use of compression garments has been proposed to reduce the perception of effort during exercise (Ballmann et al., 2019). However, it should be reiterated that the published research literature has consistently failed to definitively evidence any beneficent physiological mechanisms when wearing compression garments during exercise.

The typically equivocal findings of compression garment research studies may be a result of the heterogeneity of study designs which makes comparisons between the research difficult. For example, there has been a large diversity of exercise modalities, garment types and coverage, garment elicited pressures, duration of wear and study populations used in the published compression garment research literature (Beliard et al., 2014; Hill et al., 2014; MacRae et al., 2011). Inherent limitations in the procedures and methods adopted by compression garment research studies may also contribute to the disparate and often conflicting findings that are apparent when seemingly similar studies are compared. Many studies typically use ‘off the shelf’ standard sized compression garments, which are often sized on anthropometric features such as body mass and stature, or sized based on other specific categorisations such as small, medium and large (MacRae et al., 2011). However, it is likely that even individuals who fit within the same garment sizing category will have different body shapes and size, as well as variations in tissue structure (Hill et al., 2014). As a result, different pressures and pressure gradients may be experienced by a study’s participants and many individuals may experience pressures below those required for haemodynamic improvements (Brown et al., 2020), which may limit the efficacy of a compression garment intervention. Therefore, it may be beneficial to use made-to-measure compression garments which are sized specifically for an individual based on their specific body geometry. This may provide an optimal fit as well as allow similar pressures to be experienced within a study population. Recently some studies have been published that investigated the effect of made-to-measure compression garments, designed using 3D scanning of the participants’ body geometry, on recovery from exercise (Brown et al., 2020; Brown et al., 2021). However, no research has been conducted to investigate the effect of such garments during exercise.

Given that made-to-measure compression garments may not be feasible for some studies, the pressure elicited by the standard sized garments, used as the alternative, must be directly measured and reported. To not do so is a crucial limitation of any study performed in this area of research. However, much of the published compression garment research literature that has used standard sized compression garments have not reported the pressures elicited by the garments they used, or they have relied on manufacturer reported values rather than directly measuring the pressures elicited by the garment used (Hill et al., 2015). As a result, any benefits of wearing compression garments cannot be accurately linked to specific elicited pressures, particularly when it has been demonstrated that manufacturer reported pressure values (typically generated using wooden leg models) are not necessarily accurate indicators of the actual pressures elicited in human participants (Partsch, et al., 2006). The accurate reporting of the pressures elicited by specific compression garments would aid considerably the future prescription of the optimal pressure values that should be applied given specific sporting requirements. Furthermore, by measuring and reporting the elicited pressures of standard sized compression garments, the variation of pressures experienced within a study population could be identified and quantified. However, there is no definitive standard methodology used within the published research literature to measure garment elicited pressures. As a result, a standard methodology to measure the elicited pressure of compression garments is required.

The placebo effect is a potential issue that must be controlled for within compression garment research, as participants may have preconceived beliefs in their efficacy (MacRae et al., 2011). Some of the published research literature has used loose fitted clothing or garments with elicited pressure that is greatly reduced (Armstrong et al., 2015; de Glanville & Hamlin, 2012; Higgins et al., 2009). However, non-compressive or loosely fitted clothing can be easily distinguished from a compression garment (Kraemer et al., 1996). Brophy-Williams and colleagues (2018) highlighted a potential placebo effect as they found that participants who believed in the efficacy of compression garments performed better in consecutive 5 km time trials compared to participants that did not believe in the efficacy of such garments. Systematic reviews have highlighted the difficulty of developing an appropriate placebo design and the requirement for further investigation of strategies to overcome the possible placebo effects within compression garment research studies is clearly required (da Silva et al., 2018; MacRae et al., 2011). Therefore, the development of an effective placebo to offset any placebo effects within compression garment research has potential utility.

1.4. Type of Sports Compression Garments

There are many different types of sports compression garments that are used in the research literature, which provide coverage over different areas of the body. Some garments are designed for the lower body such as compression socks, tights, shorts and calf sleeves. Conversely, some compression garments are designed for the upper body such as compression tops and arm sleeves. Moreover, compression suits are also available which offer whole body coverage **(Figure 1.1).**

Figure 1.1. Demonstrates different forms of sports compression garments which are used within the compression garment research literature.

1.5. Summary and General Aims

There is an accumulation of evidence to support the use of compression garments in clinical practice. However, such evidence to support their use within sporting environments and situations, particularly with respect to improving exercise performance or enhancing the recovery process, is limited at best. The ambiguity within the findings of the research that has been conducted previously is likely due to many factors including the use of standard sized garments and the lack of measuring and reporting elicited garment pressures. Therefore, the general aim of this PhD was to overcome the identified limitations of the previously published research by using made-to-measure compression garments in the studies conducted in this thesis, as well as by developing a novel method to directly measure pressures elicited by the compression garments used. Furthermore, the PhD aimed to examine the use of made-to-measure compression garments on running biomechanics and thermal responses which has received limited examination up to now. The specific studies described in the remainder of this thesis are outlined in **Figure 1.2**

1.6 Thesis Experimental Chapters, Aims and Structure

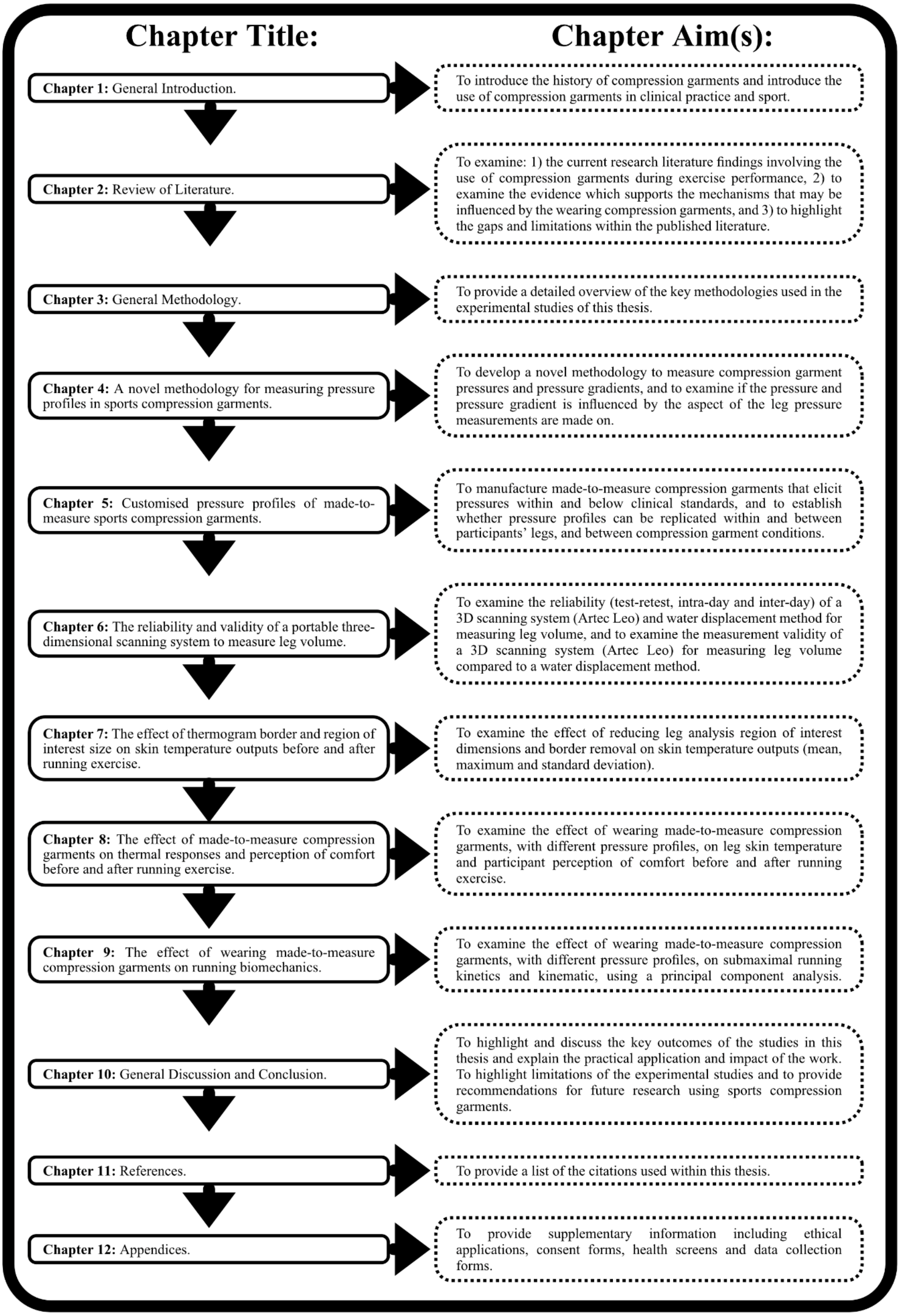


Figure 1.2. An overview of the thesis structure and chapter titles and aims.

Chapter 2: Review of the Literature

2.1 Introduction

This chapter discusses the beneficial, negative and trivial effects of wearing of compression garments in various sporting situations. Furthermore, the chapter critically discusses factors which may contribute to the equivocal research findings that are typically seen when the compression garment literature is interrogated. The chapter also summarises the published research literature which has investigated the potential mechanistic explanations for why wearing compression garments could improve exercise performance and / or enhance the recovery process following exercise. Finally, the literature review discusses the sizing and fit of compression garments as well as the pressure devices and techniques used to quantify the pressures elicited by compression garments. Tables, succinctly summarising the design and findings of published research studies which have examined the effects of wearing compression garments, have been specifically developed for each section of the literature review.

2.2 Maximal and Submaximal Endurance Performance

A number of research studies have investigated whether compression garments aid endurance performance (Burden & Glaister, 2012; Dascombe et al., 2011; Kerhervé et al., 2017; Scanlan et al., 2008; Sperlich et al., 2010). Successful endurance performance is not dependent on a single underpinning mechanism or characteristic, rather, there are many simultaneous mechanisms or characteristics which contribute to the endurance capabilities of a sports performer when exercising. The mechanisms which contribute to exercise endurance are: maximal oxygen uptake, lactate threshold, muscle capillary density, stroke volume, maximum heart rate, haemoglobin content, anaerobic enzyme activity, power output, muscle fibre composition, cardiac function, muscle blood flow, muscle oxygenation, metabolite clearance, biomechanics and economy (Fallowfield & Wilkinson, 1999; Joyner & Coyle, 2008). Many studies have examined the effect of wearing compression garments on different endurance exercise tasks such as time to exhaustion (Kemmler et al., 2009; Rimaud et al., 2010; Sperlich et al., 2010), time trials (Brophy-Williams et al., 2019; Scanlan et al., 2008; Kerhervé et al., 2017;

MacRae et al., 2012) and fixed-load exercise (Ali et al., 2010; Areces et al., 2015). Although compression garments have been shown to both improve (Kemmler et al., 2009) and impair (Rider et al., 2014) endurance performance, arguably, the weight of evidence in the existing published research literature suggests that compression garments provide no improvements to endurance performance. Rider and colleagues (2014) examined the effect of wearing below the knee compression stockings on running endurance. Ten, cross-country runners performed a run to exhaustion on a treadmill with and without (control) wearing compression stockings that elicited pressure of 20 and 15 mmHg at the ankle and calf respectively (manufacturer reported values). The study's results showed that wearing compression garments reduced time to exhaustion compared to the control condition (compression stocking: 23.57 ± 2.39 min vs. control: 23.93 ± 2.49 min, $P = 0.04$). Although statistically different, the difference between time to exhaustion was less than half a minute. Kemmler and colleagues (2009) also examined the effect of wearing below knee compression stockings on running endurance. Twenty-one moderately trained athletes performed a run to exhaustion on a treadmill with and without (control) wearing compression stockings that elicited pressure of 24 and 18-20 mmHg at the ankle and calf respectively (manufacturer reported values). Wearing compression garments increased time to exhaustion compared to the control condition (compression stocking: 36.44 ± 3.49 min vs. control: 35.03 ± 3.55 min, $P < 0.05$, $d = 0.40$). In another study, Sperlich and colleagues (2010) examined the effect of wearing different types of compression garments on running endurance. Fifteen trained runners performed a run to exhaustion on a treadmill wearing compression stockings (below knee), tights, a whole body garment or no compression garment (control). The elicited pressure of each garment was targeted to be 20 mmHg, but this was not measured directly (a common issue with many studies). The study's results indicated that there were no differences for run to exhaustion time between any of the conditions ($P > 0.05$). Similar results, namely little evidence of a beneficial effect of wearing compression garments, have been observed in studies that have used cycling and running time trial and fixed-load endurance exercise protocols (Ali et al., 2011; MacRae et al., 2012; Scanlan et al., 2008).

There are some factors that may explain the ambiguity of findings within the published research literature. The pressure elicited by compression garments differ between studies and a review by Beliard and colleagues (2014) showed that measured pressure in the reviewed studies varied from 1.1 to 34.3 mmHg at the ankle and from 8.0 to 27.0 mmHg at the calf. Furthermore, they found no influence of the level of compression on exercise performance outcomes, which was also noted more recently (Mota et al., 2020). However, the vast majority of the studies in the published literature which have examined the efficacy of compression garments have not directly quantified the elicited pressure of the compression garments used and only report the manufacturer claimed pressure values. If garment pressures are not directly measured it is difficult to be confident of the pressures elicited by the garment, particularly when it has been shown that garment pressures can vary between individuals even if they fit within the same sizing category (Brophy-Williams et al., 2015; Hill et al., 2015). Given that pressures vary between participants, it may be beneficial to investigate individual participant responses to establish if the performance outcome of a participant is related to the pressures experienced (i.e., high pressures = beneficial effects; low pressures = no effect). The type of compression garment used also differs between studies with compression socks (stockings), tights, calf sleeves, shirts and whole-body suits all reported in the literature. It is possible that the type of compression garment used may influence exercise performance and the effect of different types of garment requires further investigation. However, regardless of the influence of the factors discussed above, currently the weight of evidence in the existing published research literature suggests that compression garments have no effect on endurance performance (and this is clear from the final column "Outcomes" in **Table 2.1**.

Table 2.1. Summary of the published research literature investigating the influence of compression garments on endurance performance.

Authors	**Participants**	**Design**	**Protocol**	**Exercise Modality**	**Garment**	**Garment Pressures (mmHg)**	**Performance Measures**	**Outcomes**
Areces et al., (2015)	40, male, marathon runners	Between group (compression vs. control)	Marathon running	Endurance	Socks	20 – 25 (manufacturer values)	Marathon performance time	↔ No effect on marathon performance ($P > 0.05$)
Dascombe et al., (2011)	11, male, competitive runners	Within group (RCT: regular fit vs. undersized fit vs. control)	Progressive max running test (PMT) & time to exhaustion run @ 90% VO_{2max}	Endurance	Tights	**Regular-sized** Upper Leg: 13.7 ± 2.3 Lower Leg: 19.2 ± 3.2 **Undersized** Upper Leg: 15.9 ± 2.6 Lower Leg: 21.7 ± 4.3	Time to exhaustion performance time	↔ No effect on time to exhaustion performance ($P > 0.05$)
Sperlich et al., (2010)	15, well trained, endurance athletes	Within group (RCT: compression socks vs. compression tights vs. whole body compression vs. control)	Run to exhaustion test	Endurance	Socks, tights & whole body	20 (not measured – based on previous article)	Run to exhaustion performance time	↔ No effect on run to exhaustion performance ($P = 0.16$)
Kemmler et al., (2009)	21 males	Within group (RCT: compression vs. control)	Run to exhaustion test	Endurance	Stockings	Calf: 18-20 Ankle: 24 (manufacturer values)	Run to exhaustion performance time	↑ Increase in time to exhaustion ($P < 0.05$, $d = 0.4$)

Table 2.1. Summary of the published research literature investigating the influence of compression garments on endurance performance (*continued*).

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Ménétrier et al., (2011)	14, male, moderately trained	Within group (RCT: compression vs. control)	Run to exhaustion @ 100% max aerobic ventilation	Endurance	Calf sleeves	Calf: 27 Ankle: 15 (manufacturer values)	Run to exhaustion performance time	↔ No effect on run to exhaustion performance ($P > 0.05$)
Del Coso et al., (2014)	40 triathletes	Between group (compression vs. control)	Half-iron-man triathlon	Endurance	Ankle-to-knee stockings	Not reported	Half-iron-man triathlon race time	↔ No effect on triathlon race performance ($P > 0.05$)
Rider et al., (2014)	7 male, 3 female, cross-country runners	Within group (RCT: compression vs. control)	Treadmill run to exhaustion	Endurance	Stockings	Ankle: 20 Calf: 15 (manufacturer values)	Run to exhaustion performance time	↓ Decrease in time to exhaustion ($P < 0.05$)
Brophy-Williams et al., (2019)	12, male, trained runners	Within group (RCT: compression vs. control)	5 km running TT (TT1) & 60 min rest & subsequent 5 km running TT (TT2)	Endurance	Socks	Calf: 37 ± 4 Upper ankle: 31 ± 4 Lower ankle: 23 ± 4	TT1 & TT2 performance time	↔ No effect on TT1 and TT2 between conditions ($P > 0.05$) ↓ Performance decrement was significantly reduced from TT1 to TT2 in the compression condition ($P < 0.001$, $d = 0.67$)
Scanlan et al., (2008)	12, male, trained cyclists	Within group (RCT: compression vs control)	1 hr cycling TT & incremental cycle to exhaustion test	Endurance	Tights	GM: 9.1 ± 2.2 VL: 14.9 ± 2.3 Calf: 17.3 ± 3.0 Ankle: 19.5 ± 3.4	TT cycling performance time & cycle to exhaustion performance time	↔ No effect on TT cycling performance ($P > 0.05$) ↔ No effect on incremental cycle to exhaustion time ($P > 0.05$)

Table 2.1. Summary of the published research literature investigating the influence of compression garments on endurance performance (*continued*).

Authors	**Participants**	**Design**	**Protocol**	**Exercise Modality**	**Garment**	**Garment Pressures (mmHg)**	**Performance Measures**	**Outcomes**
Berry & McMurra, (1987)	6, highly fit, males	Within group (compression vs. control	VO_{2max} test in 2 min stages (time to exhaustion)	Endurance	Stockings	Ankle: 18 Calf: 8	VO_{2max} test (time to exhaustion) time	↔ No effect on cycle to exhaustion performance ($P > 0.05$)
Rimaud et al., (2010)	8, trained males	Within group (compression vs. control	Maximal incremental cycling test to exhaustion (work increased 30 W every 2 min)	Endurance	Stockings	Calf: 22 Ankle: 12 (manufacturer values)	Cycling test to exhaustion performance time	↔ No effect on cycle to exhaustion performance ($P > 0.05$)
Ali et al., (2011)	9 male, 3 female runners	Within group (low vs. med vs. high compression vs. control)	10 km running TT on an outdoor track	Endurance	Below knee stockings	**Low** Ankle: 15 Knee: 12 **Med** Ankle: 21 Knee: 18 **High** Ankle: 32 Knee: 23 (manufacturer values)	10 km running TT performance time	↔ No effect on running 10 km TT time ($P = 0.99$)
Bieuzen et al., (2014)	11 male, trained runners	Within group (RCT: compression vs. control)	Simulated 15.6 km trail race (6.6 km uphill & 9.0 km downhill)	Endurance	Below knee stockings	25 (constant pressure)	Simulated trail race performance time	↔ No effect on 15.6 km trail race performance ($P > 0.05$)

Table 2.1. Summary of the published research literature investigating the influence of compression garments on endurance performance (*continued*).

Authors	**Participants**	**Design**	**Protocol**	**Exercise Modality**	**Garment**	**Garment Pressures (mmHg)**	**Performance Measures**	**Outcomes**
Varela-Sanz et al., (2011)	**Part 2:** 12, endurance trained runners	**Part 2:** Between group (compression vs. control)	**Part 2:** Run to exhaustion test @ 105% participants' best 10 km time (17 ± 2 $km \cdot h^{-1}$)	Endurance	Socks	15 – 22 (manufacturer values)	Run to exhaustion time	↔ No effect on run to exhaustion test ($P > 0.05$) Note: participants ran for 13% longer in the compression group (d = 0.32)
MacRae et al., (2012)	12, trained male cyclists	Within group (RCT: over-sized (OSG) vs. correctly sized (CSG) compression garment vs. control)	60 min fixed-load cycling at ~65% VO_{2max} & 6 km time trial	Endurance	Full Body	**CSG** Forearm: 13 Thigh: 11 Calf: 15 **OSG** Forearm: 9 Thigh: 8 Calf: 13	Cycling 6 km time trial performance	↔ No effect on cycling 6 km TT performance time ($P > 0.05$)
Kerhervé et al., (2017)	14, trained males	Within group (RCT: compression vs. control)	24 km trail run	Endurance	Calf sleeves	Calf: 23 ± 2	24 km trail run performance time	↔ No effect on 24 km trail run performance time ($P > 0.05$)

VL = Vastus Lateralis; GM = Gluteus Maximum; RCT = Randomised Control Trial; VO_{2max} = Maximal Oxygen Consumption; VO_2 = Oxygen Consumption; W = Watts; CSG = Correctly Sized Garment; OSG = Over Sized Garment; TT = Time Trial; ↓ significant decrease; ↑ significant increase; ↔ no change

2.3 High Intensity Sprint Performance

Single and repeated sprints that are separated by short recovery periods are routine in team sports such as football, rugby and hockey (Di Salvo et al., 2007; Spencer et al., 2005). There are multiple factors which may contribute to repeated sprint performance including neuronal and metabolic factors such as muscle fiber recruitment, aerobic and anaerobic energy production, and the ability to recover between repeated sprints or short duration, high intensity exercise (Bishop et al., 2011; Bishop & Edge, 2006; Turner & Stewart, 2013). Given that compression garments may influence the factors that contribute to successful single and repeated sprint exercise, some research has suggested that wearing compression garments during sprints may be beneficial for performance (Born et al., 2013). It has been shown that wearing a whole body compression garment during high intensity intermittent exercise increased muscle oxygenation compared to wearing no garment (Sear et al., 2010). The increase in oxygenation availability may delay the progression of fatigue during intense intermittent exercise (Tachi et al., 2004). Furthermore, blood flow has been shown to increase during submaximal and maximal exercise, when wearing compression garments (Broatch et al., 2017; Dascombe et al., 2011). The increase of blood flow during exercise, particularly during repeated sprint exercise, has been suggested to improve anaerobic waste removal (i.e., lactate) (Berry & McMurray, 1987). Although some evidence suggests that the removal of lactate is increased following exercise (Rider et al., 2014), the existing research does not support this notion during exercise as blood lactate concentrations do not seem to be influenced by wearing compression garments (Born et al., 2014; Broatch et al., 2017; Faulkner et al., 2013). The wearing of compression garments increases muscle pump function and venous return in clinical practice (Agu et al., 1999; Watanuki & Murata, 1994) and it has been suggested that these mechanisms may explain the elevated blood flow during exercise. Many different single sprint and repeated exercise tests have been utilised within the published compression garment literature which include different sprint distances (15 m - 400 m) (Houghton et al., 2009; Venckunas et al., 2014) and different exercises tasks such as cycling, running and team sport simulations (Ballmann et al., 2019; Faulkner et al., 2013; Higgins et al., 2009). However, inconsistent findings exist within the published literature. In a two part study by Born and colleagues (2014) participants performed 30 x 30 m sprints with an active recovery jog back to the start line in part one and part two of the study, with and without wearing compression tights. In part one of the study, sprint time, cardio-respiratory, metabolic, haemodynamic and perceptual responses were examined during the exercise. In part two of the study, sprint time, neuronal and biomechanical responses were examined. The results in part one showed sprints 21-30 were completed faster in the compression garment condition (P = 0.02, d = 0.37) and these results were replicated in part two (P = 0.01, d = 0.61) of the study. Participants' rating of perceived exertion was lower, hip flexion was reduced and step length was increased in the compression garment condition. The authors concluded that compression garments improve 30 m repeated sprint performance by reducing perceived exertion and by altering running technique. Broatch and colleagues (2017) also found beneficial effects of wearing compression tights during 4 sets of 10 x 6 second cycling sprints. The results showed that when averaged over all of the sprints, peak power was higher in the compression garment condition compared to the no compression (control) condition (compression = 773.4 ± 198.3 watts; control = 733.6 ± 196.0 watts, $P < 0.05$). Conversely, other research has found no benefits of wearing compression garments on single or repeated sprint exercise. Doan and colleagues (2003) examined the effect of wearing compression shorts on 60 m sprint performance. Participants performed 2 x 60 m sprints while wearing compression shorts or without compression shorts (control). Hip and knee joint range of motion were measured during each 60 m sprint. The results showed that during the 60 m sprint, hip range of motion was reduced in the compression garment condition (P = 0.04). The reduction of hip range of motion agrees with the findings of Born and colleagues (2014). However, 60 m sprint times were not different between conditions ($P > 0.05$). Other studies have also found no effect of wearing compression garments on high intensity sprint performance (Bernhardt & Anderson, 2005; Duffield et al., 2008; Duffield & Portus, 2007). Given, that wearing compression garments have been shown to improve high intensity sprint performance for some exercise tests but not others, it may be possible that beneficial effects are test and mode specific. For example, in **Table 2.2** the included studies that involved cycling sprints typically benefitted from wearing compression garments, whereas the included studies that involved 20 m running sprints showed no benefits. Furthermore, as seems emblematic of research in this area, many of the studies did not measure or report the pressures elicited by the garment they used (Bernhardt & Anderson, 2005; Doan et al., 2011;

Duffield & Portus, 2007; Higgins et al., 2009; Houghton et al., 2009). As such, while it is possible that compression garments may produce beneficial effects on high intensity sprint performance, until elicited pressures are accurately quantified, this hypothesis is difficult to examine robustly. Thus, further research is warranted to examine the effect of different garment pressures on sprint performance using a range of sprint tests and distances.

Table 2.2. Summary of the published research literature investigating the influence of compression garments on sprint performance.

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Born et al., (2014)	12, female athletes	Within group (compression vs. control)	**Sub study 1:** 30 x 30 m sprints **Sub study 2:** 30 x 30 m sprints	Running maximal sprints	Tights	**Sub study 1:** GM: 18.3 ± 4.1 RF: 19.0 ± 4.9 VL: 17.5 ± 4.4 BF: 19.6 ± 4.7 Gast: 21.7 ± 6.0 **Sub study 2:** GM: 20.2 ± 4.3 RF: 20.2 ± 4.9 VL: 18.2 ± 4.1 BF: 19.5 ± 5.6 Gast: 19.9 ± 5.6	30 x 30 m sprint time	**Sub study 1:** ↑ Faster 30 m sprint time for sprints 11-20 ($P = 0.09$, $d = 0.14$) and sprints 21-30 ($P = 0.02$, $d = 0.37$). **Sub study 2:** ↑ Faster 30 m sprint time for sprints 11-20 ($P = 0.08$, $d = 0.25$) and sprints 21-30 ($P = 0.01$, $d = 0.61$).
Higgins et al., (2009)	9, netball players	Within group (RCT: compression vs. placebo vs. control)	15 min simulated netball circuit with 20 m sprints in the 14th min	Running maximal sprints	Tights	Not reported	20 m sprint time	↔ No effect on 20 m sprint time ($P > 0.05$, $d = 0.23$)
Duffield & Portus, (2007)	10, male, club level cricketers	Within group (RCT: 3 different compression garment brands vs. control)	30 min intermittent, repeat-sprint exercise protocol consisting of a 20 m sprint every 1 min, separated by 45 s of submaximal exercise	Running maximal sprints	Whole body (Skins, Adidas & Under Armour	Not reported	20 m repeated sprint time	↔ No effect on 20 m repeated sprint time ($P > 0.05$)

Table 2.2. Summary of the published research literature investigating the influence of compression garments on sprint performance (*continued*).

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Faulkner et al., (2013)	11, male, 400 m runners	Within group (RCT: compression tights vs. compression shorts vs. compression calf sleeves vs. control)	Six, 400 m sprints	Running maximal sprints	Tights, shorts & calf sleeves	**Tights:** ACH: 6.2 ± 1.2 MTJ: 10.1 ± 2.7 MG: 13.2 ± 2.5 LG: 13.2 ± 2.9 ITB: 5.6 ± 0.7 MQ: 7.1 ± 0.6 TFL: 2.0 ± 1.0 MGL: 6.2 ± 1.2 **Sleeves:** ACH: 14.2 ± 2.4 MTJ: 16.6 ± 2.2 MG: 19.9 ± 2.4 LG: 20.7 ± 1.5 **Shorts:** ITB: 5.4 ± 1.5 MQ: 7.6 ± 1.3	400 m sprint time	↔ No effect on 400 m sprint time ($P > 0.05$)
(Ballmann et al., (2019)	12, male, collegiate basketball players	Within group (RCT: compression vs. control)	2 x 30 sec Wingate test	Cycling maximal sprints	Tights	Ankle: 15 – 20 Thigh: 6 – 10 (manufacturer values)	2 x 30 sec Wingate test power & work	↑ Increased mean power output ($P = 0.028$, $d = 0.35$) ↑ Increased total work ($P = 0.027$, $d = 0.36$)
Doan et al., (2003)	10, male & female, track athletes	Within group (RCT: compression vs. control)	60 m sprint	Running maximal sprints	Shorts	Not reported	60 m sprint time	↔ No effect on 60 m sprint time ($P > 0.05$)

Table 2.2. Summary of the published research literature investigating the influence of compression garments on sprint performance (*continued*).

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Bernhardt & Anderson, (2005)	10 males & 3 females	Within group (RCT: compression vs. control)	One, 20m sprint	Running maximal sprints	Shorts	Not reported	20m sprint time	↔ No effect on 20 m sprint time ($P > 0.05$)
Houghton et al., (2009)	10, male, field hockey players	Within group (RCT: compression vs control)	4 x 15 min LIST protocol including a 15 m sprint at the end of each stage	Running maximal sprints	Shorts & top	Not reported	15 m sprint time	↔ No effect on 15 m sprint time ($P > 0.05$)
Broatch et al., (2017)	9 males & 11 females, recreationally active	Within group (RCT: compression vs. control)	4 sets of 10 x 6 s max sprints with 24 s recovery between sprints & 2 min recovery between sets	Cycling maximal sprints	Tights	Thigh: 11.7 ± 2.3 Calf: 26.4 ± 6.4 Ankle: 21.5 ± 8.2	Sprint peak power	↑ Increased peak power during the repeated sprints ($P = 0.001$)
Duffield et al., (2008)	14, male, rugby players	Within group (RCT: compression vs. control)	5 x 20 m repeated sprints protocol following a simulated team sport exercise	Running maximal sprints	Tights	Not reported	20 m sprint time	↔ No effect on 20 m sprint time ($P > 0.05$)
Venckunas et al., (2014)	13, healthy, females	Within group (RCT: compression vs. control)	400 m sprint following 30 min steady state (7:30 min/mile pace for 4 km)	Running maximal sprints	Tights	Thigh: ~ 17 Calf: ~ 18	400 m sprint time	↔ No effect on 400 m sprint time ($P > 0.05$)

RCT = Randomised Control Trial; GM = Gluteus Maximum; RF = Rectus Femoris; VL = Vastus Lateralis; BF = Biceps Femoris; Gast = Gastrocnemius; ACH = Achilles; MTJ = Musculotendinous Junction of Gastrocnemius and Achilles; MG = Medial Gastrocnemius; LG = Lateral Gastrocnemius; ITB= Midiliotibial Band; MQ = Mid-quadriceps; TFL = Tensor Fascia Latae; MGL: Mid-gluteal; LIST = Loughborough Intermittent Shuttle Test; ↑ significant increase; ↔ no change

2.4 Running Economy and Biomechanics

Running economy is defined as the energy required for a standardised velocity of submaximal running and is established by measuring the steady state oxygen consumption ($\dot{V}O_2$) as well as the respiratory exchange ratio at a particular velocity (Saunders et al., 2004). Running economy is strongly correlated with running performance and a 5% improvement in running economy may translate into a 3.8% improvement in distance running performance (Fallowfield & Wilkinson, 1999). In elite runners, running economy has been shown to be a superior predictor of performance compared to maximal oxygen uptake ($\dot{V}O_{2max}$) (Morgan et al., 1989). Runners with good running economy use less oxygen compared to runners with poor running economy when running at identical steady-state speeds (Thomas et al., 1995). It has been shown that when two elite runners with a similar $\dot{V}O_{2max}$ but a one-minute difference in their time to complete 10 km were compared, the athlete with the better running economy completed the 10 km run faster (Saunders et al., 2004). It has been found that running economy can vary up to 30% between runners with a similar $\dot{V}O_{2max}$ (Daniels, 1985). There are multiple factors which may influence running economy. There are many intrinsic and extrinsic factors such as: heart rate, minute ventilation (V_E), core temperature, blood lactate, muscle fiber distribution, muscle metabolism and body composition (stature and body mass) that have been demonstrated to influence running economy (Adams & Bernauer, 1968; Daniels & Daniels, 1992; Morgan et al., 1989; Pate et al., 1992; Saunders et al., 2004; Thomas et al., 1995; Williams & Cavanagh, 1987). Clothing has also been purposed to influence running economy (Daniels, 1985). As such, some authors have suggested that wearing compression garments during exercise may positively influence running economy (Bringard et al., 2006).

Bringard and colleagues (2006) found that wearing compression garments (tights) significantly improved running economy compared to wearing loose shorts (control) whilst running at 12 $km\cdot h^{-1}$. Furthermore, compression garments seemed to improve running economy at 10 $km\cdot h^{-1}$ but it was not statistically different between conditions. No differences in running economy were discerned at 14 and 16 $km\cdot h^{-1}$ running speeds (small sample size, n = 6). A study by Dascombe and colleagues (2011) found that wearing undersized and regular sized compression garments (tights) both negatively influenced running economy compared to wearing shorts (control) whilst running at 8 $km \cdot h^{-1}$. No differences were observed between conditions at 10, 12, 14, 16 and 18 $km \cdot h^{-1}$ running speeds. The authors suggested that the mechanical support applied by the compression garment may have increased resistance to movement whilst running and subsequently increased the oxygen consumption requirement. In contrast, Bringard and colleagues (2006) suggested that the improvements in running economy evident when wearing compression garments may be a result of increased proprioception, muscle coordination, and the propulsive force due to the mechanical support provided by the garment. It may be possible that compression garments which cover joint structures such as the knee (tights), may influence the range of movement of the joint if the elicited pressures of the garment are high enough. Indeed, previous research has found reductions of both hip and knee range of movement when wearing long compression shorts, that covered the hip and knee joints, during running (Borràs et al., 2011). However, the actual pressures elicited by the compression garment which produced these changes were not reported. Given the potential for compression garments to influence running biomechanics, some research has attempted to examine the effect of wearing compression garments on running biomechanics and the subsequent influence on exercise performance and running economy (Stickford et al., 2015; Varela-Sanz et al., 2011).

Biomechanical factors which have been associated with improved running economy include: lower vertical oscillation; greater leg stiffness; low lower limb moment of inertia; less leg extension at toe-off; larger stride angles; alignment of the ground reaction force and leg axis during propulsion; maintaining arm swing; low thigh antagonist–agonist muscular coactivation; and low activation of lower limb muscles during propulsion (Moore, 2016). However, few studies have directly examined the influence of wearing compression garments on biomechanics and running economy. Varela-Sanz and colleagues (2011) investigated the use of compression stockings on running economy, biomechanics and running performance. In part one of the study, 16 endurance trained athletes performed 4 x 6-min running bouts at a recent half-marathon pace (14.8 ± 2.2 $km \cdot h^{-1}$) with and without wearing compression stockings, to examine running economy. In part two of the study, 12 endurance trained athletes were divided into two groups: compression garment group (n = 6) and no compression garment control group (n = 6). Both groups completed a time to exhaustion running test on a treadmill at a gradient of 1% and a speed of 105% of the athletes' recent 10-km time (mean running speed: 17 ± 2 $km \cdot h^{-1}$). Performance time, running economy, heart rate, and biomechanical variables of contact time, flight time, foot height, power generated, frequency, and stride length were examined during the run to exhaustion. In part one of the study, the results showed that running economy was not different between conditions ($P > 0.05$). In part two of the study, although the percentage of maximum heart rate was significantly lower in the compression garment group ($P > 0.05$), this did not correspond to a difference in running economy ($P > 0.05$). For the run to exhaustion, no group differences were found for performance time and any of the running biomechanical variables ($P > 0.05$). Stickford and colleagues (2015) investigated the effect of lower leg compression garments on running biomechanics and economy. Sixteen, highly trained male distance runners ran in 4-min stages at speeds of 14 $km \cdot h^{-1}$, 16 $km \cdot h^{-1}$, and 18 $km \cdot h^{-1}$ on a treadmill either wearing compression calf sleeves (15-20 mmHg) or a no compression control. Various running biomechanical variables, including ground-contact time, swing time, step frequency, and step length, were measured during submaximal running stages. No differences were found between conditions for running economy and running biomechanics at all running speed stages ($P > 0.05$).

Relatively few studies have examined the effect of wearing compression garments on both running biomechanics and running economy. However, the evidence suggests that compression garments may have little to no influence on running biomechanics and running economy (**Table 2.3** and **Table 2.4**). The studies by Stickford and colleagues (2015) and Varela-Sanz and colleagues (2011) both used compression garments that were applied to the lower leg (calf sleeves and socks respectively). The limited contact of these lower leg compression garments over upper leg joint structures may explain the findings as some evidence suggests garments that cover the hip and knee may influence biomechanics (Born et al., 2014; Borràs et al., 2011). Moreover, Stickford and colleagues (2015) and Varela-Sanz and colleagues (2011) did not measure elicited pressure of the compression garments used and opted to report the manufacturer stated pressures. This approach makes it difficult to correlate any biomechanical or physiological changes to elicited garment pressures and it has been shown that standard sized compression garments may elicit pressures lower than published recommendations (Hill et al., 2015). As a result, relying on manufacturer stated garment pressures is a major limitation of research studies in this area. Therefore, future research is clearly warranted which examines the influence of compression tights with different levels of compression (directly measured and accurately quantified) on running biomechanics, and whether changes in running biomechanics influences running economy.

Table 2.3. Summary of the published research literature investigating the influence of compression garments on biomechanics.

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Born et al., (2014)	12 females	Within group (compression vs. control)	30 x 30 m sprints	Maximal sprints	Tights	GM: 20.2 ± 4.3 RF: 20.2 ± 4.9 VL: 18.2 ± 4.1 BF: 19.5 ± 5.6 Gast: 19.9 ± 5.6	Hip flexion, step length, step frequency & muscle activation (EMG) during the 30 m sprints	↓ Reduced hip flexion (P = 0.01, *d* = 2.28) ↑ Increased step length (P = 0.01, *d* = 0.91) ↔ No effect on step frequency (P = 0.34, *d* = 0.20) ↑ Increased muscle activation of the RF muscle (P = 0.01, *d* = 1.24)
Borràs et al., (2011)	9, active, males	Within group (compression on one leg vs. control on the other leg)	40 min run @ anaerobic threshold and -10% gradient	Endurance	Shorts	Not reported	Muscle oscillation, stride frequency & stride length during 40 min run	↔ No effect on stride frequency ($P > 0.05$) ↔ No effect on stride length ($P > 0.05$) ↓ Reduced muscle oscillation on the leg with compression ($P < 0.05$)
Borràs et al., (2011)	8, active, males	Within group (compression shorts vs. standard Lycra shorts vs. control)	Running @ 10, 11, 12 and 13 $km{\cdot}h^{-1}$	Endurance	Shorts (covering knee)	Not reported	Hip angle, knee angle, stride length and stride frequency during the run	↓ Reduced hip range of movement ($P < 0.05$) ↓ Reduced knee range of movement ($P < 0.05$) ↔ No effect on stride length ($P > 0.05$) ↔ No effect on stride frequency ($P > 0.05$)

Table 2.3. Summary of the published research literature investigating the influence of compression garments on biomechanics (*continued*).

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Stickford et al., (2015)	16, male, trained runners	Within group (RCT: compression vs. control)	Running 4 min stages at 3 speeds of 233, 268, and 300 m/min	Submaximal running	Calf sleeve	15 – 20 (manufacturer values)	Ground contact time, swing time, step frequency & step length during each 4 min running stage	↔ No effect on ground contact time (P > 0.05) ↔ No effect on swing time (P > 0.05) ↔ No effect on step length (P > 0.05) ↔ No effect on step frequency (P > 0.05)
(Varela-Sanz et al., 2011)	16, endurance trained runners	Between group (compression vs. control)	Run to exhaustion test @ 105% of participants best 10 km time (17 ± 2 $km \cdot h^{-1}$)	Endurance	Socks	15 – 22 (manufacturer values)	Ground contact time, flight time, foot height, generated power, step frequency & step length during the run to exhaustion test	↔ No effect on ground contact time (P = 0.90) ↔ No effect on flight time (P = 0.75) ↔ No effect on foot height (P = 0.75) ↔ No effect on power (P = 0.75) ↔ No effect step frequency & length (P = 0.82 & P = 0.32)

Table 2.3. Summary of the published research literature investigating the influence of compression garments on biomechanics (*continued*).

Authors	**Participants**	**Design**	**Protocol**	**Exercise Modality**	**Garment**	**Garment Pressures (mmHg)**	**Performance Measures**	**Outcomes**
Hsu et al., (2016)	8, male, recreational runners	Within group (RCT: compression vs. control)	40 min, treadmill running @ 75 % VO_{2max}	Submaximal running	Tights	Shank: 32 ± 2 Thigh: 22 ± 2 Hip: 16 ± 2	Muscle activation (EMG) during the 40 min run	↓ Reduced gastrocnemius muscle activation ($P < 0.05$) ↓ Reduced rectus femoris muscle activation ($P < 0.05$) ↓ Reduced gluteus maximus muscle activation ($P < 0.05$)
Lucas-Cuevas et al., (2015)	20 male & 20 female, recreational runners	Within group (RCT: compression vs. control)	30 min treadmill run @ 80% of participants max aerobic speed	Submaximal running	Below knee stockings	Ankle: 24 Calf: 21 (manufacturer values)	Head & tibia acceleration, step frequency & step length during the 30 min run	↔ No effect on step length & step frequency ($P > 0.05$) ↔ No effect on head peak acceleration ($P > 0.05$) ↓ Reduced tibial peak acceleration ($P < 0.05$) ↓ Reduced shock attenuation ($P < 0.05$)
Lucas-Cuevas et al., (2017)	21 males & 15 females	Within group (RCT: compression vs. control)	20 min treadmill run @ 75% of participants max aerobic speed	Submaximal running	Below knee stockings	Ankle: 24 Calf: 21 (manufacturer values)	Muscle activation (EMG) during the 20 min run	↓ Reduced gastrocnemius lateralis muscle activation at 0 & 5 min ($P < 0.05$, $\eta_p^2 = .245$ & $P < 0.05$, $\eta_p^2 = .326$) ↓ Reduced gastrocnemius medialis muscle activation at 0 min ($P < 0.05$, $\eta_p^2 = .233$)

Table 2.3. Summary of the published research literature investigating the influence of compression garments on biomechanics (*continued*).

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Broatch et al., (2020)	**Sub study 1:** 13 male, recreationally active **Sub study 2:** 14 male, recreationally active	**Sub study 1:** Within group (compression vs. control) **Sub study 2:** Within group (Nike compression vs. 2XU compression vs. Under Armour compression vs. Control)	**Sub study 1:** 2 x 4 min treadmill run @ 12 & 15 km·h^{-1} (2 min at each speed) **Sub study 2:** 4 x 9 min treadmill runs @ 8, 10 & 12 km·h^{-1} (3 min at each speed)	Submaximal running	Tights	**2XU** A: 13.2 ± 2.9 B: 17.2 ± 6.2 C: 21.8 ± 6.0 D: 12.0 ± 2.2 E: 12.1 ± 2.3 F: 10.7 ± 2.9 **Nike** A: 9.1 ± 2.5 B: 14.6 ± 4.9 C: 21.5 ± 5.1 D: 11.3 ± 2.1 E: 12.9 ± 2.7 F: 12.7 ± 2.1 **Under Armour** A: 7.7 ± 3.1 B: 11.4 ± 4.7 C: 18.9 ± 6.3 D: 13.3 ± 3.1 E: 13.2 ± 3.1 F: 12.6 ± 2.9	**Sub study 1:** Muscle displacement (oscillation) & muscle acceleration during each running speed **Sub study 2:** Muscle displacement (oscillation), tissue vibration & muscle activation (EMG)	**Sub study 1:** ↔ No effect on thigh & calf muscle displacement at 12 & 15 km·h^{-1} ($P > 0.05$) ↓ Reduced thigh & calf muscle acceleration at 12 km·h^{-1} ($P < 0.05$) **Sub study 2:** ↓ Reduced thigh & calf displacement at 8 km·h^{-1} [2XU garment] ($P < 0.05$) ↓ Reduced thigh & calf displacement at 10 km·h^{-1} [2XU & Under Armour garments] ($P < 0.05$) ↔ No effect on thigh & calf muscle displacement at 15 km·h^{-1} ($P > 0.05$) ↓ Reduced thigh & calf tissue vibrations at 8 km·h^{-1} [thigh; 2XU & Nike garments, calf; 2XU garment] ($P < 0.05$) ↓ Reduced calf tissue vibrations at 10 km·h^{-1} [Under Armour garment] ($P < 0.05$) ↓ Reduced thigh tissue vibrations at 12 km·h^{-1} [2XU garment] ($P < 0.05$) ↓ Reduced thigh & calf muscle activation at 8, 10 & 12 km·h^{-1}[all garments] ($P < 0.05$)

Table 2.3. Summary of the published research literature investigating the influence of compression garments on biomechanics (*continued*).

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Kerhervé et al., (2017)	14, trained males	Within group (RCT: compression vs. control)	24 km trail run	Endurance	Calf sleeves	Calf: 23 ± 2	Ground contact time, ariel time, stride frequency, leg stiffness & vertical stiffness during the 24 km trail run	↑ Increased aerial time ($P < 0.05$) ↑ Increased leg stiffness ($P < 0.05$) ↓ Reduced ground contact time ($P < 0.05$) ↑ Higher vertical stiffness ($P < 0.05$)

GM = Gluteus Maximum; RF = Rectus Femoris; VL = Vastus Lateralis; BF = Biceps Femoris; Gast = Gastrocnemius; EMG = Electromyography; RCT = Randomised Control Trial; A = 5 cm Proximal to Medial Malleolus; B = 10 cm Proximal to Medial Malleolus; C = Medial Maximal Calf Girth; D = 10 cm below E; E = Midpoint of Thigh; 5 cm Proximal to E; ↓ significant decrease; ↑ significant increase; ↔ no change

Table 2.4. Summary of the published research literature investigating the influence of compression garments on running economy.

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Dascombe et al., (2011)	11, male, competitive runners	Within group (RCT: regular fit vs. undersized fit vs. control)	Progressive max running test (PMT) @ 8-10 $km{\cdot}h^{-1}$ & 12-18 $^{km{\cdot}}h^{-1}$	Endurance	Tights	**Regular-sized** Upper Leg: 13.7 ± 2.3 Lower Leg: 19.2 ± 3.2 **Undersized** Upper Leg: 15.9 ± 2.6 Lower Leg: 21.7 ± 4.3	Running economy during progressive max running test	↓ Decreased (improved) running economy at 8 $km{\cdot}h^{-1}$ ($P < 0.05$) ↔ No effect on running economy at 10-16 $km{\cdot}h^{-1}$ ($P > 0.05$)
Bringard et al., (2006)	6, male, trained runners	Within group (RCT: compression tights vs. elastic tights vs. control shorts)	**Part 1:** Running @ 10, 12, 14 & 16 $km{\cdot}h^{-1}$	Submaximal Running	Tights	Not reported	Running economy during submaximal running (part 1)	↓ Decreased (improved) running economy at 12 $km{\cdot}h^{-1}$ ($P < 0.05$) ↔ No effect on running economy at 10, 14 and 16 $km{\cdot}h^{-1}$ ($P > 0.05$)

Table 2.4. Summary of the published research literature investigating the influence of compression garments on running economy (*continued*).

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Broatch et al., (2020)	**Sub study 2:** 14 male, recreationally active	**Sub study 2:** Within group (Nike compression vs. 2XU compression vs. Under Armour compression vs. Control)	**Sub study 2:** 4 x 9 min treadmill runs @ 8, 10 & 12 km·h^{-1} (3 min at each speed)	Submaximal running	Tights	**2XU** A: 13.2 ± 2.9 B: 17.2 ± 6.2 C: 21.8 ± 6.0 D: 12.0 ± 2.2 E: 12.1 ± 2.3 F: 10.7 ± 2.9 **Nike** A: 9.1 ± 2.5 B: 14.6 ± 4.9 C: 21.5 ± 5.1 D: 11.3 ± 2.1 E: 12.9 ± 2.7 F: 12.7 ± 2.1 **Under Armour** A: 7.7 ± 3.1 B: 11.4 ± 4.7 C: 18.9 ± 6.3 D: 13.3 ± 3.1 E: 13.2 ± 3.1 F: 12.6 ± 2.9	Running economy during submaximal running (part 2)	↔ No effect on running economy at 8, 10 and 12 km·h^{-1} ($P > 0.05$)

Table 2.4. Summary of the published research literature investigating the influence of compression garments on running economy (*continued*).

Authors	**Participants**	**Design**	**Protocol**	**Exercise Modality**	**Garment**	**Garment Pressures (mmHg)**	**Performance Measures**	**Outcomes**
Varela-Sanz et al., (2011)	**Part 1:** 16, endurance trained runners **Part 2:** 12, endurance trained runners	**Part 1:** Within group (compression vs. control **Part 2:** Between group (compression vs. control)	**Part 1:** 4 x 6 min running @ recent half marathon pace (14.8 ± 2.2 km·h^{-1}) (running economy test) **Part 2:** Run to exhaustion test @ 105% of participants best 10 km time (17 ± 2 km·h^{-1})	Endurance	Socks	15 – 22 (manufacturer values)	Running economy during submaximal (part 1) and maximal run to exhaustion test (part 2)	↔ No effect on running economy during submaximal running ($P > 0.05$) ↔ No effect on running economy during run to exhaustion test ($P > 0.05$)
(Stickford et al., 2015)	16, male, trained runners	Within group (RCT: compression vs. control)	Running 4 min stages at 3 speeds of 233, 268, and 300 m/min	Submaximal running	Calf sleeve	15 – 20 (manufacturer values)	Running economy during each 4 min running stage	↔ No effect on running economy at the speeds of 233 m/min (14 km·h^{-1}), 268 m/min (16 km·h^{-1}), and 300 m/min (18 km.h^{-1}) ($P > 0.05$)
(Ali et al., 2010)	9 male, 1 female runners	Within group (control vs. low vs. high compression)	40-min treadmill running @ 80 ± 5% maximal oxygen uptake	Submaximal running	Below knee stockings	**Control** Ankle: 4 ± 1 Calf: 4 ± 1 **Low** Ankle: 11 ± 2 Calf: 8 ± 1 **High** Ankle: 26 ± 3 Calf: 15 ± 2	Running economy during 40-min run	↔ No effect on running economy during submaximal running ($P > 0.05$)

RCT = Randomised Control Trial; A = 5 cm Proximal to Medial Malleolus; B = 10 cm Proximal to Medial Malleolus; C = Medial Maximal Calf Girth; D = 10 cm below E; E = Midpoint of Thigh; 5 cm Proximal to E; ↓ significant decrease; ↔ no change

2.5 Recovery from Exercise and Subsequent Performance

A primary desired effect of wearing compression garments to is improve recovery from one bout of exercise to another subsequent bout (MacRae et al., 2011). Ultimately, if compression garments could aid the short-term recovery process from exercise, this may provide benefit when performing subsequent exercise. It has been suggested that wearing compression garments following intense exercise may enhance recovery by influencing markers of exercise induced muscle damage. This includes: reducing the loss of muscle strength, maintaining range of motion, decreasing the sensation of muscle soreness and enhancing the clearance of metabolites such as blood lactate and creatine kinase (Marqués-Jiménez et al., 2016). For short duration exercise such as squat and countermovement jump, as well as sprint and agility the published literature has typically demonstrated no clear benefits of wearing compression garments to improve subsequent exercise performance (Ali et al., 2010; Duffield et al., 2008; Davies et al., 2009; Kraemer et al., 2010).

Although there is limited evidence which supports the use of compression garments to aid subsequent short duration exercise performance (i.e., jumping and sprinting) following an initial bout of exercise, recently some research has demonstrated that compression garment may aid subsequent performance for longer endurance-based exercise. Brophy-Williams and colleagues (2019) examined the effect of wearing compression socks on an initial running 5km time trial and a subsequent running 5km time trial following a one-hour recovery period between the two time trials. The results demonstrated that the time decrement from the first and second 5km time trial was significantly greater in the control (no garment) condition (15.9 ± 8.5 secs) compared to the compression garment condition (6.4 ± 1.9 secs). These results suggest that wearing compression garments during a short one-hour recovery period improves subsequent endurance performance. Similar results have been demonstrated by Driller & Halson (2013) who examined the effect of wearing compression tights on an initial 15min cycling time trial and a subsequent 15min cycling time trial following a one-hour recovery period between the two bouts. The results demonstrated that the mean power output (Watts) decrement from the from the first and second 15 min time trial was significantly greater in the control (no garment) condition (-2.15%) compared to the compression garment condition (-0.20%). The study also found that blood lactate concentrations were significantly lower following the one hour recovery period in the compression garment condition (3.0 ± 1.0 mmol$\cdot$L^{-1}) compared to the control condition (4.0 ± 1.1 mmol$\cdot$L^{-1}). Given that compression garments have been suggested to enhance metabolite clearance following exercise, this may explain the improvement in exercise performance. However, the reduction of blood lactate in a one-hour recovery period following exercise, whilst wearing compression garments, was not found by Brophy-Williams and colleagues (2019).

The discrepancy of results which exists in the published compression garment literature is likely caused by the inconsistent exercise tests applied, body coverage of the compression garments, pressure elicited by the garments and the duration recovery period used. The wearing of compression garments following an initial bout of endurance exercise seems to have a beneficial effect on subsequent exercise (**Table 2.5**).

Table 2.5. Summary of the published research literature investigating the influence of compression garments on subsequent exercise performance following an initial exercise bout and recovery period.

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Brophy-Williams et al., (2018)	12, male runners	Counter-balanced crossover (compression vs. control)	Initial running 5km TT (TT1) followed by 1 hour recovery with or without compression followed by running 5km TT (TT2)	Endurance	Knee high socks	Calf: 37 ± 4 Upper Ankle: 31 ± 4 Lower Ankle: 23 ± 4	Time decrement from TT1 and TT2.	↓ Time difference between TT1 and TT2 was smaller in the compression garment condition ($P < 0.01$).
Driller & Halson (2013)	12, highly trained cyclists	Randomised crossover (compression vs. control)	Initial cycling 15min TT (TT1) followed by 1 hour recovery with or without compression followed by running 15min TT (TT2)	Endurance	Tights	Calf: 20.5 ± 3.1 Thigh: 11.8 ± 2.6	Mean power output decrement from TT1 and TT2.	↓ Mean power output difference between TT1 and TT2 was smaller in the compression garment condition ($P < 0.05$).
De Glanville et al., (2012)	14, trained males	Randomized single-blind crossover (compression vs. control)	Initial cycling 40km TT (TT1) followed by 24 hours recovery with or without compression followed by cycling 40km TT (TT2)	Endurance	Tights	Ankle: 6.0 ± 2.4 Calf: 14.7 ± 2.5 Thigh: 11.8 ± 2.5	Performance time of TT2 and mean power output.	↓ Substantial reduction in time to complete TT2 in the compression garment condition (1.2% vs control). ↑ Mean power output was greater for TT2 in the compression garment condition (3.3% vs control). *P values not reported.

Table 2.5. Summary of the published research literature investigating the influence of compression garments on subsequent exercise performance following an initial exercise bout and recovery period (*continued*).

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Atkins et at., (2020)	30, male basketball players	Between group (compression vs. control)	Baseline performance testing followed by BEST to cause fatigue, immediately followed by performance testing, followed by 15 hours rest with or with compression, followed by final performance testing.	Jumping, sprinting and agility	Tights	Ankle: 7 ± 3 Calf: 10 ± 3 Thigh: 8 ± 2	Vertical jump height, 20-m sprint time, and 5-0-5 agility time.	↔ No effect on vertical jump, 20-m sprint time and agility time for any time points between compression and control groups ($P > 0.05$).
Duffield et al., (2008)	14, male, rugby players	Within group (RCT: compression vs. control)	Simulated team sport exercise, followed by 24 hours of recovery with or without compression, followed by 5 x 20 m repeated sprints protocol.	Running maximal sprints	Tights	Not reported	20m sprint time	↔ No effect on 20 m sprint time ($P > 0.05$)
Jakeman et al., (2010)	17, active females	Between group (compression vs. control)	Baseline jump assessment followed by EIMD protocol, followed by, recovery with or without compression. Jump assessment performed @ 1, 24, 48, 72 and 96 hours post EIMD.	Jumping	Tights	Calf: 17.9 Thigh: 14.9 (based on another study)	Squat and CMJ height	↓ Squat jump decrement was smaller in the compression garment condition @ 24, 48, 72 and 96 hours post EIMD ($P < 0.05$). ↓ CMJ decrement was smaller in the compression garment condition @ 24 hours post EIMD ($P < 0.05$).

Basketball Exercise Simulation Test = BEST; km = Kilometre; m = Metre; TT = Time Trial; ↑ significant increase; ↓ significant decrease; ↔ no change

2.6 Muscle Oscillation

Large impacts occur during exercise, which cause muscle oscillations, also known as muscle vibrations. Muscle oscillation is present during jumping exercise (landing) as well as during the ground contact phase of running. Repeated or long-term muscle oscillations can have detrimental effects on soft tissues, including pain and loss of function, reductions in motor unit firing rates and in muscle contraction force (Broatch et al., 2020; Cronin et al., 2004). Wearing compression garments has been suggested as a potential method to attenuate soft tissue oscillations during dynamic activities (Doan et al., 2003). It has been shown that muscle oscillation of the thigh was reduced during repeated vertical jump exercise when compressive shorts were worn compared with when the shorts were simply 'loose' (Kraemer et al., 1998). Compression garments may assist in supporting muscles during high impact exercise such as running and jumping. A reduction of muscle oscillations may reduce the amount of fatigue sustained due to enhanced neurotransmission and improved mechanics at a molecular level within the muscle (Kraemer et al., 1998). Moreover, it has been suggested that reduced muscle oscillation may optimize the contraction of muscle fibres, thereby assisting mechanical efficiency (Nigg & Wakeling, 2001). If compression garments can enhance mechanical efficiency during exercise, this may have subsequent benefits by reducing energy loss (economy) and muscle fatigue (Bringard et al., 2006).

A study by Broatch and colleagues (2020) was one of the first to show that compression garments reduced muscle oscillation during running exercise. This research was divided into two studies. In the first study, 13 Australian-rules footballers performed 4-min of running on a treadmill at 12 km·h^{-1} (2-min) and at 15 km·h^{-1} (2-min). Reflective markers were placed on vastii (VAS) and gastrocnemii (GAS) muscles and three-dimensional motion capture was used to measure soft tissue oscillation and acceleration. Participants performed each run wearing either loose clothing (control) or compression tights. The study's results showed that wearing the compression tights reduced calf musculature displacement in the medial–lateral axis at 12 km·h^{-1} (1.3 mm, ~13%) and in the anterior–posterior axis at both speeds (up to 1.9 mm, ~20%). Moreover, compression tights reduced thigh musculature displacement in the vertical axis when running at 12 km·h^{-1} (3.1 mm, ~23%). In the second study, 14 recreationally active participants performed a 4 x 9-min treadmill run in 4-min stages at speeds of 8 km·h^{-1}, 10 km·h^{-1} and 12 km·h^{-1}. Participants performed each run whilst wearing either loose clothing (control), 2XU compression tights, Nike compression tights or Under Armor compression tights. Pressures were measured for each garment at 6 anatomical landmarks: A (5 cm proximal to the distal border of the medial malleolus), B (5 cm proximal to A), C (medial aspect of the maximal calf girth), D (anterior aspect of the thigh 10 cm below landmark E), E (midpoint between the inguinal crease and the superior–posterior border of the patella), and F (5 cm proximal to landmark E). The pressures recorded for the 2XU garment were: (A) 13.2 ± 2.9, (B) 17.2 ± 6.2, (C) 21.8 ± 6.0, (D) 12.0 ± 2.2, (E) 12.1 ± 2.3 and (F) 10.7 ± 2.9 (all mmHg). The corresponding pressures for the Nike garment were: (A) 9.1 ± 2.5, (B) 14.6 ± 4.9, (C) 21.5 ± 5.1, (D) 11.3 ± 2.1, (E) 12.7 ± 2.1 and (F) 12.7 ± 2.1 (all mmHg). The pressures for the Under-Armour garment were: (A) 7.7 ± 3.1, (B) 11.4 ± 4.7, (C) 18.9 ± 6.3, (D) 13.3 ± 3.1, (E) 13.2 ± 3.1 and (F) 12.6 ± 2.9 (all mmHg). Similar to study one, three-dimensional motion capture was used to measure soft tissue oscillation. In addition, electromyography (EMG) was used to measure muscle activation of the vastus lateralis (VL), vastus medialis (VM), lateral gastrocnemius (LG), and medial gastrocnemius (MG). Average EMG values were obtained for the VAS and GAS and were used as indicators of vastii and gastrocnemii activation during treadmill running. The second study's results showed that wearing any of the compression garments reduced thigh musculature displacement in the vertical axis for the VAS by up to 4.7 mm (~10%). The 2XU garments were the only garments to reduce GAS displacement, which was evident in the medial–lateral (1.8 mm, ~11%) and vertical (up to 1.1 mm, ~4%) axes. Interestingly, the 2XU garment provided the highest pressures for the lower leg when the garments were compared, which may be a contributing factor to this outcome. Muscle activation was significantly lower in all the garment conditions at all speeds compared to the control condition. Moreover, results showed that activation of the GAS was significantly lower than the VAS at all running speeds. It is possible that a relationship exists between muscle activation and muscle oscillation when wearing compression garments during exercise. Compression garments have been shown to reduce oscillation during high impact exercises (Broatch et al., 2020; Doan et al., 2003). This reduced oscillation seems to provide external support and stability to a muscle; thus, muscle activation is reduced. As muscle activation is reduced, this may allow for greater mechanical efficiency, reduced energy loss and reduced muscle fatigue (Bringard et al., 2006; Nigg & Wakeling, 2001). A reduction in muscle activation may have a beneficial impact on running economy.

The muscle activation changes caused by the use of compression garments (**Table 2.6**) may have an effect on muscle tuning. Muscle tuning is the muscular activation process which responds to the excitation frequency of the impact shock during exercise (i.e., heel strike) (Wakeling et al., 2001). Repeated exposure to large vibrations can have detrimental effects on soft tissue, including pain and loss of function (Cronin et al., 2004). Muscle turning reduces tissue vibrations through increased muscle activation. Therefore, if compression garments can effectively reduce vibration and muscle oscillation during large, frequent impacts, it may reduce the dependence on muscle tuning. As a result, muscle tuning may reduce the activation of a muscle as compression garments provide additional support.

Table 2.6. Summary of the published research literature investigating the influence of compression garments on muscle oscillation during exercise.

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Borràs et al., (2011)	9, active, males	Within group (Compression on one leg vs. control on other)	40 min run @ anaerobic threshold and -10% gradient	Endurance	Shorts	Not Reported	Muscle oscillation during 40 min run	↓ Reduced muscle oscillation
Broatch et al., (2020)	**Sub study 1:** 13, Australian-Rules players **Sub study 2:** 14 male, recreationally active	**Sub study 1:** Within group (compression vs. control) **Sub study 2:** Within group (Nike compression vs. 2XU compression vs. Under Armour compression vs. Control)	**Sub study 1:** 2 x 4 min treadmill run @ 12 & 15 km·h^{-1} (2 min at each speed) **Sub study 2:** 4 x 9 min treadmill runs @ 8, 10 & 12 km·h^{-1} (3 min at each speed)	Submaximal running	Tights	**2XU** A: 13.2 ± 2.9 B: 17.2 ± 6.2 C: 21.8 ± 6.0 D: 12.0 ± 2.2 E: 12.1 ± 2.3 F: 10.7 ± 2.9 **Nike** A: 9.1 ± 2.5 B: 14.6 ± 4.9 C: 21.5 ± 5.1 D: 11.3 ± 2.1 E: 12.9 ± 2.7 F: 12.7 ± 2.1 **Under Armour** A: 7.7 ± 3.1 B: 11.4 ± 4.7 C: 18.9 ± 6.3 D: 13.3 ± 3.1 E: 13.2 ± 3.1 F: 12.6 ± 2.9	**Sub study 1:** Muscle displacement (oscillation) & muscle acceleration during each running speed **Sub study 2:** Muscle displacement (oscillation), soft tissue vibrations during the running bouts	**Sub study 1:** ↔ No effect on thigh & calf muscle displacement at 12 & 15 km·h^{-1} ($P > 0.05$) ↓ Reduced thigh & calf muscle acceleration at 12 km·h^{-1} ($P < 0.05$) **Sub study 2:** ↓ Reduced thigh & calf displacement at 8 km·h^{-1} [2XU garment] ($P < 0.05$) ↓ Reduced thigh & calf displacement at 10 km·h^{-1} [2XU & Under Armour garments] ($P < 0.05$) ↔ No effect on thigh & calf muscle displacement at 15 km·h^{-1} ($P > 0.05$) ↓ Reduced thigh & calf tissue vibrations at 8 km·h^{-1} [thigh; 2XU & Nike garments, calf; 2XU garment] ($P < 0.05$) ↓ Reduced calf tissue vibrations at 10 km·h^{-1} [Under Armour garment] ($P < 0.05$) ↓ Reduced thigh tissue vibrations at 12 km·h^{-1} [2XU garment] ($P < 0.05$)

Table 2.6. Summary of the published research literature investigating the influence of compression garments on muscle oscillation during exercise (*continued*).

Authors	**Participants**	**Design**	**Protocol**	**Exercise Modality**	**Garment**	**Garment Pressures (mmHg)**	**Performance Measures**	**Outcomes**
Doan at al., (2003)	10, male & female, track athletes	Within group (RCT: compression vs. control)	2 – 3 maximal counter-movement jumps	Power	Shorts	Not reported	Muscle oscillation during the jumps	↓ Reduced longitudinal and anterior-posterior thigh musculature oscillation ($P < 0.05$)
Kraemer et al., (1998)	5 male, 5 female, participants	Within group (RCT: compression vs. control)	3 x 6 maximal vertical jumps	Power	Shorts	Not reported	Muscle oscillation during the maximal vertical jumps	↓ Reduced vertical thigh musculature oscillation ($P < 0.05$) ↔ No effect on horizontal thigh musculature oscillation ($P > 0.05$)
Dandrieux et al., (2020)	12, healthy, males	Within group (RCT: compression vs. control)	Running at different intensities (8, 10, 12 $km{\cdot}h^{-1}$ without gradient, 8 km h^{-1} with 10% gradient & 8, 10, 12 $km{\cdot}h^{-1}$ with 10% gradient	Endurance	Shorts	Not reported	Muscle oscillation during each running intensity stage	↓ Reduced thigh musculature oscillation at each intensity level [mean reduction was 31% vs. control] ($P < 0.05$)

RCT = Randomised Control Trial; A = 5 cm Proximal to Medial Malleolus; B = 10 cm Proximal to Medial Malleolus; C = Medial Maximal Calf Girth; D = 10 cm below E; E = Midpoint of Thigh; 5 cm Proximal to E ; ↓ significant decrease; ↔ no change

2.7 Thermal Responses

It is important that sports clothing allows sufficient levels of heat transfer from the athlete to the environment and it is suggested that clothing, including compression garments, may cause excessive thermal insulation and limit sweat transfer, which may prove detrimental for exercise performance (Brownlie et al., 1987; Gavin, 2003). To provide efficient temperature regulation, sweat on the inner layer of clothing must be able to transfer to the outer layer and subsequently evaporate (Zhuang et al., 2002). Some compression garment manufacturers claim their garments aid moisture wicking which may help keep the wearer dry as well as aid thermoregulatory homeostasis (Skins Technology, 2021). Some studies have shown that wearing compression garments during exercise increases skin temperature in the areas covered by the garment at a range of ambient temperatures (16.0 – 23.7°C) (Duffield et al., 2008; Houghton et al., 2009; Priego Quesada et al., 2015). However, the increased skin temperature caused by wearing a compression garment did not correspond to a higher core temperature compared to a no garment control (Duffield et al., 2008; Houghton et al., 2009). Thermal responses to wearing compression garments during exercise have also been investigated in hot and cold environmental temperatures. Goh and colleagues (2011) investigated the effect of wearing compression tights on thermal responses and running performance in hot and cold conditions. Participants ran on a treadmill for 20-min at an intensity of their predetermined ventilatory threshold (submaximal) followed by a run to exhaustion at an intensity equivalent to their maximal oxygen uptake. Participants performed the exercise in four separate conditions: 32°C with compression garment; 32°C without compression garment; 10°C with compression garment; and 10°C without compression garment. Results showed that wearing the compression garment had no effect on core temperature during exercise in both the hot and cold environments compared to wearing no garment ($P > 0.05$). In the recovery period following exercise, core temperature was higher when wearing the compression garment in the hot and cold environments ($P = 0.026$ and $P = 0.028$ respectively). During exercise, thigh and calf skin temperature was higher in the compression garment condition compared to the no garment condition in the cold environment ($P = 0.018$ and $P = 0.01$ respectively). In the hot environment, no differences were evident for the thigh and calf skin temperature between conditions ($P > 0.05$). However, the thermal responses of wearing the compression garment had no effect on time to exhaustion performance in both hot and cold environments between conditions ($P > 0.05$), although a moderate effect size ($d = 0.48$) was found in the hot environment between conditions with participants running on average 16% longer in the compression garment condition. Barwood and colleagues (2013) found that wearing a compression garment during a 5-km time trial, in 35.2°C ± 0.1°C heat, had no effect on aural temperature ($P > 0.05$) but significantly increased quadricep skin temperature compared to the no garment control condition ($P = 0.041$). However, the increase in skin temperature in the compression garment condition had no effect on time trial performance, which was not different between conditions ($P > 0.05$). It has been suggested that the material of which compression garments are composed may insulate the body and limit sweat evaporation and consequently prevent optimal heat transfer (Corbett et al., 2015; Gavin, 2003). However, sweat rate has been shown to be unaffected by the wearing of compression garments during exercise in moderate (17°C) or hot conditions (40°C) when compared to wearing no compression garment ($P > 0.05$) (Houghton et al., 2009; Leoz-Abaurrea et al., 2019).

The published research literature suggests that wearing compression garments elevates skin temperature, but does not increase core temperature in cold or hot conditions (10°C - 35°C), compared to responses seen when wearing no compression garment (**Table 2.7**). Nor does it increase sweat rate in moderate or hot conditions (17°C - 40°C). Furthermore, the increase of skin temperature does not seem to influence exercise performance. Relatively few studies have examined the effect of wearing compression garments on thermal responses and subsequent exercise performance. Therefore, further research is clearly warranted to examine the influence of wearing compression garments using different types of garment, garment pressures, exercise tasks, and exercise durations, in environmental conditions with varying temperature and humidity.

Table 2.7. Summary of the published research literature investigating the influence of compression garments on thermal responses during exercise.

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Goh et al., (2011)	10, male, recreational runners	Within group (RCT: compression @ 10°C vs. control @ 10°C and compression @ 32°C vs. control @ 32°C	Run to exhaustion @ 10°C & 32°C	Endurance	Tights	Calf: 13.6 ± 3.4 Thigh: 8.6 ± 1.9	Run to exhaustion performance time, core temp and skin temp	↔ No effect on core temp during exercise ($P > 0.05$) ↑ Increased (higher) core temp after exercise (recovery period) at 10°C and 32°C ($P = 0.026$ and $P = 0.028$ respectively) ↑ Increased (higher) calf and thigh skin temp during exercise at 10°C ($P = 0.018$ and $P = 0.01$ respectively) ↔ No effect on calf and thigh skin temp during exercise at 32°C ($P > 0.05$) ↔ No effect on time to exhaustion performance at 10°C and 32°C ($P > 0.05$) (On average participants ran 16% longer when wearing compression garments at 32°C)

Table 2.7. Summary of the published research literature investigating the influence of compression garments on thermal responses during exercise (*continued*).

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Barwood et al., (2013)	8, recreationally active males	Within group (RCT: compression tights vs. oversized compression tights (SHAM) vs. control	15 min fixed load running & subsequent 5-km TT @ 35°C	Endurance	Tights	**Compression** Calf: 20 ± 3 Thigh: 11 ± 2 **SHAM** Calf: 17 ± 4 Thigh: 10 ± 2	5-km TT completion time, aural temp, skin temp, TS and TC	↔ No effect on 5-km completion time ($P > 0.05$) ↔ No effect on aural temp during exercise ($P > 0.05$) ↑ Increased (higher) quadriceps skin temp during exercise ($P = 0.041$) ↔ No effect on TS and TC during exercise ($P > 0.05$)
Houghton et al., (2009)	12, male, hockey players	Within group (RCT: normal hockey attire (NORM) vs. compression shorts and top (COMP)	LIST protocol (4 x 15 min exercise bouts) @ 17°C	Intermittent	Shorts and top	Not reported	15 m sprint time, core temp, skin temp and sweat loss	↔ No effect on 15 m sprint time ($P = 0.10$) ↔ No effect on core temp during exercise ($P = 0.25$) ↑ Increased (higher) skin temp during exercise ($P = 0.03$) ↔ No effect on sweat rate during exercise ($P = 0.06$)

Table 2.7. Summary of the published research literature investigating the influence of compression garments on thermal responses during exercise (*continued*).

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Leoz-Abaurrea et al., (2019)	16 (12 males; 4 females), recreational cyclists	Within group (RCT: compression vs. control)	Four bouts of cycling at a fixed load (~50% VO_{2peak}) for 14 min (1 min rest) at 23°C	Intermittent	Top	Not reported	VO_2, TS, core temp, skin temp, garment sweat retention, weight loss and sweat rate	↔ No effect on VO_2 during exercise ($P > 0.05$) ↔ No effect on TS during exercise ($P > 0.05$) ↔ No effect on core and skin temp at the end of exercise ($P > 0.05$) ↔ No effect on garment sweat retention, weight loss and sweat rate ($P > 0.05$)
Priego Quesada et al., (2015)	44 (29 males; 15 females), runners	Within group (RCT: compression vs. control)	30-min submaximal running test (10 min warm-up & 20 min at 75% of their MAS @ 23.7 ± 0.8°C	Submaximal	Below Knee Stockings	Ankle: 20-25 Knee: 15-10 (manufacturer values)	Skin temp	↑ Increased (greater) skin temp change from baseline to immediately post run for the tibialis anterior, ankle anterior, gastrocnemius, vastus lateralis, abductor and semitendinosus compared to control condition ($P = 0.001$ to 0.04) ↔ No effect for temp change from baseline to immediately post run for the rectus femoris, vastus medialis, knee, biceps femoris, popliteal and achilles ($P > 0.05$)

Table 2.7. Summary of the published research literature investigating the influence of compression garments on thermal responses during exercise (*continued*).

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Duffield et al., (2008)	14, male, rugby players	Within group (RCT: compression vs. control)	Two simulated team game protocols (walking, jogging, sprinting & agility) on two days with 24 hrs recovery between days for each condition @ 16-18°C	Intermittent	Tights	Not reported	Weight loss (sweat rate), skin temp and tympanic temp	↔ No effect on change of weight loss between conditions ($P > 0.05$) ↑ Thigh skin temp was consistently higher over the 2 trials in the compression condition ($P = 0.003$) ↔ No effect on tympanic temp at any time point between conditions ($P = 0.67$)
Venckunas et al., (2014)	13, healthy, females	Within group (RCT: compression vs. control)	4 km run @ 7 min 30 sec per km pace followed by a maximal 400 m sprint @ 20-22°C	Endurance	Tights	**Compression** Calf: ~18 Thigh: ~17 **Control** Calf: ~4 Thigh: ~4	Shivering/sweat sensation, TS, core temp and skin temp, weight loss	↔ No effect on weight loss following exercise ($P > 0.05$) ↔ No effect on shivering/sweat sensation and TS at any time point ($P > 0.05$) ↑ Calf skin temp was higher at the end of exercise and during the recovery period ($P < 0.05$) ↔ No effect on core temp at any time point ($P > 0.05$)

Temp = Temperature; RCT = Randomised Control Trial; TT = Time Trial; TS = Thermal Sensation; TC = Thermal Comfort; LIST = Loughborough Intermittent Shuttle Test; VO_2 = Oxygen Consumption; VO_{2peak} = Peak Oxygen Consumption; MAS = Maximal Aerobic Speed; ↑ significant increase; ↔ no change

2.8 Cardiovascular Function

Some compression garment manufacturers have claimed that wearing compression garments can improve cardiovascular function. As haemodynamic responses and muscle oxygenation may alter with the application of compression garments, it might be expected that changes to cardiovascular parameters could be seen as a result of wearing compression garments (Sperlich et al., 2011). However, most studies have found no effect of wearing compression garments on heart rate, stroke volume and cardiac output during maximal (Duffield & Portus, 2007; Kemmler et al., 2009; Rider et al., 2014) and submaximal exercise (Bringard et al., 2006; Houghton et al., 2009; MacRae et al., 2012; Scanlan et al., 2008; Sperlich et al., 2011) (**Table 2.8**). However, a study by Varela-Sanz and colleagues (2011) found that a participant group that wore compression garments, during a run to exhaustion test, maintained a lower percentage of maximum heart rate compared with a control group that wore no compression garment ($P < 0.05$). Furthermore, Dascombe and colleagues (2011) found that heart rate was significantly lower when wearing undersized and regular sized compression garments, compared to a control condition with no compression, during moderate submaximal running at speeds of 12 and 16 $km{\cdot}h^{-1}$. However, during a maximal exercise to exhaustion test, no differences were found for mean heart rate and maximum heart rate. The few studies that have shown reduced heart rate during exercise, have found improvements in exercise performance. At rest, the application of compression has been showed to significantly reduce heart rate in a standing position (Watanuki & Murata, 1994). As increased blood flow and muscle oxygenation has been shown at rest with the use of compression garments (Chohan et al., 2019; Lawrence & Kakkar, 1980), it is possible these changes may reach optimal levels at rest or very low exercise intensities rather than during maximal exercise. Consequently, it is likely that the cardiac and haemodynamic changes produced by more intense exercise would outweigh any measurable changes that would be caused by wearing compression garments.

Generally, compression garments seem to have no influence on oxygen uptake during maximal (Berry & McMurray, 1987; Born et al., 2014; Dascombe et al., 2011; Kemmler et al., 2009; Rimaud et al., 2010) or submaximal exercise (Broatch et al., 2020; Dascombe et al., 2011; Sperlich et al., 2010;

Stickford et al., 2015). However, a few studies have shown that wearing compression garments may lower oxygen uptake during exercise. A study by Bringard and colleagues (2006) showed a 9% reduction in the oxygen cost of running at 10, 12 and 14 $km \cdot h^{-1}$ when participants wore compression tights. However, no oxygen cost reductions were observed when running at 16 $km \cdot h^{-1}$. Whilst Varela-Sanz and colleagues (2011) showed that although running economy was unaffected during submaximal exercise whilst wearing compression garments, during maximal exercise (run to exhaustion) running economy was improved ($d = 0.90$). Given these two studies findings, one might argue it is feasible that compression garments may provide cardiovascular benefits at specific exercise intensities. However, although some studies have demonstrated better running economy whilst wearing compression garments, there is no evidence to suggest that $\dot{V}O_{2max}$ is influenced by wearing compression garments (**Table 2.8**). Further research is required in order to isolate an exercise intensity where compression garments may improve cardiovascular function. However, current research suggests improvements are unlikely at maximal and submaximal exercise intensities.

Table 2.8. Summary of the published research literature investigating the influence of compression garments on cardiovascular responses.

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Born et al., (2014)	12, female athletes	Within group (compression vs. control)	30 x 30 m sprints	Running maximal sprints	Tights	GM: 18.3 ± 4.1 RF: 19.0 ± 4.9 VL: 17.5 ± 4.4 BF: 19.6 ± 4.7 Gast: 21.7 ± 6.0	Oxygen uptake & ventilation during the 30 x 30 m sprints	↔ No effect on oxygen uptake for any of the sprints (P = 0.47 – 0.77, *d* = 0.08 – 0.17) ↔ No effect on ventilation for any of the sprints P = 0.30 – 0.68, *d* = 0.10– 0.31)
Scanlan et al., (2008)	12, male, trained cyclists	Within group (RCT: compression vs control)	1 hr cycling TT & incremental cycle to exhaustion test	Endurance	Tights	GM: 9.1 ± 2.2 VL: 14.9 ± 2.3 Calf: 17.3 ± 3.0 Ankle: 19.5 ± 3.4	VO_{2max} during the cycle to exhaustion	↔ No effect on VO_{2max} during the cycle to exhaustion (P = 0.47, η^2 = 0.22)
Dascombe et al., (2011)	11, male, competitive runners	Within group (RCT: regular fit vs. undersized fit vs. control)	Progressive max running test (PMT) & time to exhaustion run @ 90% VO_{2max}	Endurance	Tights	**Regular-sized** Upper Leg: 13.7 ± 2.3 Lower Leg: 19.2 ± 3.2 **Undersized** Upper Leg: 15.9 ± 2.6 Lower Leg: 21.7 ± 4.3	VO_{2max} during run to exhaustion	↔ No effect on VO_{2max} during the run to exhaustion (P > 0.05)
Sperlich et al., (2010)	15, well trained, endurance athletes	Within group (RCT: socks vs. tights vs. whole body vs. control)	Run to exhaustion test	Endurance	Socks, tights & whole body	20 mmHg (not measured – based on previous article)	VO_{2max} during run to exhaustion	↔ No effect on VO_{2max} during the run to exhaustion (best; P = 0.26, best; *d* = 0.31)

Table 2.8. Summary of the published research literature investigating the influence of compression garments on cardiovascular responses (*continued*).

Authors	Participants	Design	Protocol	Exercise Modality	Garment	Garment Pressures (mmHg)	Performance Measures	Outcomes
Sear et al., (2010)	8, male, amateur team sport athletes	Within group (RCT: compression vs. control)	45 min prolonged high-intensity intermittent exercise (PHIIE)	Team sport simulation	Whole body	MP: 5.3 ± 0.5 MBB: 7.3 ± 2.5 FCR: 5.8 ± 1.0 EOA: 5.9 ± 0.8 Ankle: 17.8 ± 2.2 Gast: 15.1 ± 2.0 VL: 13.1 ± 1.7 GM: 9.2 ± 1.6	VO_{2max} during PHIIE	↔ No effect on VO_{2max} during the PHIIE protocol ($P > 0.05$)
Broatch et al., (2017)	9 males & 11 females, recreationally active	Within group (RCT: compression vs. control)	4 sets of 10 x 6 s max sprints with 24 s recovery between sprints & 2 min recovery between sets	Cycling maximal sprints	Tights	Thigh: 11.7 ± 2.3 Calf: 26.4 ± 6.4 Ankle: 21.5 ± 8.2	VO_2 during the repeated sprints	↔ No effect on VO_2 during the repeated sprints ($P = 0.188$)
Bringard et al., (2006)	6, male, trained runners	Within group (RCT: compression tights vs. elastic tights vs. control shorts)	**Part 1:** Running @ 10, 12, 14 & 16 $km \cdot h^{-1}$ **Part 2:** Running @ 80% maximal VO_2 for 15 min	Submaximal Running	Tights	Not reported	VO_2 and minute ventilation during the 15 min run (part 2)	↓ Reduced (lower) VO_2 slow component during the run wearing compression ($P < 0.05$) ↔ No effect on minute ventilation during the during the run ($P > 0.05$)

Table 2.8. Summary of the published research literature investigating the influence of compression garments on cardiovascular responses (*continued*).

Authors	**Participants**	**Design**	**Protocol**	**Exercise Modality**	**Garment**	**Garment Pressures (mmHg)**	**Performance Measures**	**Outcomes**
Kemmler et al., (2009)	21 males	Within group (RCT: compression vs. control)	Run to exhaustion test	Endurance	Stockings	Calf: 18-20 Ankle: 24 (manufacturer values)	VO_{2max} during run to exhaustion	↔ No effect on VO_{2max} during the run to exhaustion ($P > 0.05$, $d = 0.18$)
Varela-Sanz et al., (2011)	**Part 1:** 16, endurance trained runners **Part 2:** 12, endurance trained runners	**Part 1:** Within group (compression vs. control) **Part 2:** Between group (compression vs. control)	**Part 1:** 4 x 6 min running @ recent half marathon pace (14.8 ± 2.2 km.h^{-1}) (running economy test) **Part 2:** Run to exhaustion test @ 105% of participants best 10 km time (17 ± 2 km.h^{-1})	Endurance	Socks	15 – 22 (manufacturer values)	VO_{2max} during run to exhaustion	↔ No effect on VO_{2max} during the run to exhaustion ($P = 0.09$) A large effect size was found between compression garment and control groups with lower a VO_{2max} in the compression garment group ($d = 1.19$)
Rimaud et al., (2010)	8, trained males	Within group (compression vs. control	Maximal incremental cycling test to exhaustion	Endurance	Stockings	Calf: 22 Ankle: 12 (manufacturer values)	VO_{2max} during cycling test to exhaustion	↔ No effect on VO_{2max} during the cycle to exhaustion ($P > 0.05$)
Rider et al., (2014)	7 male, 3 female cross-country runners	Within group (RCT: compression vs. control)	Treadmill run to exhaustion	Endurance	Stockings	Ankle: 20 Calf: 15 (manufacturer values)	VO_{2max} during run to exhaustion	↔ No effect on VO_{2max} during the run to exhaustion ($P > 0.05$)

MP = Medial Pectoralis; MBB = Medial Biceps Brachii; FCR = Flexor Carpi Radialis; EOA = External Oblique Abominus; Gast = Gastrocnemius; VL = Vastus Lateralis; GM = Gluteus Maximum; RF = Rectus Femoris; BF = Biceps Femoris; RCT = Randomised Control Trial; VO_{2max} = Maximal Oxygen Consumption; VO_2 = Oxygen Consumption; W = Watts; ↓ significant decrease; ↔ no change

2.9 Blood Flow

A purposed mechanism frequently claimed by sports compression garment manufacturers as underpinning the utility of their clothing is increased blood flow and enhanced haemodynamic responses. In clinical practice, compression garments have been shown to provide an external pressure to limbs which constrict dilated veins and reduce venous reflux and oedema (Sarin et al., 1992). In addition, clinical research has found increased ejecting capacity of the calf muscle (muscle pump) when wearing elasticated compression stockings which elicit a peak pressure of 30 mmHg at the ankle (Christopoulos et al., 1990). The muscle pump occurs when blood vessels embedded within a muscle are compressed during contraction of the muscle. The contraction elevates blood pressure which forces the blood through one-way valves and drives the blood back proximally to the heart. Individuals with venous disorders such as a weakened valvular function are susceptible to venous reflux, thus, increasing the likelihood of oedema. Lawrence & Kakkar (1980) showed that compression stockings which elicit pressure of 18, 14, 8, 10 and 8 mmHg at the ankle, calf, knee, lower thigh and upper thigh, respectively, significantly increased deep venous flow velocity in a supine position. However, higher pressures of 30, 26, 14, 18, 12 mmHg at the identical locations increased deep venous flow velocity but also caused a significant impairment of calf subcutaneous tissue flow. Liu and colleagues (2008) investigated the effect of differently pressured compression stockings on venous flow velocity in the lower limbs. Four compression stockings were used in the study which were light, mild, moderate and strong which elicited corresponding pressures of 10.0 – 14.0, 18.4 – 21.2, 25.1 – 32.1, 36.4 – 46.5 mmHg. The results found that venous peak blood flow velocities increased in the popliteal veins by 9.64%, 25.74%, 29.91% and 26.47% from baseline values, in the light, mild, moderate and strong conditions respectively, when applied for 170 min. It is proposed that compression garments compress superficial tissues which subsequently compress underlaying veins to reduce their diameter, increasing velocity and reducing venous pooling (MacRae et al., 2011). However, haemodynamic changes seem to greatly depend on the position of the individual. Venous pressures are low when in a supine position and are higher in a standing position because of the effects of gravity, as a result when standing venous compression and altering haemodynamic responses becomes more difficult (MacRae et al., 2011). In healthy participants, it has been shown that compression increased venous flow velocity, however, in a standing position these same changes were not evident (Lawrence & Kakkar, 1980). The potential increases in venous flow whilst wearing compression garments is associated with increased clearance of metabolites and delivery of nutrients (Chatard et al., 2004). Given that in healthy individuals compression garments seem to alter haemodynamic responses only in supine positions, it would appear that wearing compression garments would have particular utility during recovery following exercise and that perhaps such garments should be worn specifically during sleep or rest.

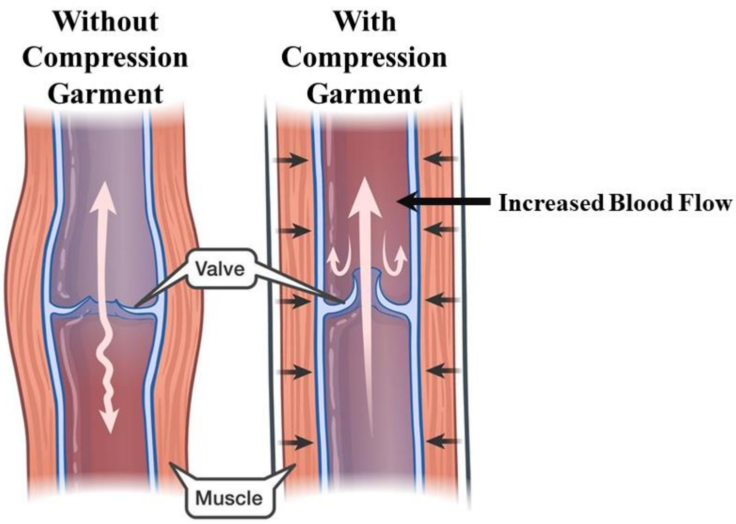


Figure 2.1. Illustration showing the influence of wearing compression garments on blood flow. Adapted from: https://www.aboutkidshealth.ca/article?contentid=2883&language=english

2.10 Muscle Oxygenation

Muscle oxygenation is related to the relationship between oxygen consumption rate and the rate of oxygen supply. Typically, while muscle oxygen consumption is constant for a specific task, the oxygen replenishing rate can vary and is related to the muscle blood flow (Coza et al., 2012). The use of compression garments has been shown to increase muscle oxygenation in static positions. For instance, Chohan and colleagues (2019) found that the application of compression increased muscle oxygenation by 32.25% in a seated position when compared to no compression. In addition, Dermont and colleagues (2015) used fifteen differently pressured calf compression sleeves and measured muscle oxygenation in a seated position. The authors found a dose response to compression as calf muscle oxygenation increased 6.9% for the lowest pressured garment up to 22.6% for the highest pressured garment. However, beneficial effects of compression garments on muscle oxygenation during dynamic movement such as exercise are more difficult to demonstrate. During the first two minutes of exercise oxygen use is greater than oxygen supply; thus, at the onset of exercise, muscle oxygenation is reduced (Coza et al., 2012). Muscle oxygenation subsequently recovers and this change back to normal muscle oxygenation is an index for rate of recovery. In a study by Coza and colleagues (2012) participants performed 40 heel raises per minute for 2 min whilst wearing a compression calf sleeve or no compression. Muscle oxygenation of the calf was measured using near infrared spectroscopy. The results showed that calf muscle oxygenation recovery rate was 24% higher during the heeled raise exercise when wearing compression garments compared to no compression. Conversely, Broatch and colleagues (2017) found that, during 4 sets of 10 x 6 second maximal cycle sprints, muscles oxygenation of the vastus lateralis was not different when wearing compression tights compared to no compression ($P > 0.05$). However, blood flow of the vastus lateralis was 18.4 ± 11.1% higher when wearing compression tights compared to no compression. In addition, peak power was 5.3 ± 2.6% higher when wearing compression tights compared to no compression. It is possible that an increase in muscle oxygenation at the onset of exercise produced by wearing compression garments, could have a positive effect on exercise performance and recovery by increasing the oxygen availability to the muscles (Coza et al., 2012). However, further research is required to examine the effect of wearing compression garments on muscle oxygenation during exercise.

2.11 Interface Pressures and Pressure Monitoring Devices

Although sports compression garments are used within different sports, little is known regarding the optimal pressure a compression garment should elicit to a specific area of the body to provide the greatest physiological benefit (Brophy-Williams et al., 2014). In clinical practice, compression garments undergo standardised assessments to quantify the elicited pressures on patients (Stout et al., 2012). As a result, recommendations and prescriptions exist for the elicited pressures that should be applied to treat specific venous insufficiencies and diseases. However, this is not the case with sports compression garments. Existing published research investigating the effect of sports compression garments on exercise performance and recovery typically suffers from the serious limitation of not reporting (and often not measuring) the actual pressure elicited by the compression garment being examined (Partsch et al., 2006). Even research that has reported the compression garment elicited pressures, typically rely on the manufacturer claimed elicited pressures, rather than directly quantifying the pressures (Driller & Halson, 2013; Stickford et al., 2015; Struhár et al., 2018). Given that 'off the shelf' commercially available compression garments are typically standard sized (i.e., extra-small, small, medium, large and extra-large) it is likely that individuals who fit within the same sizing category may experience different levels of compression as body morphology may vary between individuals. There is evidence to suggest that by wearing standard sized compression garments and using manufacturer-estimated size categories, measured garment pressures vary between individuals even if individuals fit within the same sizing category (Brophy-Williams et al., 2015; Hill et al., 2015). Therefore, it is likely that while reporting the manufacturer claimed elicited pressures these do not in reality accurately describe the pressures experienced by the study population. If sports compression garment research accurately quantified the elicited pressures of the garment used, this would enable more confident prescription of optimal pressure and pressure gradients to apply with compression garments to potentially enhance exercise performance and recovery (Brophy-Williams et al., 2014).

The first techniques used to measure compression garment elicited pressure used electro-pneumatic and fluid-filled pressure transducers (Ferguson-Pell et al., 2000; Partsch, 2005). Piezoresistive pressure sensors have also been used to measure compression garment elicited pressure (Burke et al., 2014). Piezoresistive pressure sensors function by measuring the change in resistance under mechanical load. The sensor of these devices is typically thin and suitable for applying between the compression garment and skin interface. However, piezoresistive pressure sensors are susceptible to hysteresis and drift, and are not suitable for long time-scale measurements, or for measuring objects with sharp curvature, or for measuring low pressures (Ferguson-Pell et al., 2000; Partsch et al., 2006; Tamez-Duque et al., 2015). Current guidelines list 22 portable pressure sensor devices for application in-vivo, including pneumatic, piezoelectric, resistive and capacitive pressure sensors (Partsch et al., 2006). However, some of these devices have not been validated (McManus et al., 2020). Pneumatic-based pressure sensor devices such as MediGroup Kikuhime, Microlab PicoPress and Salzmann MST have been used to measure the pressure elicited by sports compression garments (Brophy-Williams et al., 2015; Partsch & Mosti, 2010; Troynikov et al., 2013). These devices are the most commonly utilised within compression garment research studies (Burke et al., 2014). Pneumatic-based pressure sensors typically consist of a thin, air filled bladder connected to a pressure transducer via flexible tubing (Flaud et al., 2010). When the bladder of the pressure sensor is placed between the skin and compression garment interface, pressure is applied to the bladder and the volume of the bladder decreases thus increasing the internal bladder pressure. It is assumed that the internal bladder pressure is equal to the external applied pressure of the compression garment (Flaud et al., 2010). Although pneumatic-based pressure sensor devices have been shown to provide repeatable results, they may be sensitive to temperature changes (Partsch et al., 2006). Moreover, these devices can be sensitive when placed on areas with sharp curvature which can result in an over estimation of pressure by up to 150% (Burke et al., 2014). Pneumatic-based pressure sensors are suited for static measurements only, due to limited portability and capacity during exercise (Scanlan et al., 2008; Wang et al., 2011). For example, the Kikuhime pressure sensor device measures pressure 'live' and displays the pressure value on the pressure transducer. However, during exercise, pressure applied to the sensor is likely to change drastically and quickly due to shape changes of underlying tissues during exercise such as muscle contraction and relaxion. As the measured pressures cannot be saved or tracked it may be difficult to accurately trace interface pressures during exercise. Furthermore, the sensor and transducer must be connected via tubing which may cause practical problems such as restriction of movement during exercise. The PicoPress pressure sensor device can be used to measure pressures elicited by a compression garment during exercise. This device can be synchronised to a compatible computer via software and record up to 100 live pressure measurements, thus pressure can be tracked during exercise. Currently, in the compression garment research literature there seems little agreement as to the most appropriate pressure sensor device to use to measure garment interface pressure. However, the sports compression garment studies that have directly measured garment elicited pressure have typically used the Kikuhime pressure sensor device (Atkins et al., 2020; Barwood et al., 2013; Brophy-Williams et al., 2019; Hill et al., 2017; Toolis & McGawley, 2020).

The Kikuhime pressure sensor device has been shown to be a reliable and valid method to measure compression in-vitro using a water column reference standard (Brophy-Williams et al., 2014; Van den Kerckhove et al., 2007). However, recently the device has been shown to produce unacceptable validity in-vivo at different orientations (anterior, lateral, medial and posterior) on the maximal circumferences of the calf and to consistently overestimate measured pressures (McManus et al., 2020a). McManus and colleagues (2020) recommended the use of the PicoPress pressure sensor device as an alternate device for measuring sports compression garment pressure (in-vivo) as it provided smaller mean bias and limits of agreement when both devices were compared to a Hohenstein System (HOSY) reference standard. Interestingly, the authors found that when the Kikuhime and PicoPress pressure sensor devices were compared in-vitro using a water column reference standard, they both showed excellent reliability (r = 0.99). Consequently, it would seem that factors relating to the human body may cause the evidenced change in reliability between the two devices. The most likely cause of the observed differences is the ability of the pressure sensor device to measure pressure over areas with sharp curvature. Sharp curvature can result in an over estimation of pressure by 150% (Burke et al., 2014). The results showed that with both pressure sensor devices, the measured pressures were consistently highest at the anterior orientation of the leg. This is likely due to the anatomical structure and tissue architecture within the anterior leg. According to Laplace's law, the pressure elicited by a compression garment is inversely proportional to the radius of curvature at the measured location (McManus et al., 2020). Therefore, following this principle, pressure applied at the tibialis anterior muscle may be higher due to a sharp radius of curvature compared to the larger, more obtuse curvature of the gastrocnemius muscle.

The size of the air-filled sensor (bladder) may also contribute to differences in measured pressure between devices. In the study by McManus and colleagues (2020) the Kikuhime pressure sensor device incorporated a 38 x 30 mm oval air-filled sensor whereas, the PicoPress incorporated a 50mm circular sensor. A smaller sensor may provide a reduced radius of curvature which may be more pronounced on areas with sharp curvature. In addition, a larger sensor size may distribute the pressure within the sensor over a larger area when measuring over sharp curvature thus showing lower pressure.

The Kikuhime pressure sensor device incorporates a 3 mm foam insert within the sensor making it 2 mm deeper than the PicoPress device. It is possible that the deeper protrusion of the Kikuhime sensor may distend the material of the compression garment and subsequently increase the tension of the garment over the sensor location. Furthermore, the protrusion of the foam insert may reduce the radius of curvature which would result in an increase in elicited pressure (Vinckx et al., 1990). Given that both the location of measurement and the sensor dimensions may influence the pressure measurement, it is important that these factors are considered when measuring compression garment interface pressures.

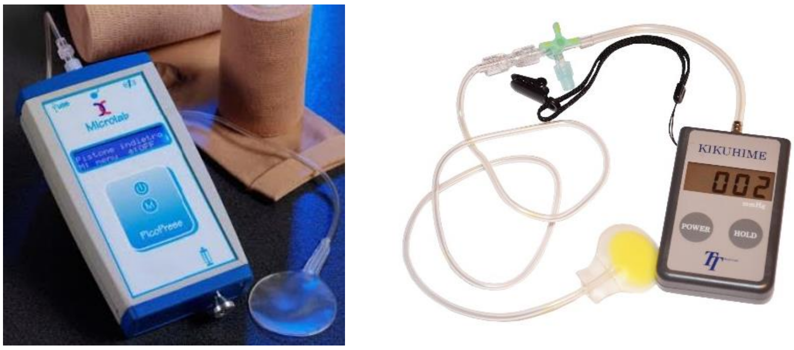


Figure 2.2. Examples of pneumatic based pressure sensor devices typically used in compression garment research; (A) Microlab PicoPress https://www.vipmedikal.com.tr/picopress/ & (B) MediGroup Kikuhime https://www.varodem.nl/webshop/kikuhime-meter/

2.12 Compression Garment Sizing and Fit

Commercially available compression garments are required to fit individuals whose body morphologies are unknown to the manufacturer; thus, generalized sizing systems are typically applied (MacRae et al., 2011). Furthermore, garments are sized differently depending on the specific type of garment. Typically, compression arm sleeves are sized in standard extra-small (XS), small (S), medium (M), large (L) and extra-large (XL). These sizes correspond to specific bicep and forearm circumferences, likewise for compression calf sleeves the size corresponds to maximum calf girth. Compression tops are sized using the circumference of the chest, and compression tights are typically sized according to the stature and body mass of an individual which corresponds to XS, S, M, L and XL sizes. However, manufacturers provide different size classifications with some providing a greater range of sizes. Although commercially available garments are available in a range of standard sizes, they may not offer optimum fit as these garments do not consider the contrasting shape and architecture of the human body, rather they rely on a single point such as the maximal circumference of the calf or bicep. As a result, it has been found that compression garments elicit different pressures between individuals even if they fit within the same sizing category (Brophy-Williams et al., 2015; Hill et al., 2015).

Compression garments are typically developed using Laplace's law to calculate the pressure elicited by the garment (Troynikov et al., 2010). However, the use of Laplace's law to calculate elicited pressure depends on the object the pressure being applied to is cylindrical in shape. Pressures calculated using Laplace's law provide an average pressure applied around the cylindrical shape. However, in humans, the limbs are not strictly cylindrical and this is a limitation of the measurement approach utilized in the manufacture of commercially available compression garments. Macintyre & Baird (2006) evaluated Laplace's law for pressure prediction on cylinders with different curvature radiuses. The authors found that the Laplace formula overestimated pressure exerted on small cylinders with circumferences less than 30 cm. Given, that the lower leg, specifically at the ankle, may have a circumference less than 30 cm, this supports the notion that the standard sized compression garment may not provide an optimal fit (**Figure 2.3**).

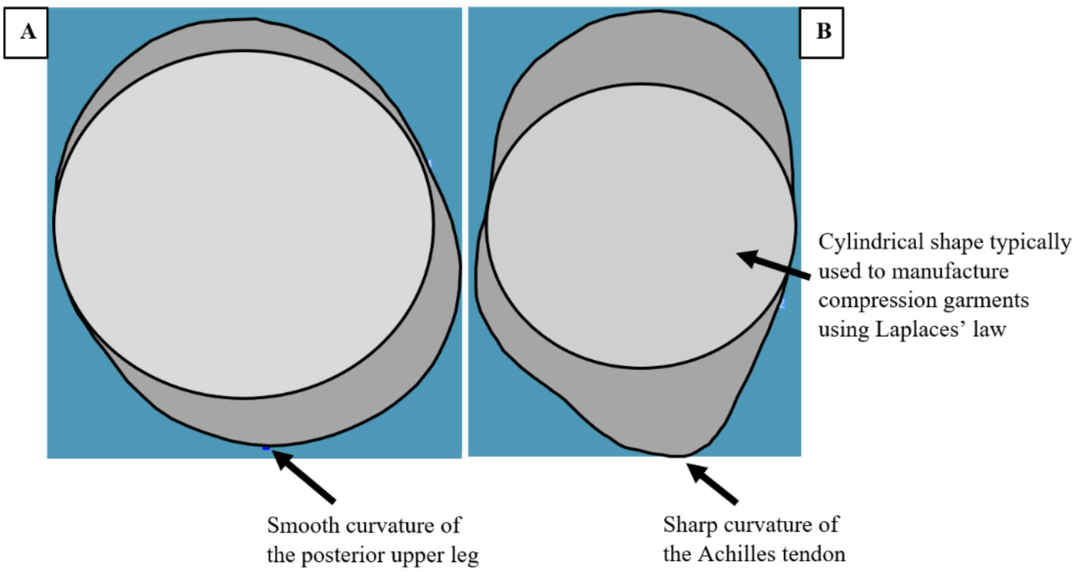


Figure 2.3. Cross sectional view of the upper and lower leg. The dark grey shapes represent the upper leg (midthigh) (A) and lower leg (above the ankle) (B) curvature using a 3D scan model. The light grey shapes represent the cylindrical shape typically used in commercially available compression garments.

As standard sized compression garments may not fit optimally, there has been development of made-to-measure compression garments which are fitted according to the wearer's specific body shape. Recently, the use of 3D scanning has been used to manufacture made-to-measure compression garments. The 3D scanning acquires a 3D model of the wearer which is then used to optimally shape and size the garment specifically for their body. Only a few studies have used 3D scanned, made-to-measure compression garments, in the form of tights, within sport (Brown et al., 2020; Brown et al., 2021). Furthermore, Brown and colleagues (2021) demonstrated that 3D scanned, made-to-measure compression garments elicited linear graduated pressure from distal to proximal (ankle: 29 ± 5 mmHg, calf: 25 ± 5 mmHg, and thigh 19 ± 4 mmHg), which it is suggested aids venous flow and return (Agu et al., 1999). Conversely, a study by Broatch and colleagues (2020) showed that in three commercially available, standard sized compression garments (Nike, 2XU and Under Armour) the peak pressure was located at the maximal circumference of the calf; thus, a reversed pressure gradient was experienced in the lower leg, which may negatively affect venous flow and return. Therefore, it would seem that made-to-measure compression garments may provide a better fit compared to standard sized garments. However, although some studies (Brown et al., 2020) have used made-to-measure compression garments to examine their efficacy on recovery from exercise, no research has used such garments to examine their efficacy on exercise performance.

2.13 Summary

Research investigating the efficacy of wearing compression garments during exercise is of real interest to athletic populations, particularly as such clothing may have ergogenic properties. Heterogeneity exists within the sports compression garment research literature due to differences in the study designs, type of compression garments, the elicited pressures of the garments, the duration of wear, the study populations and the type of exercise performed (MacRae et al., 2011). The fragmented and equivocal nature of the research literature complicates reaching a consensus regarding the beneficial effects (or otherwise) of wearing compression garments during exercise performance or in the period of recovery following it. Although studies have examined the use of compression garments on different modalities of exercise, these studies have used standard sized compression garments which have been shown to elicit different pressures between participants, even if individuals fit within the same sizing category (Brophy-Williams et al., 2015; Hill, et al., 2015). Furthermore, studies typically do not measure the elicited pressure of the compression garments they have used, which adds further uncertainty and difficulty when comparing the findings of the various studies in the published research literature. Therefore, the development of a made-to-measure compression garment, based on the three-dimensional geometry of the wearer, that elicits prescribed pressures and pressure gradients which are the same between participants, has promising utility for future research. Moreover, a novel methodology to measure compression garment pressures is required to help establish accurate pressure-response relationships in studies that examine whether wearing compression garments improve exercise performance or enhance the recovery process following exercise. Although some research has investigated the effect of wearing standard sized compression garments on running biomechanics and thermal responses, no study has used made-to-measure compression garments, with prescribed pressure profiles, to investigate such variables.

Chapter 3: General Methodology

3.1 Introduction

This chapter describes the methodological procedures that were used in the experimental studies of this PhD including participants and recruitment, ethical review, data collection, data processing and data analysis techniques. For this PhD, two main data collections were performed, which were subsequently divided into six experimental chapters. Any procedures that apply to a particular study are described in detail in the methodology section of the individual chapter. All the studies were performed in laboratories located at Nottingham Trent University's Clifton Campus.

3.2 Participants and Recruitment

For all experimental chapters, healthy, recreationally active individuals volunteered to participate. Participants were recruited from the University and local communities through 'word of mouth' and recruitment posters located in communal areas within the University Campus. A potential participant was provided with a 'participant information' document that described the study aims, design, procedures, techniques, and the commitment required from the participant. Also, the document highlighted the possible risks and discomforts, as well as the benefits of participating in the study (**Appendix 1**). In addition, the procedures of the study were explained verbally to the participant. All participants were given the opportunity to ask questions or raise concerns regarding study participation. Subsequently, if a participant indicated they still wanted to participate in the study, a statement of informed consent (**Appendix 2**) and health screen questionnaire (**Appendix 3**) were completed prior to commencement of the study. For the second data collection (Chapter 4 and 6), additional COVID-19 participant information was collected. The 'participant information' document was adapted to highlight COVID-19 related risks to participating in the study (**Appendix 4**). The 'health screen questionnaire' was adapted to include whether participants had previously contracted COVID-19 (**Appendix 5**). Also, a separate 'COVID-19 symptoms questionnaire' was completed by the participants to screen for COVID-19 symptoms prior to attending experimental trials (**Appendix 6**). The 'COVID-19 symptoms questionnaire' was completed by the participant 7-days prior to a trial and they were subsequently asked if any of the initial information had changed 24-hours prior to a trial. If a participant indicated any COVID-19 symptoms, the trial would be postponed and rescheduled for an appropriate date.

The work conducted within the thesis was performed with male participants only. Clearly, this is a limitation of the work as including female participants would allow the results to be representative of both sexes. Females were not recruited as the menstrual cycle would need to be controlled for. Given that certain phases of the menstrual cycle may change: 1) blood flow and skin temperature (Bartelink et al., 1990); 2) running exercise performance (Shakhlina et al., 2016); and 3) limb volume (Sawai et al., 2018) and that the work within this thesis incorporated measurements of these variables, the decision was made to exclude females from the study recruitment. Of course, females could have been tested in the identical phase of the menstrual cycle for each experimental trial to control for the effects of the menstrual cycle. However, with the limited time available to complete the research, caused by COVID-19, this was not a viable option.

3.3 Inclusion and Exclusion Criteria

For the first data collection (Chapter 5, 7, 8 and 9), participants had to be older than 18 years of age, have no medical conditions and be free from injury during the study period. Also, participants had to be recreationally active, which in this data collection corresponded to a minimum of running exercise for at least one hour, twice weekly.

For the second data collection (Chapter 4 and 6), participants had to be older than 18 years of age, have no medical conditions and be free from injury during the study period. For both data collections, any criteria which would exclude the participant from the data collection was identified on the ‘health screen questionnaire’. Also, the physical activity level of a participant was determined prior to data collection.

3.4 Ethical Review

Ethical approval for the first data collection (Chapter 5, 7, 8 and 9), and the second data collection (Chapter 4 and 6) was obtained from the University Ethics Committee, (Nottingham Trent University Ethical Committee Application for Human Biological Investigation). For the second data collection, as a result of the COVID-19 pandemic and subsequent University closure, the ethical application was resubmitted, with COVID-19 related amendments, and approved by the University Ethics Committee, (Nottingham Trent University Ethical Committee Application for Human Biological Investigation).

3.5.1 Measurement of Stature and Body Mass

Participant stature was measured to the nearest 0.1 cm using a stadiometer. Participants were instructed to remove their footwear and step onto the base of the stadiometer with their heels together and against the back-plate of the stadiometer. The investigator ensured that the participants' buttocks, back and head were in contact with the vertical board of the stadiometer. Participants were instructed to stand straight and asked to breathe in deeply and the stadiometer headboard was positioned down to the most superior aspect of the head ensuring any hair was compressed. The stature was then recorded, and the participant was asked to step off the stadiometer.

Participant body mass was measured to the nearest 0.01 kg using digital scales. Participants were instructed to remove footwear and clothing, excluding underwear, and stand on the scales with their legs shoulder width apart. Participants were instructed to stand still in an upright position and to look forward. Body mass was then recorded, and the participants were asked to step off the scales.

3.5.2 Pressure Profile Assessment

The pressures elicited by the made-to-measure compression garments were measured in Chapter 4, 5, 8 and 9. Although the pressure measurement methodology remained identical between chapters, the aspect of the leg where pressure measurements were made (anterior, posterior, medial and lateral) differed, and the aspect of the leg used is described in each chapter. The pressure profiles, defined as the peak pressure and pressure gradient, of the compression garments were assessed using a Kikuhime pressure-monitoring device (MediGroup, Melbourne, Australia). Previous research has assessed the accuracy and reliability of the pressure monitoring device using a water column reference method (typical error of measurement = ±1 mmHg) (Brophy-Williams et al., 2014). The three-dimensional location of pressure sensor measurement sites was acquired simultaneously with pressure measurements using a thirteen-camera 3D motion capture system (Qualisys AB, Göteborg, Sweden) sampling at 100 Hz. Participants put on the compression garment and eight reflective markers were applied to the legs, using bi-adhesive tape, to represent the line of the leg. Four markers were placed on each leg at the following landmarks: 1) the lateral malleolus (ankle); 2) the lateral femoral condyle (knee); 3) the greater trochanter; and 4) the iliac crest. The anatomical marker locations and marker placement was performed by a trained anthropometrist (ISAK level 1). Marker locations 2 and 3 were removed after an initial baseline static standing measurement and were reconstructed from ankle and iliac crest markers for all subsequent measurements. The pressure sensor was placed 5 cm above the malleolus, between the garment and skin interface, and then pulled up the leg in approximately 5 cm increments. Measurements were stopped when the sensor reached the line of the gluteal fold. Following each measurement increment, and prior to reading the pressure value, a reference 'reflective wand marker' was placed on the sensor location for a minimum of two seconds to define the exact measurement location with reference to the length of the leg. The length of the leg was defined by the line between the lateral malleolus and greater trochanter markers (**Figure 3.1**).

To extract the pressure measurement locations from reflective marker trajectories, the Qualisys motion capture files were used, and the reflective markers were labelled relative to specific landmarks to indicate the marker location (i.e., left leg medial ankle). Once labelled, the files were exported as .MAT files and a custom programme (MathWorks Inc., MA, USA) was used to select each pressure measurement location (location of the wand marker during measurement). Each location was expressed as a percentage, relative to the length of the leg. The measurement locations were subsequently written into a Microsoft Excel sheet and paired with the corresponding pressure measurement (mmHg).

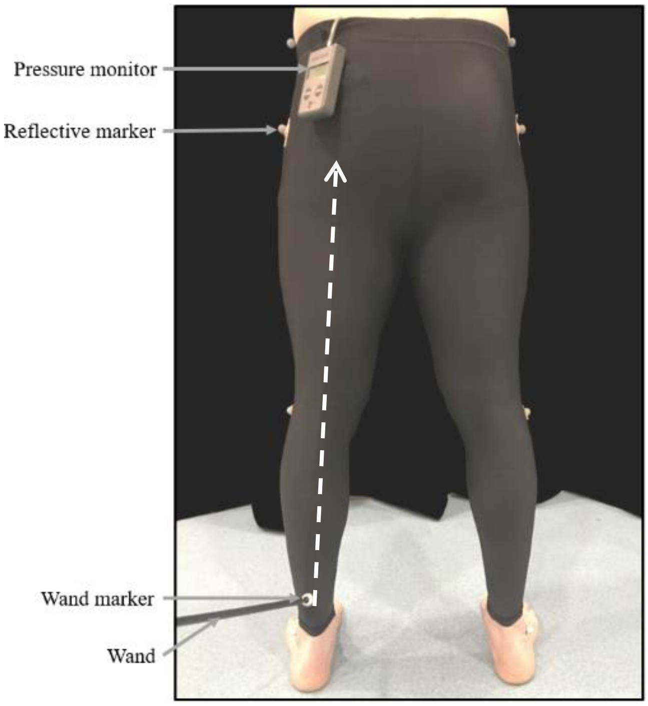


Figure 3.1. Participant wearing the compression garment during the pressure profile assessment. The ‘reflective markers’ applied to define leg length, the ‘pressure monitor’ in place to measure pressure elicited by the garment (distal to proximal), the ‘wand’ and the ‘wand marker’ applied before each pressure measurement to reference the measurement location relative to leg length, are indicated in the figure.

3.5.3 Infrared Thermal Imaging

Infrared thermal imaging was used in Chapter 7 and 8 to measure skin temperature and the imaging procedures were identical (detailed description below). Skin temperature was measured using a FLIR T1020 infrared thermal imaging camera (FLIR Systems Inc., Wilsonville, Oregon, USA) with an infrared sensor resolution of 1024 x 768 pixels, thermal sensitivity of < 0.02 at 30°C, frame rate of 30 Hz and spectral range between 7.5µm - 14µm. The studies within this thesis that used infrared thermal imaging applied specific participant restrictions prior to the experimental trial, following recommendations by Moreira and colleagues (2017a; 2017b). These restrictions were: refrain from alcohol consumption and strenuous exercise 24-hour prior to an experimental trial; refrain from smoking, caffeine consumption, large meals, ointments, cosmetics, showering, excessive ultraviolet light (sun) exposure, massage, electrotherapy, cryotherapy, ultrasound and excessive heat or cold exposure on the day of an experimental trial; finally, attend the experimental trials at least 3-hours postprandial. Thermograms (thermal images) of the anterior and posterior upper and lower legs were captured. Prior to infrared thermal imaging, participants rested for 20-min to acclimate to the room temperature. Also, prior to infrared thermal imaging, 1 x 1cm thermally inert tape markers were placed at six specific locations on the anterior and posterior aspects of the left and right legs and marked with indelible ink. The locations were: (A) 5 cm proximal from the centre of the ankle malleolus (anterior); (B) the most proximal aspect of the patella (anterior); (C) parallel to the gluteal fold (anterior); (D) 5 cm proximal from the centre of the ankle malleolus (posterior); (E) parallel to the most proximal aspect of the patella (posterior); and (F) on the gluteal fold (posterior), (**Figure 3.2**). The marker tape was visible on the thermograms as the tape was consistently lower in temperature compared to the leg. These locations were subsequently applied to standardise segment regions of interest (defined as the selected area on the leg of which temperature data is extracted from pixels (**Figure 3.3**). For the studies in this thesis, the regions of interest were selected as the area between the distal and proximal marker tape locations (**Figure 3.3**). Separate thermograms were captured for the anterior lower and upper legs and posterior lower and upper legs, and these segments were used for the temperature extraction and analysis. All thermograms were captured at approximately 1m from the participant. The distance of the camera was adjusted for taller individuals to certify that the relevant regions of interest were captured and to ensure a similar amount of the legs was present in the thermogram between participants. The infrared thermal imaging camera was positioned on a tripod to ensure a still image and placed perpendicular to the participant for each thermogram capture. The tripod was adjusted up and down to capture thermograms of the upper legs and lower legs. For each thermogram, participants stood with their legs shoulder width apart with relaxed musculature and their arms crossed over their chest. Participants stood on an exercise step to avoid contact with the cold floor. Furthermore, a foam mat was placed next to the exercise step which allowed participants to remove footwear and clothing without contacting the cold floor. Prior to infrared thermal imaging, objective parameters of reflective temperature and emissivity (described below) were input into the infrared thermal camera settings using protocols by the International Organisation for Standardisation (ISO 18434-1:2008). The infrared thermal imaging camera was manually focused prior to taking the image to ensure a clear thermogram.

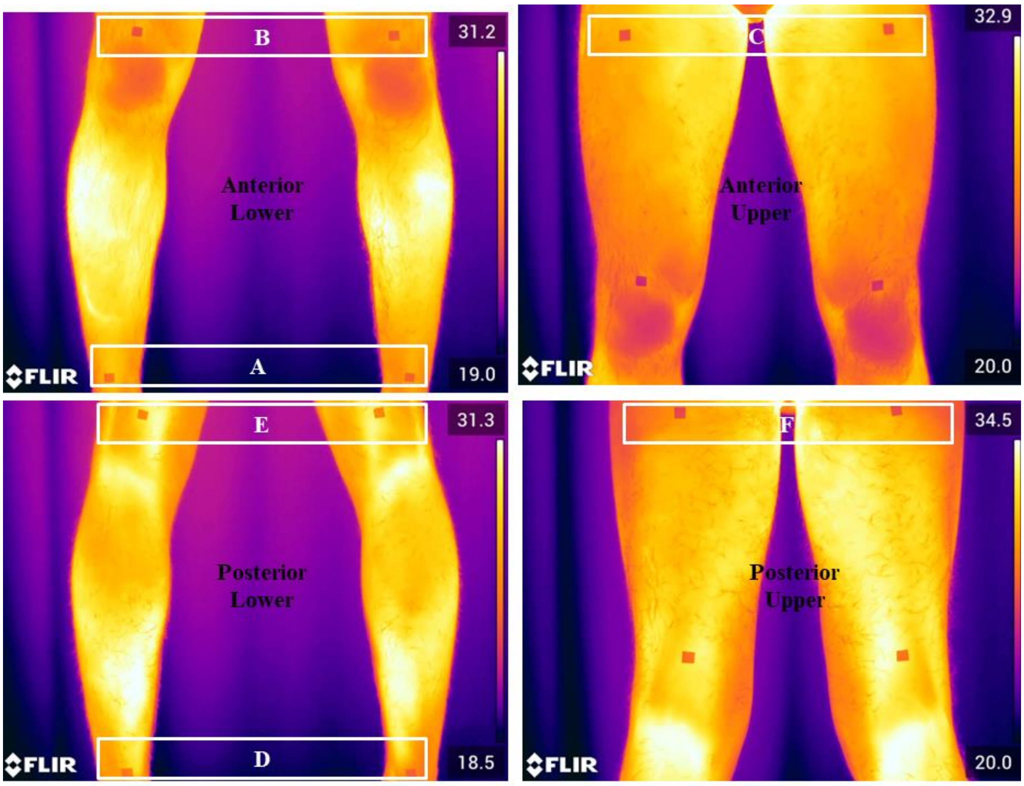


Figure 3.2. Thermally inert tape marker locations (A, B, C, D, E and F) on the anterior and posterior aspect of the legs, which were used to standardise the leg segment regions of interest.

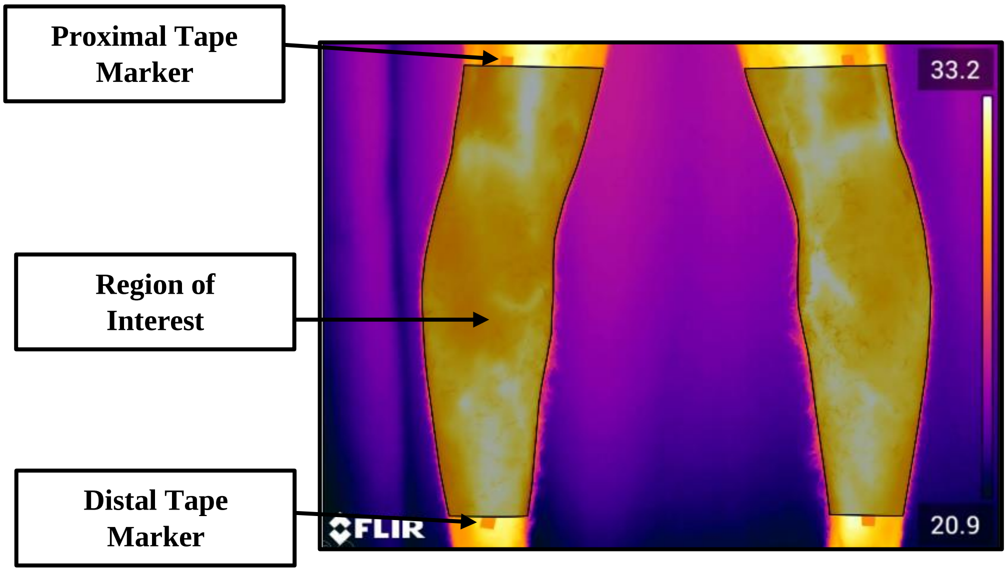


Figure 3.3. The shaded area of the lower leg is an example of a region of interest, defined by the area between the distal and proximal tape markers, used for temperature extraction in the studies of this thesis.

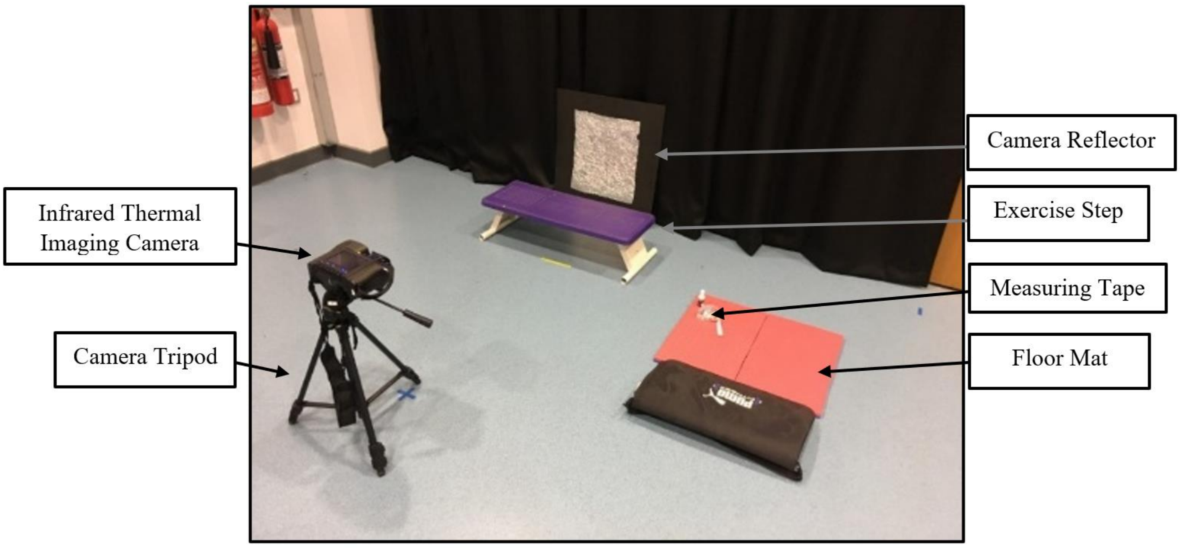


Figure 3.4. Equipment used for conducting the infrared thermal imaging on participants; including the infrared thermal imaging camera, tripod, exercise step (used for participants to stand on during image capture), floor mat (used to limit participant contact with cold floor), tape measure (used to define landmarks), and camera reflector (used to measure reflected temperature).

Reflected temperature is defined as the thermal radiation originating from other objects that reflect off the object being measured (ISO, 2008). Reflected temperature is used by the camera as an adjustment to accurately calculate temperature. The reflected temperature may be influenced by ambient temperature conditions; therefore, reflected temperature was measured at the start of each experimental trial. Reflected temperature was measured using the ‘reflector method’ as described by the ISO (18434-1:2008). This method consisted of: 1) inputting the camera distance from the imaged object as 0m and an emissivity value of 1; 2) positioning a cardboard square with aluminium foil fixed to it, in front of the camera; 3) selecting a rectangle region of interest on the camera, which covered the aluminium foil and recording the average temperature of the foil; and 4) inputting the obtained average temperature into the camera settings. The presence of external sources of infrared radiation, located in close proximity to the measured object, may influence measurement accuracy. Potential external sources of infrared radiation in this study were: electronic devices, humans, radiators, water pipes and lights. To limit the influence of these external sources of infrared radiation, a 2m cordon, with no sources of external infrared radiation inside, was applied prior to taking any thermal image.

The emissivity of an object is the ratio of the actual amount of infrared energy emitted compared to the theoretical maximum amount of energy that could be emitted using a 'black body' reference, and can range from 0 to 1 (Bernard et al., 2013). A black body is used as a reference as it is one of a limited number of objects that has an emissivity of 1. Emissivity of clean human skin has been reported to be 0.98, and this value has been determined and applied in previous research when assessing skin temperature using infrared thermal imaging (Priego Quesada et al., 2015; Villaseñor-Mora et al., 2009; Watmough & Oliver, 1968). As a result, an emissivity of 0.98 was used for the studies within this thesis and input into the infrared thermal imaging camera settings and subsequently used by the camera to calculate temperature.

Ambient temperature and relative humidity were measured using a digital weather station and were input into the infrared thermal imaging camera settings. The distance between the infrared thermal imaging camera and the participant was measured with a flexible tape measure and input into the infrared thermal imaging camera settings. Finally, external infrared window compensation was left unactive in the infrared thermal imaging camera settings as no window compensation was used for the studies in this thesis. The input of these parameters into the thermal imaging camera settings aids measurement accuracy and are defined below.

- Emissivity – How much infrared radiation an object emits compared to a theoretical maximum amount using a reference 'black body'.
- Reflected Temperature – This is used for compensating for the radiation from the surrounding area reflected by the object into the thermal imaging camera.
- Atmospheric Temperature - The temperature of the air between the camera and the object being examined.
- Relative Humidity – Defined as the ratio of the amount of water vapor present in the air (between the thermal imaging camera and the object being examined) compared to the greatest amount possible at the identical temperature.
- Object Distance - The distance between the thermal imaging camera and the object being examined.

- External Infrared Window Compensation – the temperature of protective windows/shields or external lenses that are located between the thermal imaging camera and object being examined.

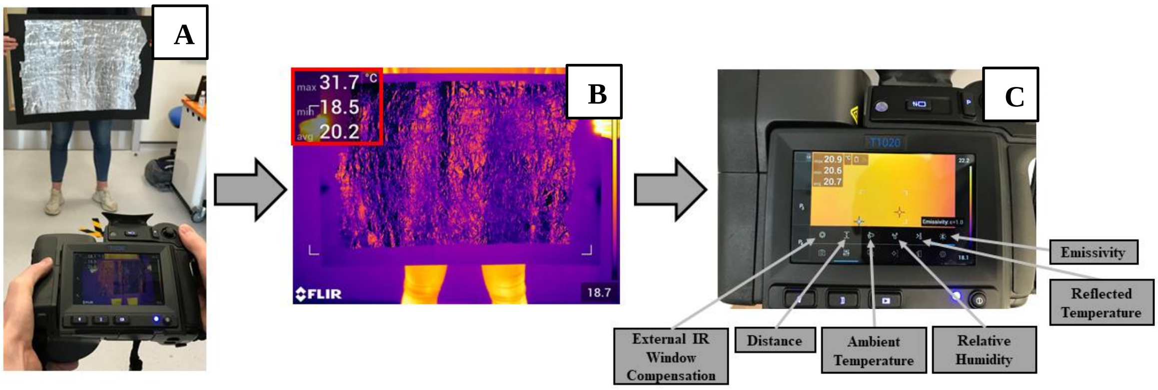


Figure 3.5. Method of measuring reflected temperature: A) image the aluminium foil, B) record the average temperature of the aluminium foil, and C) input reflected temperature as well as emissivity, relative humidity, ambient temperature, distance and external infrared radiation window compensation into the infrared thermal imaging camera settings.

3.5.4 Kinematic Data Acquisition

In Chapter 9, kinematic data during exercise was measured using a three-dimensional (3D) motion capture system (Qualisys, Gothenburg, Sweden). The system comprised of twelve Oqus 400 cameras, and one high speed Oqus 310 camera, and the appropriate computer hardware and software (Qualisys Track Manager version 2019.3, Gothenburg, Sweden). The identical camera configuration was used for the pressure profile assessment. Reflective markers (14 mm) were attached to specific body landmarks and kinematic data was measured as the participant exercised within the performance volume (**Figure 3.6**) and each camera recorded images of the reflective markers. A detailed description of the reflective marker locations is provided in the appropriate experimental chapters.

To identify 3D coordinates of the reflective markers using two-dimensional (2D) images of the cameras, a linear relationship must exist between the 2D images and the corresponding 3D coordinates (Payton & Bartlett, 2007). To establish the relationship between 2D images and 3D coordinates, a calibration of the motion capture system was performed which accurately scaled the 2D camera images to 3D coordinates. To calibrate the system, an L-frame was used which consisted of a rigid 'L' shaped structure with four reflective makers, with known dimensions, fixed to the frame (**Figure 3.7**). The reflective markers of the L-frame were used as control points during the calibration. The L-frame was placed stationary in the same coordinate axis as the force platforms of the instrumented treadmill ensuring that it was captured by all the cameras. A 60 second calibration motion capture was subsequently performed whilst a T-shaped wand with reflective markers fixed to either end was moved around the laboratory with specific focus within the performance volume. During the calibration motion capture, the marker location of both the L-frame and T-shaped wand were measured. These measurements were subsequently used to scale digitised coordinates into metric units using Functional Linear Transformation (FLT) or Direct Linear Transformation (DLT) methods (Robertson et al., 2013). A visual inspection of the laboratory was performed prior to calibration to ensure that the camera view was not obstructed and that no unwanted reflective markers were captured (i.e., reflective clothing). The 3D motion capture measurement accuracy was dependent on the accuracy of the calibration, which was determined by the residual error of each camera. The residual error shows the precision of locating the position of a marker. For the research conducted in this thesis, a residual error threshold below 2 mm was set. Thus, if a residual error greater than 2 mm was acquired during the calibration, the 3D motion capture system was recalibrated.

The calibration of the 3D motion capture system created a laboratory coordinate system (z – vertical, y – anterior/posterior and x –medial/lateral), using the reflective markers located on the L-frame. The reflective markers attached to landmarks of a participant also created a local coordinate system. The laboratory coordinate system is fixed, whereas the local coordinate system moves depending on the specific movements of a participant. The movement of a segment can be defined using either the laboratory or local coordinate systems.

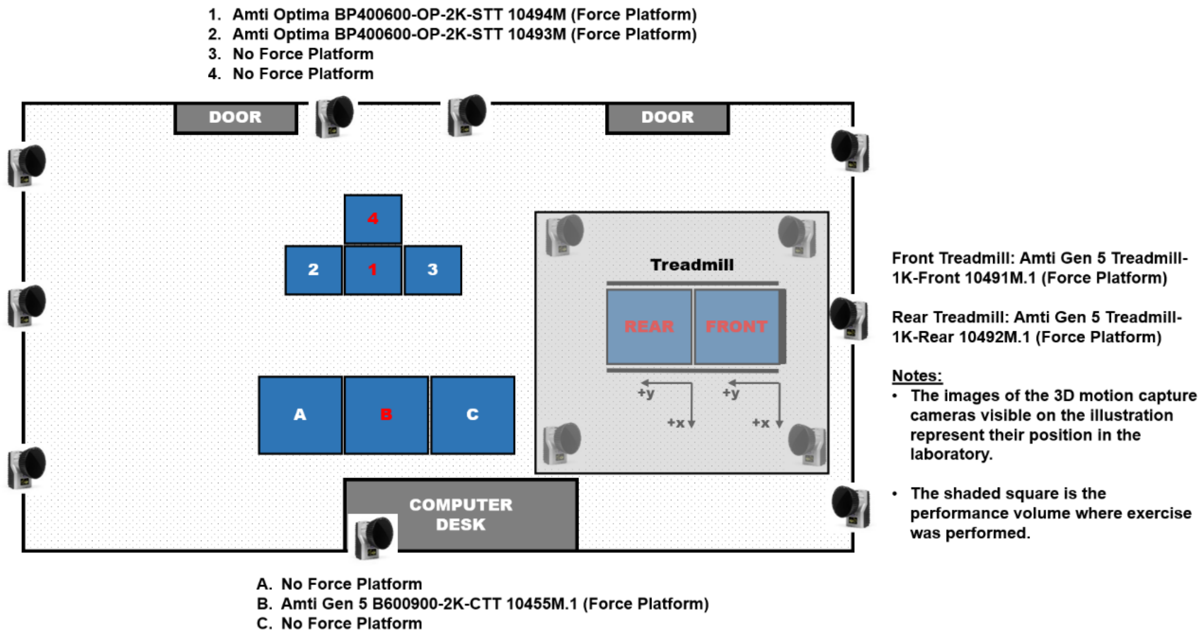


Figure 3.6. Illustration of the laboratory set up for collection of kinematic and kinetic data.

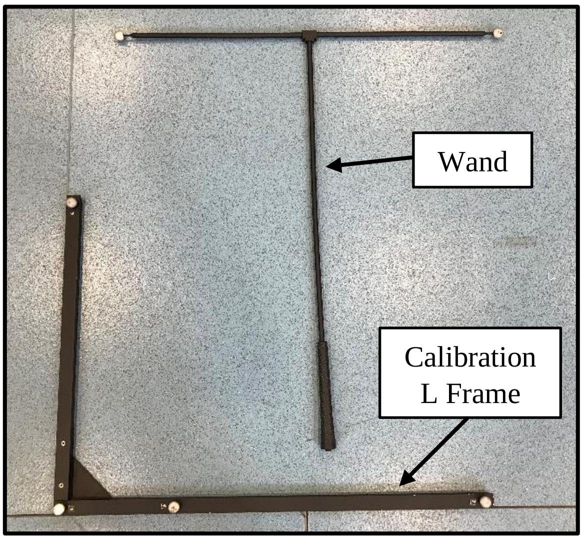


Figure 3.7. T-shaped wand and L-shaped reference frame used for 3D motion capture calibration.

3.5.5 Kinetic Data Acquisition

In Chapter 9, ground reaction force (GRF) data was measured using two AMTI force platforms (10492M.1) which were incorporated into an instrumented tandem treadmill (AMTI, MA, US). The force platforms were located below two separate treadmill belts, with a 1 mm clearance between the two belts (**Figure 3.8**). The GRF was recorded simultaneously with 3D motion capture during exercise and was measured when the participants' foot contacted the force platform. The GRF measurements were made in three axes which were: vertical, anterior-posterior and medio-lateral. The specific processing of kinematic and kinetic data is described appropriately in relevant chapters.

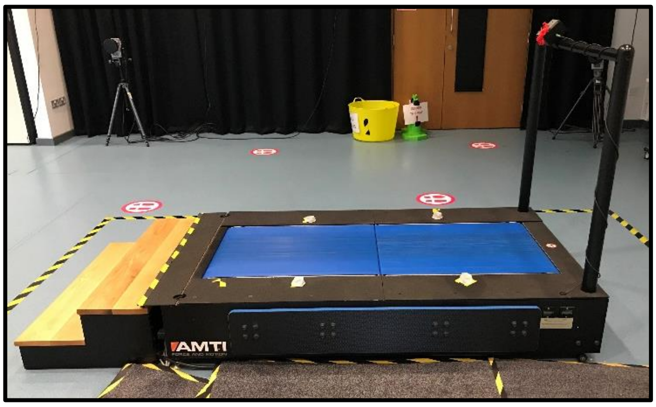


Figure 3.8. AMTI instrumented treadmill, used in Chapter 9, which comprises of two separate treadmill belts with a force platform located under each belt.

3.5.6 Three-dimensional Scanning

Two handheld 3D scanners were used within the research presented within this thesis. In Chapter 5, 8 and 9 the Artec Eva was used (Artec Group, Luxembourg, Luxembourg). In Chapter 4 and 6 the Artec Leo was used (Artec Group, Luxembourg, Luxembourg). Both 3D scanners are based on structured light technology whereby a structured light pattern, typically a grid, is projected onto the object being scanned. The light pattern is then repeatedly photographed and the deformation/distortion of the projected pattern onto the object identifies the distance and 3D geometry of the object which can then be reconstructed as a 3D image. The largest difference between the two scanning systems is that the Artec Leo is a wireless device which provided more efficient scanning. The technical specifications of both 3D scanners are reported in **Table 3.1**.

Table 3.1. Technical specifications for the Artec Eva and Artec Leo 3D scanners.

Technical Specification	Artec Eva	Artec Leo
3D Point Accuracy (up to)	0.1 mm	0.1 mm
3D Resolution (up to)	0.2 mm	0.2 mm
Data Type Captured	Geometry and Texture	Geometry and Texture
Working Distance	0.4 – 1 m	0.35 – 1.2 m
Texture Resolution	1.3 mp	2.3 mp
Capture Rate (up to)	16 fps	80 fps
Data Acquisition Speed (up to)	18 million points/sec	35 million points/sec
Volume Capture Zone	61,000 cm^3	160,000 cm^3

mm = millimetres; m = metres; mp = mega-pixels; fps = frames per second; cm^3 = centimetres cubed.

Two scanning methodologies were developed to perform 3D scanning measurements which were dependent on the 3D scanner system used. When using the Artec Eva, the participants stood on a turntable with their legs shoulder width apart and their arms crossed over their chest. The turntable was slowly rotated, and the 3D scanner captured a lower body 3D scan. The Artec Eva required a wired connection to a computer during scanning, therefore, when a lower body 3D scan was completed, it was inspected on the computer for any errors before saving for subsequent processing. The Artec Leo is wireless, therefore, the turntable was not used when using this device. Participants stood still with their legs shoulder width apart and arms crossed over their chest whilst the scanner was moved around the participant to capture the lower body 3D scan. Furthermore, the Artec Leo incorporated an interactive touch screen which displayed the live 3D scans. Therefore, the scan was inspected for errors before being transferred to the computer for processing. All scans were processed using Artec Studio software (Artec Group, Luxembourg, Luxembourg). The processing procedure of 3D scans is described in detail in Chapter 6.

Figure 3.9. Images of the Artec Leo (A) and the Artec Eva 3D (B) scanning systems https://www.artec3d.com/portable-3d-scanners/artec-eva-v2 & https://www.artec3d.com/portable-3d-scanners/artec-leo#overview.

3.5.7 Compression Garments

The compression garments used in the studies presented within this thesis were made-to-measure, full leg compression tights (Kurio 3D Compression Ltd, Nottingham, UK) and were fitted from the malleolus to the iliac crest. Three-dimensional scanning systems were used to acquire a 3D model of each participants' lower body. The geometry of the lower body 3D model was calculated and ultimately implemented into the compression garment to provide a garment that provides an optimal fit and a fit which is the same between participants. The pressure profile of each compression garment was implemented into the garment using a specifically designed software programme developed by the company. The compression garments were made using a composite of Elastane (22%) and Nylon (78%), in two sections as left and right legs with a seam up the centre line. The properties of the material were determined by the companies' in-house testing processes. An assessment of the material was made following the standard for evaluating the 'Determination of the elasticity of fabrics' (BS EN 14704-1:2005) then further evaluated against in vivo measurements of pressure obtained from individuals outside of the study population (n = 30) to establish the relationship between material reductions, body geometry and elicited pressure. The measured properties were then used to determine the material size reduction required to generate intended pressures for all garments according to Laplace's Law (Liu et al., 2017). The elastic material used for the garment facilitates dressing, such that the garment can be stretched over various joint structures. Furthermore, this stretching ensures that the garment sits on the appropriate surface of the leg without slipping. The specific intended peak pressures and pressure gradients of the compression garments are described in each chapter.

Chapter 4: A novel methodology for measuring pressure profiles in sports compression garments.

4.1 Rationale

In the literature review of this thesis it was highlighted that the aspect of the leg on which pressure measurements are made may influence the pressure value recorded, with measurements taken on hard tissues, or taken on tissues with sharp curvature, typically eliciting higher pressures (McManus et al., 2020). There is actually no standard methodology for measuring the pressures elicited by a compression garment. Some studies have opted to measure garment pressure at three locations on the medial lower leg and three locations on the anterior upper leg (Broatch et al., 2020; Brophy-Williams et al., 2014; Brophy-Williams et al., 2015). However, using these different aspects of the leg may not be optimal, particularly if the underlying characteristics of the tissue on which the pressure measurement is determined varies. Therefore, the aims of this chapter were to examine if pressure profile (peak pressure and pressure gradient) differences existed when pressure measurements were made on different aspects of a human leg (anterior, posterior, medial and lateral). The study also compared these (novel method) pressure profiles with an established methodology (Brophy-Williams et al., 2014), frequently used in the research literature.

4.2 Introduction

Compression garments are specialised clothing which consist of elastomeric fibres and yarns used to apply an external, mechanical pressure on the surface of the body for compressing and supporting underlying tissues (MacRae et al., 2011). In recent years, compression garments have been used within sport as a potential aid for exercise performance and recovery. Sports compression garments are available in many forms for use on different parts of the human body such as: knee-high socks, tights, shorts, full body suits, arm and calf sleeves (Armstrong et al., 2015; Martínez-Navarro et al., 2020; Mizuno et al., 2016; Sperlich et al., 2013; Struhár et al., 2018; Winke & Williamson, 2017). There are many proposed mechanisms which support the use of compression garments within sport. The external pressure applied by compression garments has been suggested to enhance blood flow which may assist the removal of metabolites during both exercise and recovery (Davies et al., 2009).

Moreover, the increase in blood flow has been associated with enhanced oxygen delivery and increased muscle oxygenation (Agu et al., 1999). It has also been suggested that compression garments reduce muscle oscillation during exercise which may contribute to a reduced recruitment of muscle fibres, in turn, allowing improved economy during exercise and hence attenuating the fatigue process (Doan et al., 2003; Hsu et al., 2016). Following exercise, the external pressure applied by compression garments may reduce the space for swelling to develop (Davies et al., 2009), and may reduce the sensation of post-exercise delayed onset muscular soreness (Duffield & Portus, 2007). Therefore, at least theoretically, there are a number of reasons for hypothesising that the wearing of compression garments could enhance sporting performance itself or augment the recovery from it.

Although some evidence supports the use of compression garments, the published research literature examining variables such as rating of perceived exertion (Davies et al., 2009; Varela-Sanz et al., 2011), sprint performance (Born et al., 2014), counter-movement jump performance (Higgins et al., 2009; Rugg & Sternlicht, 2013), running economy (Bringard et al., 2006; Broatch et al., 2020), maximal oxygen uptake (VO_{2max}) (Dascombe et al., 2011; Rimaud et al., 2010), muscle oxygenation (Ménétrier et al., 2011; Sperlich et al., 2010), and exercise capacity (Kemmler et al., 2009; Rider et al., 2014) is, at best, equivocal. Likewise, there is no obvious consensus when the published literature examining the effect of compression garments on variables linked to the recovery from sporting performance such as muscle soreness (Govus et al., 2018; Kraemer et al., 2001), muscle swelling (French et al., 2008; Heiss et al., 2018), strength recovery (Hill et al., 2017; Upton et al., 2017), blood creatine kinase reduction (Jakeman et al., 2010; Kraemer et al., 2010), and blood lactate reduction (Lovell et al., 2011; Pruscino et al., 2013) is consulted. Ultimately, the findings from the existing published research literature investigating the efficacy of wearing compression garments for sporting performance or recovery from it are very unclear.

A factor which may contribute to some of the inconsistent research findings is that the pressures elicited by the compression garments used in the research studies are typically not directly quantified (Bernhardt & Anderson, 2005; Bringard et al., 2006; Cerqueira et al., 2015; Duffield et al., 2010; Higgins et al., 2009; Houghton et al., 2009; Kraemer et al., 2010; Pereira et al., 2014; Perrey et al., 2008; Shimokochi et al., 2017; Winke & Williamson, 2017). If elicited pressures of compression garments are not measured and reported, it becomes impossible to associate specific pressures with any beneficial effects of wearing such garments. Some published literature rely on manufacturer estimated values of elicited pressure (Armstrong et al., 2015; Ballmann et al., 2019; Davies et al., 2009; French et al., 2008; Govus et al., 2018; Heiss et al., 2018; Kim et al., 2017; Rugg & Sternlicht, 2013). However, compression garment manufacturers typically measure elicited pressures in vivo using wooden leg models which may not reflect the pressures elicited on a human leg (Partsch et al., 2006). Partsch and colleagues (2006) compared elicited pressures between several compression stockings on a wooden leg (vivo) and human leg (vitro). Four conditions were used which consisted of different clinical standard compressions garments which were: Class 1 garment; two Class 1 garments overlayed; Class 2 garment; and Class 3 garment. Elicited pressures were measured on six participants at the ankle behind the inner malleolus (A), 8 cm above location A, where the tendinous part changes into the calf muscle (B), 19 cm above the ankle at the mid-calf (C) and 30 cm above the ankle (D). The identical locations were used when measuring the garment pressures on the wooden leg. Three different sized wooden legs were used (small, medium and large) to correspond with the human participants leg size. The study concluded that pressures measured in vitro generally correlate well with in vivo measurements. However, at location A, in a standing position, pressure values were greater in the wooden leg model compared to the human leg by 4.5, 8.2, 11.6 and 13.4 (all mmHg) in the Class 1, Class 1 overlayed, Class 2 and Class 3 compression stockings, respectively. Conversely, at location C, pressure values were greater in the human leg compared to the wooden leg by 2.4, 2.5, 2.6 and 2.2 (all mmHg) in the Class 1, Class 1 overlayed, Class 2 and Class 3 compression stocking, respectively. It may well be that the wooden leg model does not replicate the shape and curvature of a human leg in terms of its musculature nor in terms of its variation in the shape of specific landmarks such as the Achilles tendon where acute angles typically cause pressures elicited by a garment to be elevated. In addition, a wooden leg cannot simulate the various tissues, with their diverse compressive characteristics, of a real human leg, which cause the leg to be hard or soft in different locations. For example, the anterior surface of the shank is hard due to the ridge of the tibia, conversely, the posterior surface of the shank is soft due to the musculature of the calf. The results of this study emphasise the inherent methodological limitations of research which relies on manufacturer reported values of pressure as these may deviate considerably from the actual pressures elicited by a compression garment on a living human participant.

Most of the published research literature has used standard sized ‘off the shelf’ compression garments. It is important to highlight that such garments are based on a cylindrical shape, therefore areas such as the maximal circumference of the calf typically elicit the highest pressure (peak pressure) as the garment may undergo the greatest stretch at this point. The location of peak pressure may be important for establishing a pressure gradient. Compression garments are typically designed with the intention of providing graduated compression, with pressures highest at the distal end of the garment and reducing toward the proximal end (MacRae et al., 2011). It has been proposed that applying a pressure gradient improves venous blood flow and venous return (Agu et al., 1999). The study by Partsch and colleagues (2006) demonstrated a clear linear pressure gradient for their wooden leg model, for each garment condition, with the highest pressure elicited at the ankle, and this was the intention for the garment they examined. However, the pressure gradient on the human leg showed a reversed pressure gradient from the locations A (ankle) to B (gaiter), with the peak pressure consistently existing at location B. A pressure gradient may be easier to elicit on a wooden leg as the surface of the leg is consistent (i.e., a hard wooden surface throughout). Whereas, on a human leg the tissue structure is much more complex as a mixture of hard tissues (bone, ligaments and tendons) and soft tissues (muscle) exist, potentially making it more difficult to produce a pressure gradient.

Some studies have measured garment pressure at only two locations (Dascombe et al., 2011; Hill et al., 2014; Trenell et al., 2006; Upton et al., 2017). Typically, the two locations specified for pressure assessment are the maximum calf circumference (medial) and the mid-point of the thigh between the patella and inguinal crease (anterior). However, compression garment elicited pressures may vary over small areas because of the contrasting shape and tissue structure of the human leg. Therefore, it is plausible that the use of just two pressure measurements, on the lower and upper leg, although giving some indication of the elicited pressure, may not provide an accurate reflection of the elicited pressure over the whole leg. For example, Brophy-Williams and colleagues (2015) measured elicited pressure at three locations on the medial lower leg and three locations on the anterior upper leg whilst participants wore undersized, recommended size and oversized compression tights. When wearing recommended sized compression tights, the mean pressure measured at the calf was 20.5 mmHg, whereas the mean pressure at the mid-thigh was 12.4 mmHg. Therefore, it could be assumed that the examined garment elicited a graduated pressure gradient from distal to proximal. However, the mean pressure measured at the ankle was 9.4 mmHg, which showed that, in fact, there was a reversed pressure gradient elicited on the lower leg as the pressure at the calf was greater than that at the ankle. Therefore, the use of two pressure measurements (upper leg and lower leg), commonly used in research studies that have directly determined the pressures elicited by compression garments may still be limited, as the two pressure measurements alone may not provide an accurate reflection of a garment's pressure profile, (defined as the peak pressure and pressure gradient applied by a compression garment). Therefore, a greater number of pressure measurements may be required to provide a more definitive indication of the actual pressure profile of a compression garment.

A method to measure the pressure profile elicited by a compression garment was adopted by Brophy-Williams and colleagues (2014). In this method, pressure was determined by placing an appropriate pneumatic sensor between the garment and skin interface. Pressure was recorded at six anatomical locations: 5 cm proximal to the distal border of the medial malleolus (A); 5 cm proximal to A (B); on the medial aspect of the maximal calf girth (C); on the anterior aspect of the thigh 10 cm below landmark E (D); the mid-point between the inguinal crease and the superior-posterior border of the patella (E); and 5 cm proximal to landmark E (F). However, these measurement locations are derived from clinical practice and research with individuals that typically have oedema in the legs (Partsch, et al., 2006; Stolk et al., 2004). Oedema increases leg volume, thus, the shape and tissue characteristics of the leg becomes more uniform. For example, the acute curvature of the Achilles tendon is reduced due to swelling caused by the oedema. Ultimately, the lower leg becomes more cylindrical and similar in shape to the upper leg. Therefore, the aforementioned pressure locations may be adequate and appropriate when used in clinical populations, as the lower and upper leg locations may well be similar in shape and tissue characteristics. However, in healthy sporting individuals the lower leg will not mirror the shape of the upper leg. In addition, the contrast in shape and tissue characteristics between lower and upper leg may well depend on the aspect of the leg being examined. For example, the anterior lower leg consists of hard tissues such as the tibia bone. Conversely, the posterior lower leg consists of soft tissues such as the calf muscle. Typically, hard tissues and landmarks which have an acute angular shape will cause the pressure elicited by a compression garment to be elevated (Nandasiri et al., 2020). According to Laplace's law, the pressure elicited by a compression garment is inversely proportional to the radius of curvature at a given location. Indeed, McManus and colleagues (2020) reported that the pressure elicited by compression garments was consistently higher on the anterior lower leg compared to pressure on the posterior, medial and lateral leg. Given that on the lower leg, the tibialis anterior muscle and tibia bone has a smaller radius of curvature compared with the larger radius of the gastrocnemius muscle on the posterior leg, it is likely this causes the elevated pressure on the anterior leg. However, the study by McManus and colleagues (2020) only measured compression garment pressure at the maximal circumference of the calf muscles. Therefore, the peak pressure and pressure gradient differences between different aspects of the whole length of a leg (anterior, posterior, medial and lateral) are unknown. Given that different tissue structures and characteristics may influence the pressure elicited by a compression garment, ensuring pressure is measured on tissue with similar characteristics would seem to be the optimal approach (particularly when establishing pressure gradients). However, understanding the consequences of making pressure measurements on differing types of tissue over the length of a limb such as a leg is also crucial.

Given that there is currently no standard methodology of assessing pressure profiles (peak pressure and pressure gradient) in sports compression garments in healthy individuals, the aim of this study was to examine if pressure profile differences existed when pressure measurements were made on different aspects of a human leg (anterior, posterior, medial and lateral). The study also compared these (novel) pressure profiles with an established methodology (Brophy-Williams et al., 2015), frequently used in the research literature.

4.3 Methodology

4.3.1 Participants

Fifteen healthy, recreationally active participants (age 24.6 ± 2.0 years, stature 178.9 ± 4.5 cm, body mass 77.4 ± 6.5 kg) volunteered and provided informed consent to participate in the study. All participants completed a health screen questionnaire before involvement in the study, to ensure they had no medical or other conditions that would have prevented them from taking part. Participants were instructed to refrain from strenuous exercise and alcohol consumption 24 hours prior to the experimental trials and to avoid caffeine consumption on the day of a trial whilst attending the laboratory at least 3 hours postprandial. The study was approved by a University Ethics Committee, (Nottingham Trent University Ethical Committee Application for Human Biological Investigation reference number: 559).

4.3.2 Experimental Design

In this study, participants visited the laboratory on two separate occasions. The first visit was a familiarisation trial, which consisted of a baseline 3D scan that was subsequently used to support the manufacture of the made-to-measure compression garments for each participant. The subsequent experimental trial comprised of wearing a made-to-measure lower body compression garment whilst pressure profiles, defined as the peak pressure and pressure gradient across the whole leg, were measured using a novel methodology and an established method used in previous research (Broatch et al., 2020; Brophy-Williams et al., 2014; Brophy-Williams et al., 2015).

4.3.3 Compression Garments and 3D Scan

A detailed description of the Artec Leo 3D scanner, scanning procedure and compression garments is provided in the General Methodology (*Section 3.5.6* and *Section 3.5.7*).

Briefly, this study used made-to-measure, full leg compression tights (Kurio 3D Compression Ltd, Nottingham, UK) which were fitted from the malleolus to the iliac crest. An Artec Leo 3D scanner (Artec Group, Luxembourg, Luxembourg) was used to capture a lower-body 3D scan performed during the familiarisation trial and used by the company to support the manufacture of the compression garments. The garment was designed to elicit peak pressure within Class three (25 – 35 mmHg) of UK clinical compression standards (BS-6612; 1985) and to elicit a linear pressure gradient. As each garment was specifically made-to-measure for each participant it was intended that each individuals' garment would provide the same fit (peak pressure and pressure gradient) and that the fit would not vary between participants.

4.3.4 Pressure Profile Assessments

The pressure profiles of the compression garments were assessed using a Kikuhime pressure-monitoring device (MediGroup, Melbourne, Australia) placed between the garment and skin interface. The 3D location of pressure sensor measurement sites was acquired simultaneously with pressure measurements using a thirteen-camera 3D motion capture system (Qualisys AB, Göteborg, Sweden) sampling at 100 Hz. Eight reflective markers were applied to the legs, using bi-adhesive tape, to represent the line of the leg. Four markers were placed on each leg at the following landmarks: 1) the lateral malleolus (ankle); 2) the lateral femoral condyle (knee); 3) the greater trochanter; and 4) the iliac crest. The anatomical marker locations and marker placement was performed by a trained anthropometrist (ISAK level 1). The pressure assessment using the novel method was performed firstly on the posterior of the right leg. The pressure sensor was placed 5 cm above the malleolus and then pulled up the leg in approximately 5 cm increments. Measurements were stopped when the sensor reached the line of the gluteal fold. Following each measurement increment, and prior to reading the pressure value, a reference 'reflective wand marker' was placed on the sensor location to define the exact measurement location with reference to the length of the leg, defined by the line between the lateral malleolus and greater trochanter markers. Once pressures were measured for the posterior of the leg, the protocol was repeated for the lateral, anterior and medial anatomical aspect of the leg.

Finally, the garment pressure was recorded at six anatomical locations used in previous research (established method): 5 cm proximal to the distal border of the medial malleolus (A), 5 cm proximal to A (B), on the medial aspect of the maximal calf girth (C), on the anterior aspect of the thigh 10 cm below landmark E (D), the mid-point between the inguinal crease and the superior-posterior border of the patella (E) and 5 cm proximal to landmark E (F). Prior the pressure measurement, the six locations were marked with indelible ink and covered with reflective tape, which was visible through the garment.

Preliminary data showed that the reflective tape did not affect pressure measurements compared to measurements made with no tape on the identical location. The sensor was placed on the first pressure location and held in place whilst the garment was fitted by the participant. Once pressure from the first location was measured, the pressure sensor was adjusted over the second pressure location, this was repeated until pressure for all six locations was recorded. The use of the reflective tape prevented the requirement to pull the garment down and up for each pressure measurement of the established method. Identical to the novel method, the exact location of each pressure measurement was determined using 3D motion capture and the reference 'reflective wand marker'. To identify the pressure measurement locations, the Qualisys motion capture files were used, and the reflective markers were labelled to represent the lateral malleolus (ankle), the lateral femoral condyle (knee), the greater trochanter and the iliac crest anatomical landmarks. Once labelled, the files were exported as .MAT files and a custom programme (MathWorks Inc., MA, USA) was used to select each pressure measurement location (location of the wand marker during measurement). Each location was measured as a percentage relative to the length of the leg. The pressure measurement locations were subsequently written into a Microsoft Excel sheet and paired with the corresponding pressure measurement (mmHg).

4.3.5 Data Analysis

A root mean squared difference (RMSD) analysis was used to calculate the in-vivo (worn) linear graduation parameters of peak pressure and pressure gradient. This analysis was used to assess differences of peak pressure and pressure gradient between aspects of the leg (anterior, posterior, medial and lateral) for the whole leg, lower leg and upper leg. For this approach, individual participants' measured pressure data were fitted with the equation of a straight-line (see equation 1) to identify the two parameters of peak pressure (p_{max}) and the pressure gradient (Δ_p). For lower leg measurements the peak pressure was located at the ankle malleolus and pressure gradient was the reduction in pressure between the ankle malleolus and the knee (50% leg length). For upper leg measurements the peak pressure was located at the knee and pressure gradient was the reduction in pressure between the knee and the greater trochanter. For whole leg measurements the peak pressure was located at the ankle malleolus and pressure gradient was the reduction in pressure between the ankle malleolus and the greater trochanter.

A straight line was fitted to the data using

$$\boldsymbol{P = \Delta_p x + p_{max}} \qquad [1]$$

Where $\boldsymbol{p_{max}}$ is the peak pressure, $\boldsymbol{\Delta_p}$ is the pressure gradient and $\boldsymbol{x}$ is the percentage of leg length.

The parameters and RMSD values were used to analyse garment pressure profiles between participants on each aspect of the leg (anterior, posterior, medial and lateral). When calculating RMSD at participant leg level, the fitting of individual leg pressure measurements was made by minimising a conventional RMS, squaring each pressure measurement, then calculating their mean and square root (see equation 2).

The difference between a participants' measured pressure and the predicated pressure for the same measurement location was calculated using

$$\boldsymbol{RMS_{ind} = \sqrt{\frac{\sum_{i=1}^{n}(Pa_i - Pb_i)^2}{n}}} \qquad [2]$$

Where $\boldsymbol{P_{ai}}$ is the participants' measured pressure, $\boldsymbol{P_{bi}}$ is the participants' model calculated pressure and $\boldsymbol{n}$ is the total number of pressure measurements.

4.3.6 Statistical Analysis

The peak pressure (intercept) and pressure gradient (gradient) data used for analysis, and subsequently reported in the results, was derived from linear regression performed for the RMSD analysis. A one-way repeated measures ANOVA was conducted to examine lower leg, upper leg, and whole leg peak pressure and pressure gradient differences for each aspect of the leg (anterior, posterior, medial and lateral). A one-way repeated measures ANOVA was conducted to examine lower leg, upper leg, and whole leg RMSD differences for each aspect of the leg (anterior, posterior, medial and lateral). Significant effects were further analysed using a Bonferroni post-hoc test. Paired samples t-tests were conducted to examine differences of peak pressure, pressure gradient and RMSD between the novel method and the established method. For the ANOVA analysis, effect sizes were calculated as partial eta squared (ηp^2) and interpreted as 0.01 = small, 0.06 = medium and 0.14 = large (Cohen, 1988). For the t-tests and post-hoc tests analysis, effect sizes were calculated as Cohens *d*, and interpreted as 0.20 = small, 0.50 = medium and 0.80 = large (Cohen, 1988). Data are presented as mean and standard deviation (mean ± SD), unless otherwise stated. A significance level of $P < 0.05$ was applied throughout.

4.4 Results

Novel Method Garment Pressure Profiles (Peak Pressure and Pressure Gradient)

Peak Pressure Whole Leg

There was a difference in peak pressure between the posterior, anterior, lateral and medial aspects of the whole leg using the novel method (main effect condition [$F(3, 42) = 23.146$, $P = 0.001$ $\eta p^2 = .623$]). The peak pressure was higher on the posterior compared to the lateral and medial aspects of the leg (pairwise comparison, $P = 0.001$ $d = 3.07$ and $P = 0.001$ $d = 2.02$ respectively) and was higher on the anterior compared to the lateral and medial aspects of the leg (pairwise comparison, $P = 0.001$ $d = 1.91$ and $P = 0.005$ $d = 1.33$ respectively). There was no difference in peak pressure between the anterior and posterior aspects of the leg ($P = 1.000$ $d = 0.03$), or between the lateral and medial aspects of the leg ($P = 0.101$ $d = 0.82$), (**Table 4.1**).

Peak Pressure Lower Leg

There was a difference in peak pressure between the posterior, anterior, lateral and medial aspects of the lower leg using the novel method (main effect condition [$F(3, 42) = 25.812$, $P = 0.001$ $\eta p^2 = .648$]). The peak pressure was higher on the posterior compared to the lateral and medial aspects of the leg (pairwise comparison, $P = 0.001$ $d = 2.56$ and $P = 0.001$ $d = 2.32$ respectively) and was higher on the anterior compared to the lateral and medial aspects of the leg (pairwise comparison, $P = 0.001$ $d = 1.33$ and $P = 0.002$ $d = 1.26$ respectively). There was no difference in peak pressure between the anterior and posterior aspects of the leg ($P = 1.000$ $d = 0.55$), or between the lateral and medial aspects of the leg ($P = 0.693$ $d = 0.00$), (**Table 4.1**).

Peak Pressure Upper Leg

There was a difference in peak pressure between the posterior, anterior, lateral and medial aspects of the upper leg using the novel method (main effect condition [$F(3, 42) = 13.098$, $P = 0.001$ $\eta p^2 = .483$]). The peak pressure was higher on the posterior compared to the lateral and medial aspects of the leg (pairwise comparison, $P = 0.001$ $d = 1.74$ and $P = 0.001$ $d = 2.00$ respectively) and was higher on the anterior compared to the medial aspect of the leg (pairwise comparison, $P = 0.001$ $d = 1.54$). There was no difference in peak pressure between the anterior and posterior aspects of the leg ($P = 1.000$ $d = 0.57$), between the lateral and anterior aspects of the leg ($P = 0.068$ $d = 1.31$), or between the lateral and medial aspects of the leg ($P = 1.000$ $d = 0.06$), (**Table 4.1**)

Table 4.1. Whole, lower and upper leg peak pressure (mmHg) for pressure values recorded on the posterior, lateral, anterior and medial aspect of the right leg using the novel method (mean ± standard deviation).

	Posterior (Novel)	**Lateral (Novel)**	**Anterior (Novel)**	**Medial (Novel)**
Peak Pressure Whole Leg	27.5 ± 2.2 $^{b, d}$	21.2 ± 2.1 $^{a, c}$	27.6 ± 4.5 $^{b, d}$	23.0 ± 2.4 $^{a, c}$
Peak Pressure Lower Leg	28.3 ± 1.4 $^{b, d}$	21.2 ± 1.9 $^{a, c}$	27.5 ± 3.8 $^{b, d}$	22.7 ± 3.2 $^{a, c}$
Peak Pressure Upper Leg	18.3 ± 3.3 $^{b, d}$	12.4 ± 3.7 ^{a}	16.6 ± 2.9 ^{d}	12.2 ± 3.0 $^{a, c}$

a = significantly different to posterior, b = significantly different to lateral, c = significantly different to anterior and d = significantly different to medial of the same leg segment (whole, lower and upper).

Pressure Gradient Whole Leg

There was a difference in the pressure gradient between the posterior, anterior, lateral and medial aspects of the whole leg using the novel method (main effect condition [$F(3, 42) = 11.338$, $P = 0.001$ $\eta p^2 = .447$]). The pressure gradient was shallower on the lateral compared to the posterior, anterior and medial aspects of the leg (pairwise comparison, $P = 0.001$ $d = 2.36$, $P = 0.003$ $d = 1.65$ and $P = 0.003$ $d = 1.40$ respectively). There was no difference in the pressure gradient between the posterior and anterior aspects of the leg (pairwise comparison, $P = 1.000$ $d = 0.20$), between the posterior and medial aspects of leg (pairwise comparison, $P = 0.368$ $d = 0.81$), or between the anterior and medial aspects of the leg (pairwise comparison, $P = 0.279$ $d = 0.69$), (**Table 4.2**).

Pressure Gradient Lower Leg

There was a difference in the pressure gradient between the posterior, anterior, lateral and medial aspects of the lower leg using the novel method (main effect condition [$F(3, 42) = 3.664$, $P = 0.020$ $\eta p^2 = .207$]). The pressure gradient was shallower on the lateral compared to the posterior aspect of the leg (pairwise comparison, $P = 0.039$ $d = 1.43$). There was no difference in the pressure gradient between the posterior and anterior aspects of the leg (pairwise comparison, $P = 1.000$ $d = 0.40$), between the posterior and medial aspects of leg (pairwise comparison, $P = 0.072$ $d = 0.96$), or between the anterior and medial aspects of the leg (pairwise comparison, $P = 1.000$ $d = 0.38$). There was also no difference in the pressure gradient between the lateral and anterior aspects of the leg (pairwise comparison, $P = 0.828$ $d = 0.70$), or between the lateral and medial aspects of the leg (pairwise comparison, $P = 1.000$ $d = 0.37$) (**Table 4.2**).

Pressure Gradient Upper Leg

There was a difference in the pressure gradient between the posterior, anterior, lateral and medial aspects of the upper leg using the novel method (main effect condition [$F(3, 42) = 3.813$, $P = 0.001$ $\eta p^2 = .381$]). The pressure gradient was shallower on the lateral compared to the posterior aspect of the leg (pairwise comparison, $P = 0.001$ $d = 1.79$) and was shallower on the medial compared to the posterior and anterior aspects of the leg (pairwise comparison, $P = 0.016$ $d = 1.41$ and $P = 0.019$ $d = 0.90$ respectively). There was no difference in the pressure gradient between the posterior and anterior aspects of the leg (pairwise comparison, $P = 1.000$ $d = 0.42$), between the lateral and anterior aspects of the leg (pairwise comparison, $P = 0.080$ $d = 1.22$), or between the lateral and medial aspects of the leg (pairwise comparison, $P = 1.000$ $d = 0.28$) (**Table 4.2**).

Table 4.2. Whole, lower and upper leg pressure gradient (mmHg) for pressure values recorded on the posterior, lateral, anterior and medial aspect of the right leg using the novel method (mean ± standard deviation).

	Posterior (Novel)	Lateral (Novel)	Anterior (Novel)	Medial (Novel)
Pressure Gradient Whole Leg	-21.7 ± 2.9 [b]	-15.3 ± 2.7 [a, c, d]	-22.4 ± 5.7 [b]	-19.3 ± 3.2 [b]
Pressure Gradient Lower Leg	-26.2 ± 8.0 [b]	-14.6 ± 8.8 [a]	-22.1 ± 12.9	-17.9 ± 9.8
Pressure Gradient Upper Leg	-26.9 ± 7.7 [c, e]	-11.0 ± 10.5 [b]	-23.2 ± 10.2 [e]	-13.9 ± 11.1 [b, d]

a = significantly different to posterior, b = significantly different to lateral, c = significantly different to anterior and d = significantly different to medial of the same leg segment (whole, lower and upper).

Root Mean Squared Difference (RMSD) Whole Leg

There was a difference in the RMSD between the posterior, anterior, lateral and medial aspects of the whole leg using the novel method (main effect condition [$F(3, 42) = 9.902$, $P = 0.001$ $\eta p^2 = .414$]). The RMSD was smaller on the posterior compared to the lateral, anterior and medial aspects of the leg (pairwise comparison, $P = 0.001$ $d = 2.06$, $P = 0.005$ $d = 1.63$ and $P = 0.001$ $d = 1.75$ respectively). There was no difference in the RMSD between the lateral and anterior aspects of the leg ($P = 1.000$ $d = 0.49$), between the lateral and medial aspects of the leg ($P = 1.000$ $d = 0.61$), or between the anterior and medial aspects of the leg ($P = 1.000$ $d = 0.09$), (**Table 4.3**).

Root Mean Squared Difference (RMSD) Lower Leg

There was a difference in the RMSD between the posterior, anterior, lateral and medial aspects of the lower leg using the novel method (main effect condition [$F(3, 42) = 11.323$, $P = 0.001$ $\eta p^2 = .447$]). The RMSD was smaller on the posterior compared to the lateral, anterior and medial aspects of the leg (pairwise comparison, $P = 0.002$ $d = 1.62$, $P = 0.049$ $d = 1.37$ and $P = 0.001$ $d = 2.21$ respectively) and was smaller on the lateral compared to the medial aspect of the leg (pairwise comparison, $P = 0.027$ $d = 0.97$). There was no difference in the RMSD between the lateral and anterior aspects of the leg ($P = 1.000$ $d = 0.32$), or between the anterior and medial aspects of the leg ($P = 0.609$ $d = 0.48$), (**Table 4.3**).

Root Mean Squared Difference (RMSD) Upper Leg

There was a difference in the RMSD between the posterior, anterior, lateral and medial aspects of the upper leg using the novel method (main effect condition [$F(3, 42) = 6.015$, $P = 0.002$ $\eta p^2 = .301$]). The RMSD was smaller on the posterior compared to the anterior aspect of the leg (pairwise comparison, $P = 0.017$ $d = 1.19$). There was no difference in the RMSD between the posterior and lateral aspects of the leg ($P = 1.000$ $d = 0.16$), or between the posterior and medial aspects of the leg ($P = 1.000$ $d = 0.00$). There was also no difference in the RMSD between the lateral and anterior aspects of the leg ($P = 0.176$ $d = 0.85$), between the lateral and medial aspects of the leg ($P = 1.000$ $d = 0.15$), or between the anterior and medial aspects of the leg ($P = 0.068$ $d = 1.08$), (**Table 4.3**).

Table 4.3. Whole, lower and upper leg RMSD (mmHg) for pressure values recorded on the posterior, lateral, anterior and medial aspect of the right leg using the novel method (mean ± standard deviation).

	Posterior (Novel)	**Lateral (Novel)**	**Anterior (Novel)**	**Medial (Novel)**
RMSD Whole Leg	1.8 ± 0.4 [b, c, d]	2.7 ± 0.5 [a]	3.1 ± 1.1 [a]	3.2 ± 1.1 [a]
RMSD Lower Leg	1.4 ± 0.6 [b, c, d]	2.6 ± 0.9 [a, d]	3.0 ± 1.6 [a]	3.7 ± 1.4 [a, d]
RMSD Upper Leg	1.2 ± 0.4 [c]	1.3 ± 0.8	2.0 ± 0.9 [a]	1.2 ± 0.6

a = significantly different to posterior, b = significantly different to lateral, c = significantly different to anterior and d = significantly different to medial of the same leg segment (whole, lower and upper).

Novel Method and Established Method Garment Pressure Profiles

Using the RMSD analysis as the evaluative tool, pressure values recorded on the posterior aspect of the leg consistently provided the lowest variability when assessing pressure profiles across the length of the leg (when compared with pressure values recorded on the lateral, anterior and medial aspects of the leg). Therefore, the pressure values recorded on the posterior aspect of the leg using the novel method were subsequently compared to pressure values recorded using the “established” method (Brophy-Williams et al., 2014) typically used in the published research literature to examine differences in garment pressure profiles (see below).

Peak Pressure (Whole, Lower and Upper Leg)

The peak pressure was higher in the novel method compared to the established method when pressure values were recorded over the whole leg (t (14) = -7.054, P = 0.001 d = 2.87). The peak pressure was higher in the novel method compared to the established method when pressure values were recorded over the lower leg (t (14) = -7.056 P = 0.001 d = 2.07). The peak pressure was higher in the novel method compared to the established method when pressure values were recorded over the upper leg (t (14) = -2.531 P = 0.024 d = 1.02), (**Table 4.4**).

Table 4.4. Whole, lower and upper leg peak pressure (mmHg) for pressure values recorded using the novel method (posterior) and established method on the right leg (mean ± standard deviation).

	Novel Method	**Established Method**
Peak Pressure Whole Leg	27.5 ± 2.2 *	19.8 ± 3.0
Peak Pressure Lower Leg	28.3 ± 1.4 *	19.0 ± 2.9
Peak Pressure Upper Leg	18.3 ± 3.3 *	15.6 ± 4.2

* = significantly different to the established method of the same leg segment (whole, lower and upper).

Pressure Gradient (Whole, Lower and Upper Leg)

The pressure gradient was shallower in the established method compared to the novel method when pressure values were recorded over the whole leg (t (14) = 6.672, P = 0.001 d = 3.03). The pressure gradient was shallower in the established method compared to the novel method when pressure values were recorded over the lower leg (t (14) = 6.010, P = 0.001 d = 4.23). The pressure gradient was shallower in the established method compared to the novel method when pressure values were recorded over the upper leg (t (14) = 3.080, P = 0.008 d = 0.74), (**Table 4.5**).

Table 4.5. Whole, lower and upper leg pressure gradient (mmHg) for pressure values recorded using the novel method (posterior) and established method on the right leg (mean ± standard deviation).

	Novel Method	Established Method
Pressure Gradient Whole Leg	-21.7 ± 2.9 *	-11.2 ± 4.5
Pressure Gradient Lower Leg	-26.2 ± 8.0 *	-6.5 ± 11.4
Pressure Gradient Upper Leg	-26.9 ± 7.7 *	-16.1 ± 13.4

* = significantly different to the established method of the same leg segment (whole, lower and upper).

Root Mean Squared Difference (Whole, Lower and Upper Leg)

The RMSD was not different in the established method compared to the novel method when pressure values were recorded over the whole leg (t (14) = -.714, P = 0.487 d = 0.46). The RMSD was not different in the established method compared to the novel method when pressure values were recorded over the lower leg (t (14) = .119, P = 0.907 d = 0.00). The RMSD was lower in the established method compared to the novel method when pressure values were recorded over the upper leg (t (14) = -5.884, P = 0.001 d = 1.81), (**Table 4.6**).

Table 4.6. Whole, lower and upper leg RMSD (mmHg) for pressure values recorded using the novel method (posterior) and established method on the right leg (mean ± standard deviation).

	Novel Method	Established Method
RMSD Whole Leg	1.8 ± 0.4	1.6 ± 0.5
RMSD Lower Leg	1.4 ± 0.6	1.4 ± 0.9
RMSD Upper Leg	1.2 ± 0.4 *	0.5 ± 0.4

* = significantly different to the established method of the same leg segment (whole, lower and upper).

Novel Method and Established Method Pressure Profiles (Same Leg Aspects)

In the established method, the medial aspect of the lower leg and the anterior aspect of the upper leg are the sites for the pressure measurements. Therefore, for the final analysis, the garment pressure profile using the established method was compared to the novel method using the same aspect of the leg. For example, the lower leg pressure profile of the established method (medial) was compared to the medial aspect of the lower leg using the novel method.

Peak Pressure Lower Leg

The peak pressure was higher in the novel method compared to the established method when pressure values were recorded on the medial aspect of the lower leg (t (14) = -3.890, P = 0.002 d = 1.25), (**Table 4.7**).

Pressure Gradient Lower Leg

The pressure gradient was shallower in the established method compared to the novel method when pressure values were recorded on the medial aspect of the lower leg (t (14) = 5.218, P = 0.001 d = 1.11), (**Table 4.7**).

RMSD Lower leg

The RMSD was smaller in the established method compared to the novel method when pressure values were recorded on the medial aspect of the lower leg (t (14) = -5.716, P = 0.001 d = 2.02), (**Table 4.7**).

Table 4.7. Lower leg peak pressure, pressure gradient and RMSD (mmHg) for pressure values recorded using the novel method and established method on the medial aspect of right leg (mean ± standard deviation).

	Novel Method (Medial)	**Established Method (Medial)**
Peak Pressure Lower Leg	22.7 ± 3.2 *	19.0 ± 2.9
Pressure Gradient Lower Leg	-17.9 ± 9.8 *	-6.5 ± 11.4
RMSD Lower Leg	3.7 ± 1.4 *	1.4 ± 0.9

* = significantly different to the established method.

Peak Pressure Upper Leg

The peak pressure was not different in the novel method compared to the established method when pressure values were recorded on the anterior aspect of the upper leg (t (14) = -.740, P = 0.472 d = 0.28), (**Table 4.8**).

Pressure Gradient Upper Leg

The pressure gradient was not different in the novel method compared to the established method when pressure values were recorded on the anterior aspect of the upper leg (t (14) = 1.917, P = 0.076 d = 0.62), (**Table 4.8**).

RMSD Upper Leg

The RMSD was smaller in the established method compared to the novel method when pressure values were recorded on the anterior aspect of the upper leg (t (14) = -6.073, P = 0.001 d = 2.23), (**Table 4.8**).

Table 4.8. Lower leg peak pressure, pressure gradient and RMSD (mmHg) for pressure values recorded using the novel method and established method on the anterior aspect of right leg (mean ± standard deviation).

	Novel Method (Anterior)	**Established Method (Anterior)**
Peak Pressure Upper Leg	16.6 ± 2.9	15.6 ± 4.2
Pressure Gradient Upper Leg	-23.2 ± 10.2	-16.1 ± 13.4
RMSD Upper Leg	2.0 ± 0.9 *	0.5 ± 0.4

* = significantly different to the established method.

4.5 Discussion and Conclusion

The aims of this chapter were to examine if pressure profile (peak pressure and pressure gradient) differences existed when pressure measurements were made on different aspects of a human leg (anterior, posterior, medial and lateral). The study also compared these (novel) pressure profiles with an established methodology (Brophy-Williams et al., 2014), frequently used in the research literature. The main findings of the study were that peak pressure was typically higher when pressure values were recorded on the posterior (18.3 to 27.5 mmHg) and anterior (16.6 to 27.6 mmHg) aspects of the upper, lower and whole leg, compared to the lateral (12.4 to 21.2 mmHg) and medial (12.2 to 23.0 mmHg) aspects. The pressure gradient was also steeper when pressure values were recorded on the posterior (-21.7 to -26.9 mmHg) and anterior (-22.1 to -23.2 mmHg) aspects of the upper, lower and whole leg, compared to the lateral (-11.0 to -15.3 mmHg) and medial (-13.9 to -19.3 mmHg) aspects. The RMSD was lowest when pressure values were recorded on the posterior aspect of the upper, lower and whole leg (1.2 to 1.8 mmHg), compared to the anterior, lateral, and medial aspects (1.2 to 3.7 mmHg). These findings clearly show that the aspect of the leg on which pressure values are taken influences the magnitude of the values recorded. When the novel method of measuring pressure from the current study (posterior aspect) was compared with the established method, peak pressure was higher (posterior vs. established: 27.5, 28.3, 18.3 vs. 19.8, 19.0, 15.6 mmHg, for the whole, lower and upper legs respectively) and the pressure gradient was steeper (posterior vs. established: -21.7, -26.2, -26.9 mmHg vs. -11.2, -6.5, -16.1 mmHg, for the whole, lower and upper legs respectively) when using the novel method. The RMSD of pressure values was similar between the novel (posterior aspect) and established method for the whole leg (1.8 ± 0.4 vs. 1.6 ± 0.5 mmHg) and for the lower leg (1.4 ± 0.6 vs. 1.4 ± 0.9 mmHg). The RMSD of pressure values was larger for the novel method (posterior) (1.2 ± 0.4 mmHg) compared to the established method (0.5 ± 0.4 mmHg), when recorded on the upper leg. The results of this study suggest that the made-to-measure compression garment pressure profile is significantly influenced by the aspect of the leg on which the pressure values are recorded, with pressure values recorded on the anterior and posterior aspects of the leg eliciting higher pressures and steeper pressure gradients compared to the medial and lateral aspects of the leg. However, with respect to the variability of pressure values over the whole leg, the values recorded on the posterior aspect provided the smallest RMSD which is likely due to the consistent tissue structures and obtuse curvature found on this aspect, which may have less influence on the pressure values compared to the anterior aspect of the leg where tissue structures and characteristics are less consistent. This study also suggests that the novel method using only the posterior aspect of the leg elicited significantly higher peak pressures and steeper pressure gradients compared to the established method. Various factors may explain these differences between methods such as the different leg aspects used, and the number of pressure values recorded. However, the greater number of pressure values recorded with the novel method may provide a more detailed and hence informative assessment of a compression garment pressure profile, particularly when measured on the posterior aspect of the leg which is predominantly muscular tissue.

Typically, in the published literature, the actual pressures elicited by the compression garments examined are not directly measured (Bernhardt & Anderson, 2005; Bringard et al., 2006; Cerqueira et al., 2015; Duffield et al., 2010; Higgins et al., 2009; Houghton et al., 2009; Kraemer et al., 2010; Pereira et al., 2014; Perrey et al., 2008; Shimokochi et al., 2017; Winke & Williamson, 2017). In some other published research studies authors report the manufacturer estimated values to indicate the pressures elicited by the compression garments they have examined (Armstrong et al., 2015; Ballmann et al., 2019; Davies et al., 2009; French et al., 2008; Govus et al., 2018; Heiss et al., 2018; Kim et al., 2017; Rugg & Sternlicht, 2013). Clearly, both of these approaches are far from optimal. When standard sized compression garments are used in research studies, which is typically the case (as opposed to the made-to-measure garments utilized in the present study), these will elicit variable levels of pressure in different participants due to variations in body geometry, even when individuals ‘fit’ within the same sizing category (Hill et al., 2015). Furthermore, manufacturer reported pressure values of a compression garment are often attained using pressure measurements made on a wooden leg (Partsch et al., 2006). As a wooden leg does not replicate the complex tissues structures and curvature of a human leg the pressures applied to a wooden leg may differ significantly to those generated and experienced when a compression garment is worn by a human (Partsch et al., 2006). Therefore, using manufacturer estimated values may be inaccurate for a given population. A method to measure the pressure profile elicited by a compression garment was adopted by Brophy-Williams and colleagues (2014). For this method, garment pressure was recorded at six anatomical locations: three on the lower medial leg and three on the anterior upper leg. However, the differences in leg tissue structure and curvature between the upper and lower leg may influence the pressure values recorded by this method. For example, measurements on the medial lower leg may pass over the tibia (hard tissue with sharp curvature), whereas measurements made on anterior upper leg are made on the quadriceps (soft tissue with minimal curvature). The location at which pressure values are recorded is critical, because, according to Laplace's Law, if measurements are made over bony prominences the pressure values may well be excessively high. This was demonstrated by Veraart and colleagues (1997) who showed that the pressures produced by Class II elastic stockings around the ankle ranged from 18.3 mmHg at the medial site to 33.9 mmHg at the pretibial zone (anterior). As a result, the current study examined the influence of the aspect of the leg on the pressure values recorded.

In the current study, peak pressure was measured over the whole leg, as well as the lower leg and upper leg independently. When peak pressure was modelled using pressure data across the whole leg, the anterior aspect elicited the highest peak pressure (27.6 ± 4.5 mmHg), followed by the posterior (27.5 ± 2.2 mmHg), medial (23.0 ± 2.4 mmHg) and lateral aspects of the leg (21.2 ± 2.1 mmHg). The findings, showing that the highest peak pressure is recorded on the anterior aspect of the leg is supported by the existing literature (McManus et al., 2020; Veraart et al., 1997). McManus and colleagues (2020) measured the elicited pressure of compression tights on the anterior, posterior, medial and lateral aspects of the maximal circumference of the calf, using a Kikuhime pressure monitoring device (the same device used in the present study). The study showed that elicited pressure was highest when pressure values were recorded on the anterior aspect of the calf (21.0 ± 4.4 mmHg) compared to the posterior (15.9 ± 2.2 mmHg), medial (15.1 ± 3.4 mmHg) and lateral (16.8 ± 2.1 mmHg) aspects. The research literature that has investigated the influence of the aspect of the leg on pressure values typically uses only one pressure measurement on the calf to compare garment pressure differences, whereas the current study used multiple pressure measurements across the whole length of the leg (ankle to gluteal fold) on each leg aspect. As a result, this provided a more complete and detailed indication of the influence of the aspect of the leg on the pressure outputs. The higher peak pressure elicited on the anterior aspect of the leg is likely due to the anatomic structure, tissues and curvature present on this aspect of the leg caused by the tibia. Sharp curvature can result in an over estimation of pressure by 150% (Burke et al., 2014) and according to Laplace's law, the pressure elicited by a compression garment is inversely proportional to the radius of curvature at the measured location (McManus et al., 2020). Therefore, following this principle, pressure applied at the tibia may be higher due to a sharp radius of curvature compared to the larger, more obtuse curvature found on the posterior leg.

The variability of pressure values recorded on a particular aspect of the leg was examined using a RMSD analysis. The results showed that the RMSD was smaller for pressure values recorded on the posterior (1.8 ± 0.4 mmHg) aspect of the whole leg compared to the lateral (2.7 ± 0.5 mmHg), anterior (3.1 ± 1.1 mmHg) and medial (3.2 ± 1.1 mmHg) aspects of the whole leg, when pressure values were recorded using the novel method. Also, the RMSD of pressure values was larger for the lower leg compared to the upper leg for all leg aspects. The absolute difference between the lower and upper leg RMSD values for the posterior, lateral, anterior and medial aspects of the leg were: 0.2, 1.3, 1.0 and 1.5 mmHg respectively. This indicates that pressure values recorded on the lower leg have larger variability compared with the upper leg. The structure of tissues and the curvature of the leg may contribute to these findings. For example, the lower leg consists of predominately hard tissues and sharp curvature which increases the variability in pressure values as when pressures are measured over such areas, the pressure is elevated (Nandasiri et al., 2020). Conversely, the pressure measurements made on the upper leg had smaller variability in pressure values, but these were similar in magnitude when the four different aspects of the leg were compared. Given that the upper leg consists of large muscle groups such as the quadriceps and hamstrings, the tissue and curvature is more consistent throughout, and this probably explains the smaller variability in pressure values that was observed. Furthermore, the RMSD for the upper leg was similar between the posterior (1.2 ± 0.4), lateral (1.3 ± 0.8), anterior (2.0 ± 0.9) and medial (1.2 ± 0.6) aspects of the leg. The posterior aspect of the leg showed the smallest variability in pressure values for measurements made on both the lower and upper leg. Furthermore, given that the absolute difference in RMSD values between the lower and upper posterior leg was small (0.2 mmHg), this highlights that any effect of tissue structure and curvature were similar between the lower and upper leg. This is likely due to the upper and lower posterior leg consisting of similar soft, muscular tissues (calf and hamstrings). In addition, measuring over consistent, predominantly muscular tissue, may be the optimal approach as ultimately, many of the proposed beneficial effects of wearing compression garments seem to be derived from their influence on aspects of muscle function such as blood flow, oxygenation and muscle displacement (during exercise), and therefore the particular pressure values recorded on this type of tissue is what is likely to be eliciting any positive effects of wearing compression garments that may be occurring. As a result of the smaller variability in pressure values and the practical relevance of pressure measurements over the posterior leg, we purpose that using the posterior of the lower and upper leg is the optimal aspect on which to make pressure measurements when examining the effect of sports compression garments worn by healthy individuals.

In the current study, pressure measurements made on the posterior leg consistently provided the lowest variability in pressure values compared to the lateral, anterior and medial aspects of the leg, using the novel method. Therefore, the pressure values recorded on the posterior aspect of the leg using the novel method were compared to those recorded using the established method typically used in the published research literature, to examine differences in garment pressure profiles between methods. The modelled peak pressure at the ankle was higher when using the novel method (27.5 ± 2.2 mmHg) compared to the established method (19.8 ± 3.0 mmHg), when pressure values were recorded over the whole leg. Unsurprisingly, the pressure gradient was also steeper using the novel method (-21.7 ± 2.9 mmHg) compared with the established method. However, these differences are likely because the aspect of the leg and exact measurement sites that pressure values were recorded on differed as the novel method used measurements on the posterior leg, whereas the established method used the medial (lower leg) and anterior (upper leg). Therefore, as previously highlighted, the underlying tissue and shape differences that exist on different aspects of the leg will influence the pressure values recorded.

To determine whether the observed peak pressure and pressure gradient differences occurred due to pressure measurements made on different aspects of the leg between methods. Pressure data using the same aspect of the leg were also compared. As such, for the lower leg, the medial pressure values were used and for the upper leg the anterior pressure values were used to compare the novel and established methods. The results showed that peak pressure at the ankle, modelled using only lower leg pressure values, was significantly higher using the novel method (22.7 ± 3.2 mmHg) compared to the established method (19.0 ± 2.9 mmHg). The pressure gradient from the ankle to the knee (lower leg) was significantly steeper using the novel method (-17.9 ± 9.8 mmHg) compared to the established method (-6.5 ± 11.4 mmHg). Moreover, the results showed that peak pressure at the knee, modelled using only upper leg pressure values, was similar between the novel method (16.6 ± 2.9 mmHg) and established method (15.6 ± 4.2 mmHg). The pressure gradient from the knee to the gluteal fold (upper leg) was similar between the novel method (-23.2 ± 10.2 mmHg) and the established method (-16.1 ± 13.4 mmHg). There may be two main factors which contribute to the differences in peak pressure and pressure gradient observed in the lower leg: 1) although the pressure measurements were made on the same aspect of the leg, the exact location of each pressure measurement differed between methods, therefore, it is possible that measurements were made over slightly different tissue structures and that the curvature was not the same; and 2) more pressure values were recorded using the novel method (5-6) compared to the established method (3), for the lower leg. However, it could be argued that by attaining a larger number of pressure values this may more accurately and informatively reflect the pressure profile elicited by the compression garment. For example, for the established method the pressure measurement locations on the lower leg were: 5 cm proximal to the distal border of the medial malleolus (A), 5 cm proximal to A (B), and on the medial aspect of the maximal calf girth (C). These locations are not equally spaced across the length of the lower leg, therefore, the pressure between location B and C is unknown. Furthermore, given that the lower medial leg has changes in curvature caused by muscles such as the soleus and gastrocnemius the three locations used for the established method excludes a large portion of the lower leg where curvature changes (curvature change from the soleus to the gastrocnemius). However, the novel method uses ~5 cm measurement increments from the first pressure measurement site (5cm proximal to the ankle) which may better reflect the pressures elicited by the compression garment over the contrasting curvature of the lower leg. To further evidence this point, the peak pressure and pressure gradient of the upper leg was not different between pressure measurement methods. Given that the anterior upper leg has similar muscular tissues and limited curvature change, this may explain why no differences of peak pressure and pressure gradient were observed between methods for the upper leg.

The established method has been used frequently within compression garment research (Broatch et al., 2020; Brophy-Williams et al., 2014; Brophy-Williams et al., 2015) and the pressure locations used with this method are derived from clinical practice and research on individuals that typically have oedema in the legs (Partsch, et al., 2006; Stolk et al., 2004). Oedema increases leg volume; thus, the shape of the leg becomes more uniform in terms of tissue structure and curvature. For example, the acute curvature of the Achilles tendon is reduced. Ultimately, the lower leg becomes more cylindrical and consequently similar in shape and characteristics to a ‘normal’ upper leg. However, the aforementioned measurement locations of the established method may not be suitable for healthy individuals as a healthy leg typically has variable tissue structures (i.e., bone and muscle) as well as sharp curvature (Achilles tendon and tibia). Therefore, in healthy individuals an aspect of the leg which in consistent in tissue structure and curvature may be more appropriate for establishing pressure values. The results of the current study suggest that the posterior aspect of the leg provides the required consistent tissue structure and minimal sharp curvature which was demonstrated by this aspect eliciting the lowest variability of pressure values along the whole length of the leg compared to the anterior, medial and lateral aspects of the leg.

The established method used in previous research may have practical limitations. This method may be time-consuming, as the compression garment needs to be pulled down after each pressure measurement to allow the appropriate relocation of the pressure sensor, and the garment is subsequently pulled up and refitted (Brophy-Williams et al., 2014). In this study, the established approach was adjusted so that the number of fitting cycles was minimised by identifying the six pressure measurement locations with visible tape markers, and subsequently adjusting the pressure sensor to align with the tape markers to ensure the correct position of the sensor. However, although this approach reduced the time commitment of such a method, the adjustment of the sensor for each measurement location was tedious and potentially error prone, particularly as the sensor needed be adjusted from the medial to the anterior aspect of the leg whilst positioned under the garment. However, the novel method eradicated this issue as the sensor was consistently placed 5 cm above the ankle malleolus on the posterior aspect of the leg and subsequently pulled up the leg in approximately 5 cm increments. Therefore, the novel method required only one fitting cycle for the initial placement of the sensor and given that pressure measurements were made on the posterior aspect of the leg the positioning of the sensor was more efficient compared to the established method. Furthermore, the application of 3D motion capture during the pressure measurements of the novel method allowed the quantification of pressure measurement locations. The novel method also consisted of 11 ± 1 pressure measurements on the posterior of the leg compared to 6 ± 0 measurements for the established method. As such, the novel method may provide a more detailed reflection of the pressure profile (peak pressure and pressure gradient) of a compression garment.

Limitations

The small sample size (n = 15) may be a limiting factor which likely caused the insignificant *P* values, but large corresponding effect sizes demonstrated in the current study. Performing a sample size estimation would identify a suitable number of participants required to allow the study to be appropriately powered, however, this was not performed. Therefore, we cannot be certain that the sample size used in this study was sufficient.

In conclusion, peak pressure at the ankle was highest at the anterior aspect of the leg (27.6 ± 4.5 mmHg), followed by the posterior (27.5 ± 2.2 mmHg), medial (23.0 ± 2.4 mmHg) and lateral aspects of the leg (21.2 ± 2.1 mmHg). The RMSD was smallest for pressure values recorded on the posterior (1.8 ± 0.4 mmHg) aspect of the whole leg compared to the lateral (2.7 ± 0.5 mmHg), anterior (3.1 ± 1.1 mmHg) and medial (3.2 ± 1.1 mmHg). Therefore, the results suggest that the posterior aspect of the leg may be optimal for pressure measures due to the consistent tissue structure and curvature found here. The novel method (posterior leg) was subsequently compared to pressure values recorded using the established method. The peak pressure at the ankle was higher when using the novel method (posterior leg) (27.5 ± 2.2 mmHg) compared to the established method (19.8 ± 3.0 mmHg), when pressure values were recorded over the whole leg, and the pressure gradient was also steeper using the novel method (posterior leg) (-21.7 ± 2.9 mmHg) compared to the established method (-11.2 ± 4.5 mmHg). Ultimately, the results of the current study suggest that the novel method, using the posterior aspect of the leg, provides optimal pressure measurement due to the consistent tissue structure and curvature found here. In addition, using the posterior aspect of the leg with the novel method means the inclusion of more pressure measurements which provides a more detailed and better reflection of the pressure profile elicited by a compression garment, compared to an established pressure measurement method, which is currently typically used in the published research literature.

Chapter 5: Customised pressure profiles of made-to-measure sports compression garments.

5.1 Rationale

The previous chapter presented the development of a novel methodology for measuring compression garment pressures. As a result, the novel methodology was used in the current chapter to measure compression garment pressures. In the published compression garment literature, a major limitation is that standard sized compression garments are used which may not elicit high enough pressures and may not provide the same fit between participants due to dimension and tissue structure differences within a study population (Davies et al., 2009). Therefore, it has been recommended that made-to-measure compression garments are developed based on an individual's body geometry and used to provide an optimal and consistent fit within a study population (Born et al., 2013; MacRae et al., 2011). As a result, this chapter aimed to examine if it was possible to make made-to-measure compression garments that elicit pressures that fit within and below clinical pressure standards and elicit the same pressure profiles between participants.

5.2 Introduction

Compression garments are worn to apply an external, mechanical pressure on the surface of the body, which may compress and support underlying tissues and have been shown to reduce muscle oscillation during exercise (Doan et al., 2003; MacRae et al., 2011). In clinical practice, guidelines have been developed to ensure appropriate prescription of compression garment pressures for specific conditions. However, it should be noted that agreed pressure guidelines do not necessarily result in the same classifications in all countries; for example, in the UK, France and Germany, specific compression garment pressures correspond to different classifications (Todd, 2015). In the UK, the guidelines have three pressure classifications (BS-6612; 1985): Classes one (14 – 17 mmHg), two (18 – 24 mmHg) and three (25 – 35 mmHg). Wearing compression garments is common in sporting environments (Xiong & Tao, 2018; Yang et al., 2020). Some manufacturers claim that their garments elicit 'graduated compression'. Such claims of graduated compression implies that a garment elicits high pressures at the distal end, with the pressure gradually reducing towards the proximal end, which may improve venous flow and return (Agu et al., 1999). Some research has found positive effects of wearing compression garments on exercise performance, or during recovery from exercise (Broatch et al., 2017; Kemmler et al., 2009; Kim et al., 2017; Kraemer et al., 2010; Rugg & Sternlicht, 2013; Sear et al., 2010). However, other research has not been able to demonstrate such effects (Del Coso et al., 2014; Govus et al., 2018; Sperlich et al., 2013; Stickford et al., 2015; Struhár et al., 2018; Winke & Williamson, 2017). Consequently, with such equivocal research findings, it is unknown whether compression garments aid exercise performance and recovery.

A factor that may explain the equivocal findings in the sport related research literature is that many studies do not measure the pressure elicited by the compression garment, often reporting only manufacturer-estimated values typically taken from standardised wooden-leg models (Partsch, et al., 2006). The inadequate quantification of between-human differences in leg geometry, and the different stiffness characteristics of leg tissues such as bone, tendon and muscle, probably contributes to a limited understanding of the actual in-vivo pressures elicited by compression garments. The ambiguity in the results of sport related research involving compression garments is therefore perhaps unsurprising. If pressure is not measured, then linking the pressure profile elicited by a compression garment with any associated performance changes and physiological adaptations is impossible.

Commercially available compression garments are required to fit individuals whose body morphologies are unknown to the manufacturer, thus, generalized sizing systems are typically applied (MacRae et al., 2011). Such compression garments are typically available in five alphanumerical sizes i.e., extra-small, small, medium, large and extra-large. This lack of customization could lead to garments that fit poorly. Therefore, if the pressures applied by commercially available compression garments were measured, these pressures could vary between individuals. Indeed, Brophy-Williams and colleagues (2015) found the pressure elicited by compression garments to be affected by sizing. Furthermore, it was found that by wearing commercially available compression garments and using manufacturer- recommended sizing, the measured pressures varied between individuals even if individuals were fitted within the same sizing category. As such, if a compression garment fits poorly there could be differences in pressure profiles experienced by participants. The requirement for a compression garment to provide the same fit between legs is also of importance. It is common to have size and shape differences between dominant and non-dominant legs. Rauter and colleagues (2017) showed knee and calf circumferences to differ between left and right legs in young, male road cyclists. Such leg asymmetry could result in commercially available compression garments eliciting more pressure on one leg than the other, as well as providing an inconsistent fit between participants. To ensure robust research study design with sufficient reliability and validity, it may be beneficial for participants to wear made-to-measure compression garments, to allow all participants to experience equivalent pressure profiles. However, whether made-to-measure compression garments can be manufactured to ensure similar pressure profiles across individuals is unknown.

This study had three aims, firstly, to examine if it was possible to make a made-to-measure compression garment that elicits graduated pressures that fit within clinical pressure standards and a control compression garment with pressures below clinical standards. It also aimed to examine whether pressures and gradients can be replicated within and between participants' legs and for separate compression garment conditions. Finally, it aimed to examine made-to-measure compression garment fit between conditions and between participants' legs.

5.3 Methodology

5.3.1 Participants

Ten healthy, recreational male runners (age 24.3 ± 4.6 years, stature 181.5 ± 1.8 cm, body mass 75.7 ± 3.8 kg, mean ± standard deviation) volunteered and provided informed consent to participate in the study. All participants completed a health screen questionnaire before involvement in the study, to ensure they had no medical or other conditions that would have prevented them from taking part. All participants refrained from strenuous exercise 24 hours before each trial and refrained from caffeine on the day of a trial. The study was approved by a University Ethics Committee, (Nottingham Trent University Ethical Committee Application for Human Biological Investigation reference number: 560).

5.3.2 Experimental Design

Participants visited the laboratory four times. The first visit was a familiarisation trial, which consisted of a baseline three-dimensional (3D) scan that was used to support the manufacture of made-to-measure compression garments for each participant. Each experimental trial consisted of wearing a different lower body compression garment whilst pressure profiles, defined as the peak pressure and pressure gradient from the distal to the proximal end of both legs, were measured. The compression garment conditions were: 1) control, 2) high gradient and 3) asymmetrical (see below).

5.3.3 Compression Garments and 3D Scan

The study used made-to-measure, full leg compression tights (Kurio 3D Compression Ltd, Nottingham, UK) and were fitted from the malleolus to the iliac crest. Within each trial, the compression garment used differed in pressure and graduation of pressure. The pressure profile of each garment was implemented into the garment using a specifically designed software programme developed by the company. The compression garments were made using a composite of Elastane (22%) and Nylon (78%), in two sections as left and right legs with a seam up the centre line. The properties of the material were determined by the company's in-house testing processes. An assessment of the material was made following the standard for evaluating the 'Determination of the elasticity of fabrics' (BS EN 14704-1:2005) then further evaluated against in-vivo measurements of pressure obtained from individuals outside of the study population (n = 30) to establish the relationship between material reductions, body geometry and elicited pressure. The measured properties were then used to determine the material size reduction required to generate intended clinical and non-clinical pressures for all garments according to Laplace's Law (Liu et al., 2017). The elastic material used for the garment facilitates dressing, such that the garment can be stretched over various joint structures. Furthermore, this stretching ensures that the garment sits on the appropriate surface of the leg without slipping. The control garment was designed to elicit pressure below clinical standards (< 14 mmHg) with no pressure gradient. The high gradient garment was designed to elicit pressure within clinical standards (14 – 35 mmHg) and to include a linear pressure gradient from distal to proximal (graduated compression). The asymmetrical garment was designed to elicit control conditions in the left leg and graduated compression in the right.

The pressure classifications used in this study corresponded to UK compression standards (BS-6612; 1985): Classes one (14 – 17 mmHg), two (18 – 24 mmHg) and three (25 – 35 mmHg).

To develop the made-to-measure compression garments an Artec Eva 3D scanner (Artec Group, Luxembourg, Luxembourg) captured a lower-body 3D scan of each participant whilst they slowly rotated on a turntable, standing with their legs shoulder width apart. Scans were processed using Artec Studio 13 software (Artec Group, Luxembourg, Luxembourg) and exported to a custom-built programme (Kurio 3D Compression LTD), where identical garment re-sizing parameters were used for each participant to produce material templates that elicited the required pressures in the control, symmetrical and asymmetrical garment conditions.

5.3.4 Pressure Profile Assessment

The pressure profiles of the compression garments were assessed using a Kikuhime pressure-monitoring device (MediGroup, Melbourne, Australia). Pressure elicited by the garments was measured at multiple sites on the mid-line of the posterior surface of each leg. The location of the pressure sensor measurement sites was acquired simultaneously with pressure measurements using a thirteen-camera 3D motion capture system (Qualisys AB, Göteborg, Sweden) sampling at 100 Hz. Eight reflective markers were applied to the legs, using bi-adhesive tape, to represent the line of the leg. Four markers were placed on each leg at the following landmarks: 1) the lateral malleolus (ankle); 2) the lateral femoral condyle (knee); 3) the greater trochanter; and 4) the iliac crest. The anatomical marker locations and marker placement was performed by a trained anthropometrist (ISAK level 1). Before the pressure profile assessment participants would have been standing for 20 minutes. During the pressure profile assessment, participants stood with their legs shoulder width apart with their arms crossed over their chest. Participants were instructed to stand still and to keep their musculature relaxed during the pressure measurement. The pressure monitoring device was placed between the garment and skin interface and repeatedly relocated by pulling the pressure monitoring device up the leg for each measurement. Pressure measurements were collected at about 5 cm increments up the posterior surface of both legs from the malleolus. To obtain a precise location for the pressure measurements, a reflective wand marker was briefly placed on the pressure measurement site before reading the pressure (**Figure 5.1**). The pressure profile assessment of both legs lasted about eight minutes.

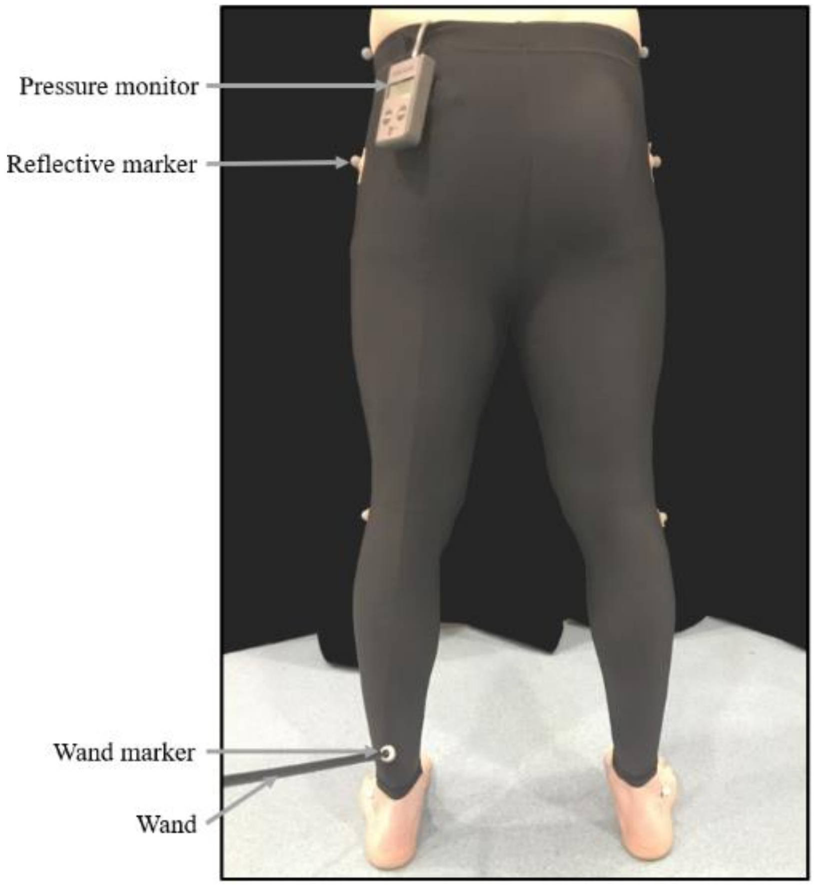


Figure 5.1. Participant wearing the compression garment during the pressure profile assessment. The 'reflective markers' applied to define leg length, the 'pressure monitor' in place to measure pressure elicited by the garment (distal to proximal), the 'wand' and the 'wand marker' applied before each pressure measurement to reference the measurement location relative to leg length, are indicated in the figure.

5.3.5 Data Analysis

A root mean squared difference (RMSD) analysis was used to calculate the in-vivo (worn) linear graduation parameters of peak pressure and graduation. This analysis was used to assess differences of peak pressure and pressure gradient between conditions and between a participants' legs, to determine how well the garments fitted at both group and individual level. For this approach, individual participants' pressure data for each leg were fitted with the equation of a straight-line (see equation 1) to identify the two parameters which minimised the difference between measured and predicted pressures using a simulated annealing algorithm (Corana et al., 1987). The two parameters identified were peak pressure at the ankle malleolus (p_{max}) and the pressure gradient (Δ_p). The predicted pressure corresponded to the line of best fit generated by the algorithm.

A straight line was fitted to the data using

$$\boldsymbol{P = \Delta_p x + p_{max}} \qquad [1]$$

Where $\boldsymbol{p_{max}}$ is the peak pressure at the ankle, $\boldsymbol{\Delta_p}$ is the pressure gradient (the reduction in pressure between the ankle malleolus and the greater trochanter) and $\boldsymbol{x}$ is the percentage of leg length.

The parameters and RMSD values were used to analyse garment fit between participants within a garment condition. When calculating RMSD at participant leg level, the fitting of individual leg pressure measurements was made by minimising a conventional RMSD, squaring each pressure measurement, then calculating their mean and square root (see equation 2).

The difference between a participants' measured pressure and the predicated pressure for the same measurement location was calculated using

$$\boldsymbol{RMS_{ind} = \sqrt{\frac{\sum_{i=1}^{n}(Pa_i - Pb_i)^2}{n}}} \qquad [2]$$

Where $\boldsymbol{P_{ai}}$ is the participants' measured pressure, $\boldsymbol{P_{bi}}$ is the participants' model calculated pressure and $\boldsymbol{n}$ is the total number of pressure measurements.

At group level, rather than square each participants' difference between measured and model calculated pressure, we instead adopted an approach of calculating the mean difference between measured and model calculated pressures for a participant and then calculated the sum of squares of these mean values (see equation 3). This acquires a better representation of the garment fit at group level and is less sensitive to outliers in individual participant pressure measurements.

$$\boldsymbol{RMS_{group} = \sqrt{\frac{\sum_{j=1}^{m}\left(ya_j\right)^2}{m}}} \qquad [3]$$

Where $\boldsymbol{m}$ is the total number of participants and where the mean difference between participants' measured pressure and model calculated pressure (ya_j) was calculated using

$$\boldsymbol{ya_j} = \frac{(\sum_{i=1}^{n} Pa_i - Pb_i)}{n} \qquad [4]$$

5.3.6 Statistical Analysis

All measurements of length were defined from the ankle malleolus relative to the length of the leg which for this study, was defined as the shortest distance between the ankle malleolus and the greater trochanter. The peak pressure and pressure gradient data used for analysis, and subsequently reported in the results, was derived from the RMSD method. A one-way repeated measures ANOVA was conducted to examine peak pressure and pressure gradient in the left and the right legs of the participants in the three garment conditions. Significant effects were further analysed using a Bonferroni post-hoc test. Paired samples t-tests were conducted to assess for differences of peak pressure and pressure gradient between legs of each garment condition. Effect sizes were calculated as partial eta squared (ηp^2) and interpreted as 0.01 = small, 0.06 = medium and 0.14 = large (Cohen, 1988). Data are presented as mean and standard deviation (mean ± SD), unless otherwise stated. A significance level of $P < 0.05$ was applied throughout.

5.4 Results

Root Mean Squared Difference

The RMSD (equation 3) between predicted and actual pressures in the left and right leg respectively were: control garment, 2.1 and 2.1; asymmetrical garment, 2.0 and 2.5; high gradient garment, 2.1 and 2.1 (all mmHg). The inter-individual RMSD (equation 2) ranged from: control garment, 1.5 to 3.5; asymmetrical garment, 1.2 to 6.3; high gradient garment, 1.5 to 4.5 (all mmHg).

Pressure Gradients Between Garment Conditions

Left Leg

There was a difference in pressure gradient between garments for the left leg (main effect condition [$F(2, 18) = 79.527$, $P = 0.001$ $\eta p^2 = .898$]. The pressure gradient was shallower in the control and asymmetrical garments than in the high gradient garment (pairwise comparison, P = 0.001 in both instances). As intended the pressure gradient in the left leg of the asymmetrical garment was the same as in the control garment (pairwise comparison, P = 1.000), (**Table 5.1**)

Right Leg

There was a difference in pressure gradient between garments for the right leg (main effect condition [$F(2, 18) = 89.661$, $P = 0.001$ $\eta p^2 = .909$]. The pressure gradient was shallower in the control garment than in both the asymmetrical and high gradient garments (pairwise comparison, P = 0.001 in both instances). As intended the pressure gradient in the right leg of the asymmetrical garment was the same as in the high gradient garment (pairwise comparison, P = 1.000), (**Table 5.1**)

Table 5.1. Pressure gradient in the left and right legs in the control, asymmetrical and high gradient compression garment conditions (mean ± standard deviation).

	Control	Asymmetrical	High Gradient
Left Leg (mmHg)	-8.9 ± 3.5	-7.5 ± 3.9	-25.0 ± 4.1 †
Right Leg (mmHg)	-7.4 ± 3.0	-21.9 ± 3.2 * †	-22.3 ± 3.6 †

* significantly different between legs, † significantly different to control garment (P < 0.05)

Peak Pressure Between Garment Conditions

Left Leg

There was a difference in peak pressure between garments for the left leg (main effect condition [$F(2, 18) = 115.299$, $P = 0.001$ $\eta p^2 = .933$]. The peak pressure was lower in the control and asymmetrical garments than in the high gradient garment (pairwise comparison, P = 0.001 in both instances). As intended the peak pressure in the left leg of the asymmetrical garment was the same as in the control garment (pairwise comparison, P = 1.000), (**Table 5.2**).

Right Leg

There was a difference in peak pressure between garments for the right leg (main effect condition [$F(2, 18) = 111.708$, $P = 0.001$ $\eta p^2 = .925$]. The peak pressure was lower in the control garment than in both the asymmetrical and high gradient garments (pairwise comparison, P = 0.001 in both instances). As intended the peak pressure in the right leg of the asymmetrical garment was the same as in the high gradient garment (pairwise comparison, P = 1.000), (**Table 5.2**).

Table 5.2. Peak pressure at the ankle in the left and right legs in the control, asymmetrical and high gradient compression garment conditions (mean ± standard deviation).

	Control	**Asymmetrical**	**High Gradient**
Left Leg (mmHg)	13.5 ± 2.3	12.7 ± 2.5	27.7 ± 2.2 †
Right Leg (mmHg)	12.9 ± 2.6	26.3 ± 3.4 * †	27.5 ± 1.6 †

* significantly different between legs, † significantly different to control garment (P < 0.05)

Within Garment Between Leg Pressure Gradient Differences

There was a difference in pressure gradient between legs in the asymmetrical garment (t (9) = 14.068, P = 0.001) and no differences in the control and high gradient garments (t (9) = -1.324, P = 0.218) and (t (9) = -1.975, P = 0.080, respectively).

3.5. Within Garment Between Leg Peak Pressure Differences

There was a difference in peak pressure between legs in the asymmetrical garment (t (9) = -23.141, P = 0.001) and no differences in the control and high gradient garments (t (9) = .442, P = 0.669) and (t (9) = .262, P = 0.799, respectively).

Elicited Pressures Within Clinical Standards

As intended, for the control garment and the left leg of the asymmetrical garment, elicited pressure was below Class one of clinical compression standards over all of the legs. For the right leg of the asymmetrical garment, 5, 32, 20 and 43% of elicited pressures were within Class three, Class two, Class one and below clinical compression standards, respectively. For the left leg of the high gradient garment, 12, 31, 17 and 45% of elicited pressures were within Class three, Class two, Class one and below clinical compression standards, respectively. Finally, for the right leg of the high gradient garment, 9, 30, 16 and 45% of elicited pressures were within Class three, Class two, Class one and below clinical compression standards, respectively, (**Figure 5.2**)

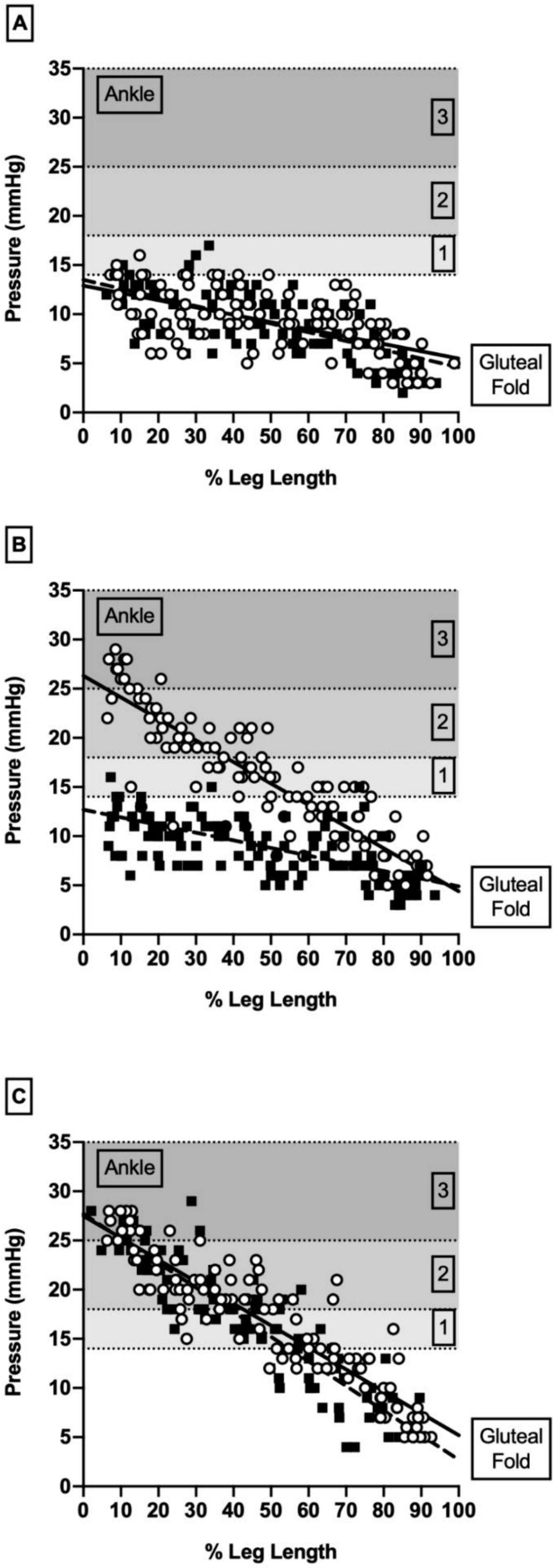


Figure 5.2. Pooled data presenting pressure profiles for the left and right legs in the (A) control, (B) asymmetrical and (C) high gradient compression garment conditions. Class one (14 – 17 mmHg) clinical compression threshold indicated by light grey shading, Class two (18 – 24 mmHg) clinical compression threshold indicated by medium grey shading and Class three (25 – 35 mmHg) clinical compression threshold indicated by dark grey shading (BS-6612; 1985). The dashed trendline corresponds to the left leg pressure gradient and the filled trendline corresponds to the right leg pressure gradient.

5.5 Discussion and Conclusion

This study shows that it was possible to make made-to-measure compression garments that elicit pressures within and below clinical standards. Furthermore, it was shown that pressures and gradients can be replicated within and between participants legs, and between separate compression garments. The control over elicited pressure was evidenced by peak pressure of 27.7 ± 2.2 mmHg and 27.5 ± 1.6 mmHg for the high gradient garment in the left and right legs of participants (within Class three of clinical compression standards), while for the control garment, the corresponding values were 13.5 ± 2.3 mmHg and 12.9 ± 2.6 mmHg (below clinical compression standards). The use of individual 3D scans ensured that made-to-measure compression garments consistently elicited prescribed pressure profiles in participants' legs and between different garment conditions. Therefore, no differences in peak pressure or pressure gradient were found between legs in the control and high gradient garment conditions ($P < 0.05$). Many compression garment studies have either not measured the pressure elicited by a garment (Cerqueira et al., 2015; Duffield et al., 2010; Pereira et al., 2014; Shimokochi et al., 2017; Winke & Williamson, 2017) or they have relied on pressures stated by the manufacturer (Govus et al., 2018; Heiss et al., 2018; Kim et al., 2017). As such, it is difficult, if not impossible, to link a particular garment pressure or profile to a particular performance or recovery outcome. In the current study, peak pressures at the ankle for the high gradient garment were within Class three of the clinical compression standards and within clinical standards over 55 to 60% of the leg length. Similarly, peak pressures at the ankle for the control garment were below clinical compression standards for both legs. Hill and colleagues (2017) showed that medical-grade II compression stockings, which elicited pressures of 24.3 ± 3.7 mmHg and 14.8 ± 2.2 mmHg at the calf and thigh respectively, improved maximal voluntary contractions and countermovement jump recovery ($P < 0.05$). These peak pressures are similar to those elicited by the high gradient garment in the current study.

The current study sought to develop compression garments that provided the same fitting between a participants' legs, as well as between participants within the same garment condition. This was achieved as evidenced by the pressure gradients between legs showing absolute differences of only 1.4 and 2.7 mmHg for the control and high gradient garments, respectively, and the corresponding absolute differences in peak pressure at the ankle were also small (0.6 and 0.2 mmHg respectively). Previous research has found size and symmetry differences between legs, in male cyclists of up to 2% at the calf and knee (Rauter et al., 2017). As commercially available compression garments are made assuming the geometry of both legs is the same, this may lead to an inconsistent fit on an individuals' legs. The studies that have measured the pressure elicited by a compression garment, only measured pressure on one leg (Brophy-Williams et al., 2015, Brophy-Williams et al., 2017; Hamlin et al., 2012) or did not report pressure data between legs (Born et al., 2014; Hill et al., 2017; Scanlan et al., 2008), which presents a challenge when comparing the current results to previous research. However, any effect of leg asymmetry and between participant differences was not a factor in the current study, as the made-to-measure compression garments were individually designed and made for each participant. The RMSD for the fit of each garment showed a good fit between legs within each garment condition (control: < 2.1 mmHg; high gradient < 2.5 mmHg) as well as between participants (control: 1.5 - 3.5 mmHg; high gradient: 1.2 - 6.3 mmHg; asymmetrical 1.5 - 4.5 mmHg). These results demonstrate that made-to-measure compression garments can compensate for leg asymmetry and participant-specific differences.

Compression garment manufacturers claim that their garments elicit graduated compression, whereby the highest pressure is located at the distal end of the garment and reduces proximally (MacRae et al., 2011). Therefore, peak pressure would be located at the ankle when wearing lower body compression garments. It has been found that in undersized, recommended sized and oversized commercially available compression tights, peak pressure was located at the maximal circumference of the calf (Brophy-Williams et al., 2015). As a result, a linear pressure gradient was not present within the examined compression garments. This means that standard sized commercially available compression garments may not elicit a pressure gradient suitable to aid venous flow. In the current study, as intended, a linear pressure gradient was evident within the high gradient garment as peak pressure was located at the ankle and this reduced linearly towards the gluteal fold. In clinical practice, when wearing a compression garment, it is recommended that pressure at the thigh is 40% lower than at the ankle (Oğlakcıoğlu & Marmaralı, 2014). This pressure gradient is proposed to increase arterial pressure and subsequently elevate venous return thus reducing venous pooling in the lower extremities (Oğlakcıoğlu & Marmaralı, 2014). In the current study, pressure in the high gradient garment reduced by >80% at the gluteal fold from peak pressure at the ankle. However, there is no evidence to suggest that the pressure gradients used in clinical practice provide performance or recovery benefits when applied in healthy sports participants. In addition, while a range of elicited pressures have been reported at different leg locations for commercially available compression garments (19.0 to 30.0 mmHg at the ankle, 17.6 to 25.0 mmHg at the calf and 9.1 to 18.0 mmHg at the thigh), typically these pressures have not been measured in participants whilst wearing the compression clothing (Hill et al., 2015). An advantage with the made-to-measure garments used in the current study is that they can be adjusted to elicit different pressures and pressure gradients, which could be useful for future research to determine whether wearing compression garments influences exercise performance and recovery.

At the time the current study was conducted the Kikuhime pressure monitoring device was an established method for measuring the pressures elicited by compression garments (Brophy-Williams et al., 2014; Van den Kerckhove et al., 2007). Recent research has challenged the validity of the Kikuhime pressure monitoring device and recommended the use of an alternative device (PicoPress) (McManus et al., 2020). The study by McManus and colleagues (2020) demonstrated that the Kikuhime pressure monitoring device overestimated criterion pressure (as established using the Hohenstein System) by 2.9 mmHg (compared with 0.2 mmHg for the PicoPress pressure monitoring device). However, on the other two analytical methods of assessment used in the study to compare the pressures derived from the measuring devices with a criterion (that is Bland and Altman's limits of agreement (Bland & Altman, 1986) and regression analysis), the Kikuhime pressure monitoring device outperformed the PicoPress device when the measurements were made at the posterior aspect of the calf and the compression garments being worn were tights (Kikuhime vs. PicoPress: Limits of Agreement, ±4.2 vs. ±4.9 mmHg; Regression slope parameter estimate 0.2 vs. 1.3[1]). Given: i) the smaller limits of agreement and slope

1 The more consistent the value given by the pressure monitoring device as the criterion pressure changes, the closer the parameter estimate is to zero, zero being the ideal.

parameter noted above; ii) that the differences measured in the current study were >3 mmHg; and iii) that all pressure measurements were made along the posterior aspect of the leg as recommended by (McManus et al., 2020); it can be concluded that the Kikuhime pressure monitoring device was adequate for making the measurements here. Another recent study by Nandasiri and colleagues (2020) noted that the dimensions of the air-filled sensor on a pressure monitoring device may influence the accuracy of the pressure measurement, and the PicoPress has a relatively large sensor area (50 mm) which may limit its ability to measure pressure accurately on small or curved areas. Conversely, the Kikuhime device has a smaller sensor area (38 x 30 mm) which makes it more suitable for measuring pressure on areas with high curvatures that are found on parts of the human leg (i.e., Achilles tendon).

Limitations

In the high gradient garment elicited pressures were below clinical compression standards from 55 and 60% of the leg length for the left and right legs respectively. As a result, the majority of the upper legs did not experience pressures within clinical compression standards (< 14 mmHg). Although the exact elicited pressures for exercise performance and recovery benefits are unknown, Brown and colleagues (2020) found that strength recovery following strenuous exercise was enhanced when wearing compression garments eliciting pressure of 19 ± 3 mmHg at the thigh. Moreover, Lee and colleagues (2021) found that cycling performance was also enhanced when wearing compression garments eliciting pressure of 24.1 ± 2.4 mmHg at the thigh. Given that the aforementioned studies have found performance and recovery benefits when wearing compression garments which elicit pressures within clinical compression standards on the upper leg. It could be argued that in the current study it may have been beneficial for the high gradient garment to elicit pressure within clinical compression standards on the whole upper leg.

In conclusion, the current study demonstrated that made-to-measure compression garments can be made to elicit pressures within and below clinical compression standards and elicit equivalent pressures and pressure gradients in different participants. The results suggest that made-to-measure compression garments could be used within sport to provide an optimum fit between and within individuals by using measurements from individuals' bodies rather than generic manufacturer sizing.

Further research is warranted to investigate the effect of made-to-measure compression garments on exercise performance and recovery.

Chapter 6: The reliability and validity of a portable three-dimensional scanning system to measure leg volume.

6.1 Rationale

The previous chapter demonstrated that it was possible to make made-to-measure compression garments that elicit pressures within and below clinical standards and elicit the same pressure profiles between participants. This was established through the use of three-dimensional (3D) scans of each participants' lower body acquired using a portable 3D scanner. The ability to capture 3D models of limbs usinga fast, non-invasive approach may have utility for limb volumetric measurements. Currently, limb volume is typically measured using tape measures (Cerqueira et al., 2015; Tan et al., 2013) and water displacement (Man et al., 2004; Pasley & O'Connor, 2008). However, tape measure measurements may have poor inter- and intra-observer reliability and may overestimate volume (Fernie & Holliday, 1982; Kremer et al., 2020). Furthermore, water displacement is time consuming and relies on individuals to stay motionless to reduce measurement error which may be difficult over prolonged periods (Devoogdt et al., 2019). The portable 3D scanner has the potential to overcome the limitations of the aforementioned methods. Therefore, this chapter aimed to examine the reliability and validity of a structured light 3D scanning system (Artec Leo) for measuring leg volume compared to a 'criterion' water displacement method.

6.2 Introduction

The measurement of limb volume in clinical practice is used to detect oedemas, lymphedemas, carcinomas and fibrosis (Brijker et al., 2000; Ribeiro-Cristina et al., 2010; Ridner et al., 2007). As well as establishing the presence of disease, the accurate quantification of limb volume can be used to examine the efficacy of clinical treatments, such as compression therapy, on a specific disorder. In sporting environments, the measurement of limb volume can be used to examine muscle growth and the efficacy of training programmes, but also to detect the seriousness of an injury and to establish the magnitude of exercise induced muscle damage (Chromy et al., 2015). It has been suggested that the swelling associated with exercise induced muscle damage is the result of an accumulation of intracellular enzymes, fluids and other constituents, present as a result of inflammation, but which ultimately assist with muscle repair (MacRae et al., 2011). Clearly, the ability to accurately and reliably measure swelling, namely changes in limb volume, may have multiple beneficial applications in clinical and sporting environments.

In both clinical and sporting environments, previously published research studies have assessed limb circumference and volume using a wide variety of methodological approaches including: measuring tape (Cerqueira et al., 2015; Tan et al., 2013); water displacement (Man et al., 2004; Pasley & O'Connor, 2008); magnetic resonance imaging (Heiss et al., 2018); mathematical modelling (Chromy et al., 2015); bioelectrical impedance spectroscopy, computed tomography and optoelectrical infrared scanning (Perometer) (Kremer et al., 2020; Sharkey et al., 2018). However, many of the existing methods currently used to quantify limb circumference and volume may have limitations when utilized in particular clinical and sporting settings. While an anthropometric method using a tape measure may be practical and cost effective, its utility is heavily dependent on the researcher's ability to competently perform the measurements and to perform the measurements at identical locations. Unfortunately, inter- and intra-observer reliability can be poor and the method may not provide sufficient accuracy to determine relatively small changes in limb volume, particularly if an aim is to compare limb volume over time (Fernie & Holliday, 1982). Furthermore, calculating limb volume using a tape measure requires multiple measurements on the limb, which are subsequently incorporated into a truncated cone formula that typically overestimates limb volume because the actual geometry of a limb is typically not well represented by a smooth cone shape (Kremer et al., 2020). Magnetic resonance imaging and computed tomography do not have many of the methodological problems noted above, and so do provide a valid and reliable solution to the problem of accurately measuring limb volume. However, these methods require expensive equipment, expert staff to perform and interpret the scans, are time consuming, and consequently will not be generally accessible in sporting environments, or even in many clinical situations (Seminati et al., 2017). Historically, water displacement volumetry has been the 'gold standard' and reference method for evaluating limb volumes (Rabe et al., 2010). This method involves measurement of the amount of water displaced when a limb is submerged in a container full of water. The water displaced is equal to the volume of the submerged limb (Archimedes' principle). Although water displacement is considered to be cost effective and reliable, it is not without its drawbacks: it may be time consuming, it requires the participant to keep their limb motionless to ensure measurement accuracy and to ensure the correct portion of the limb is submerged, and it is not suitable for clinical populations with open wounds such as burns or venous ulcers (Deltombe et al., 2007; Megens et al., 2001; Sander et al., 2002). Furthermore, there is a possible risk of cross infection, particularly in clinical populations, using water displacement, due to the challenges of sterilising the equipment between measurements (Ridner et al., 2007). Consequently, it is clear that while currently there are a number of different methods that can be used to quantify limb volume, considered against the generic methodological requirements of most clinical and sporting situations (reliability, validity, cost, simple implementation in terms of expertise and time, minimal contamination risk) none is without its limitations.

Three-dimensional scanning has recently been examined as a potential method to measure limb volume (Buffa et al., 2015; Cau et al., 2016; Seminati et al., 2017). The advantages of 3D scanning systems are that they are non-invasive, contactless, fast to acquire a 3D scan and have been reported to be "accurate" (Harrison et al., 2004). Therefore, if 3D scanning systems are time efficient, reliable and valid this would make them very attractive within sport and clinical practice as a greater number of individuals could be assessed compared to other methods such as water displacement and tape measure methods. Also, although 3D scanning systems are more expensive than the water displacement and tape measure methods, the development of new technology has allowed 3D scanning systems to become more affordable (Barker et al., 2018). There are many types of 3D scanning systems and laser systems, which are based on time-of-flight technology, and they beam a laser repeatedly onto an object, and a receiver located on the scanner measures the time taken for the laser beam to reflect off the object back to the receiver to calculate distance, using triangulation, and from the calculated distance, the shape of the object can be determined. Previous research suggests that 3D laser scanning systems can accurately and reliably measure limb volume, when compared with the 'gold standard' water displacement method (McKinnon et al., 2007; Mestre et al., 2014). Structured light 3D scanning systems can also be used to measure limb volume. These 3D scanning systems project a light (typically LED) and a patterned image such as a grid onto the object. The patterned image is then repeatedly photographed as it is projected onto the object. The deformation/distortion of the projected patterned image onto the object identifies the distance and 3D geometry of the object which can then be reconstructed as a 3D image. Seminati and colleagues (2017) examined the reliability and validity of a structured light 3D scanning system (Artec EVA Scanner, Artec Group, Luxembourg City, Luxembourg) when measuring the volume of a residual limb model (which was a mould of an amputee's leg), compared to a 3D laser scanning system (Romer Scanner, CMS108, Hexagon, UK), which was used as the criterion measure. Three observers completed three repeated scans of the residual limb models using the Artec EVA and Romer 3D scanning systems. The results showed that the mean percentage error (validity) for the Artec EVA 3D scanning system was 1.4% (~30 ml difference) compared to the Romer 3D scanning system (criterion). Also, for the Artec EVA 3D scanning system, intra-rater and inter-rater reliability coefficients were 0.5% and 0.7%, respectively, for residual limb model volume measurements. Seminati and colleagues (2017) showed that the structured light 3D scanning system (Artec EVA) was a valid and reliable method for measuring residual limb model volume. However, only a few studies have used structured light 3D scanning systems with human participants (Modabber et al., 2016; Yamamoto et al., 2016), and these studies have focused on facial 3D scanning rather than quantification of limb volume measurements. Currently, no research has examined the reliability and validity of structured light 3D scanning for measuring lower body limb volume in healthy individuals. Furthermore, given that 3D scanning is non-invasive, contactless and fast to perform, it could be an incredibly useful tool for accurately quantifying limb volume in both clinical and sporting environments, and hence could make important contributions to the assessment of the extent of disease or injury, for example. However, before adopting this tool in such environments, it is necessary to determine its reliability and validity with respect to the quantification of lower body limb volume.

The aims of this study were: 1) to examine the reliability (test-retest, intra-day and inter-day) of a structured light 3D scanning system (Artec Leo) and water displacement method for measuring leg volume; and 2) to examine the measurement validity of a structured light 3D scanning system (Artec Leo) for measuring leg volume compared to a water displacement method.

6.3 Methodology

6.3.1 Participants

Fifteen, healthy males, (age 24.6 ± 2.0 years, stature 178.9 ± 4.5 cm, body mass 77.5 ± 6.8 kg, mean ± standard deviation) volunteered and provided informed consent to participate in the study. All participants completed a health screen questionnaire before involvement in the study, to ensure they had no medical or other conditions that would have prevented them from taking part. Participants were instructed to refrained from strenuous exercise in the 48 hours prior to an experimental trial, to avoid alcohol consumption 24 hours prior to an experimental trial and to avoid caffeine consumption on the day of a trial. The study was approved by a University Ethics Committee, (Nottingham Trent University Ethical Committee Application for Human Biological Investigation reference number: 559).

6.3.2 Experimental Design

Participants visited the laboratory three times. During the first visit, participants were familiarised with the water displacement and the 3D scan procedures. The two subsequent experimental trials were performed on two consecutive days at the same time of day. The first experimental trial comprised of baseline 3D scans of the participant's leg volume, followed by assessment of leg volume by water displacement. One hour following baseline measurements, the procedures were repeated to examine intra-day reliability of each volume measurement method. The following day, leg volume was measured using both methods for a third time to examine inter-day reliability of each method (**Figure 6.1**). At the start of both experimental trials, urine osmolality was measured to examine hydration status and body mass was also measured.

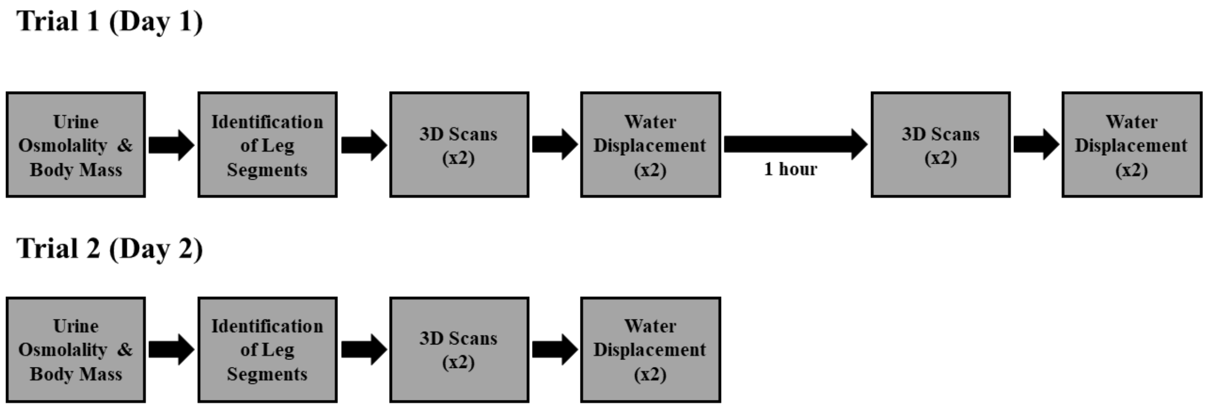


Figure 6.1. Displays a schematic of the study protocols of the first and second experimental trials.

6.3.3 Leg Volume Locations

The volumes of lower and upper leg segments were quantified in the current study. Using semi-permanent ink, the left and right leg of each participant was divided into foot, lower leg and upper leg segments. Initially, a first mark was made 5 cm above the proximal malleolus (A), which separated the foot from the lower leg. A second mark was made on the most proximal aspect of the patella (B), which separated the lower leg and upper leg. The most proximal aspect of the patella was used to separate the lower and upper leg as it was an easily identifiable (via palpation) anatomical landmark which aided segment standardisation between days. Finally, a third mark was placed 60 % proximal from the patella mark (C), which defined the upper leg (**Figure 6.2**). Each mark was then extended around the circumference of the leg. Using a mark that covered the circumference of the leg assisted segment volume comparisons between measurement methods. Each mark, and the associated circumference, was made whilst the participant was in a standing position, as participants maintained a standing position during the water displacement and 3D scan volume measurements. Participants were instructed not to erase the marks to ensure identical locations could be used the following day. Prior to performing the 3D scans, textured tape (3 x 1 cm) was applied to the anterior aspect of each marked segment in line with the original inked mark. This textured tape assisted the tracking of the 3D scanner to identify the texture and geometry of the leg.

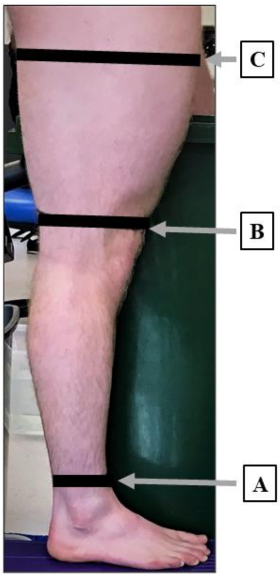


Figure 6.2. Leg segments A (5 cm above the proximal malleolus), B (the most proximal aspect of the patella) and C (60 % proximal from the patella mark) which separated the foot, lower leg and upper leg, respectively.

6.3.4 3D Scanning Procedure

The 3D scans were performed using a handheld Artec Leo 3D scanner (Artec Group, Luxembourg, Luxembourg). Two consecutive scans were performed at each of the study's timepoints: at baseline, 1 hour after baseline (both Trial 1) and 24 hours after the baseline (Trial 2). To perform the 3D scans, participants stood with their legs shoulder-width apart with their arms crossed over their chest. The participants were asked to refrain from any additional movement during the scan to reduce scan error. During the 3D scan the anterior of the lower body was captured, the scanner was rotated around the body until the lateral, posterior, and medial aspects of the lower body were imaged to create a 3D scan of the participants' lower body (**Figure 6.3**). When scanning, the 3D scanner was held parallel to the participant at an optimal distance between 0.35 – 1.20 m (manufacturer recommendations). The 3D scanner incorporates an integrated touchscreen display and performs real-time fusion of the captured frames. Therefore, after each competed scan, the 3D scan of the lower body was visually checked to ensure no faults existed in the scan such as large holes or significant misalignment of frames. If faults existed, a third scan was performed which replaced the insufficient scan and the subsequent two appropriate scans were used for analysis. All 3D scans were performed by a trained operator. The completed raw 3D scans were subsequently exported from the 3D scanner to a compatible computer for scan processing.

Figure 6.3. Example of a completed raw 3D scan of a participant's lower body (anterior and posterior views).

6.3.5 3D Scan Processing

The 3D scanner captured geometry and texture data, the geometry data were used to determine the shape of the lower body, whereas the texture data were used to determine the inked markers on the scans and used for lower and upper leg segment selection. The raw lower body 3D images (scans) were processed using Artec Studio 14 software (Artec Group, Luxembourg, Luxembourg). The scans were aligned manually in the reference system x (anterior/posterior), y (medial/lateral) and z (vertical). To process the 3D scans, unwanted data such as the waist, feet and floor were removed using an 'eraser' tool. This removal was performed conservatively as the segment lines were not visible at this stage of the processing. Therefore, a second detailed data removal was performed once the texture of the scan was applied (see below). A 'global registration' algorithm was subsequently applied which finely aligned all the individual frames captured that contribute to the 3D scan. Once 'global registration' was performed, 'maximum error' values were calculated, by the software, for each frame of the scan. The 'maximum error' is a metric specific to the Artec Studio software and provides a meaningful indicator of the quality of the overall 3D scan. The 'maximum error' for each 3D scan in the study was set at 0.6 (manufacturer recommendations). Any frames above a 'maximum error' threshold of 0.6 were subsequently deleted. Next, an 'outlier removal' algorithm was applied which removed outlying data not connected to the main 3D surface of the scan. The outlier-removal calculated, for every surface point, the mean distance between that point and a number of neighbouring points, as well as the standard deviation of these distances. All points that had mean distances greater than a threshold defined by the global distances mean and standard deviation were then classified as outliers and removed from the scan. The threshold of outlier removal was manually defined and a value of 0.7 was used in the current study. It was important that the chosen threshold was not smaller than the 'maximum error' of the 3D scan as this may remove valuable data mistakenly labelled as outliers. A 'smooth fusion' was applied which is a process that creates a polygonal 3D scan. It effectively solidifies all individual frames into a fused 3D scan. A 'small object filter' was then applied to the fusion scan which removed any outlying data located close to the scan surface. The texture of the 3D scan was then implemented, using the 'texture' algorithm to allow identification of the leg segment markers (A, B and C). The 'eraser' tool was again used to remove data from the scan which were not required for volume analysis, thus any scan data below the segment A line and above the segment C line was removed (**Figure 6.4**). A 'hole filling' algorithm was then performed which filled any holes within the 3D scan to provide a closed scan. 'Hole filling' removed the texture of the 3D scan so the 'texture' algorithm was repeated so that each section of the leg could be identified for volume analysis.

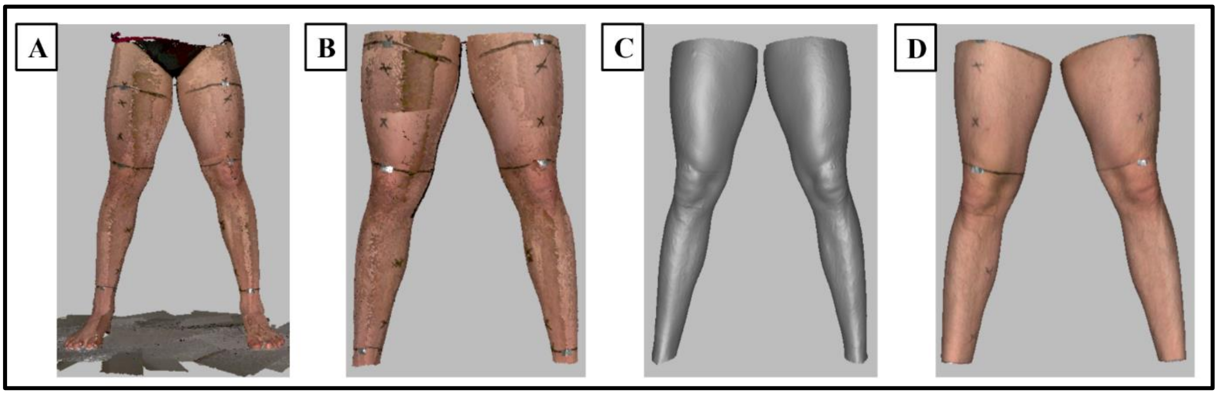


Figure 6.4. Pictorial representation of the 3D scan processing procedures utilized in the current study: (A) the raw unprocessed 3D scan; (B) the 3D scan with conservative data removal and applied 'global registration' of frames; (C) the 3D scan with applied 'outlier removal' and 'smooth fusion'; (D) the processed 3D scan with detailed data removal and applied 'small object filter', 'hole filling' and 'texture'.

6.3.6 3D Scan Volume Extraction

The volume measurements were performed using Artec Studio 14 software with the 'measures' tool. A coordinate axis square was inserted and aligned with the axis of the 3D lower body scan. The coordinate axis square was then located so that it aligned with the B marker segment line on the leg. The coordinate axis square was used to define the origin of the volume data to be measured. Once in position, volume above and below the coordinate axis square were measured separately which corresponded to upper leg volume and lower leg volume (**Figure 6.5**). The accurate positioning of the coordinate axis square ensured that the same segments were compared between the 3D scanner and the water displacement methods. To calculate the volume of the 3D scan, the programme calculates the volume of tetrahedrons composed from the vertices of each polygon within the scan and the origin of the coordinate system as the 4th vertex. Calculating the sum of each tetrahedron provided the total volume of the 3D scan. The scan leg volumes were exported in mm^3 and converted to ml using the following conversion: 1000 mm^3 = 1 ml. Volume was measured for both left and right legs and the 3D scan procedure was also performed 1 hour and 24 hours after the baseline 3D scans, using identical procedures. As two 3D scans were performed at each time point (baseline, 1 hour, and 24 hours), the means of the two scans were used for subsequent analysis.

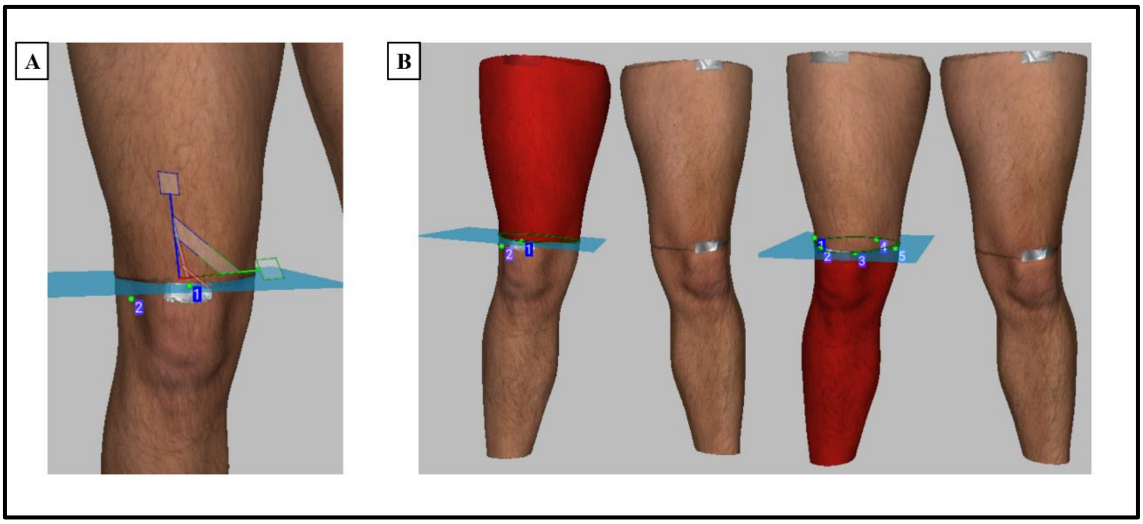


Figure 6.5. Pictorial representation of the positioning of the coordinate axis square to align with the B marker line (proximal patella) of the leg segment (A), and the subsequent volume measurement of the upper and lower leg using the coordinate axis square as the origin for volume measurements (B).

6.3.7 Water Displacement Procedure

Two custom-built volumeters were used during the water displacement measurements. A small volumeter (42 x 32 x 25 cm) was used to measure the foot volume and a large volumeter (88 x 48 x 48 cm) was used to measure the volume of the lower and upper leg. The volume of both left and right legs was measured. The volumeters were filled with water until the water spilled out of the overflow spout. The water was left to overflow until no more water spilled from the overflow spout. Prior to immersion of the foot and lower leg and upper leg, water temperature was measured using a mercury thermometer (Fisherbrand, Loughborough, United Kingdom). The study researcher sought to ensure the temperature of the water was maintained between 20ºC and 32ºC as this temperature range has been shown to have minimal effects on limb volume (Boland & Adams, 1996). For all trials, the water temperature was 30 ± 1ºC (mean ± standard deviation) for both volumeters. To ensure consistency with the volume measurements made using the 3D scanning method, participants performed the water displacement method in a standing position. For each leg segment (A, B and C) two measurements of volume were performed for both left and right legs of the participants. To measure foot volume, participants slowly immersed their foot into the water until the water surface was level with the inked mark (A). Once in position, participants rested their foot against the back of the volumeter to reduce movement. Once the excess water had flowed to less than one drip per second (Man et al., 2004), the water collection container was removed and weighed using calibrated weighing scales measuring to two decimal places (kg). The volumes were converted to ml using the following conversion: 1g = 1ml. The water in the collection container was poured back into the volumeter for the next immersion. Once foot volume measurements on one leg were completed, the foot volume of the other leg was measured using identical procedures. For lower leg volume participants immersed their leg into the water until the water surface was level with the inked mark (B). The excess water was subsequently collected and weighed. The identical procedure was then performed for the upper leg mark (C). During the volume measurements, participants were instructed to keep their leg as still as possible to reduce water surface tension caused by movement. The water displacement procedure was also performed 1 hour and 24 hours after the baseline water displacement, using identical procedures. Although the foot volume was measured using water displacement, this volume was not used for the analysis between methods and was only used for the calculation to measure lower and upper leg volume. To calculate the volume of individual sections of the leg, the prior segment(s) and water collection container weight were deducted. For example, for the upper leg volume, the weight of the lower leg, foot and water container were subtracted from the whole leg weight. The water displacement was consistently performed following the two 3D scans as pilot testing revealed that in some cases, 3D scanning wet skin produced substandard scans which was likely due to the reflectiveness of the skin whilst wet. Although a randomised order of water displacement and 3D scanning would have been beneficial. It was clear that 3D scanning wet skin would not be appropriate to attain accurate scans of the legs.

6.3.8 Data Analysis

Two volume measurements were performed using the 3D scanner method and then using the water displacement method, for each leg segment at baseline, 1 hour post and 24 hours post baseline. The test-retest reliability of both methods was established by calculating the volume difference between the first and second duplicate measurements, for all leg segments at baseline, 1 hour post and 24 hours post baseline. To calculate intra-day reliability, the mean volume of duplicate measurements was calculated at baseline and 1 hour post baseline. To calculate inter-day reliability, the mean volume of duplicate measurements was calculated at baseline and 24 hours post baseline. To calculate the validity of the 3D scanner measurements, mean leg volume was compared to the same value measured using the criterion water displacement method. The mean volume was calculated from the two duplicate volume measurements for the 3D scanner and water displacement methods, for all leg segments at baseline, 1 hour post and 24 hours post baseline. As volume measurements were performed on both legs of each of the 15 participants, 30 individual legs were used to examine test-retest reliability, intra- and inter-day reliability and validity.

6.3.9 Statistical Analysis

All data were analysed using the Statistical Package for the Social Sciences (SPSS: Version 26, Chicago, Illinois, USA), GraphPad Prism (GraphPad Software: Version 9.0.2, San Diego, California USA) and Microsoft Excel. To assess test-retest reliability of the 3D scanner method and the water displacement method, the first and second volume measurements for the lower leg and upper leg were compared at baseline, 1 hour post and 24 hours post baseline for each method. This was performed using the Bland and Altman limits of agreement method and the raw and logarithmic transformed systematic bias and 95% limits of agreement were calculated (Bland & Altman, 1986). In addition, Pearson's product moment correlation coefficient was calculated to examine the relationship between duplicate volume measurements of each method and was interpreted as: negligible (0.00 – 0.10), weak (0.10 – 0.39), moderate (0.40 – 0.69), strong (0.70 – 0.89) and very strong (0.90 – 1.00) (Schober & Schwarte, 2018). Also, paired samples t-tests were conducted to examine if volume differences existed between duplicate volume measurements of each method at baseline, 1 hour post and 24 hours post baseline. The intra- and inter-day reliability of the 3D scanner method and the water displacement method was examined using identical methods as those used to establish test-retest reliability. The mean upper and lower leg volume at baseline were compared to the corresponding volume measured at 1 hour post (intra-day) and 24 hours post (inter-day). The validity of the 3D scanner method to measure lower and upper leg volume was compared to the water displacement (criterion) at baseline, 1 hour post, 24 hours post baseline, using the Bland and Altman 95% limits of agreement method, Pearson's product moment correlation coefficients and paired samples t-tests. Paired samples t-tests were conducted to examine differences of hydration status and body mass between trial one and trial two. A significance level of $P < 0.05$ was applied throughout.

6.4 Results

Reliability of 3D Scanning (Lower Leg)

The systematic bias in the lower leg varied from just under 15 ml to just over 35 ml when the first and second 3D scanner volume measurements were compared (**Table 6.1**), suggesting that the second 3D scanner measurement consistently overestimated the lower leg volume (by 0-1%). The positive correlation between volume measurements varied from 0.98 to 0.99 (very strong correlations). Paired samples t-tests revealed that the 3D scanned lower leg volume was larger for the second volume measurement compared with the first volume measurement at baseline ($P < 0.05$). No differences were revealed between the first and second volume measurements at 1 hour post baseline and 24 hours post baseline ($P > 0.05$).

Table 6.1. Absolute and relative test-retest reliability of lower leg volume based on two 3D scanner measurements.

	Baseline	**1 Hour Post Baseline**	**24 Hours Post Baseline**
Sample Size	n = 30	n = 30	n 30
Measurement 1 (X ± SD) [ml]	3405 ± 330	3466 ± 372	3413 ± 306
Measurement 2 (X ± SD) [ml]	3443 ± 355	3483 ± 369	3427 ± 316
Systematic Bias (ml)	38	17	14
LOA (ml)	134	126	134
Lower; Upper LOA (raw)	-97; 172	-109; 143	-120; 148
Systematic Bias (ln)	1.01	1.01	1.00
LOA (ln)	1.04	1.04	1.04
Lower; Upper LOA (ln)	0.97; 1.05	0.97; 1.04	0.96; 1.05
Pearsons *r*	0.98 ($P < 0.001$)	0.99 ($P < 0.001$)	0.98 ($P < 0.001$)
t-test	$P = 0.005$	$P = 0.150$	$P = 0.271$

X ± SD = mean ± standard deviation; ml = millilitres; ln = logarithmic transformation; LOA = limits of agreement.

Reliability of Water Displacement (Lower Leg)

The systematic bias in the lower leg varied from just under -15 ml to just over -55 ml when the first and second water displacement volume measurements were compared (**Table 6.2**), suggesting that the second water displacement method consistently underestimated the lower leg volume (by 1-2%). The positive correlation between volume measurements varied from 0.98 to 0.99 (very strong correlations). Paired samples t-tests revealed that the water displacement lower leg volume was larger for the first volume measurement compared with the second volume measurement at baseline and 24 hours post baseline (P < 0.05). No differences were revealed between the first and second volume measurements at 1 hour post baseline (P > 0.05).

Table 6.2. Absolute and relative test-retest reliability of lower leg volume based on two water displacement measurements.

	Baseline	1 Hour Post Baseline	24 Hours Post Baseline
Sample Size	n = 30	n = 30	n = 30
Measurement 1 (X ± SD) [ml]	3086 ± 502	3359 ± 519	3149 ± 478
Measurement 2 (X ± SD) [ml]	3052 ± 497	3346 ± 568	3092 ± 478
Systematic Bias (ml)	-33	-13	-56
LOA (ml)	168	187	190
Lower; Upper LOA (raw)	-202; 135	-200; 174	-246; 134
Systematic Bias (ln)	0.99	0.99	0.98
LOA (ln)	1.05	1.06	1.07
Lower; Upper LOA (ln)	0.94; 1.04	0.94; 1.05	0.92; 1.05
Pearsons *r*	0.99 (P < 0.001)	0.99 (P < 0.001)	0.98 (P < 0.001)
t-test	P = 0.042	P = 0.462	P = 0.003

X ± SD = mean ± standard deviation; ml = millilitres; ln = logarithmic transformation; LOA = limits of agreement.

Reliability of 3D Scanning (Upper Leg)

The systematic bias in the upper leg varied from just under -10 ml to just over 50 ml when the first and second 3D scanner volume measurements were compared (**Table 6.3**), suggesting that the second 3D scanner measurement both overestimated and underestimated the upper leg volume (by 0-1%). The positive correlation between volume measurements was 0.99 (very strong correlations). Paired samples t-tests revealed that the 3D scanned upper leg volume was larger for the second volume measurement compared with the first volume measurement at baseline (P < 0.05). No differences were revealed between the first and second volume measurements at 1 hour post baseline and 24 hours post baseline ($P > 0.05$).

Table 6.3. Absolute and relative test-retest reliability of upper leg volume based on two 3D scanner measurements.

	Baseline	1 Hour Post Baseline	24 Hours Post Baseline
Sample Size	n = 30	n = 30	n = 30
Measurement 1 (X ± SD) [ml]	5288 ± 664	5283 ± 685	5280 ± 662
Measurement 2 (X ± SD) [ml]	5343 ± 655	5305 ± 679	5274 ± 671
Systematic Bias (ml)	55	22	-6
LOA (ml)	219	173	176
Lower; Upper LOA (raw)	-164; 274	-151; 195	-183; 170
Systematic Bias (ln)	1.01	1.00	1.00
LOA (ln)	1.05	1.03	1.04
Lower; Upper LOA (ln)	0.97; 1.06	0.97; 1.04	0.96; 1.04
Pearsons *r*	0.99 ($P < 0.001$)	0.99 ($P < 0.001$)	0.99 ($P < 0.001$)
t-test	$P = 0.012$	$P = 0.183$	$P = 0.703$

X ± SD = mean ± standard deviation; ml = millilitres; ln = logarithmic transformation; LOA = limits of agreement.

Reliability of Water Displacement (Upper Leg)

The systematic bias in the upper leg varied from just under -35 ml to just over -45 ml when the first and second water displacement volume measurements were compared (**Table 6.4**), suggesting that the second water displacement method consistently underestimated the upper leg volume (by 1%). The positive correlation between volume measurements varied from 0.97 to 0.99 (very strong correlations). Paired samples t-tests revealed that the water displacement lower leg volume was larger for the first volume measurement compared with the second volume measurement at 1 hour post baseline ($P < 0.05$). No differences were revealed between the first and second volume measurements at baseline and 24 hours post baseline ($P > 0.05$).

Table 6.4. Absolute and relative test-retest reliability of upper leg volume based on two water displacement measurements.

	Baseline	1 Hour Post Baseline	24 Hours Post Baseline
Sample Size	n = 30	n = 30	n = 30
Measurement 1 (X ± SD) [ml]	5355 ± 658	5461 ± 662	5349 ± 665
Measurement 2 (X ± SD) [ml]	5325 ± 692	5413 ± 673	5308 ± 654
Systematic Bias (ml)	-30	-48	-41
LOA (ml)	315	186	272
Lower; Upper LOA (raw)	-344; 285	-233; 138	-313; 231
Systematic Bias (ln)	0.99	0.99	0.99
LOA (ln)	1.06	1.04	1.06
Lower; Upper LOA (ln)	0.94; 1.05	0.96; 1.03	0.94; 1.05
Pearsons *r*	0.97 ($P < 0.001$)	0.99 ($P < 0.001$)	0.98 ($P < 0.001$)
t-test	$P = 0.314$	$P = 0.010$	$P = 0.119$

X ± SD = mean ± standard deviation; ml = millilitres; ln = logarithmic transformation; LOA = limits of agreement.

3D Scanner Intra- and Inter-day Reliability (Lower Leg)

The systematic bias in the lower leg was just under 55 ml when the baseline and 1 hour post baseline 3D scan volume measurements were compared (intra-day) (**Table 6.5**), suggesting that the 1 hour post baseline 3D scan measurement overestimated the lower leg volume (by 2%). The positive correlation between volume measurements was 0.96 (very strong correlations). Paired samples t-tests revealed that the 3D scanned lower leg volume was smaller at baseline compared with the 1 hour post baseline measurement ($P < 0.05$). The systematic bias in the lower leg was just under -20 ml when the baseline and 24 hours post baseline 3D scan volume measurements were compared (inter-day) (**Table 6.5**), suggesting that the 24 hours post baseline 3D scan measurement underestimated the lower leg volume (±1%). The positive correlation between volume measurements was 0.97 (very strong correlations). Paired samples t-tests revealed no differences between the 3D scanned lower leg volume at baseline compared with the 24 hours post baseline measurement ($P > 0.05$).

Table 6.5. Absolute and relative intra- and inter-day reliability of lower leg volume measured by the 3D scanner.

	Baseline vs. 1 Hour Post Baseline	Baseline vs. 24 Hours Post Baseline
Sample Size	n = 30	n = 30
3D Scan (X ± SD) [ml]	3404 ± 382	3404 ± 382
3D Scan (X ± SD) [ml]	3456 ± 386	3388 ± 347
Systematic Bias (ml)	52	-16
LOA (ml)	208	191
Lower; Upper LOA (raw)	-155; 260	-207; 174
Systematic Bias (ln)	1.02	1.00
LOA (ln)	1.07	1.06
Lower; Upper LOA (ln)	0.95; 1.08	0.99; 1.05
Pearsons *r*	0.96 ($P < 0.001$)	0.97 ($P < 0.001$)
t-test	$P = 0.011$	$P = 0.362$

3D = three-dimensional; X ± SD = mean ± standard deviation; ml = millilitres; ln = logarithmic transformation; LOA = limits of agreement.

Water Displacement Intra and Inter Day Reliability (Lower Leg Volume)

The systematic bias in the lower leg was just under 265 ml when the baseline and 1 hour post baseline water displacement volume measurements were compared (intra-day) (**Table 6.6**), suggesting that the 1 hour post baseline water displacement measurement overestimated the lower leg volume (by 9%). The positive correlation between volume measurements was 0.82 (strong correlations). Paired samples t-tests revealed that the water displacement lower leg volume was smaller at baseline compared with the 1 hour post baseline measurement ($P < 0.05$). The systematic bias in the lower leg was just under 45 ml when the baseline and 24 hours post baseline water displacement volume measurements were compared (inter-day) (**Table 6.6**), suggesting that the 24 hours post baseline water displacement measurement overestimated the lower leg volume (by 2%). The positive correlation between volume measurements was 0.87 (strong correlations). Paired samples t-tests revealed no differences between the water displacement lower leg volume at baseline compared with the 24 hours post baseline measurement ($P > 0.05$).

Table 6.6. Absolute and relative intra- and inter-day reliability of lower leg volume measured by the water displacement.

	Baseline vs. 1 Hour Post Baseline	Baseline vs. 24 Hours Post Baseline
Sample Size	n = 30	n = 30
WD (X ± SD) [ml]	3102 ± 507	3102 ± 507
WD (X ± SD) [ml]	3366 ± 532	3143 ± 462
Systematic Bias (ml)	263	40
LOA (ml)	615	485
Lower; Upper LOA (raw)	-351; 878	-445; 525
Systematic Bias (ln)	1.09	1.02
LOA (ln)	1.20	1.16
Lower; Upper LOA (ln)	0.91; 1.30	0.87; 1.18
Pearsons *r*	0.82 ($P < 0.001$)	0.87 ($P < 0.001$)
t-test	$P = 0.001$	$P = 0.379$

WD = water displacement; X ± SD = mean ± standard deviation; ml = millilitres; ln = logarithmic transformation; LOA = limits of agreement.

3D Scan Intra- and Inter-day Reliability (Upper Leg Volume)

The systematic bias in the upper leg was just under 25 ml when the baseline and 1 hour post baseline 3D scan volume measurements were compared (intra-day) (**Table 6.7**), suggesting that the 1 hour post baseline 3D scan measurement overestimated the upper leg volume (by 1%). The positive correlation between volume measurements was 0.98 (very strong correlations). Paired samples t-tests revealed no differences between the 3D scanned lower leg volume at baseline compared with the 1 hour post baseline measurement ($P > 0.05$). The systematic bias in the upper leg was just under 5 ml when the baseline and 24 hours post baseline 3D scan volume measurements were compared (inter-day) (**Table 6.7**), suggesting that the 24 hours post baseline 3D scan measurement overestimated the upper leg volume (±1%). The positive correlation between volume measurements was 0.98 (very strong correlations). Paired samples t-tests revealed no differences between the 3D scanned upper leg volume at baseline compared with the 24 hours post baseline measurement ($P > 0.05$).

Table 6.7. Absolute and relative intra- and inter-day reliability of upper leg volume measured by the 3D scanner.

	Baseline vs. 1 Hour Post Baseline	Baseline vs. 24 Hours Post Baseline
Sample Size	n = 30	n = 30
3D Scan (X ± SD) [ml]	5311 ± 654	5311 ± 654
3D Scan (X ± SD) [ml]	5334 ± 646	5315 ± 622
Systematic Bias (ml)	23	4
LOA (ml)	224	258
Lower; Upper LOA (raw)	-201; 247	-254; 262
Systematic Bias (ln)	1.01	1.00
LOA (ln)	1.04	1.05
Lower; Upper LOA (ln)	0.97; 1.05	0.95; 1.06
Pearsons *r*	0.98 ($P < 0.001$)	0.98 ($P < 0.001$)
t-test	$P = 0.274$	$P = 0.865$

3D = three-dimensional; X ± SD = mean ± standard deviation; ml = millilitres; ln = logarithmic transformation; LOA = limits of agreement.

Water Displacement Intra- and Inter-day Reliability (Upper Leg Volume)

The systematic bias in the upper leg was just under 85 ml when the baseline and 1 hour post baseline water displacement volume measurements were compared (intra-day) (**Table 6.8**), suggesting that the 1 hour post baseline water displacement measurement overestimated the upper leg volume (by 2%). The positive correlation between volume measurements was 0.96 (very strong correlations). Paired samples t-tests revealed that the water displacement upper leg volume was smaller at baseline compared with the 1 hour post baseline measurement ($P < 0.05$). The systematic bias in the upper leg was just under -15 ml when the baseline and 24 hours post baseline water displacement volume measurements were compared (inter-day) (**Table 6.8**), suggesting that the 24 hours post baseline water displacement measurement underestimated the upper leg volume (±1%). The positive correlation between volume measurements was 0.94 (very strong correlations). Paired samples t-tests revealed no differences between the water displacement upper leg volume at baseline compared with the 24 hours post baseline measurement ($P > 0.05$).

Table 6.8. Absolute and relative intra- and inter-day reliability of upper leg volume measured by the water displacement.

	Baseline vs. 1 Hour Post Baseline	Baseline vs. 24 Hours Post Baseline
Sample Size	n = 30	n = 30
WD (X ± SD) [ml]	5351 ± 657	5351 ± 657
WD (X ± SD) [ml]	5431 ± 638	5340 ± 654
Systematic Bias (ml)	80	-10
LOA (ml)	365	448
Lower; Upper LOA (raw)	-285; 445	-458; 438
Systematic Bias (ln)	1.02	1.00
LOA (ln)	1.08	1.09
Lower; Upper LOA (ln)	0.95; 1.09	0.91; 1.09
Pearsons *r*	0.96 (P < 0.001)	0.94 (P < 0.001)
t-test	P = 0.026	P = 0.806

WD = water displacement; X ± SD = mean ± standard deviation; ml = millilitres; ln = logarithmic transformation; LOA = limits of agreement.

Validity of 3D Scanning (Lower Leg)

The systematic bias in the lower leg varied from just under 95 ml to just over 300 ml when the volumes calculated by the 3D scanner were compared with those calculated from the water displacement method (**Table 6.9**), suggesting that the 3D scanner method consistently overestimated the lower leg volume (by 3-10%). The positive correlation between volume measurement methods varied from 0.71 to 0.92 (strong to very strong correlations). Paired samples t-tests revealed that the 3D scanned lower leg volume was larger than the water displacement volume at baseline, 1 hour post baseline and 24 hours post baseline ($P < 0.05$).

Table 6.9. Absolute and relative validity of lower leg volume measured by the water displacement and 3D scanner.

	Baseline	1 Hour Post Baseline	24 Hours Post Baseline
Sample Size	n = 30	n = 30	n = 30
WD Volume (X ± SD) [ml]	3102 ± 507	3366 ± 532	3143 ± 462
3D Scan Volume (X ± SD) [ml]	3404 ± 382	3456 ± 386	3388 ± 347
Systematic Bias (ml)	302	91	245
LOA (ml)	696	464	544
Lower; Upper LOA (raw)	-394; 998	-373; 554	-299; 789
Systematic Bias (ln)	1.10	1.03	1.08
LOA (ln)	1.27	1.15	1.20
Lower; Upper LOA (ln)	0.87; 1.40	0.90; 1.19	0.90; 1.30
Pearsons *r*	0.71 ($P < 0.001$)	0.92 ($P < 0.001$)	0.80 ($P < 0.001$)
t-test	$P = 0.001$	$P = 0.045$	$P = 0.001$

WD = water displacement; 3D = three-dimensional; X ± SD = mean ± standard deviation; ml = millilitres; ln = logarithmic transformation; LOA = limits of agreement.

Validity of 3D Scanning (Upper Leg)

The systematic bias in the upper leg varied from just under -45 ml to just over -95 ml when the volumes calculated by the 3D scanner were compared with those calculated from the water displacement method (**Table 6.10**), suggesting that the 3D scanner method consistently underestimated the upper leg volume (by 0-2%). The positive correlation between volume measurement methods varied from 0.95 to 0.97 (very strong correlations). Paired samples t-tests revealed that the 3D scanned upper leg volume was smaller than the water displacement volume at 1 hour post baseline (P < 0.05). There were no differences between the 3D scanned and water displacement upper leg volume at baseline and 24 hours post baseline ($P > 0.05$).

Table 6.10. Absolute and relative validity of the upper leg volume measured by water displacement and 3D scanner.

	Baseline	1 Hour Post Baseline	24 Hours Post Baseline
Sample Size	n = 30	n = 30	n = 30
WD Volume (X ± SD) [ml]	5351 ± 657	5431 ± 638	5340 ± 654
3D Scan Volume (X ± SD) [ml]	5311 ± 654	5334 ± 646	5315 ± 622
Systematic Bias (ml)	-40	-96	-25
LOA (ml)	324	365	408
Lower; Upper LOA (raw)	-364; 284	-491; 299	-433; 383
Systematic Bias (ln)	0.99	0.98	1.00
LOA (ln)	1.07	1.08	1.09
Lower; Upper LOA (ln)	0.93; 1.06	0.91; 1.06	0.91; 1.09
Pearsons *r*	0.97 (P < 0.001)	0.95 (P < 0.001)	0.95 (P < 0.001)
t-test	P = 0.195	P = 0.014	P = 0.521

WD = water displacement; 3D = three-dimensional; X ± SD = mean ± standard deviation; ml = millilitres; ln = logarithmic transformation; LOA = limits of agreement

Hydration Status and Body Mass

Paired samples t-tests revealed that hydration status was similar between trials one and two (t(14) = -.317, P = 0.756, trial 1: 668 ± 287 vs. trial 2: 685 ± 251 mOsm/kg). Body mass was also similar between trials one and two (t(14) = 1.469, P = 0.164, trial 1: 77.4 ± 6.5 vs. trial 2: 77.1 ± 6.5 mOsm/kg).

6.5 Discussion and Conclusions

This study sought to examine the reliability (test-retest, intra-day, inter-day) of a structured light 3D scanning system (Artec Leo) and also a water displacement method for measuring leg volume. It also examined the measurement validity of the 3D scanning system for measuring leg volume compared to the water displacement method. The results revealed that test-retest reliability for the lower leg was better for the 3D scanner method compared to the water displacement method. This was evidenced by smaller systematic bias and narrower limits of agreement for the 3D scanner method (±1%, and 4% respectively) compared to the water displacement method (1-2%, and 5-7%

respectively). The test-retest reliability for the upper leg was also better for the 3D scanner method compared to the water displacement method. This was evidenced by smaller systematic bias and narrower limits of agreement for the 3D scanner method (±1%, and 3-5% respectively) compared to the water displacement method (1%, and 4-6% respectively). Interestingly, for both volume measurement methods the test-retest reliability was consistently poorer on the lower leg compared to the upper leg which was supported by wider limits of agreement on the lower leg. The test-retest reliability differences may be caused by the shape differences between the lower and upper leg as it may be argued that the lower leg has a more complex shape in terms of its curvature of tissues such as the Achilles tendon and calf which may create a more difficult shape to capture the geometry using the 3D scanner compared to the upper leg which is more cylindrical and consistent in shape. For the water displacement method, the poorer test-retest reliability on the lower compared to the upper leg may be caused by the methodological approach of acquiring volume from each segment. In the current study, measuring the lower leg volume may have been more demanding for the participants as they were required to suspend their lower leg in the water container and support themselves with the other leg, which may have allowed for greater movement of the submerged lower leg, in turn, increasing the disruption of the water tension and spillage of water which ultimately may have increased the error within each measurement. Conversely, to measure the upper leg volume, the whole leg was submerged in the water container and participants were able to gently rest their foot on the bottom of the water container. Therefore, the participants were supported by both legs rather than one leg used for the lower leg volume measurements. As a result, less water may have been spilt to attain a measurement with less error and better reliability between duplicate measurements.

The lower leg intra-day reliability was better for the 3D scanner method compared to the water displacement method and was evidenced by smaller systematic bias and narrower limits of agreement for the 3D scanner method (2%, and 7% respectively) compared to the water displacement method (9%, and 20% respectively). The upper leg intra-day reliability was also better for the 3D scanner method compared to the water displacement method and was evidenced by smaller systematic bias and narrower limits of agreement for the 3D scanner method (1%, and 4% respectively) compared to the water displacement method (2%, and 8% respectively). The lower leg inter-day reliability was better for the 3D scanner method compared to the water displacement method and was evidenced by smaller systematic bias and narrower limits of agreement for the 3D scanner method (±1%, and 6% respectively) compared to the water displacement method (2%, and 16% respectively). The upper leg inter-day reliability was also better for the 3D scanner method compared to the water displacement method. Although the systematic bias for both methods was similar (±1%), the limits of agreement were narrower for the 3D scanner method (5%) compared to the water displacement method (9%). The Pearson's correlation coefficient for the inter-day reliability of the lower leg volume using the 3D scanner method was r = 0.97 which is in agreement with findings of previous research that showed correlation coefficients ranged between r = 0.95-0.99 (Pasley & O'Connor, 2008). However, for the water displacement method used in the current study, the corresponding correlation coefficient was r = 0.87 which is lower than that reported in the research. Therefore, it could be argued that the 3D scanner is better for measuring lower leg volume changes between days.

In the current study, leg volume test-retest reliability of the 3D scanner and water displacement methods was examined using the systematic bias and limits of agreement between the first and second volume measurements (Bland & Altman, 1986). The mean systematic bias and limits of agreement between duplicate leg volume measurements for the 3D scanner were 1%, and 4% for the lower leg and ±1%, and 4% for the upper leg respectively. The corresponding values for the water displacement were 1%, and 6% for the lower leg and 1%, and 5% for the upper leg respectively. In comparison, the mean systematic bias and limits of agreement were 3% and 38% respectively, for 13 different of sports medicine and sports science measurements (i.e., grip strength, leg strength, Wingate maximum power and Fitech step test) examined by (Nevill & Atkinson, 1997). Therefore, in comparison with typical measurements made in sports medicine and sports science, the test-retest reliability of both the 3D scanner and water displacement methods appear to be very good and this supports the contention that both methods are appropriate tools for measuring leg volume. Although the 3D scanning method demonstrates excellent test-retest reliability compared to other measurements typically made in sports medicine and sports science, the test-retest reliability must be sufficient for its purposed use, which in this study was to measure leg volume and ultimately to identify changes in leg volume as a result of clinical dysfunction or sporting activities. Few studies have investigated the reliability and validity of 3D scanning to measure the volume of human legs. The test-retest reliability of the 3D scanner method found in the current study was better than the findings of McKinnon and colleagues (2007) who found that for arm volume measurements the test-retest reliability systematic bias was 174 ml and 451 ml for the 3D laser scanner and water displacement methods respectively. In the current study, regardless of the leg segment examined, the mean test-retest reliability systematic bias was 23 ml which is similar to the findings by Seminati and colleagues (2017) who found test-retest reliability of 14 ml when measuring amputee residual limb models using a structured light 3D scanner (Artec EVA). However, the test-retest reliability, using the 3D scanner in the current study ranged up to 55 ml which is poorer than the 14 ml found by Seminati and colleagues (2017). However, given that static residual limb models were used by Seminati and colleagues (2017) and non-static humans were used in the current study, the small movement (*postural sway)* of participants during the scanning procedure may reduce the quality of the 3D scan and increase error and ultimately the volume test-retest reliability.

Some research has investigated intra- and inter-day leg volume changes to establish the magnitude of volume change (Engelberger et al., 2014; Hebeda et al., 1993; Pasley & O'Connor, 2008; Zhou et al., 2019). Pasley and colleagues (2008) measured lower leg volume over five consecutive days using a water displacement method. The results showed that Pearson's correlation coefficients for volume measurements between days varied between r = 0.95-0.98 which are similar to the correlation coefficients found in the current study between baseline and 24 hours post baseline (inter-day reliability) which were r = 0.87 and 0.94 for the lower and upper leg volume. Both the 3D scanner and water displacement methods showed that volume differences were smallest between baseline and 24 hours post baseline for the lower and upper leg. Furthermore, both methods showed that leg volume increased from baseline to 1 hour post baseline measurements and decreased from 1 hour post baseline to 24 hours post baseline measurements, reducing to near baseline volumes. These observed changes of leg volume suggest that both the 3D scanner and water displacement methods can detect intra- and inter-day volume changes, but the magnitude of change was greater with the water displacement compared to the 3D scanner. However, given that both the intra- and inter-day reliability for the 3D scanner had smaller systematic bias and narrower limits of agreement compared to the water displacement for the lower and upper leg, the 3D scanner may be a better method to examine intra- and inter-day volume changes. Previous research has found diurnal lower leg volume changes, with the volume typically increasing throughout the day (Angelhed et al., 2008; Engelberger et al., 2014). Engelberger and colleagues (2014) measured lower leg volume of obese and non-obese participants, using an optoelectronic scanner (Perometry), in the morning and afternoon of the same day. The results showed that in both groups, lower leg volume increased during the day, with a mean increase of 59 ± 47 ml in obese participants and 54 ± 24 ml in non-obese participants. These results are similar to the intra-day lower leg volume increase found in the current study (52 ± 106 ml) between baseline and 1 hour post baseline measurements, when measured using the 3D scanner. Conversely, the corresponding lower leg volume increase was much larger when using water displacement (263 ± 314 ml). The limits of agreement were consistently narrower for the 3D scanner compared to the water displacement method for the lower and upper leg volume for intra- and inter-day comparisons. Therefore, given that both the 3D scanner and water displacement methods were measuring the identical lower and upper leg segments, this highlights that the 3D scanner is more reliable for examining both intra- and inter-day volume changes compared to water displacement.

It is important to establish the test-retest reliability of structured light 3D scanning as this method may provide advantages over current methods used to measure leg volume, such as those based on water displacement and tape measures. In clinical practice, diagnostic criteria thresholds for determining lymphedema were reported by Stout and colleagues (2012) who proposed four stages for evaluating early lymphedema based on leg volume change: 0-3% (at risk for lymphedema), 3-5% (pre-clinical lymphedema), 5-8% (mild lymphedema) and > 8% (moderate-severe lymphedema). However, most studies have used a > 10% volume increase as a diagnostic threshold (Armer & Stewart, 2005; Asim et al., 2012; Johansson et al., 2001). In a sporting context, studies of eccentric biased exercise performed by healthy, untrained, individuals have found that total lower leg volume increased by ~3%, 72 hours after eccentric exercise (Whitehead et al., 1998, 2001). The test-retest reliability results of the current study suggest that both the 3D scanner and water displacement methods may be used to measure lymphedema, in clinical practice, as the measurement systematic bias and limits of agreement were always less than the 10% volume change threshold. As such, if 10% changes were discerned using either method, one could be confident that the change in volume was a genuine leg volume change rather than potentially explainable by measurement error. The test-retest systematic bias for the 3D scanner ranged from ±1-1% and the limits of agreement ranged from 3-5%. As a result, the 3D scanning method may be used to establish pre-clinical lymphedema (3-5% volume change). Conversely, both methods may not be appropriate to determine leg volume changes following eccentric exercise as although the systematic bias was below the 3% threshold, the limits of agreement were greater than the ~3% volume change previously reported following eccentric exercise (Whitehead et al., 1998, 2001). Therefore, we cannot be confident that the change is a genuine leg volume change as it could be measurement error. However, the results of this study suggest that if lower leg volume change is greater than 4%, the 3D scanner would be sufficient to discern such changes given the limits of agreement (4%) whereas, for the upper leg if the volume changes were greater than 5% then the 3D scanner would be sufficient to identify these changes given the limits of agreement (3-5%).

Water displacement is considered the 'gold standard' method for measuring leg volume (Kaulesar Sukul et al., 1993; Megens et al., 2001). However, limitations have been reported with using the method. The method is time consuming and in the current study each volume measurement lasted between 10 – 20 minutes which is consistent with previous reports (Pasley & O'Connor, 2008). The time constraints of water displacement may increase the difficulty of measuring leg volume in both sporting and clinical environments where multiple individuals may require volume assessment in a short time period. Water displacement may not be suitable for some medical applications with individuals with open wounds (Deltombe et al., 2007; Sander et al., 2002). Furthermore, there is an elevated infection transmission risk with the water displacement method, particularly if multiple individuals undergo the volume assessment using the same volumeter. Therefore, the equipment used for the water displacement method must be effectively sterilised (i.e., the volumeter sterilised and the water changed between participants) to reduce the infection risk (Ridner et al., 2007). The accuracy of the water displacement method is largely dependent on the participants ability to keep their leg motionless for up to 20 minutes as any disturbance to the water tension may add error to the measurement (McKinnon et al., 2007). The latter may have impacted the results in the current study as participants were required to stand on one leg and support their balance with their arms when measuring the leg volume. As a result, this may have been a factor that contributed to the lower test-retest reliability of the water displacement compared to the 3D scanner. It should also be noted that the participants in the current study were relatively young, healthy individuals for whom standing motionless is likely to be much easier than for many older and clinically impaired individuals. The application of 3D scanning to measure leg volume may address some of the limitations found with the water displacement method. In the current study, each 3D scan measurement lasted between 2-4 minutes which was significantly faster than the water displacement method (10-20 minutes), thus, 3D scanning may be more suitable if multiple volume measurements are required on various individuals both in clinical and sporting environments. Also, minimal contact is required to identify the volume analysis sections when using the 3D scanning method which may reduce the risk of transmitting infections as the scanning procedure is contactless. Finally, although participant movement during the 3D scan may add error similar to the water displacement method, the time participants are required to stand motionless is substantially reduced and this may have beneficial impacts on some clinical patients who may have difficulty holding a leg still. Furthermore, in the current study, during the 3D scan participants were able to stand on both legs whilst the lower body was scanned and the legs were subsequently separated for analysis. Conversely, for the water displacement measurements participants legs could only be measured individually which relied on participants predominantly standing on one leg particularly for the lower leg measurements. The application of 3D scanning to measure leg volume seems to address the challenges of the water displacement method. This study demonstrated that the test-retest reliability of the 3D scanner may not be suitable for measuring volume change following exercise induced muscle damage (typically ~3% change) as the limits of agreement were greater than 3% for the lower and upper leg. Therefore, future research is required to examine if the 3D scanner measurement could be more reliable such as reducing the postural sway when scanning a participant to minimise measurement error. With a 1-2% reduction in the limits of agreement for the test-retest reliability, the 3D scanner method would then be sufficiently reliable to measure leg volume changes following exercise induced muscle damage.

Limitations

In this study, the water displacement procedure used may have provided additional sources of error which could have been controlled for. Although the water container was refilled to the same level at each time point of the study (baseline, 1 hour post baseline and 24 hours post baseline), the water container was not refilled between repeated immersions within the same time point. Therefore, when the participant removed their leg following the first water displacement measurement some of the water would remain on the leg, thus, the volume of water in the container would lower following the first measurement. Given that the test-retest reliability results demonstrated that the lower and upper leg volume was consistently smaller for the second water displacement measurement compared to the first, this supports the notion that not refilling the water container following every measurement may have increased the error of the measurement. Refilling the water container after each measurement would no doubt be beneficial, however, it must be acknowledged that this would incur a substantial increase in time to complete each experimental trial.

In conclusion, the 3D scanner method provided better test-retest reliability than the water displacement method as the 3D scanner had smaller systematic bias and limits of agreement (±1-1%, and 3-5% respectively) compared to the water displacement method (1-2% and 4-7% respectively), for lower leg and upper leg volume measurements. The intra- and inter-day reliability was also better for the 3D scanner evidenced by narrower limits of agreement for intra-day reliability (3D scanner: 4-7%, and water displacement: 8-20%) and inter-day reliability (3D scanner: 5-6%, and water displacement: 9-16%). The 3D scanner also measured volume changes similar to changes reported in previous research, whereas the water displacement method seemed to overestimate such changes. The 3D scanner was also showed to be a valid method for measuring upper leg volume as the systematic bias and limits of agreement were within 10% of volume measurements made using a criterion water displacement method. The results of this study show that a 3D structured light scanning system (Artec Leo) is a reliable and valid tool for measuring leg volume, certainly in most clinical settings.

Chapter 7: The effect of thermogram border and region of interest size on skin temperature outputs before and after exercise.

7.1 Rationale

The previous chapter demonstrated that the 3D scanner had better test-retest reliability than the water displacement method for measuring leg volume. This was evidenced by smaller systematic bias and narrower limits of agreement for the 3D scanner method (±1%, and 3-5% respectively) compared to the water displacement method (1-2%, and 4-7% respectively). As a result, 3D scanning may be a useful technique for measuring leg volume. Another technique used within this thesis is infrared thermal imaging, which was used to measure skin temperature. There are few industry standardised frameworks that have been established for using infrared thermal imaging on the human body, particularly within sporting environments (Ammer, 2008). Skin temperature is typically extracted and analysed using regions of interest which are manually drawn onto thermal images (thermograms). The nature of manually defining regions of interest is subjective and susceptible to sources of error (Maniar et al., 2015). Therefore, an automated methodology of selecting regions of interest may have utility. Furthermore, previous research does not consider the effect of including the 'cold' image border, as well as the influence of the region of interest sized on output skin temperatures. As a result, this chapter aimed to develop a novel methodology to automatically select regions of interest on thermograms of the lower body and examined the effect of the thermogram border and region of interest size (length) on skin temperature outputs.

7.2 Introduction

Infrared thermal imaging to measure skin temperature is widely used within sports medicine. It has been applied for a range of purposes including to evaluate the efficacy of cryotherapy (Costello et al., 2014), screen and assess injuries (Hildebrandt et al., 2010), detect delayed onset muscle soreness and examine the effect of compression clothing on thermal responses (Priego Quesada et al., 2015), to examine symmetry of muscle activation (Chudecka et al., 2015) and to investigate thermal responses during exercise in hot and cold environmental conditions (Bach et al., 2015; Fournet et al., 2013). All living and non-living objects, with a temperature above absolute zero (0 Kelvin or -273.15˚C or 459˚F), emit some level of infrared radiation and when the emissivity, defined as the relative ability of an object's surface to emit energy by radiation, is known, the level of infrared radiation can be used to calculate the temperature of the emitting object (Costello et al., 2013). The advantages of infrared thermal imaging over other methods are that the method is non-invasive, contactless and wireless (Hildebrandt et al., 2010; Moreira, Costello, Brito, & Sillero-Quintana, 2017; Sherman et al., 1996). Infrared thermal imaging has been shown to be a reliable method for assessing skin temperature (Wilkinson et al., 2018), which may change depending on the area of the body assessed (Rossignoli et al., 2015). However, there is mixed opinion regarding the reliability and validity of infrared thermal imaging for measuring skin temperature as James and colleagues (2014) found poor validity and reliability of infrared thermal imaging and did not recommend its application for skin temperature measurement. However, the authors used an infrared thermal imaging camera with a low infrared resolution of 160 x 120 pixels, which may explain their invalid and unreliable results of such device. In this regard, an infrared resolution of 320 x 240 pixels is typically considered to be the minimum resolution necessary for satisfactory data in assessment of skin temperature (Fernández-Cuevas et al., 2015; Hildebrandt et al., 2010). Furthermore, the considerable advances in the technology that underpins infrared thermal imaging may provide greater efficacy, reliability, and practicality to allow measurement of skin temperature (Ring & Ammer, 2012).

There are few industry standardised frameworks that have been established for using infrared thermal imaging on the human body (Ammer, 2008). In clinical practice, Ring and Ammer (2000) reported that infrared thermal imaging can produce reliable results only when established standards are adhered to, and more recently such standards have been established (Ring et al., 2007; Schwartz, 2006). However, universal guidance, and standards for using infrared thermal imaging and the subsequent analysis, in a sporting context, is limited. Moreira and colleagues (2017) developed a thermal imaging checklist to aid methodological consistency between studies, specifically in sports and exercise medicine. Furthermore, a Delphi study was also conducted by Moreira and colleagues (2017) who provided important factors to consider when using infrared thermal imaging in the form of a 15-point checklist created by the participating experts. These included detailed reporting of: participant characteristics, study restrictions, ambient temperature, camera equipment and accuracy, regions of interests used and temperature extraction and analysis methods. Although there is no doubt that these considerations will aid the application of infrared thermal imaging within sport, some factors still require evaluation such as the appropriate size of a region of interest used for body segment temperature analysis (i.e., thigh) and considerations for the inclusion/exclusion of the thermogram border area which may influence temperature outputs (described below).

It has been suggested that existing methods of infrared thermal imaging data analysis lack standardisation and reliability (Selfe et al., 2006). To analyse the temperature of thermograms, it is common practice to use the infrared thermal imaging camera manufacturer software which typically requires the researcher to manually draw regions of interest directly onto the thermogram (Drzazga et al., 2018; Merla et al., 2010; Priego Quesada et al., 2015; Tanda, 2016). A region of interest is normally constructed as a quadrilateral shape and is applied to the thermogram over the area where temperature measurements are required (Costello et al., 2012). The application of regions of interest has been recommended for extracting temperature data from thermograms as they allow the researcher to examine temperature over specific areas of the body such as a particular muscle or muscle group (Kennet et al., 2007). The temperature of each pixel within the region of interest is recorded, thus, outcome measures of mean, maximum and minimum temperature can be determined and are commonly reported in the literature. Analysis software which uses regions of interest are typically created for industrial and architectural application and may not be appropriate for human analysis (Murawski et al., 2003). Alternatively, automatic data analysis can be applied to thermograms using specific software packages which provide over 100 predetermined regions of interest in four regions of the body: upper anterior, upper posterior, lower anterior and lower posterior (ThermoHuman, PEMA Thermo Group S.L, Madrid, Spain). However, the predetermined regions of interest selected by the software may not be sufficiently specific enough or have the flexibility to examine temperature for a given location on the body. Furthermore, the effect of the cooler border surrounding the imaged object is not considered which may influence the accuracy of temperature values.

Although defining regions of interest manually has been widely applied to analyse skin temperature, it may be susceptible to sources of error. The nature of manually defining regions of interest is subjective (Maniar et al., 2015) and may rely on the researchers knowledge to accurately define the appropriate region of interest for the investigation. Moreover, the size of the regions of interest selected may affect outcome temperature. Priego Quesada and colleagues (2015) used small regions of interest (4 x 4 cm) placed on a body segment, as well as large regions of interest which outlined the whole segment under investigation. Following cycling exercise, the results showed higher temperatures in the small regions of interest compared to the large regions of interest placed on the same body segment. This is likely because both small and large regions of interest may cover different anatomical features (i.e., muscle and bone) which present different thermal outputs as bone is typically cooler than muscle due to the metabolic heat produced by the muscle and greater blood flow. Therefore, when selecting regions of interest both within a participant (between experimental conditions) and between participants, it is important that the region of interest represents the same area of a segment. If a predetermined pixel area is defined for a region of interest, then the size of a participant's body segment (i.e., leg) will affect the proportion of the segment analysed and the underlying anatomical features that it describes. Alternatively, if a predetermined proportion of a segment is to be analysed, the approach may lack resolution if the participants legs are substantially different from those of other participants, reflecting a much smaller subset of pixels. It is therefore beneficial to develop a method to standardise regions of interest both within and between participants, using known locations or landmarks as reference points on each individual. A solution to locating similar anatomical features as markers of analysis zones, has been employed by Selfe and colleagues (2006) who used thermally inert reference markers placed directly on to the body to define regions of interest for the anterior knee which could be clearly located on the thermogram. The ability of the method to select the same region of interest area between investigators was found to be reliable as the intra-class correlation coefficient for interrater reliability ranged from 0.82-0.97. As a result, this method could be adapted to standardise regions of interest on other body segments (i.e., thigh and shank).

Manufacturer software that incorporates manual region of interest selection typically use shapes to define the region such as: triangles, rectangles, squares and circles (Duarte et al., 2014). However, given that the human body has a non-uniform curved shape, particularly at the limbs, these shapes may poorly fit the body segment under investigation (Duarte et al., 2014). This may lead to error as the shapes may include regions not of interest (i.e., background), or may exclude important areas of the body, as demonstrated in **Figure 7.1**. More recently, some software packages include ‘bendable’ lines (splines) to better define the region of interest for temperature analysis (FLIR Systems Inc., Wilsonville, Oregon, USA). However, this method is time consuming as multiple points need to be selected to follow the curvature of the body segment. Also, this method may be susceptible to error due to inconsistent size of regions of interest examined between participants (Priego Quesada et al., 2015). Finally, selection bias may also be a factor when manual selection of regions of interest is performed by the investigator.

The Glamorgan Protocol was published with the aim of standardising region of interest selection in thermal imaging research (Ammer, 2008). This protocol introduced 90 different regions of interest on the human body which could be used for temperature analysis. However, some studies may have specific criteria for selecting regions of interest which may not be presented in the Glamorgan Protocol as some studies select regions of interest over a specific muscle or muscle groups (Bartuzi et al., 2012; Priego Quesada et al., 2015). Conversely, others select regions of interest to cover specific segments of the body (Chudecka & Lubkowska, 2015; Merla et al., 2010). In the absence of palpation or extensive experience, defining the location of specific muscles/zones within a thermogram is open to subjectivity and error, and the applied region of interest may not accurately represent the segment under investigation. Furthermore, the shape used to define the region of interest may not replicate the shape of the muscle or segment. A method that uses reference markers placed onto the body to subsequently determine automated regions of interest which are relative to the limb/body segment being analysed is warranted.

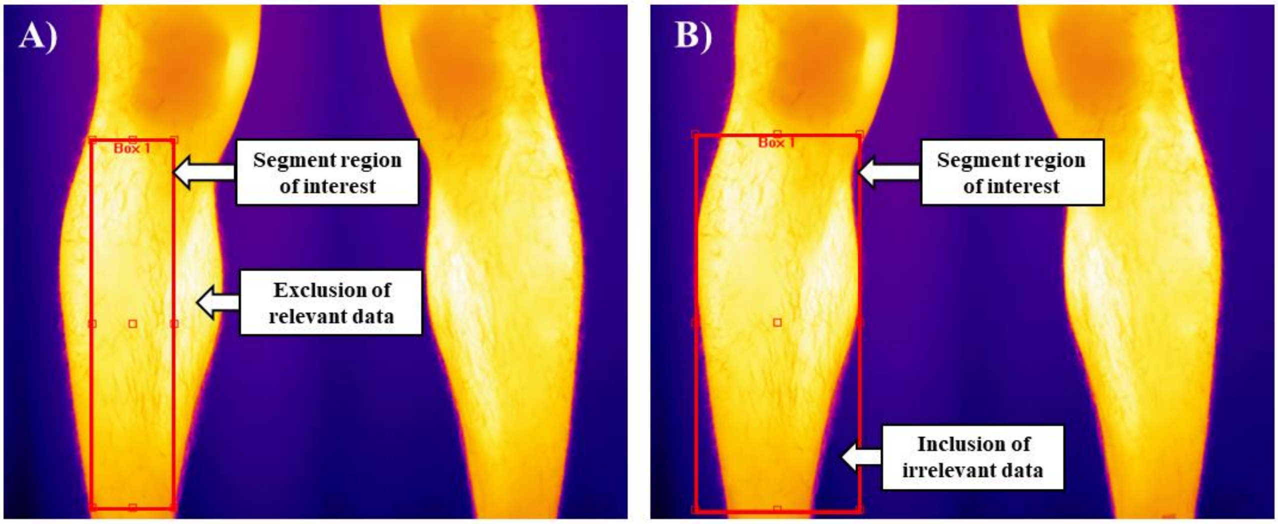


Figure 7.1. Displays the difficulty of using prismatic shapes (i.e., rectangles) to select regions of interest on the lower leg as the shape does not replicate the shape of the leg thus, relevant and irrelevant data may be excluded (A) or included (B).

A factor which requires greater consideration when using infrared thermal imaging is the possible effect of the thermogram border region on the subsequent skin temperature outputs. The thermogram border is defined as a boundary of cooler temperature around the edge of the imaged object which is caused by the contrasting temperature between the imaged object (hot) and background (cold) (**Figure 7.2**). The temperature from the thermogram border typically exhibits cooler temperature values than the imaged human (Fernández-Cuevas et al., 2015). Typically, when regions of interest are established on a thermogram, the border of the object (i.e., human) is avoided (Drzazga et al., 2018; Priego Quesada et al., 2015). This process is typically subjective, and the region removed, which may be small or large, goes un-reported. To the authors knowledge, no study has investigated the effect of removing the thermogram border on temperature analysis outcomes. Given that the border is typically cooler around the hotter human body, it might be assumed that including the border within a region of interest would reduce the overall temperature. However, the magnitude of the temperature change is unknown. Therefore, it would prove useful to understand the temperature change following specific thermogram border removal.

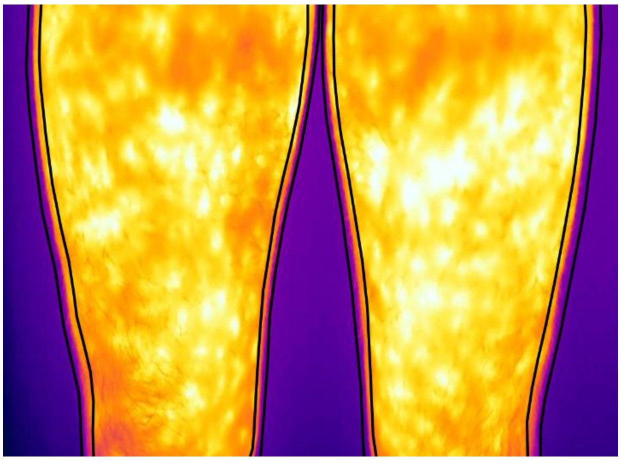


Figure 7.2. Displays the contrasting temperature of the thermogram border located around the edge of the upper legs and highlighted between the parallel black lines.

Therefore, the aim of the current study was to investigate the effect of different leg analysis region of interest dimensions on reported skin temperatures (mean, maximum and standard deviation) with primary focus on, 1) dimension reductions using border removal increments, and 2) dimension reductions using region of interest length increments

7.3 Methodology

7.3.1 Participants

Ten, healthy males (age 23.5 ± 2.8 years, stature 181.9 ± 4.8 cm, body mass 76.2 ± 5.3 kg) volunteered and provided informed consent to participate in the study. All participants completed a health screen questionnaire before involvement in the study, to ensure they had no medical or other conditions that would have prevented them from taking part. Participants were instructed to refrain from strenuous exercise and alcohol consumption 24 hours prior to the experimental trial and to avoid caffeine consumption on the day of the experimental trial whilst attending the laboratory at least 3 hours postprandial. Additional restrictions prior to the experimental trial were included relating to the infrared thermal imaging including: limiting exposure to ultra-violet (UV) radiation, refrain from application of body lotions and creams, massage, electrotherapy, ultrasound, cryotherapy and excessive heat or cold exposure. The study was approved by a University Ethics Committee, (Nottingham Trent University Ethical Committee Application for Human Biological Investigation reference number: 560).

7.3.2 Experimental Design

Participants visited the laboratory on two occasions. The first visit was a familiarisation trial, which consisted of a familiarisation with the infrared thermal imaging procedure. Participants also performed a familiarisation of a 30-minute run, on a treadmill, to determine a comfortable running speed for the subsequent experimental trial. For the experimental trial, participants performed a 30-minute run, at a self-selected 'recovery' speed, ensuring that rating of perceived exertion (RPE) did not exceed 13 (somewhat hard) on the Borg scale (Borg, 1982). The 30-minute run was performed on an instrumented treadmill (AMTI, Watertown, MA, USA). Skin temperature was assessed before and immediately following the 30-minute run (**Figure 7.3**). Experimental trials were performed in similar environmental conditions; 20.3 ± 0.6°C and 36.8 ± 3.9% relative humidity.

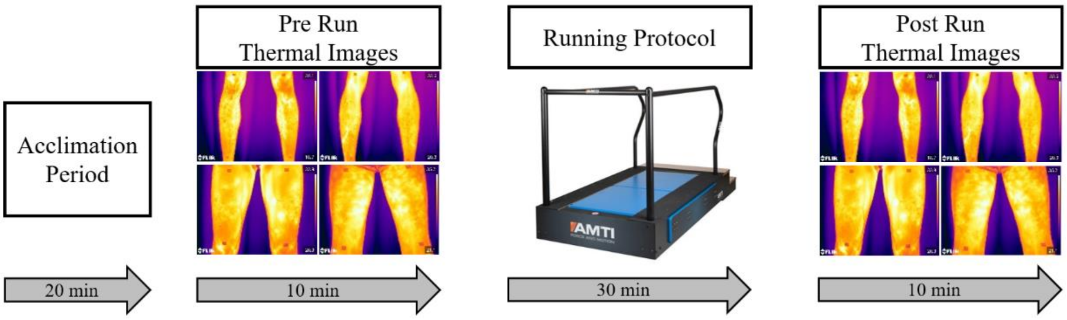


Figure 7.3. Displays a schematic of the study protocols including the acclimation period, baseline thermal images, 30-minute run and post exercise thermal images.

7.3.3 Skin Temperature and Thermal Imaging

A detailed description of the infrared thermal imaging camera and measurement procedures is provided in the General Methodology (*Section 3.5.3*).

Skin temperature was measured using a FLIR T1020 infrared thermal imaging camera (FLIR Systems Inc., Wilsonville, Oregon, USA). Thermograms of the anterior and posterior, upper and lower leg segments were captured at two occasions; 1) before the running protocol; and 2) immediately post running protocol. Prior to thermal imaging, participants rested for 20-min to acclimate to the room temperature. Also, prior to thermal imaging, 1 x 1 cm thermally inert tape markers were placed at six specific locations on the anterior and posterior of the left and right legs and marked with indelible ink to allow for subsequent standardisation of segment regions of interest (see detailed explanation below *Section 7.3.5*). The locations were: (A) 5 cm proximal from the centre of the ankle malleolus (anterior); (B) the most proximal aspect of the patella (anterior); (C) parallel to the gluteal fold (anterior); (D) 5cm proximal from the centre of the ankle malleolus (posterior); (E) parallel to the most proximal aspect of the patella (posterior); (F) on the crease of the gluteal fold (posterior), (**Figure 3.2**). Following an acclimation period, baseline thermograms were captured. Separate thermograms were captured for the anterior lower and upper leg segments and posterior lower and upper leg segments, these segments were used for temperature extraction and analysis. All thermograms were captured at a distance of ~1 m from the participant, and the distance was extended to allow for participants with longer legs to have the full leg segment shown in the camera view. The thermograms were captured by including as much of the legs in the camera view as possible without obscuring the view of the two tape markers which identify the leg segment region of interest, thus minimising the differences in leg resolution between participants which might occur if the same fixed distance from the camera were used. The infrared thermal imaging camera was positioned on a tripod to ensure a still image and placed perpendicular to the participant for each thermogram capture. The tripod was adjusted vertically to capture thermograms of the upper leg segments and lower leg segments. For each thermogram, participants stood with their legs shoulder width apart with relaxed musculature and their arms crossed over their chest. Prior to infrared thermal imaging, objective parameters of reflective temperature and emissivity were input into thermal camera settings (ISO, 2008). Emissivity of clean human skin has been widely reported to be 0.98 which was used for this study (Bernard et al., 2013). Ambient temperature and relative humidity were measured using a digital weather station and were input into the thermal imaging camera settings to aid measurement accuracy. A detailed description of the objective parameters input into the camera and procedures are provided in the General Methodology (*Section 3.5.3*).

7.3.4 Running Protocol

Participants performed a 30-minute run on an instrumented treadmill (AMTI, Watertown, MA, USA) and were instructed to run at a self-selected 'comfortable' running speed, which corresponded with an RPE of 11 or 12, an intensity less than "somewhat hard" (13) (Borg, 1982). Rating of perceived exertion was monitored using a visual 6 (no exertion) – 20 (maximal exertion) scale at rest and at six, five-minute intervals throughout the run. Participants verbally stated their RPE, with a scale positioned in view. The running speed was determined during the familiarisation trial and once the participant selected their running speed, it remained identical for the experimental trial. The running speed during the study was 2.5 ± 0.3 m/s.

7.3.5 Data Extraction

Temperature data was extracted from each thermogram using a bespoke MATLAB® program (MathWorks Inc., MA, USA). Initially, the user digitised the thermally inert tape reference markers using a graphical representation of the temperature of each pixel. The lower edge of the proximal marker and the upper edge of the distal marker, for each leg segment, were selected. The marker locations were then used for the subsequent temperature analysis by defining the proximal and distal endpoints of the segment region of interest. The length from proximal to distal markers represented an assumed 100% of the segment length. A frequency analysis was performed to identify the background and foreground (participant) data of the thermogram. Twenty bins were used to generate a histogram to divide up the temperature data range and assign a frequency for the number of temperature measurements within each bin. This approach always produces a bimodal histogram and assuming sufficient difference between the background and participant, this allows a conservative temperature threshold to be defined to distinguish between them. In this case the bin with the minimum frequency between both peaks was located and its upper edge temperature selected as the threshold. This was a conservative approach and does not remove the border zone surrounding the legs where the temperature can be lower as it transitions between two contrasting temperatures. Subsequently the threshold was used to remove background data and the left and right legs were considered separately for further analysis. To identify the mid-line of each leg segment region of interest, the proximal and distal tape markers on each leg segment were selected to define a vector. The mid-point along each vector was defined as the centre of the segment region of interest. When defining proportions of segment length for further analysis, the proportion was always aligned with equal distribution either side of this centre marker.

7.3.6 Data Analysis

A sensitivity analysis was undertaken by independently perturbing the parameters which defined the border region (the region of pixels along the outer edge of the thermogram; left and right sides of the thermogram data) and region of interest length (proportion of segment length; proximal to distal). Initially the mean width of the left and right knees of each participant was measured in pixels. This approach was used since the knee was an anatomical feature present in each thermogram (anterior, posterior, proximal and distal proportions of leg). The magnitude of the border region removed for each available row of thermogram pixel data was then increased in increments of 2% up to 20%, starting from the data available after the threshold frequency had been applied to remove background pixel data (considered to be 100% of the thermogram), (**Figure 7.4 [A]**).

The length of the segment region of interest was defined by the distance between the most distal and proximal pixels of the tape markers (assumed to be 100% of segment length). The length of the segment region of interest was reduced in 5% increments from 100% of the segment length to 25% of the segment length, essentially removing the most proximal 2.5% and distal 2.5% of the available rows of pixels with each increment, (**Figure 7.4 [B]**).

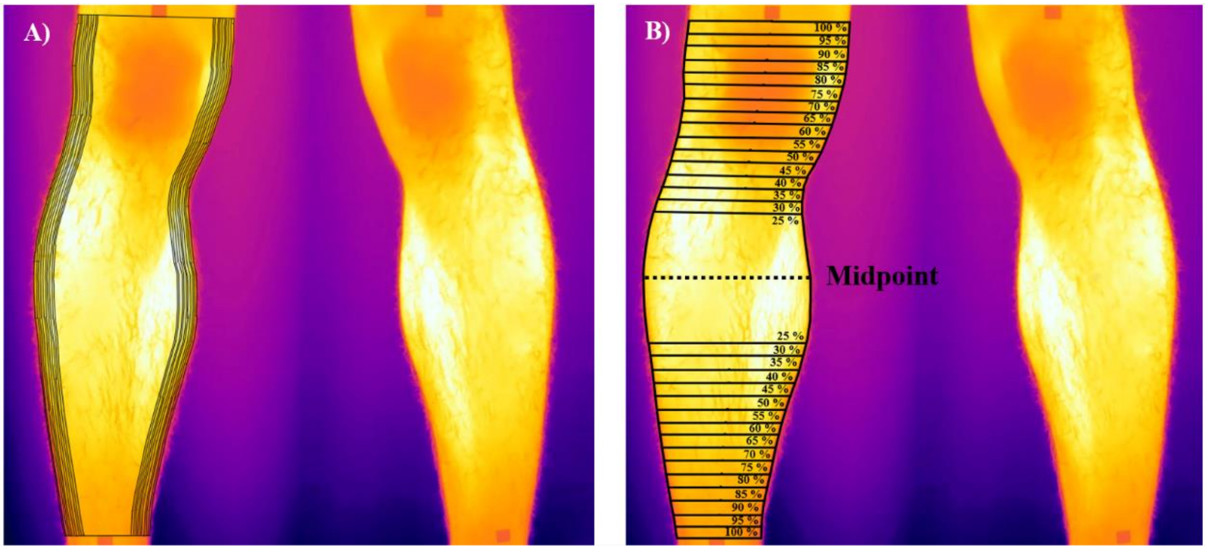


Figure 7.4. Displays the border removal increments from the unadjusted border (A) and the percentage of segment region of interest evaluated from the midpoint of the segment, the unadjusted segment length corresponded to 100% proximal and distal from the segment midpoint (B). A dashed line represents the midpoint of the segment.

Temperature data corresponding to the mean, maximum and standard deviation of temperatures was extracted for the available segment region of interest according to border region and segment length. To establish the independent effect of border removal and segment length, following every incremental reduction, the temperature properties for the full incremental range were calculated. Temperature outputs for each participant were exported into three separate 16 x 11 matrices which included the mean, maximum and standard deviation of the segment region of interest temperature (**Table 7.1**). The mean, maximum and standard deviation temperature outputs for each participant were overlayed to create a mean of all participant data for each leg segment (anterior upper left, upper right, lower left, lower right, posterior upper left, upper right, lower left and lower right), at baseline and post-run, and was subsequently used for further sensitivity analysis.

Table 7.1. Example of a 16 x 11 matrix presenting mean skin temperature outputs following border removal increments and segment region of interest length incremental reductions.

		Proportion of segment length [%]															
		25	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
Border removal region [%]	**0**	30.8	30.7	30.6	30.6	30.5	30.4	30.3	30.1	30.0	29.9	29.8	29.7	29.7	29.6	29.6	29.5
	2	31.0	30.9	30.9	30.8	30.7	30.6	30.5	30.4	30.3	30.2	30.1	30.0	29.9	29.9	29.8	29.8
	4	31.0	31.0	30.9	30.9	30.8	30.7	30.6	30.5	30.3	30.2	30.1	30.0	30.0	29.9	29.9	29.8
	6	31.1	31.0	30.9	30.9	30.8	30.7	30.6	30.5	30.4	30.3	30.2	30.1	30.0	29.9	29.9	29.9
	8	31.1	31.0	31.0	30.9	30.8	30.7	30.6	30.5	30.4	30.3	30.2	30.1	30.0	30.0	29.9	29.9
	10	31.1	31.0	31.0	30.9	30.8	30.7	30.6	30.5	30.4	30.3	30.2	30.1	30.0	30.0	29.9	29.9
	12	31.1	31.0	31.0	30.9	30.8	30.7	30.6	30.5	30.4	30.3	30.1	30.1	30.0	29.9	29.9	29.8
	14	31.1	31.0	31.0	30.9	30.8	30.7	30.6	30.5	30.4	30.2	30.1	30.0	30.0	29.9	29.9	29.8
	16	31.1	31.0	31.0	30.9	30.8	30.7	30.6	30.5	30.3	30.2	30.1	30.0	29.9	29.9	29.8	29.8
	18	31.1	31.0	31.0	30.9	30.8	30.7	30.6	30.5	30.3	30.2	30.0	30.0	29.9	29.8	29.8	29.7
	20	31.0	31.0	30.9	30.9	30.8	30.7	30.6	30.4	30.3	30.1	30.0	29.9	29.8	29.8	29.7	29.7

A sensitivity analysis was performed to examine the influence of changes in border removal and reductions of segment region of interest length on the mean, maximum and standard deviation of temperature for each leg segment at baseline and post-run. Sensitivity (S_{ij}) was calculated as the normalized change in one model output ($M_{i\mathrm{P}}$) from its unaltered value (M_{i0}) due to a change in one model parameter ($P_{j\mathrm{P}}$) normalized to the unaltered parameter value (P_{j0}), in a model which has i model outputs, and j defining parameters (Lehman & Stark, 1982) (Equation 1). For this study i = 3, where i represented the three temperature outputs: mean temperature, maximum temperature and standard deivation of temperature. The j defining parameters in this study were the purturbations of image border region (N = 10 purtubations of the border; 80% to 98% of full pixel region at increments of 2%) and proportion of segment length (N = 15 purutabations of segment length; 25% to 95% of segment length at increments of 5%).

$$S_{ij} = \frac{(M_{i\mathrm{P}} - M_{i\mathrm{O}})/M_{i\mathrm{O}}}{(P_{j\mathrm{P}} - P_{j\mathrm{O}})/P_{j\mathrm{O}}} \quad [1]$$

To explore the independent effect of border region or segment length on the sensitivity of temperature outputs, the sensitivity of outputs on border region, were calculated assuming 100% of segment length and vice versa, however we present a graphical representation of outputs for all available combinations of border region x segment length combinations. The pooled standard deviation of sensitivity values for either border region or segment length for the various temperature outputs were calculated to define the sensitivity to purturbations. The sensitivity of the model outputs were ranked into categories of: None: change less than 0.01 of perturbation; Small: change of less than the perturbation (0.01–0.99); Large: change in outputs greater than or equal to parameter perturbation (1–25); Extreme: change in the resulting value by a factor of 25 or greater (Scovil & Ronsky, 2006). When calculating sensitivity of border removal, 100% of the region of interest segment length was used to represent an unperturbed value. When calculating the sensitivity of changes to segment region of interest length 100% of the border was used to represent an unperturbed value.

7.4 Results

Pixel Contribution of Leg Segments for Thermograms

The number of pixels as a percentage of the full thermogram resolution, which represented the legs on each thermogram was similar between participants at baseline. At baseline, the percentage of pixels which represented temperature data of the legs relative to the total number of pixels of the thermogram was 58 ± 3%, 59 ± 5%, 72 ± 7% and 76 ± 9% for the lower anterior, lower posterior, upper anterior and upper posterior legs respectively, (**Table 7.2**).

Table 7.2. Displays the percentage of pixels that represent the legs relative to the total number of pixels on a thermogram for the lower anterior, lower posterior, upper anterior and upper posterior leg segment thermograms at baseline (mean ± standard deviation).

	Baseline		
	Left Leg (%)	**Right Leg (%)**	**Total (%)**
Lower Anterior	29 ± 2	29 ± 2	58 ± 3
Lower Posterior	29 ± 3	29 ± 3	59 ± 5
Upper Anterior	36 ± 5	36 ± 4	72 ± 7
Upper Anterior	38 ± 5	39 ± 4	76 ± 9

The number of pixels as a percentage of the full thermogram resolution, which represented the legs on each thermogram was similar between participants at post run. At post run, the percentage of pixels which represented temperature data of the legs relative to the total number of pixels of the thermogram was 52 ± 3%, 57 ± 3%, 70 ± 7% and 73 ± 9% for the lower anterior, lower posterior, upper anterior and upper posterior legs respectively, (**Table 7.3**).

Table 7.3. Displays the percentage of pixels that represent the legs relative to the total number of pixels on a thermogram for the lower anterior, lower posterior, upper anterior and upper posterior leg segment thermograms at post run (mean ± standard deviation).

	Post Run		
	Left Leg (%)	**Right Leg (%)**	**Total (%)**
Lower Anterior	25 ± 2	26 ± 2	52 ± 3
Lower Posterior	28 ± 2	29 ± 2	57 ± 3
Upper Anterior	35 ± 3	35 ± 4	70 ± 7
Upper Anterior	37 ± 5	36 ± 5	73 ± 9

Mean Temperature

General Features Associated with Border Removal

The largest change to the calculated mean skin temperature occurred for the initial 2% of border removal from the unaltered border, for all anterior and posterior segments. For the anterior thermograms, the mean skin temperature increased by 0.23°C, 0.23°C, 0.14°C and 0.14°C for the lower left and right leg segments and the upper left and right leg segments, following the initial 2% reduction in size of the border region (**Figure 7.5**). The corresponding mean temperature increased by 0.24°C, 0.24°C, 0.16°C and 0.17°C, at post run (**Figure 7.6**). For the posterior thermograms, the mean skin temperature increased by 0.24°C, 0.23°C, 0.15°C and 0.16°C for the lower left and right leg segments and the upper left and right leg segments following the initial 2% reduction in size of the border region (**Figure 7.7**). The corresponding mean temperature increased by 0.23°C, 0.23°C, 0.23°C and 0.23°C, at post run (**Figure 7.8**).

Border Removal Sensitivity

For the anterior and posterior leg segments, evaluation of the sensitivity of the temperature model to border region pertubations indicated that mean segment temperature had small sensitivity for the upper and lower, left and right legs, at pre and post run (**Table 7.4**).

Table 7.4. Pooled standard deviation of the sensitivity values for the model mean temperature outputs following changes to border removal. Sensitivity catergories were: none (<0.01); small (0.01-0.99); large (1-25) and extreme (>25).

	Anterior		**Posterior**	
	Left Leg	**Right Leg**	**Left Leg**	**Right Leg**
Pre Lower Leg	0.11	0.12	0.10	0.09
Post Lower Leg	0.10	0.11	0.09	0.09
Pre Upper Leg	0.06	0.06	0.06	0.07
Post Upper Leg	0.07	0.07	0.09	0.09

General Features Associated with Segment Length

The largest change to mean skin temperature did not consistently occur for any specific proportion of the segment length for anterior or posterior segments. Moreover, the change to calculated mean skin temperature changes were smaller compared to those observed for the border removal. For the anterior thermograms, the largest mean skin temperature changes from the 100% of segment length data were 0.13°C (50%), 0.04°C (60%), -0.03°C (50%) and -0.02°C (85%) (data is reported as the temperature change (°C) and corresponding proportion of segment length being evaluated) for the lower left and right legs and the upper left and right legs (**Figure 7.5**). The corresponding mean skin temperature change was 0.09°C (50%), -0.02°C (75%), 0.04°C (25%) and -0.06°C (95%), at post run

(**Figure 7.6**). For the posterior thermograms, the largest mean skin temperature changes following purturbations of segment length were 0.12°C (50%), 0.03°C (45%), -0.03°C (50%) and -0.02°C (85%) for the lower left and right legs and the upper left and right legs (**Figure 7.7**). The corresponding mean skin temperature change was 0.09°C (50%), 0.03°C (40%), 0.03°C (90%) and 0.04°C (95%), at post run (**Figure 7.8**).

Segment Region of Interest Length Sensitivity

For the anterior leg segements, evaluation of the sensitivity of the temperature model to segment length purtubations indicated that mean segment temperature had no and small sensitivity for the upper and lower, left and right legs, at pre and post run. For the posterior leg segments, mean segment temperature had no sensitivity for the upper and lower, left and right legs, at pre and post run, (**Table 7.5**).

Table 7.5. Pooled standard deviation of the sensitivity values for the model mean temperature outputs following changes the segment region of interest length evaluated. Sensitivity catergories were: none (<0.01); small (0.01-0.99); large (1-25) and extreme (>25).

	Anterior		**Posterior**	
	Left Leg	**Right Leg**	**Left Leg**	**Right Leg**
Pre Lower Leg	0.01	0.01	0.00	0.00
Post Lower Leg	0.01	0.01	0.00	0.00
Pre Upper Leg	0.00	0.00	0.00	0.00
Post Upper Leg	0.00	0.00	0.00	0.00

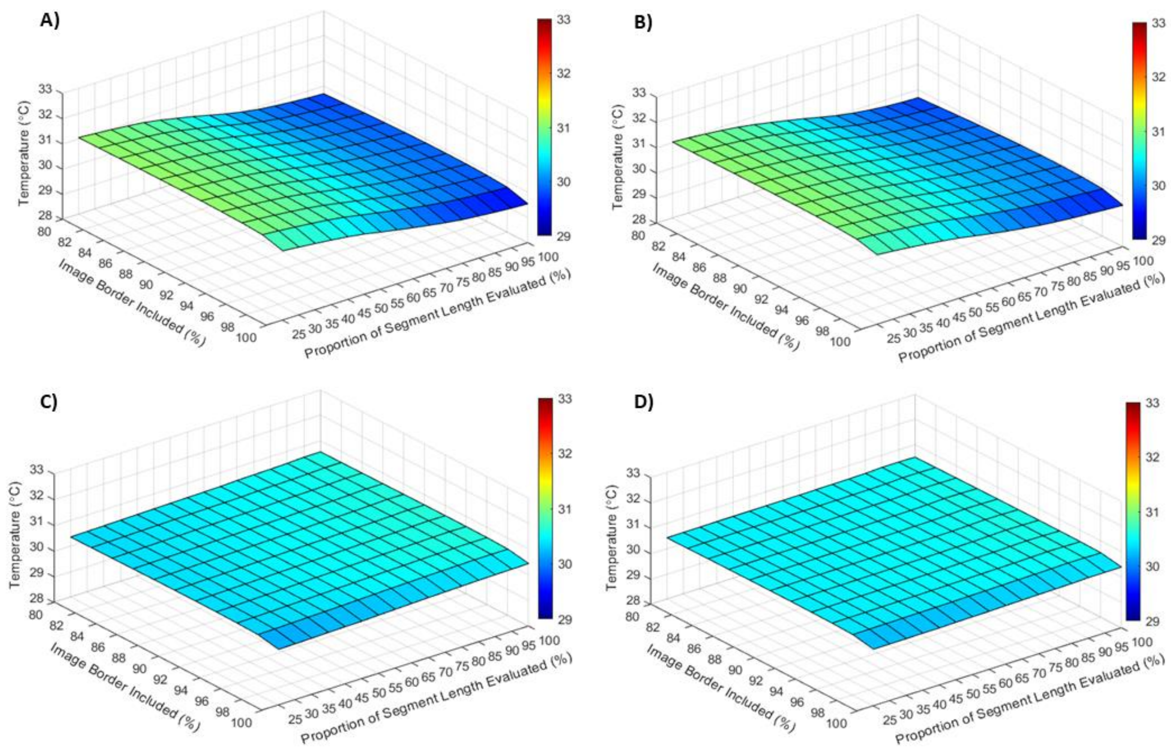


Figure 7.5. Surface plots showing the mean skin temperature associated with border region size (%) and proportion of segment evaluated increments (%) on the (A) anterior lower left leg, (B) anterior lower right leg, (C) anterior upper left leg and (D) anterior upper right leg, at pre run.

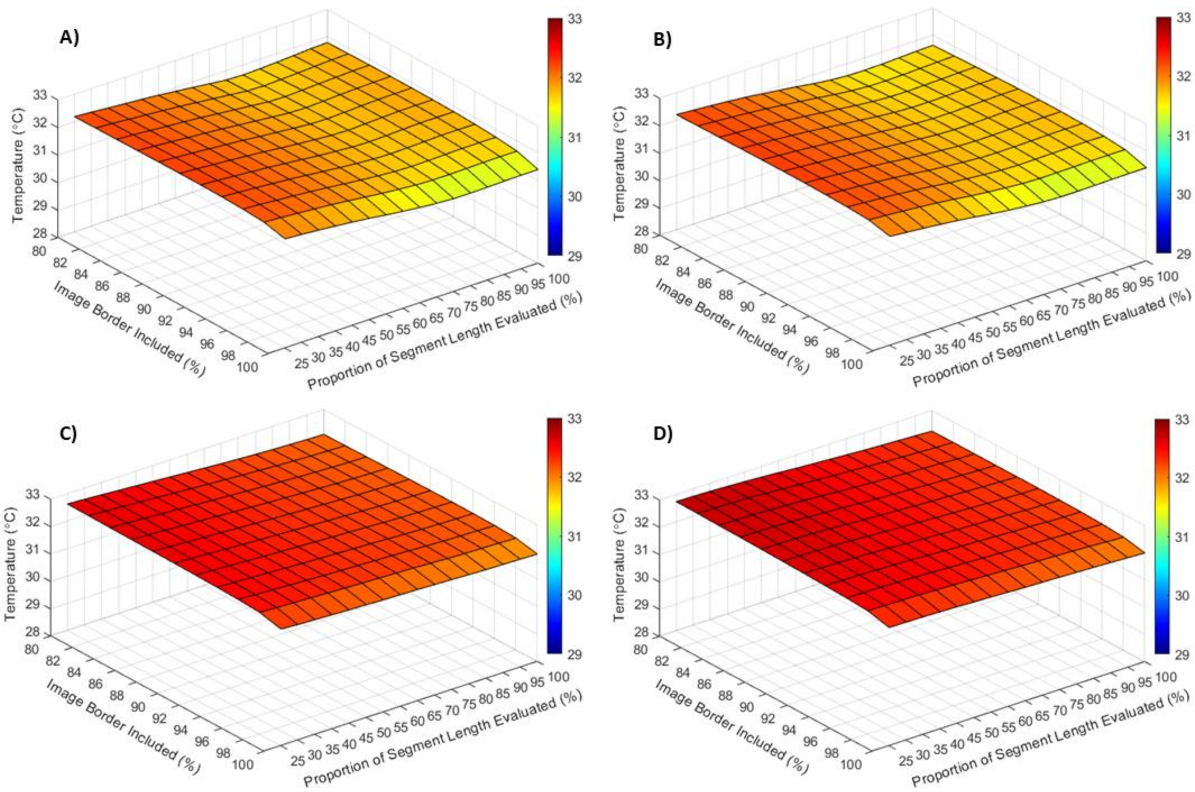


Figure 7.6. Surface plots showing the mean skin temperature associated with border region size (%) and proportion of segment evaluated increments (%) on the (A) anterior lower left leg, (B) anterior lower right leg, (C) anterior upper left leg and (D) anterior upper right leg, at post run.

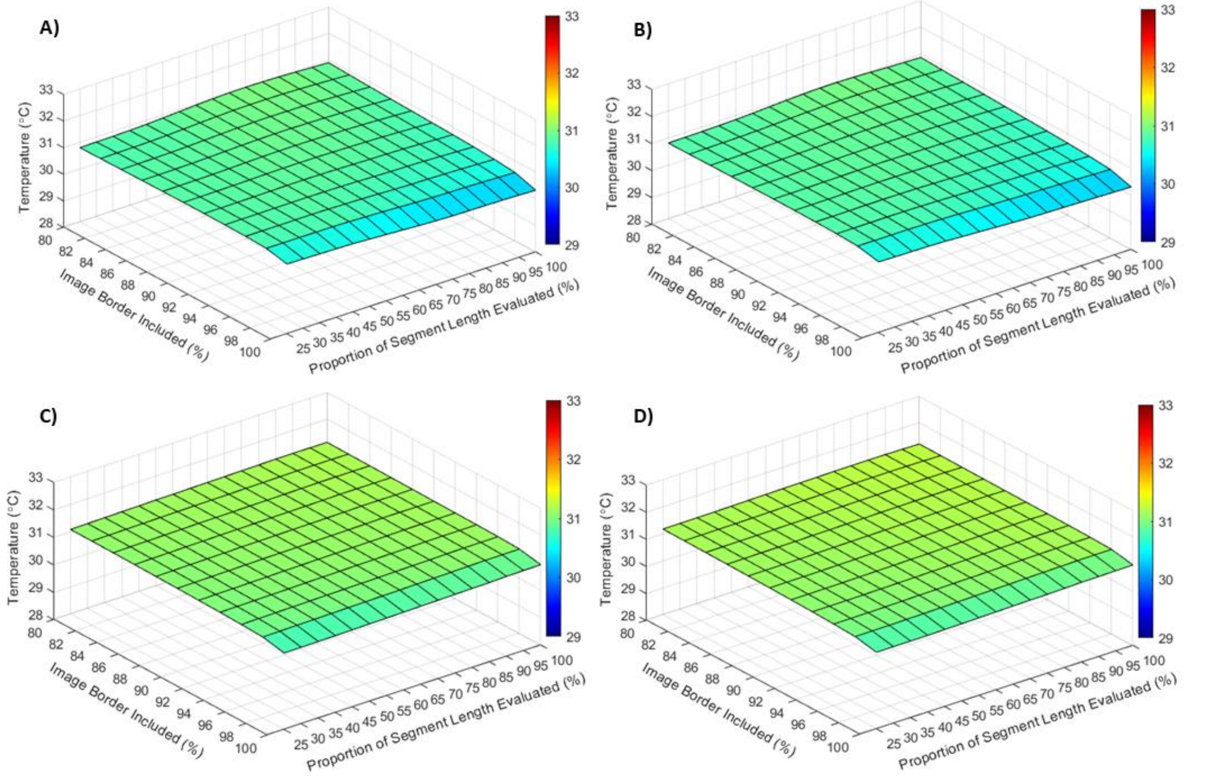


Figure 7.7. Surface plots showing the mean skin temperature associated with border region size (%) and proportion of segment evaluated increments (%) on the (A) posterior lower left leg, (B) posterior lower right leg, (C) posterior upper left leg and (D) posterior upper right leg, at pre run.

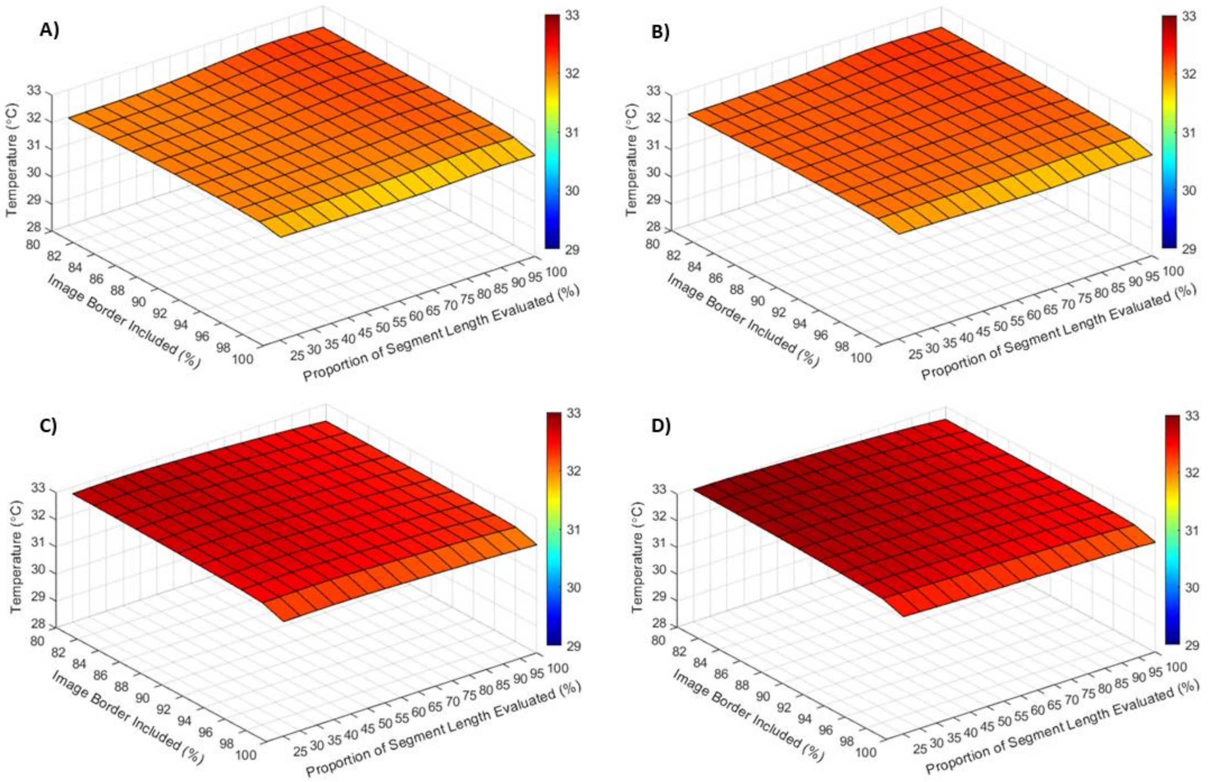


Figure 7.8. Surface plots showing the mean skin temperature associated with border region size (%) and proportion of segment evaluated increments (%) on the (A) posterior lower left leg, (B) posterior lower right leg, (C) posterior upper left leg and (D) posterior upper right leg, at post run.

Maximum Temperature

General Features Associated with Border Removal

The largest change in maximum skin temperature did not occur for a consistent border removal increment as was found for mean temperature outputs (i.e., 2%). For the anterior thermograms, the largest maximum skin temperature change following purturbations of the border removal region was -0.02 (18%), -0.02 (12%), -0.15 (6%) and -0.16°C (20%) (data is reported as the temperature change (°C) and corresponding proportion of border region removal) for the lower left and right legs and the upper left and right legs, at baseline, (**Figure 7.9**). The corresponding maximum skin temperature change following changes to border removal was -0.04 (10%), -0.04 (14%), -0.12 (2%) and -0.13°C (4%), at post run (**Figure 7.10**). For the posterior thermograms, the largest maximum skin temperature change following changes to border removal was -0.01 (16%), 0.02 (2%), -0.17 (4%) and -0.18°C (6%) for the lower left and right legs and the upper left and right legs, at baseline (**Figure 7.11**). The corresponding maximum skin temperature change following changes to border removal was < 0.01 (2 - 20%), -0.05 (16%), -0.22 (2%) and -0.14°C (4%), at post run **(Figure 7.12**).

Border Removal Sensitivity

For the anterior and posterior, upper and lower, left and right leg segments, evaluation of the sensitivity of the temperature model to border region pertubations indicated that maximum temperature outputs had no and small sensitivity at pre and post run, (**Table 7.6**).

Table 7.6. Pooled standard deviation of the sensitivity values for the model maximum temperature outputs following changes to border removal. Sensitivity catergories were: none (<0.01); small (0.01-0.99); large (1-25) and extreme (>25).

	Anterior		**Posterior**	
	Left Leg	**Right Leg**	**Left Leg**	**Right Leg**
Pre Lower Leg	0.00	0.01	0.00	0.01
Post Lower Leg	0.01	0.01	0.00	0.01
Pre Upper Leg	0.05	0.02	0.03	0.04
Post Upper Leg	0.03	0.03	0.08	0.04

General Features Associated with Segment Length

The largest change to mean skin temperature did not consistently occur for any specific proportion of the segment length for anterior or posterior segments. proportion of the segment length evaulated for all anterior and posterior segments. Moreover, the maximum skin temperature changes were smaller compared to the border removal outputs. For the anterior thermograms, the largest maximum skin temperature change following changes to the proportion of the segment length evaulated was 0.13 (50%), 0.04 (60%), -0.03 (50%) and -0.02°C (85%) (data is reported as the temperature change (°C) and corresponding proportion of segment length being evaluated) for the lower left and right legs and the upper left and right legs (**Figure 7.9**). The corresponding maximum skin temperature change following changes to the proportion of the segment length evaulated was 0.09 (50%), -0.02 (75%), 0.04 (25%) and -0.06°C (95%), at post run (**Figure 7.10**). For the posterior thermograms, the largest maximum skin temperature change following changes to the proportion of the segment length evaulated was 0.12 (50%), 0.03 (45%), -0.03 (50%) and -0.02°C (85%) for the lower left and right legs and the upper left and right legs (**Figure 7.11**). The corresponding maximum skin temperature change following changes to the percentage of segment length was 0.09 (50%), 0.03 (40%), 0.03 (90%) and 0.04°C (95%), at post run (**Figure 7.12**).

Segment Region of Interest Length Sensitivity

For the anterior and posterior, upper and lower, left and right leg segments, evaluation of the sensitivity of the temperature model to parameter pertubations indicated that maximum temperature outputs had no and small sensitivity at pre and post run (**Table 7.7**).

Table 7.7. Pooled standard deviation of the sensitivity values for the model maximum temperature outputs following changes the segment region of interest length evaluated. Sensitivity catergories were: none (<0.01); small (0.01-0.99); large (1-25) and extreme (>25).

	Anterior		**Posterior**	
	Left Leg	**Right Leg**	**Left Leg**	**Right Leg**
Pre Lower Leg	0.00	0.00	0.02	0.01
Post Lower Leg	0.01	0.00	0.01	0.01
Pre Upper Leg	0.01	0.02	0.04	0.03
Post Upper Leg	0.03	0.03	0.00	0.00

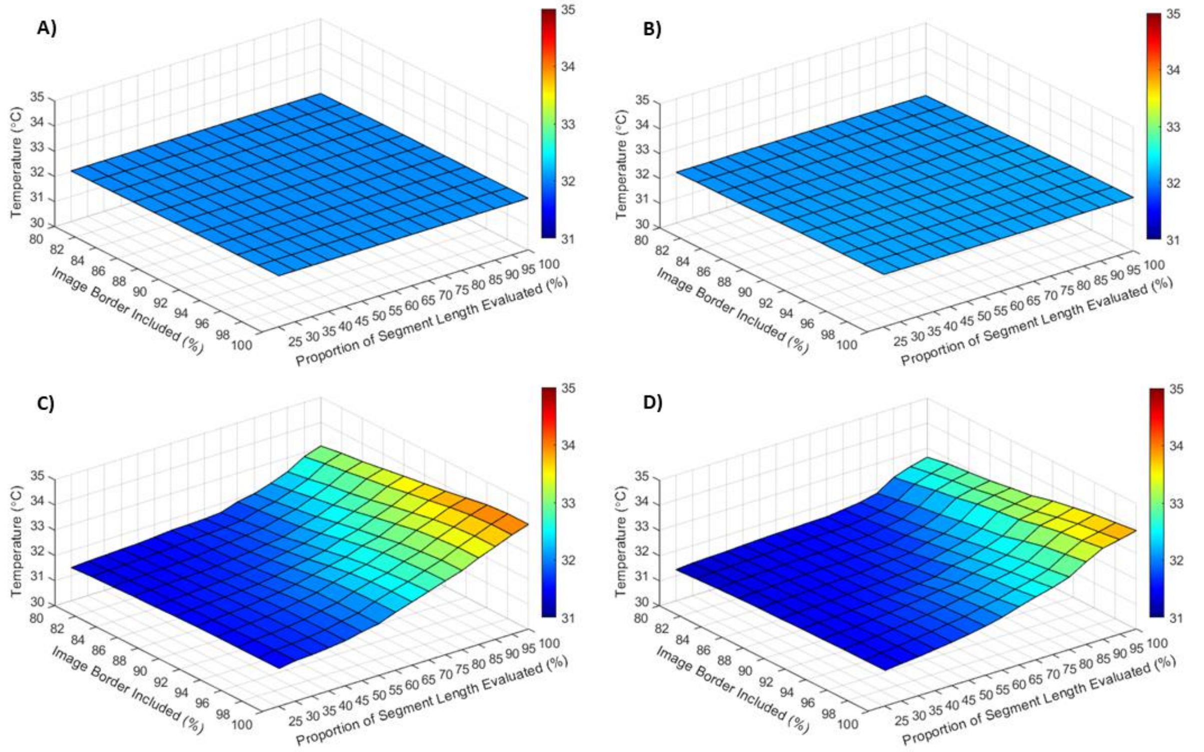


Figure 7.9. Surface plots showing the maximum skin temperature associated with border region size (%) and proportion of segment evaluated increments (%) on the (A) anterior lower left leg, (B) anterior lower right leg, (C) anterior upper left leg and (D) anterior upper right leg, at pre run.

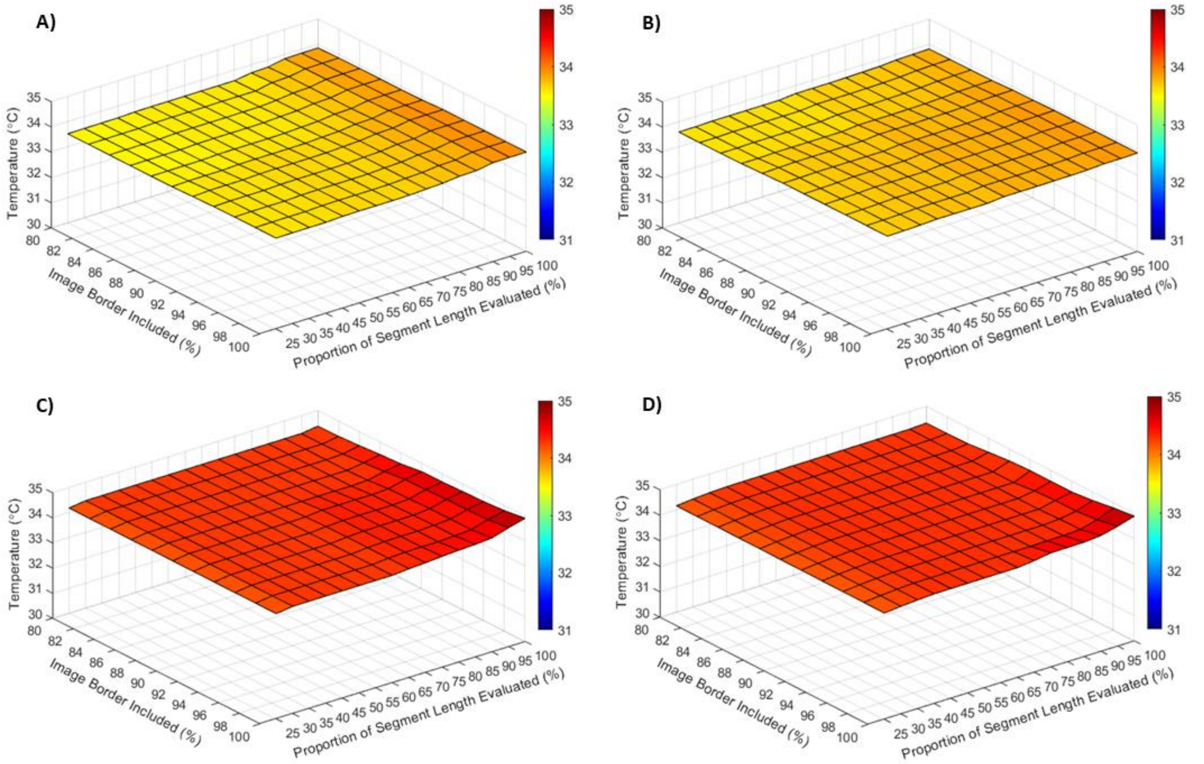


Figure 7.10. Surface plots showing the maximum skin temperature associated with border region size (%) and proportion of segment evaluated increments (%) on the (A) anterior lower left leg, (B) anterior lower right leg, (C) anterior upper left leg and (D) anterior upper right leg, at post run.

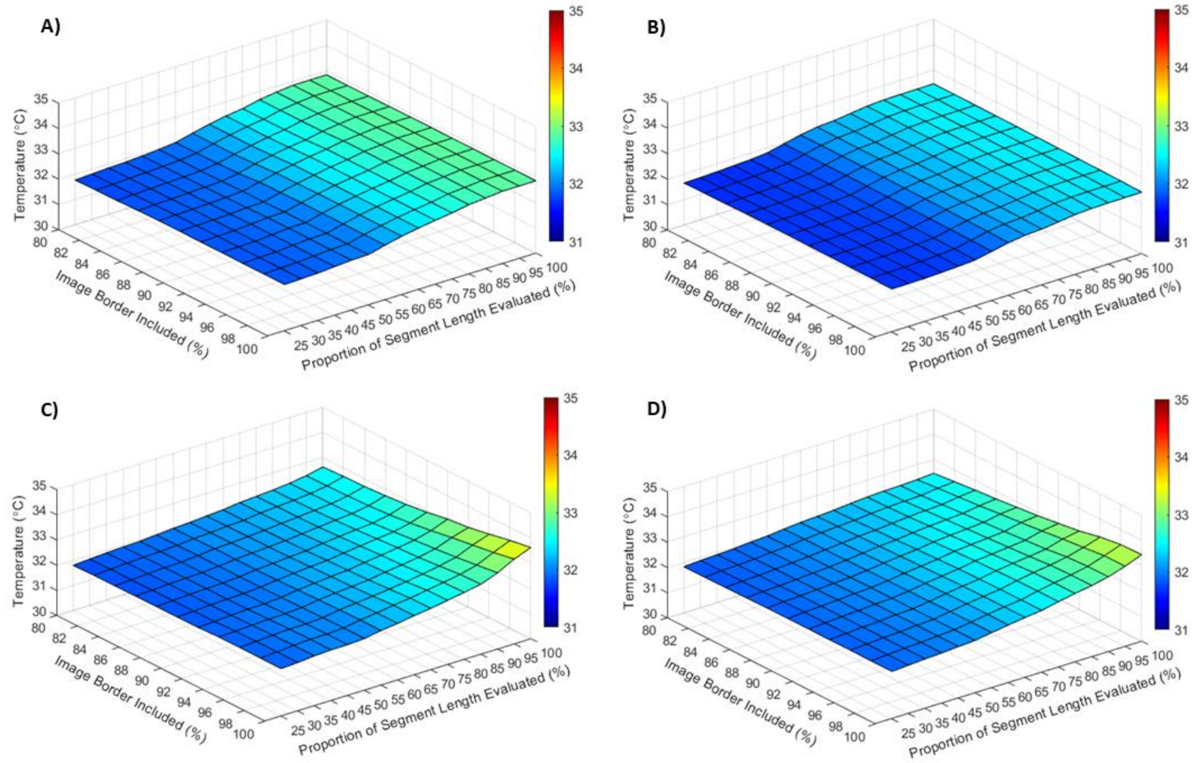


Figure 7.11. Surface plots showing the maximum skin temperature associated with border region size (%) and proportion of segment evaluated increments (%) on the (A) posterior lower left leg, (B) posterior lower right leg, (C) posterior upper left leg and (D) posterior upper right leg, at pre run.

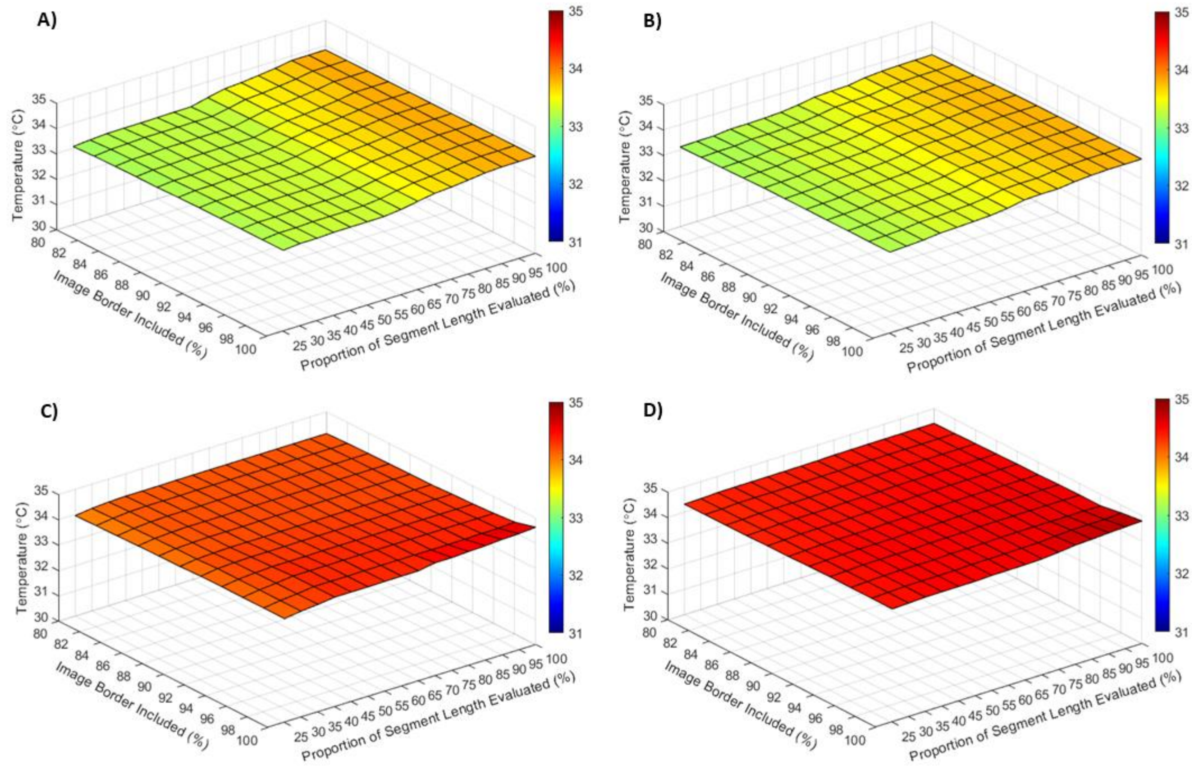


Figure 7.12. Surface plots showing the maximum skin temperature associated with border region size (%) and proportion of segment evaluated increments (%) on the (A) posterior lower left leg, (B) posterior lower right leg, (C) posterior upper left leg and (D) posterior upper right leg, at post run.

Standard Deviation of Segment Temperatures

Border Removal Sensitivity

For the anterior and posterior, upper and lower, left and right leg segments, evaluations of the sensitivity of the standard deviation of segment temperature to parameter pertubations indicated large sensitivity at pre and post run (**Table 7.8**).

Table 7.8. Pooled standard deviation of the sensitivity values for the model standard deviation of temperature outputs following changes to border removal. Sensitivity catergories were: none (<0.01); small (0.01-0.99); large (1-25) and extreme (>25).

	Anterior		Posterior	
	Left Leg	**Right Leg**	**Left Leg**	**Right Leg**
Pre Lower Leg	4.56	5.03	2.39	4.24
Post Lower Leg	1.65	2.16	4.18	3.54
Pre Upper Leg	4.93	5.09	5.77	6.89
Post Upper Leg	1.31	1.77	5.42	5.32

Segment Region of Interest Length Sensitivity

For the anterior and posterior, upper and lower, left and right leg segments, evaluation of the sensitivity of the standard deviation of segment temperature to parameter pertubations indicated small sensitivity at pre and post run, (**Table 7.9**).

Table 7.9. Pooled standard deviation of the sensitivity values for the model standard deviation of temperature outputs following changes to the segment region of interest length evaluated. Sensitivity catergories were: none (<0.01); small (0.01-0.99); large (1-25) and extreme (>25).

	Anterior		Posterior	
	Left Leg	**Right Leg**	**Left Leg**	**Right Leg**
Pre Lower Leg	0.18	0.14	0.34	0.35
Post Lower Leg	0.20	0.12	0.49	0.49
Pre Upper Leg	0.13	0.14	0.14	0.10
Post Upper Leg	0.24	0.37	0.12	0.15

7.5 Discussion and Conclusion

The current study aimed to investigate the effect of different limb analysis region dimensions on reported skin temperatures (mean, maximum, and standard deviation) with primary focus on, 1) dimension reductions using border removal increments, and 2) dimension reductions using region of interest length increments. The key findings of this study revealed that the mean and maximum skin temperature outputs had no to small sensitivity to thermogram border removal and to the reductions of the proportion of segment length for anterior and posterior leg segments, pre- and post-exercise. The standard deviation of temperature had large and small sensitivity for thermogram border removal and to the proportion of segment length evaluated, respectively, for the anterior and posterior leg segments, pre- and post-exercise.

This study identified that the removal of the thermogram border had little effect on the overall mean and maximum temperature for all leg segments at pre- and post-run. However, for specific border removal increments, the magnitude of temperature change was larger than others. For example, for all thermograms the largest change in temperature from the unadjusted border (no border removal) was consistently found when removing the first 2% of the border pixels (0.14 – 0.24°C). Furthermore, following 4% border removal, the change to mean temperature became smaller for all leg segments both pre- and post-run (0.05 - 0.09 °C). The effect of the thermogram border region on skin temperature has not to our knowledge been reported in the published literature, however, it has been proposed that the temperature from the thermogram border may exhibit lower temperatures (Fernández-Cuevas et al., 2015) and this is supported by the findings of the current study. In the published literature, some studies include the thermogram border within their selected regions of interest used to extract temperature data, however, typically any rationale or standardisation to explain the inclusion of the border is not given (Costa et al., 2018; Da Silva et al., 2018; Silva et al., 2017). The border of a thermogram is an important factor which requires consideration when selecting regions of interest for skin temperature analysis. Studies that avoid the thermogram border when selecting regions of interest may overestimate the amount of border to avoid and subsequently exclude important temperature data. This may be more prominent when standard shaped regions of interest are applied which may not follow the body segment under investigation. Conversely, studies which do include the thermogram border when selecting regions of interest may have inaccurate skin temperature outputs due to the cooler temperatures found here.

It could be argued that the mean temperature changes following thermogram border removal were so small as to be trivial. For example, the largest mean temperature change occurred following the initial 2% of border removal from the unaltered border for the anterior and posterior leg segments, pre and post run. These were changes of 0.14 – 0.24°C for the anterior and posterior, left and right legs at pre run, and 0.16 – 0.24°C at post run. However, the temperature increase found in the current study may have implications for injury screening using infrared thermal imaging. Vardasca and colleagues (2012) reported overall skin temperature symmetry differences between left and right sides of the body to be 0.25 ± 0.2°C, in healthy participants which falls within the changes that relate to the perturbations made here. Furthermore, Marins and colleagues (2014) found symmetry differences of less than 0.20°C between the upper and lower, anterior and posterior legs, in soccer players. Detection of injury or disease using infrared thermal imaging relies on skin temperature asymmetries between limbs, and differences above 0.65°C are associated with pathology (Sands et al., 2011). Given that the border can lower the mean temperature of a region of interest by up to 0.24°C, it is therefore important that the appropriate amount of the thermogram border is removed, and that this is consistent between left and right sides of the body. If the border is included within the examined region of interest, the temperature may be inaccurate, and this may influence the identification of injury. As a result, it is important that research considers the change in skin temperature that is caused by border inclusion/exclusion. This study found that including the border of a thermogram reduces the mean skin temperature of the segment region of interest by up to 0.24°C. Therefore, given that the cooler border may reduce the mean temperature output, it may be suggested that the border should be avoided when selecting a segment region of interest.

The present study showed that the border region was cooler, thus, its inclusion within the extracted temperature subsequently reduced mean skin temperature of the segment region of interest. The border region may be cooler due to body hair as it is an avascular substance that elicits a cold appearance on a thermogram (Barnes, 1963). Some researchers have removed hair on the body segment under investigation, however, the timing of hair removal has not been consistent between studies and has ranged from 4 hours to 6 days prior to infrared thermal imaging (Stewart et al., 2020; Formenti et al., 2013; Abate et al., 2013; Merla et al., 2010). In this study, the sensitivity data were pooled, so whilst removing the hair may reduce the border region, and therefore the percentage of the border region that must be removed before consistency is exhibited, this study has demonstrated that for a sample of limbs (legs) with minimal preparation, the temperature stabilises after 4-6% of border removal and therefore the effect of body hair is unlikely to interfere substantially in the results. This may be advantageous, since hair removal has been shown to increase skin temperatures as a result of abrasion and this aspect may not be appropriate for some studies such as work with children, elderly and clinical populations.

In this study, skin temperature was extracted for 5% reductions of the segment region of interest length. The length was reduced both proximally and distally with respect to the midpoint of the segment, where the unaltered segment length was defined by the full area between proximal and distal reference tape markers and with no border removal. This approach allowed investigation of specific areas of the segment which might contribute to hotter or colder skin temperatures. Unsurprisingly, mean skin temperature was largely influenced by the location of hot and cold areas of each segment. For example, at pre run, for the anterior left and right lower legs, the mean skin temperature was highest when only 25% of the segment region of interest length was evaluated, and this related to a heavy emphasis on the belly of the calf muscle where the maximum temperature for the segment was located. For the lower anterior legs, the largest change in mean temperature occurred at 50% of the segment region of interest length evaluated, which included skin temperatures on the most distal aspect of the patella. The patella does not have the same soft tissues and blood flow as muscle; therefore, the skin is cooler in this location as compared to skin located over muscle belly. Consequently, the mean temperature was lower when the maximum segment length (unadjusted) was evaluated due to colder skin temperatures over the patella as compared to when the minimum segment length was evaluated (12.5% distal and 12.5% proximal from the midpoint of the segment), which covered skin temperatures over the gastrocnemius.

Future research must consider the effect of thermal properties of different tissues located within a region of interest to ensure that the region of interest strictly covers the area under investigation.

Typically, investigators use infrared thermal imaging camera manufacturer compatible software to manually draw regions of interest on aspects of the body under investigation and the pixels within the regions of interest are subsequently analysed for temperature data (Drzazga et al., 2018; Merla et al., 2010; Priego Quesada et al., 2015; Tanda, 2016). However, this method is subjective (Maniar et al., 2015) and manually selecting regions of interest may be susceptible to human error and may be difficult to standardise between participants with different sized bodies. The manual selection of regions of interest is controversial as it has been observed that intra-examiner and inter-examiner correlation coefficients using this method are suboptimal due to the ability of the examiner to manually select the region of interest (Ring & Ammer, 2015; Zaproudina et al., 2008). Moreover, this approach typically involves looking at a thermogram to make the judgement about where to draw your region of interest. A review of infrared thermal imaging (Fernández-Cuevas et al., 2015) has recommended the use of automated methodologies to select regions of interest to improve reliability and efficiency, and allow standardised and accurate comparisons of regions of interest and subsequent skin temperatures between studies. The present study used an approach whereby thermally inert markers were placed on specific landmarks, such as the gluteal fold and most proximal aspect of the patella, to standardise segment regions of interest both within and between participants. These markers were subsequently selected using the novel methodology to determine automatic regions of interest of a segment. The use of reference markers applied directly to the participant has previously been performed (Maniar et al., 2015; Selfe et al., 2006). This approach is effective when comparing segment regions of interest between participants as the they are relative to each participants' body regardless of their size or shape, having been obtained by means of anatomical palpation. In this study, once the reference tape markers were selected using the custom written programme, an automated segment region of interest was constructed. The segment region of interest length was identified as 100% of the pixels between the reference tape markers. The segment region of interest width was identified as the most lateral and medial pixels of the segment. The advantage of this approach is that the selected region of interest follows the curvature of the segment, which overcomes the prominent issue of using standard shapes to determine region of interest as has been used in previous research (Marins et al., 2014; Jose Ignacio Priego Quesada et al., 2015). In this study, from 100% of the segment length, the length was subsequently reduced by 5% proximally and distally from the midpoint of the reference tape markers, down to 25% of the available area between the reference tape markers. This approach was also performed for the border of the segment region of interest using 2% reductions from the most medial and lateral pixels of the segment and normalised to the dimensions of the participants leg (width at knee marker). This approach enabled the selection of specific regions of interest on the body which could be replicated within and between participants, ultimately aiding standardisation of the regions of interest. Furthermore, the dependence on the investigator to define the regions of interest with this approach were minimal as the investigator was only required to select the distal and proximal reference markers for each segment. The selection of the regions of interest was therefore more objective and by virtue of automation, more reliable.

The method in this study used to capture thermograms ensured that the total number of pixels was similar between thermograms for each participant, and that the number of pixels that represented the legs in each thermogram was also similar between participants. This approach was quantified as the number of pixels which represented the legs were calculated as a percentage of the total number of pixels of the whole thermogram. The results demonstrated that when divided into left and right leg segments the mean percentage of pixels representing each leg within a thermogram were the same between legs (lower anterior left leg: 25 ± 2% and right leg: 26 ± 2%; lower posterior left leg: 28 ± 2% and right leg: 29 ± 2%; upper anterior left leg: 35 ± 3% and right leg: 35 ± 4%; and upper posterior left leg: 37 ± 5% and right leg: 36 ± 5%, mean and standard deviation). Interestingly, the results show that the number of pixels used for temperature analysis, for each leg segment, was similar between participants and differed between only 2% to 5%. This study is the first to quantify the number of pixels captured for thermograms and to identify the number of pixels that represent the legs on thermograms. Although the number of pixels that represent the legs on each thermogram were similar between participants, ultimately the size of the leg segment influenced the number of pixels that represent the leg. As such, participants with wider sized legs typically had a larger number of pixels that represent them, irrespective of controlling for the proportion of the leg length captured in each thermogram. This is because the length of the leg was the limiting factor regarding where the participant was positioned relative to the camera rather than the leg width. However, by maintaining a camera distance of ~1 m, and making small adjustments to the position for taller or shorter participants, this ensured that the between participant differences in the number of pixels that represented the legs remained minimal. Furthermore, the use of reference markers allowed the standardisation of segment regions of interest within participants. As a result, the same segments of the leg were examined at baseline and post run.

Limitations

In this study, some limitations exist which must be acknowledged. To examine the influence of reducing the thermogram border region and segment length on skin temperature outputs (mean, maximum and standard deviation), a sensitivity analysis was adopted. This analysis was used descriptively to demonstrate the magnitude of skin temperature change following each parameter perturbation (i.e., small, large and extreme sensitivity). However, parametric statistical tests such as t-tests and analysis of variance (ANOVA) could have been applied to examine if the temperature change was statistically 'significant' following a parameter perturbation. The study demonstrated that removing the first 2% of the border region from thermograms resulted in a 0.14-0.23°C increase in skin temperature, and such parametric tests would confirm this did not occur by chance.

In conclusion, this study examined the sensitivity of skin temperature measurements to changes to the dimensions of leg segment regions of interest, with consideration for the size of the border removal region and the proportion of the segment region of interest length. Mean and maximum skin temperatures had no to small sensitivity to reductions of the border region and the proportion of the segment region on interest length, whilst the standard deviation of skin temperature had large sensitivity as hot and cold spots across the leg influenced the skin temperature. The effect on skin temperature measurements by varying the dimensions of the region of interest, although small, may under some circumstances have statistical or clinical relevance. Furthermore, this study highlighted where temperature outputs were most sensitive to the dimensional changes to the region of interest. The results of this study indicate that investigators should give careful consideration to the proportion of the border region included as well as the proportion of the segment region of interest length when selecting regions of interest for analysing skin temperatures using infrared thermal imaging.

Chapter 8: Effect of made-to-measure compression garments on thermal responses and perception of comfort before and after running exercise.

8.1 Rationale

The previous chapter developed an automated methodology of selecting regions of interest on thermograms for skin temperature extraction and analysis. The results of the previous chapter showed that skin temperature was reduced by up to 0.24°C when the thermogram border was included in the analysis and that temperature within a region of interest was influenced by underlying tissues. The findings observed in the previous chapter were ultimately used to define appropriate segment regions of interest within the current chapter. A small number of studies have investigated the effect of wearing compression garments during exercise on thermoregulation (Barwood et al., 2013; Goh et al., 2011; Priego Quesada et al., 2015). However, none of these previous research studies involved made-to-measure compression garments. Furthermore, the effect of varying the pressure profiles (peak pressure and pressure gradient) elicited by compression garments on thermoregulation and comfort perception has not been thoroughly investigated. Therefore, this chapter aimed to examine the effect of wearing made-to-measure compression garments, with different pressure profiles, on thermal responses and comfort perception before and after running exercise.

8.2 Introduction

Compression garments are used in clinical practice as a conservative treatment for various venous disorders such as reticular veins, varicose veins, oedema, and venous ulcers (Xiong & Tao, 2018). The beneficial application of compression garments within clinical practice has attracted attention, and as a result many sporting participants and coaches perceive the wearing of compression garments as a possible ergogenic aid for exercise performance and recovery. Athletes such as triathletes, cyclists and runners commonly wear compression garments (Sperlich et al., 2010). In addition, compression garments are worn in many winter sports such as speed skating, bobsleigh, skeleton, alpine and cross-country skiing (Yang et al., 2020). Although a layer of clothing, such as would be provided by a compression garment, may be beneficial for regulating body temperature in cold environments, their use within winter sports is mostly attributed to the enhancement of aerodynamics (Yang et al., 2020). The effect of wearing compression garments on exercise performance and recovery has been widely investigated. However, inconsistent findings between studies question the efficacy of such garments. Some studies have shown beneficial effects on recovery parameters (Kraemer et al., 2010; Rugg & Sternlicht, 2013; Upton et al., 2017) whereas others have found no effect (Cerqueira et al., 2015; Govus et al., 2018; Trenell et al., 2006). Similarly, some studies have shown beneficial effects on exercise performance parameters (Broatch et al., 2017; Brophy-Williams et al., 2018; de Glanville & Hamlin, 2012), whereas others have found no effect (Del Coso et al., 2014; Rider et al., 2014; Scanlan et al., 2008). The inconsistent findings between studies may be a result of the myriad differences in the study design, type of compression garment, the elicited pressure of the garment, the duration of wear, the study population and the type of exercise performed, in the many studies that have investigated the effect of wearing compression garments on exercise performance and recovery (MacRae et al., 2011).

Wearing compression garments is likely to influence heat exchange between the body and the environment (MacRae et al., 2011). The material of which a compression garment is composed may create an insulative layer next to the body, and a garment may also impede sweat evaporation; consequently optimal heat transfer is prevented and the regulation of 'core' body temperature will be impaired (Corbett et al., 2015; Gavin, 2003). During exercise, evaporation is a vital mechanism for transferring heat away from the body and clothing that provides minimal resistance to evaporation may be beneficial (Gavin, 2003). To provide optimal comfort and efficient temperature regulation, sweat on the skin or the inner layer of clothing must be able to transfer to the outer layer of the clothing and subsequently evaporate (water vapor permeability) (Zhuang et al., 2002). The water vapor permeability of a clothing material is a crucial factor that helps maintain the human body at thermal equilibrium. Given that the evaporation of sweat during exercise is the primary mechanism for heat loss, the evaporative resistance of a clothing material can have a significant impact on thermoregulatory homeostasis (Huang, 2006). Some compression garment manufacturers claim their garments elicit moisture wicking which, as well as keeping the wearer dry, may ensure that any impairment of heat loss via sweating, and by implication thermoregulation, is minimised. However, it has been shown that wearing compression garments during exercise at ambient temperatures increases skin temperature in the areas covered by the garment (16.0 – 23.7°C) (Duffield et al., 2008; Houghton et al., 2009; Priego Quesada et al., 2015). Goh and colleagues (2011) investigated the effect of wearing a lower body standard sized compression garment on thermal responses and running performance in both hot and cold conditions. Participants ran on a treadmill for 20-min at an intensity equivalent to their predetermined ventilatory threshold (submaximal), followed by a run to exhaustion at an intensity equivalent to that which elicited their individual maximal oxygen uptake. Participants performed the exercise in four separate conditions: 32°C with compression garment; 32°C without compression garment; 10°C with compression garment; and 10°C without compression garment. The authors reported that time to exhaustion was not different between garment conditions in the cold and hot environments ($P > 0.05$). In the cold environment, skin temperature of the thigh and calf, measured using skin thermistors, was higher in the compression garment condition compared with no garment ($P < 0.05$). However, this response was not replicated in the hot environment ($P > 0.05$). The study concluded that lower body compression garments did not reduce running performance or negatively influence thermoregulation in hot environments. While the manufacturers of sports clothing do not set out to create insulative layers, such clothing may create excessive thermal insulation, which may subsequently impair exercise performance (Brownlie et al., 1987; Gavin, 2003). However, as the discussion of the study of Goh and colleagues (2011) above shows, this is not necessarily the case.

To date, the published literature investigating the effect of wearing compression garments on thermal responses during exercise have used standard sized garments (Barwood et al., 2013; Goh et al., 2011; Leoz-Abaurrea et al., 2019). Standard sized compression garments may provide an inconsistent fit between participants, meaning the levels of pressure produced by the garments may differ, even if participants fit within the same sizing category (Brophy-Williams et al., 2015; Hill et al., 2015). If a compression garment does not fit correctly, this may prevent tight fitting which subsequently may cause wrinkling and folds when wearing the garment. The wrinkling may have consequences on thermoregulation as sweat may not be able to wick through the garment and evaporate to assist heat transfer as easily as it would if the garment was fitted correctly. As a result, it may be beneficial to use made-to-measure compression garments, designed according to the geometry of each participants' body to provide an optimal fit which is consistent between participants. Moreover, the elicited pressure of a compression garment may influence heat transfer. Heat transfer through blood flow (i.e., vascular convective heat transfer) is an important heat transfer pathway and is particularly important when metabolic heat production increases during exercise (González-Alonso, 2012). Heat is transferred from the exercising muscles to the surrounding skin via superficial blood circulation. Compression garments may increase blood flow during exercise; however, the optimal levels of pressure and pressure gradient to encourage this are unknown (MacRae et al., 2011). As a result, wearing compression garments may influence heat transfer at the skin through increased superficial blood flow. Therefore, it would be beneficial to examine and clarify the effect on thermal responses of wearing made-to-measure compression garments that elicit different pressure profiles, defined as the peak pressure and pressure gradient of the garment.

In addition to the thermoregulatory responses, the perceived comfort of wearing a compression garment also warrants investigation. It is possible that if a compression garment is perceived to be uncomfortable by the wearer this may lead to a negative impact on exercise performance. With clothing, there are various components which interact with the body such as material properties, design and fit, elicited pressure, subjective sensations of temperature and wetness (breathability), which ultimately effect wearer comfort (Raccuglia et al., 2018; Xiong & Tao, 2018). Few studies have investigated comfort outcomes when wearing compression garments and the findings from the research that has been conducted appears equivocal. Ali and colleagues (2010) investigated three parameters of comfort including general comfort, tightness, and pain perception in differently pressured compression garments (stockings), before and after a bout of exercise. The compression garment conditions were control (ankle: 4 ± 1; calf 4 ± 1 mmHg – CON), low compression (ankle: 11 ± 2; calf 8 ± 1 mmHg – LO-GCS) and high compression (ankle: 26 ± 3; calf 15 ± 2 mmHg – HI-GCS). Participants rated their perception of garment comfort, tightness, and associated pain on three Likert scales which ranged from 1 (uncomfortable, loose/slack, no pain) to 10 (very comfortable, very tight, very painful) pre and post a

40-minute treadmill run at 80 ± 5 % VO_{2max}. The results showed that general compression garment comfort was significantly greater in the CON compared to the HI-GCS, at pre and post run ($P < 0.05$). Perception of tightness was significantly greater in the HI-GCS compared to CON and LO-GCS at pre and post run, ($P < 0.05$). Also, HI-GCS were rated as inducing the most pain when worn compared to the CON and LO-GCS, at pre and post run ($P < 0.05$). The authors also reported that pain increased for some participants during the run, which, was described as a 'dull ache' and progressed into 'numbness and pins and needles'. This sensation may have been caused by excessive compression which can lead to restricted blood flow around the foot causing discomfort (Lewis et al., 1976). Faulkner and colleagues (2013) investigated perceived tightness and comfort of different compression garments pre and post running exercise. The compression garment conditions were long length garment (ankle to hip), short length garment combination (knee to hip and calf sleeves) and a control condition (loose shorts). Compression was assessed at 8 anatomical landmarks (a) achilles, (b) musculotendinous junction of gastrocnemius, (c) medial gastrocnemius, (d) lateral gastrocnemius, (e) mid-iliotibial band, (f) mid-quadriceps, (g) tensor fascia latae, and (h) mid-gluteal. Mean applied pressure was 8.0, 17.9 and 5.7 mmHg for the long length, short length and control garment respectively. Participants rated their perception of garment tightness and comfort using two visual analogue scales ranging from 0 (uncomfortable, and extremely slack/loose) to 10 (very comfortable, and extremely tight) at pre-exercise, post–warm-up, post 6 x 400m run performance, 4-min post exercise and post warm-down. The results showed no difference of perceived tightness and comfort between the garment conditions, at any time point ($P > 0.05$). The ambiguity of findings in the research may to be caused by the type of compression garments used and the amount of pressure elicited. Only a small number of comfort parameters were measured within these studies, therefore, it may be beneficial to assess more specific comfort parameters to understand other factors which may influence compression garment comfort such as thermal comfort perception. Given that compression garments may change thermoregulation, it may be beneficial to investigate the relationship between perception of comfort and thermal responses when wearing compression garments during exercise.

This study had two aims: 1) to examine the effect of wearing made-to-measure compression garments, with different pressure profiles, on leg skin temperature before and after exercise; and 2) to examine the perception of comfort when wearing made-to-measure compression garments, with different pressure profiles, before and after exercise.

8.3 Methodology

8.3.1 Participants

Ten, healthy males (age 23.5 ± 2.8 years, stature 181.9 ± 4.8 cm, body mass 76.2 ± 5.3 kg) volunteered and provided informed consent to participate in the study. All participants completed a health screen questionnaire before involvement in the study, to ensure they had no medical or other conditions that would have prevented them from taking part. Participants were instructed to refrain from strenuous exercise and alcohol consumption 24 hours prior to the experimental trials and to avoid caffeine consumption on the day of an experimental trial, whilst attending the laboratory at least 3 hours postprandial. Participants were also asked to limit their exposure to UV radiation, to refrain from the application of body lotions and creams, and to avoid massage, electrotherapy, ultrasound, cryotherapy and excessive heat or cold exposure prior to trials. The study was approved by a University Ethics Committee, (Nottingham Trent University Ethical Committee Application for Human Biological Investigation reference number: 560).

8.3.2 Experimental Design

Participants visited the laboratory on five occasions. The first visit was a familiarisation trial, which consisted of a baseline three-dimensional (3D) scan that was used to support the manufacture of the made-to-measure compression garments for each participant. Also, participants were familiarised with the infrared thermal imaging procedures and comfort questionnaire. Finally, participants performed a familiarisation of the 30-minute run to determine a comfortable running speed for the subsequent experimental trials. For the experimental trials, participants performed the 30-minute run wearing made-to-measure compression garments which elicited different pressure profiles, defined as the peak pressure and pressure gradient from the distal to the proximal end of both legs. The order of the compression garments was randomised, and participants were blinded to the garment conditions. An experimental trial was performed as follows: participants dressed into the compression garment and the pressure profile of the garment was measured on both legs, this assessment also served as a room temperature acclimation period (~20-min) prior to thermal imaging. Following the pressure profile assessment, participants completed the comfort questionnaire and baseline thermal images were recorded. Participants then performed a 5-minute warm-up run and after the warm-up, thermal images were recorded for a second time. The 30-minute run was then performed, rating of perceived exertion (RPE) and thermal sensation was recorded during the run. Following the run, the comfort questionnaire was completed, and thermal images were recorded. Experimental trials were separated by a minimum of 48 hours. Participants were instructed to wear the same footwear for each trial and performed the 30-minute run topless. Trials were performed at the same time of day and in similar environmental conditions; 20.5 ± 0.8°C and 36.7 ± 5.3% relative humidity.

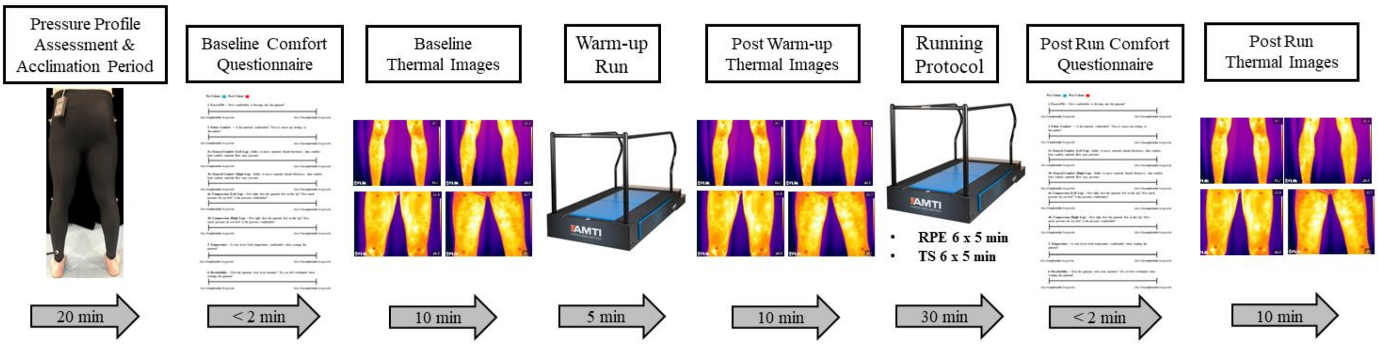


Figure 8.1. Schematic of the study protocols including the acclimation period, pressure profile assessment, comfort questionnaire, thermal imaging, warm-up run and 30-minute run.

8.3.3 Compression Garments and 3D Scan

A detailed description of the Artec Eva 3D scanner, scanning procedure and compression garments is provided in the General Methodology (*Section 3.5.6* and *Section 3.5.7*).

Briefly, this study used made-to-measure, full leg compression tights (Kurio 3D Compression Ltd, Nottingham, UK) which were fitted from the malleolus to the iliac crest. An Artec Eva 3D scanner (Artec Group, Luxembourg, Luxembourg) was used to capture a lower-body 3D scan performed during the familiarisation trial and used by the company to support the manufacture of the compression garments. For each trial, the compression garment used elicited a different pressure profile. The made-to-measure compression garment conditions were: 1) control garment, which was designed to elicit pressure below clinical standards (< 14 mmHg); 2) high gradient garment which was designed to elicit pressure within clinical standards (14 – 35 mmHg) and to include a steep pressure gradient; 3) asymmetrical garment which was designed to elicit control garment conditions in the left leg and high gradient garment conditions in the right leg; and 4) medium gradient garment which was designed to elicit pressure within clinical standards (14 – 35 mmHg) and to include a shallower pressure gradient than the high gradient garment. Peak pressure of the compression garments used in this study was located at the ankle and the pressure classifications corresponded to UK clinical compression standards (BS-6612; 1985): Class one (14 – 17 mmHg), two (18 – 24 mmHg) and three (25 – 35 mmHg).

8.3.4 Pressure Profile Assessment

A detailed description of the pressure monitoring device and the measurement procedure is provided in the General Methodology (*Section 3.5.2*).

Briefly, the pressure profiles of the compression garments were assessed using a Kikuhime pressure-monitoring device (MediGroup, Melbourne, Australia). Pressure elicited by the garments was measured at multiple sites on the mid-line of the posterior surface of each leg. The location of the pressure sensor measurement sites was acquired simultaneously with pressure measurements using a thirteen-camera 3D motion capture system (Qualisys AB, Göteborg, Sweden) sampling at 100 Hz. Eight reflective markers were applied to the legs, using bi-adhesive tape, to represent the line of the leg. Four markers were placed on each leg at the following landmarks: 1) the lateral malleolus (ankle); 2) the lateral femoral condyle (knee); 3) the greater trochanter; and 4) the iliac crest. The anatomical marker locations and marker placement was performed by a trained anthropometrist (ISAK level 1). The sensor of the pressure monitoring device was placed between the garment and skin interface starting from 5 cm proximal to the ankle malleolus and pulled up the posterior of each leg in approximately 5 cm increments. To obtain a precise location for the pressure measurements, a reflective wand marker was briefly placed on the pressure measurement site before reading the pressure. The modelled peak pressure at the ankle and pressure gradient of each compression garment for the left and right legs are displayed in **Table 8.1** and **Table 8.2** respectively. Scatter plots of the pooled pressure profile data for each garment are presented in **Appendix 7**.

Table 8.1. Peak pressure located at the ankle in the control, asymmetrical, high gradient, and medium gradient compression garments, measured on the posterior left and right legs (mean ± standard deviation).

	Control	Asymmetrical	High Gradient	Medium Gradient
Left Leg (mmHg)	13.5 ± 2.3	12.7 ± 2.5	27.7 ± 2.2	25.8 ± 2.4
Right Leg (mmHg)	12.9 ± 2.6	26.3 ± 3.4	27.5 ± 1.6	26.3 ± 3.5

Table 8.2. Pressure gradient from the ankle to the gluteal fold in the control, asymmetrical, high gradient, and medium gradient compression garments, measured on the posterior left and right legs (mean ± standard deviation).

	Control	Asymmetrical	High Gradient	Medium Gradient
Left Leg (mmHg)	-8.9 ± 3.5	-7.5 ± 3.9	-25.0 ± 4.1	-18.1 ± 5.0
Right Leg (mmHg)	-7.4 ± 3.0	-21.9 ± 3.2	-22.3 ± 3.6	-16.6 ± 4.9

8.3.5 Skin Temperature and Thermal Imaging

The measurement of skin temperature in this study was identical to that of Chapter 7. A detailed description of measuring skin temperature using infrared thermal imaging is provided in the General Methodology (*Section 3.5.3*).

Briefly, skin temperature was measured using a FLIR T1020 infrared thermal imaging camera (FLIR Systems Inc., Wilsonville, Oregon, USA). Thermograms of the anterior and posterior, upper and lower leg segments were captured on three occasions: 1) baseline; 2) post warm up; and 3) post 30-minute run. Prior to thermal imaging, 1 x 1 cm thermally inert tape markers were placed at six specific locations on the anterior and posterior of the left and right legs and marked with indelible ink and were used to standardise regions of interest for temperature extraction and analysis. The locations were: (A) 5 cm proximal from the centre of the ankle malleolus (anterior); (B) the most proximal aspect of the patella (anterior); (C) parallel to the gluteal fold (anterior); (D) 5 cm proximal from the centre of the ankle malleolus (posterior); (E) parallel to the most proximal aspect of the patella (posterior); (F) on the gluteal fold (posterior). For each thermogram, participants stood with their legs shoulder width apart with relaxed musculature and their arms crossed over their chest. Prior to thermal imaging, objective parameters of reflective temperature, emissivity, ambient temperature and humidity were input into thermal camera settings (ISO, 2008). Temperature data was extracted from each leg segment region of interest using a written MATLAB® program (MathWorks Inc., MA, USA). The program digitised the tape reference marker positions to subsequently determine the region of interest for the anterior and posterior, upper and lower, left and right legs. Results from the sensitivity analysis performed in Chapter 7 suggested that 4% of pixels from the region of interest border (defined as the cooler temperature which surrounds an imaged object) should be removed, and this guideline was used in this study and standardised for all thermograms. A border removal of less than 4% would likely include the cooler border which was shown to reduce mean temperature in Chapter 7. A border removal of greater than 4% may exclude required temperature data. For each segment region of interest, all the area between the most distal and proximal reference markers (100%) was used for temperature extraction (**Figure 8.2**).

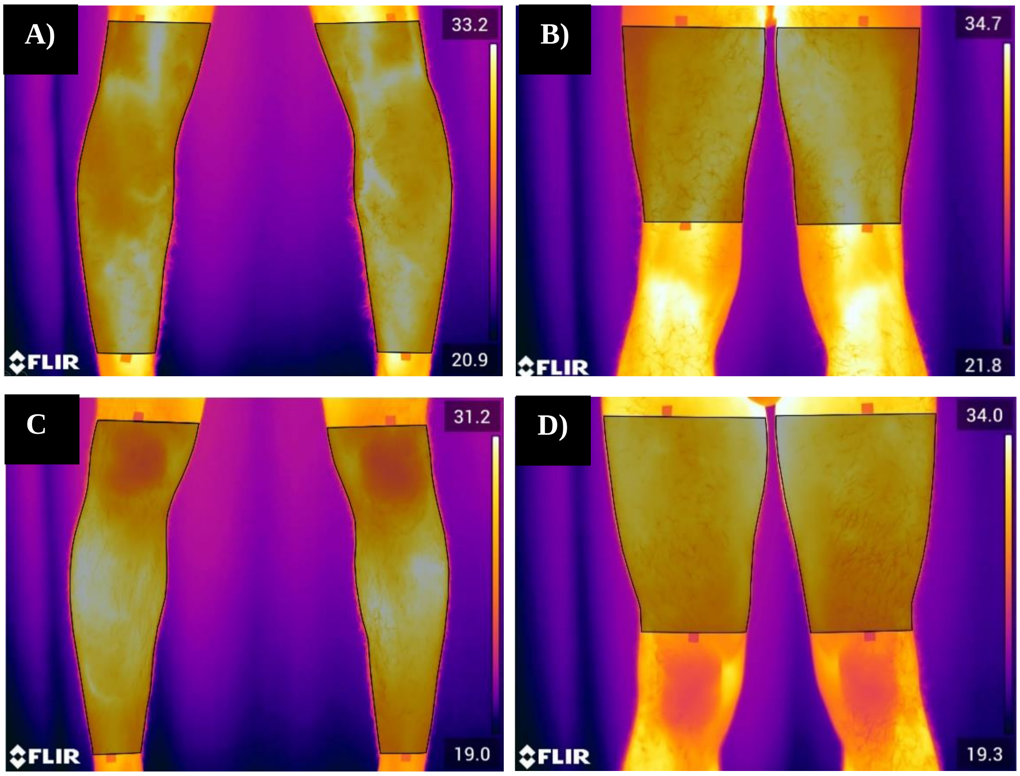


Figure 8.2. Examples of the regions of interest used for extracting temperature data, which are defined by 100% of the area between the distal and proximal reference tape markers with a 4% border removal. The regions of interest were located over the lower posterior legs (A), upper posterior legs (B), lower anterior legs (C) and upper anterior legs (D).

8.3.6 Running Protocol

Participants performed a 30-minute run on an instrumented treadmill (AMTI, Watertown, MA, USA). Participants were instructed to run at a self-selected 'comfortable' running speed, which corresponded with an RPE of 11 or 12, an intensity less than "somewhat hard" (13) (Borg, 1982). The running speed was determined during the familiarisation trial and once the participant selected their running speed, it remained identical for the remaining experimental trials. The running speed during the study was 2.5 ± 0.3 m/s (mean ± standard deviation).

8.3.7 Rating of Perceived Exertion and Thermal Sensation

Rating of perceived exertion was recorded using a visual scale (6 [no exertion] to 20 [maximal exertion]) (Borg, 1982). Thermal sensation of the lower body was recorded using a visual scale (0 [unbearably cold] to 8 [unbearably hot]). Rating of perceived exertion and thermal sensation were recorded at rest and at six, five-minute intervals during the 30-minute run. The scales were positioned in the view of the participant, and they verbally stated their RPE and thermal sensation.

8.3.8 Comfort Questionnaire

A comfort questionnaire was used to examine participants' perception of comfort for the following variables: material comfort, left leg general comfort, right leg general comfort, left leg compression comfort, right leg compression comfort, temperature comfort and breathability comfort. The comfort questionnaire consisted of seven, 15 cm visual analogue scales which corresponded to each comfort variable. The visual analogue scales were adapted from Mündermann and colleagues (2002). The phrase "Most Uncomfortable Imaginable" was located at the left end and "Most Comfortable Imaginable" located at the right end of each scale (**Appendix 8**). Material, temperature, and breathability comfort variables were assessed for the whole garment (both legs). General comfort and compression comfort were assessed for the left and right legs separately to investigate whether participants perceived differences between legs in the asymmetrical garment. Investigators gave verbal instructions that described each comfort variable to ensure participants understood each visual analogue scale. In addition, written cues were also included on each visual analogue scale. This style of visual analogue scale has been previously used to assess compression garment comfort variables (Lucas-Cuevas et al., 2015). Participants completed the comfort questionnaire whilst wearing the compression garments pre and post the 30-minute run. The participants were instructed to draw a vertical line on each visual analogue scale to indicate their perception of comfort for each comfort variable. The same comfort questionnaire was used at pre and post the 30-minute run. Participants completed the comfort questionnaire with blue ink pre-run and with red ink post the 30-minute run to distinguish between the times. Each vertical line was measured in centimetres using a ruler from left to right on each visual analogue scale, thus, a larger value corresponded with a superior comfort. Each measured value was subsequently used for the data analysis.

8.3.9 Statistical Analysis

All statistical analysis was performed using SPSS statistical software (SPSS Statistics IBM, Version 26). A two-way repeated measured ANOVA (time*condition) was used to examine for mean and maximum skin temperature differences for the anterior and posterior leg segments of the left and right legs, between the four compression garment conditions. A two-way repeated measures ANOVA (time*condition) was used to examine differences for comfort variables, RPE and thermal sensation between the four compression garment conditions. Mauchly’s test of sphericity was applied to ascertain homogeneity of variance amongst the four compression garment conditions. Where the assumption of sphericity was violated, the Greenhouse-Geisser correction was applied. Significant differences were further analysed using a Bonferroni post-hoc test. A significance level of $P < 0.05$ was applied throughout. Effect sizes were calculated as partial eta squared (ηp^2) and interpreted as 0.01 = small, 0.06 = medium and 0.14 = large (Cohen, 1988).

8.4 Results

Pixel Contribution of Leg Segments for Thermograms

The number of pixels as a percentage of the full thermogram resolution, which represented the legs on each thermogram was similar between compression garment conditions at baseline, post warm-up and post run. At baseline, the percentage of pixels which represented temperature data of the legs relative to the total number of pixels of the thermogram ranged between 58 – 60%, 59 – 60%, 72 - 76%

and 73 – 78% for the lower anterior, lower posterior, upper anterior and upper posterior legs respectively, for all four compression garment conditions (**Table 8.3**).

Table 8.3. Displays the percentage of pixels at baseline that represent the legs relative to the total number of pixels on a thermogram for the lower anterior, lower posterior, upper anterior and upper posterior leg segment thermograms in all four compression garment conditions (mean ± standard deviation).

	Control	Asymmetrical	High Gradient	Medium Gradient
Lower Anterior (%)	58 ± 3	59 ± 2	60 ± 4	59 ± 5
Lower Posterior (%)	59 ± 3	60 ± 4	59 ± 4	60 ± 3
Upper Anterior (%)	72 ± 7	73 ± 8	76 ± 4	76 ± 9
Upper Posterior (%)	76 ± 9	73 ± 8	78 ± 10	73 ± 8

At post warm-up, the percentage of pixels which represented temperature data of the legs relative to the total number of pixels of the thermogram ranged between 57 – 58%, 58 – 60%, 73 - 75% and 75 – 78% for the lower anterior, lower posterior, upper anterior and upper posterior legs respectively, for all four compression garment conditions (**Table 8.4**).

Table 8.4. Displays the percentage of pixels at post warm-up that represent the legs relative to the total number of pixels on a thermogram for the lower anterior, lower posterior, upper anterior and upper posterior leg segment thermograms in all four compression garment conditions (mean ± standard deviation).

	Control	Asymmetrical	High Gradient	Medium Gradient
Lower Anterior (%)	58 ± 3	57 ± 5	57 ± 5	58 ± 3
Lower Posterior (%)	58 ± 3	60 ± 3	60 ± 3	60 ± 3
Upper Anterior (%)	75 ± 9	73 ± 6	75 ± 10	73 ± 9
Upper Posterior (%)	75 ± 9	75 ± 6	78 ± 9	76 ± 8

At post run, the percentage of pixels which represented temperature data of the legs relative to the total number of pixels of the thermogram ranged between 52 – 56%, 57 – 58%, 70 - 73% and 71 – 73% for the lower anterior, lower posterior, upper anterior and upper posterior legs respectively, for all four compression garment conditions (**Table 8.5**).

Table 8.5. Displays the percentage of pixels at post run that represent the legs relative to the total number of pixels on a thermogram for the lower anterior, lower posterior, upper anterior and upper posterior leg segment thermograms in all four compression garment conditions (mean ± standard deviation).

	Control	Asymmetrical	High Gradient	Medium Gradient
Lower Anterior (%)	52 ± 3	56 ± 5	55 ± 3	55 ± 4
Lower Posterior (%)	57 ± 3	58 ± 5	58 ± 3	58 ± 2
Upper Anterior (%)	70 ± 7	72 ± 8	73 ± 7	73 ± 7
Upper Posterior (%)	73 ± 9	72 ± 7	73 ± 8	71 ± 6

Maximum Temperature

Lower Anterior Legs

With respect to maximum skin temperature of the lower anterior left leg, there was no effect of condition [$F(3, 27) = .119$, $P = 0.948$, $\eta p^2 = .013$]. There was a time effect [$F(2, 18) = 25.207$, $P = 0.001$, $\eta p^2 = .737$]. Pairwise comparisons showed that maximum skin temperature was higher at post run compared to baseline and post warm-up ($P = 0.001$ and $P = 0.001$, respectively). There was no interaction effect [$F(6, 54) = 2.126$, $P = 0.065$, $\eta p^2 = .191$] (**Figure 8.3**).

With respect to maximum skin temperature of the lower anterior right leg, there was no effect of condition [$F(3, 27) = .218$, $P = 0.883$, $\eta p^2 = .024$]. There was a time effect [$F(2, 18) = 26.164$, $P = 0.001$, $\eta p^2 = .744$]. Pairwise comparisons showed that maximum skin temperature was higher at post run compared to baseline and post warm-up ($P = 0.001$ and $P = 0.001$, respectively). There was no interaction effect [$F(6, 54) = 2.150$, $P = 0.062$, $\eta p^2 = .193$] (**Figure 8.3**).

Upper Anterior Legs

With respect to maximum skin temperature of the upper anterior left leg, there was no effect of condition [$F(3, 27) = .839$, $P = 0.484$, $\eta p^2 = .085$]. There was a time effect [$F(2, 18) = 10.365$, $P = 0.001$, $\eta p^2 = .535$]. Pairwise comparisons showed that maximum skin temperature was higher at post run compared to baseline and post warm-up ($P = 0.018$ and $P = 0.003$, respectively). There was no interaction effect [$F(6, 54) = .738$, $P = 0.621$, $\eta p^2 = .076$] (**Figure 8.3**).

With respect to maximum skin temperature of the upper anterior right leg, there was no effect of condition [$F(3, 27) = .772$, $P = 0.520$, $\eta p^2 = .079$]. There was a time effect [$F(2, 18) = 11.311$, $P =$

0.001, ηp^2 = .557]. Pairwise comparisons showed that maximum skin temperature was higher at post run compared to baseline and post warm-up (P = 0.002 and P = 0.007, respectively). There was no interaction effect [F(6, 54) = 1.243, P = 0.299, ηp^2 = .121] (**Figure 8.3**).

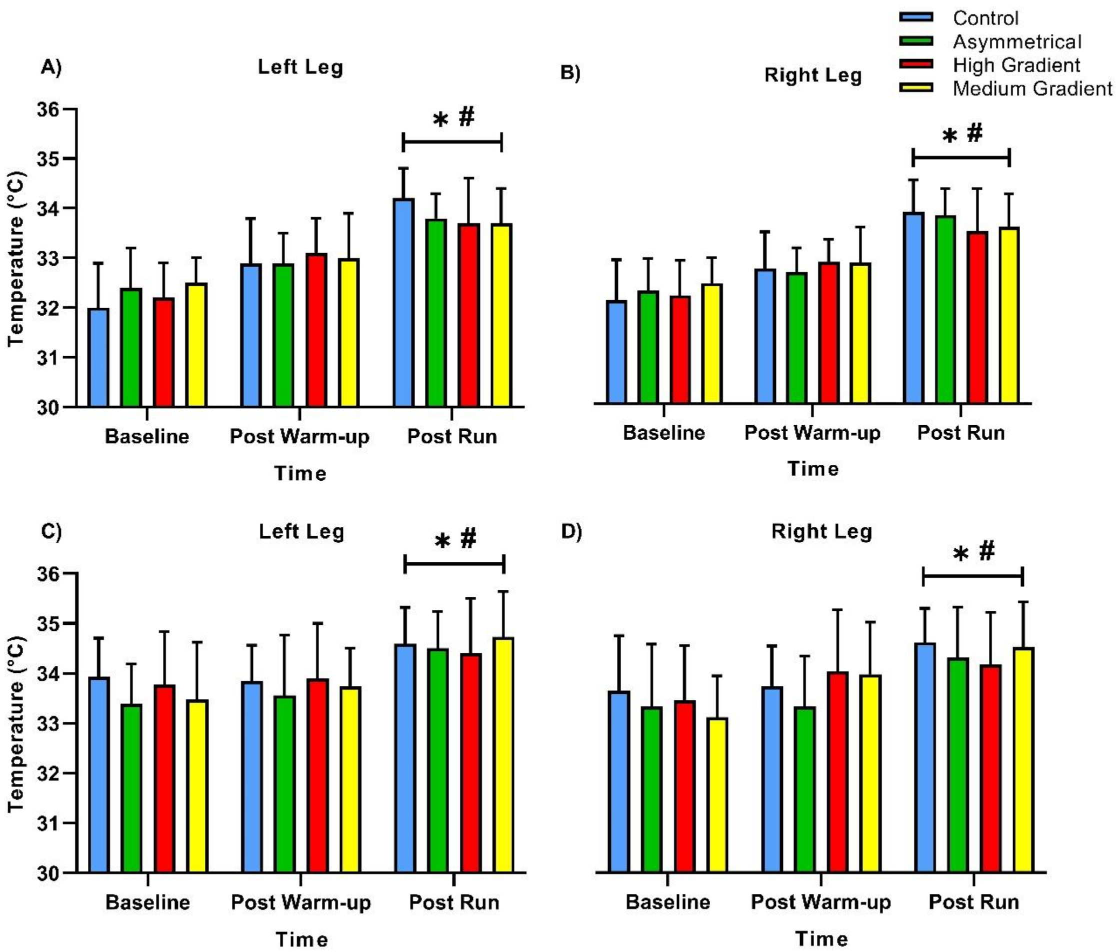


Figure 8.3. Maximum skin temperature for the lower anterior left (A) and right (B) legs and for the upper anterior left (C) and right (D) legs at baseline, post warm-up and post the 30-minute run in the control, asymmetrical, high gradient and medium gradient garment conditions (mean ± standard deviation). * significant time effect compared to baseline, # significant time effect compared to post warm-up (P < 0.05).

Lower Posterior Legs

With respect to maximum skin temperature of the lower posterior left leg, there was no effect of condition [F(3, 27) = .462, P = 0.711, ηp^2 = .049]. There was a time effect [F(2, 18) = 22.241, P = 0.001, ηp^2 = .712]. Pairwise comparisons showed that maximum skin temperature was higher at post run compared to baseline and post warm-up (P = 0.002 and P = 0.009, respectively) and was higher at post warm-up compared to baseline (P = 0.007). There was no interaction effect [$F(6, 54) = .440$, P = 0.849, $\eta p^2 = .046$] (**Figure 8.4)**.

With respect to maximum skin temperature of the lower posterior right leg, there was no effect of condition [$F(3, 27) = .844$, P = 0.482, $\eta p^2 = .086$]. There was a time effect [$F(2, 18) = 19.135$, P = 0.001, $\eta p^2 = .680$]. Pairwise comparisons showed that maximum skin temperature was higher at post run compared to baseline and post warm-up (P = 0.003 and P = 0.011, respectively) and was higher at post warm-up compared to baseline (P = 0.015). There was no interaction effect [$F(6, 54) = .744$, P = 0.616, $\eta p^2 = .076$] (**Figure 8.4)**.

Upper Posterior Legs

With respect to maximum skin temperature of the upper posterior left leg, there was no effect of condition [$F(3, 27) = .909$, P = 0.450, $\eta p^2 = .092$]. There was a time effect [$F(2, 18) = 10.365$, P = 0.001, $\eta p^2 = .535$]. Pairwise comparisons showed that maximum skin temperature was higher at post run compared to baseline and post warm-up (P = 0.004 and P = 0.002, respectively). There was no interaction effect [$F(6, 54) = .888$, P = 0.510, $\eta p^2 = .090$] (**Figure 8.4)**.

With respect to maximum skin temperature of the upper posterior right leg, there was no effect of condition [$F(3, 27) = 2.397$, P = 0.090, $\eta p^2 = .210$]. There was a time effect [$F(2, 18) = 16.041$, P = 0.001, $\eta p^2 = .641$]. Pairwise comparisons showed that maximum skin temperature was higher at post run compared to baseline and post warm-up (P = 0.008 and P = 0.001, respectively) and was higher at post warm-up compared to baseline (P = 0.015). There was no interaction effect [$F(6, 54) = .925$, P = 0.484, $\eta p^2 = .093$] (**Figure 8.4)**.

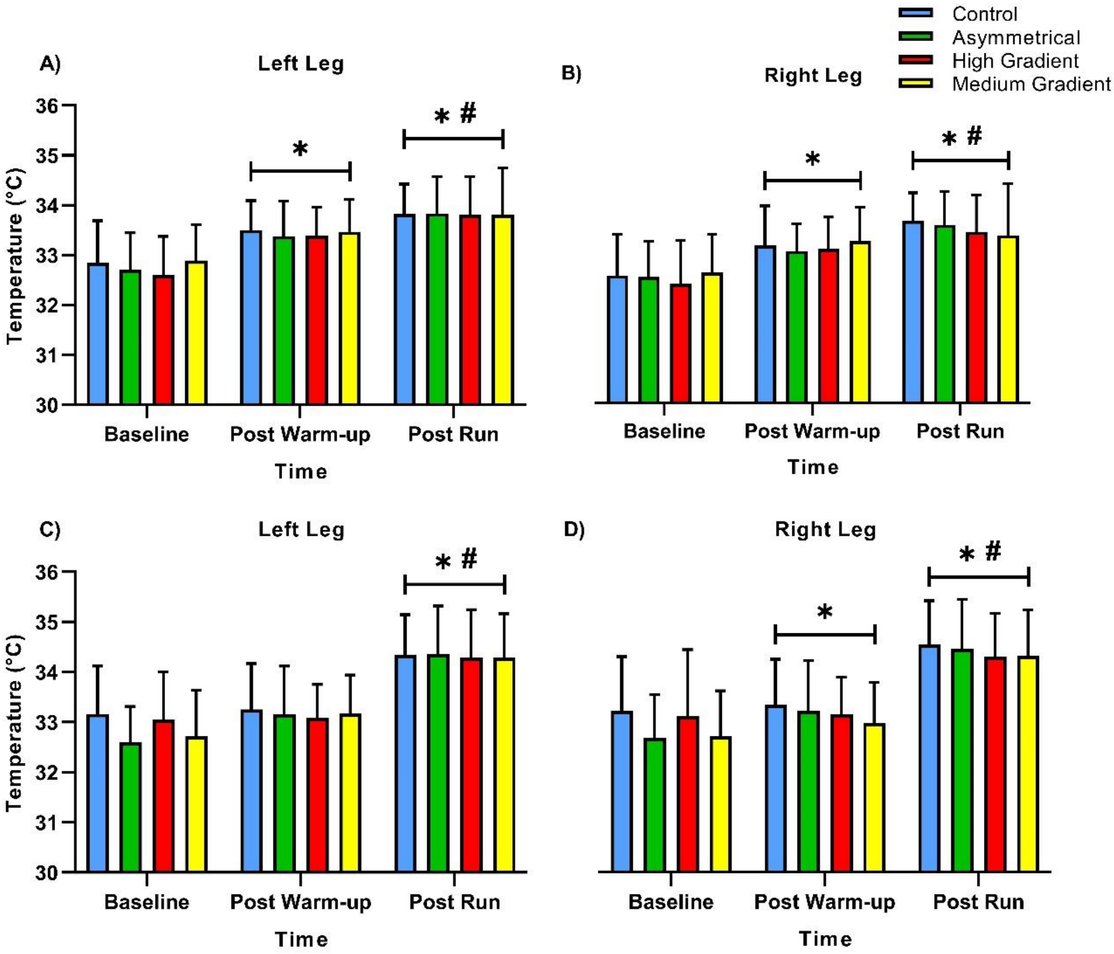


Figure 8.4. Maximum skin temperature for the lower posterior left (A) and right (B) legs and for the upper posterior left (C) and right (D) legs at baseline, post warm-up and post the 30-minute run in the control, asymmetrical, high gradient and medium gradient garment conditions (mean ± standard deviation). * significant time effect compared to baseline, # significant time effect compared to post warm-up ($P < 0.05$).

Mean Temperature

Lower Anterior Leg

With respect to mean skin temperature of the lower anterior left leg, there was no effect of condition [$F(3, 27) = .475$, $P = 0.702$, $\eta p^2 = .050$]. There was a time effect [$F(2, 18) = 33.355$, $P = 0.001$, $\eta p^2 = .788$]. Pairwise comparisons showed that mean skin temperature was higher at post run compared to baseline and post warm-up ($P = 0.001$ and $P = 0.001$, respectively). There was no interaction effect [$F(6, 54) = 1.170$, $P = 0.336$, $\eta p^2 = .115$] (**Figure 8.5**).

With respect to mean skin temperature of the lower anterior right leg, there was no effect of condition [$F(3, 27) = .342$, $P = 0.687$, $\eta p^2 = .052$]. There was a time effect [$F(2, 18) = 32.509$, $P = 0.001$, $\eta p^2 = .783$]. Pairwise comparisons showed that mean skin temperature was higher at post run compared to baseline and post warm-up ($P = 0.001$ and $P = 0.001$, respectively). There was no interaction effect [$F(6, 54) = 1.357$, $P = 0.249$, $\eta p^2 = .131$] (**Figure 8.5**).

Upper Anterior Leg

With respect to mean skin temperature of the upper anterior left leg, there was no effect of condition [$F(3, 27) = .497$, $P = 0.702$, $\eta p^2 = .050$]. There was a time effect [$F(2, 18) = 78.552$, $P = 0.001$, $\eta p^2 = .897$]. Pairwise comparisons showed that mean skin temperature was higher at post run compared to baseline and post warm-up ($P = 0.001$ and $P = 0.001$, respectively). There was no interaction effect [$F(6, 54) = .706$, $P = 0.646$, $\eta p^2 = .073$] (**Figure 8.5**).

With respect to mean skin temperature of the upper anterior right leg, there was no effect of condition [$F(3, 27) = .950$, $P = 0.431$, $\eta p^2 = .095$]. There was a time effect [$F(2, 18) = 68.205$, $P = 0.001$, $\eta p^2 = .883$]. Pairwise comparisons showed that mean skin temperature was higher at post run compared to baseline and post warm-up ($P = 0.001$ and $P = 0.001$, respectively). There was no interaction effect [$F(6, 54) = .883$, $P = 0.514$, $\eta p^2 = .089$] (**Figure 8.5**).

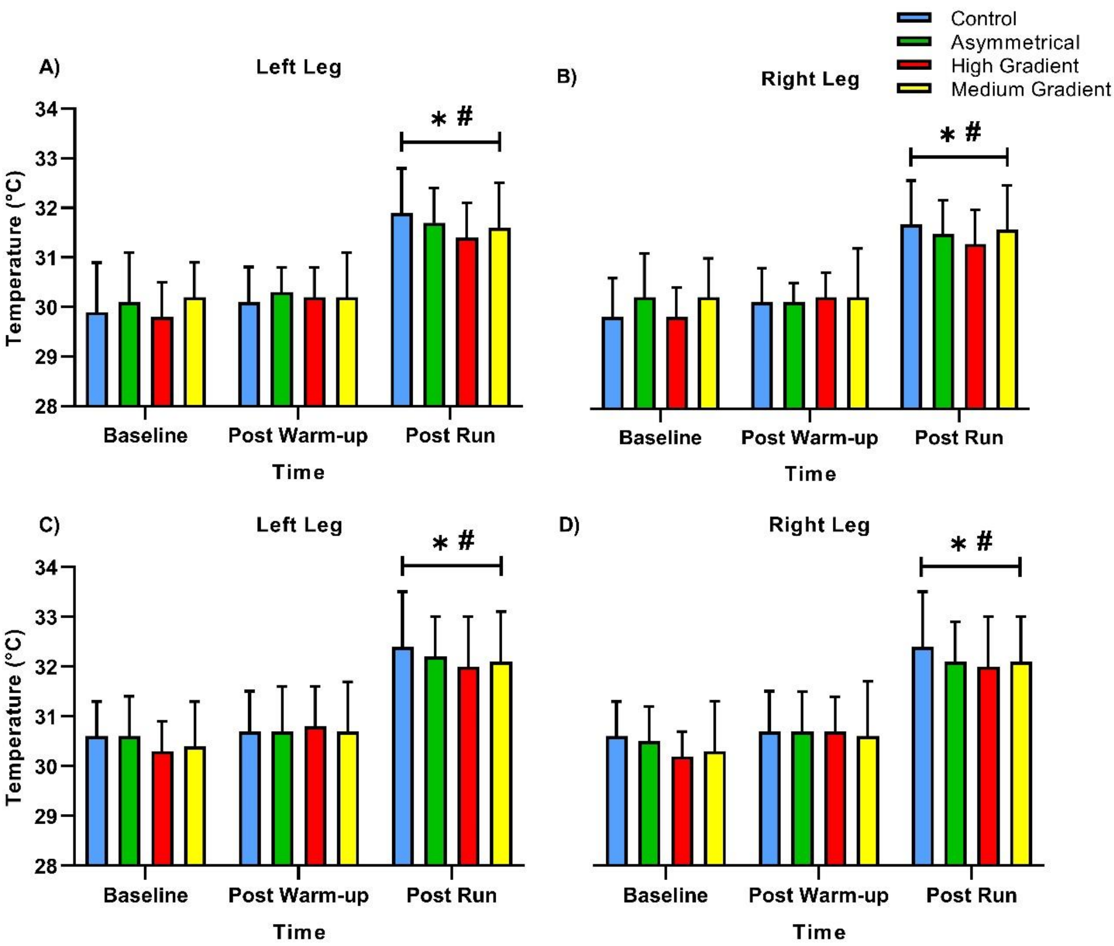


Figure 8.5. Mean skin temperature for the lower anterior left (A) and right (B) legs and for the upper anterior left (C) and right (D) legs at baseline, post warm-up and post the 30-minute run in the control, asymmetrical, high gradient and medium gradient garment conditions (mean ± standard deviation). * significant time effect compared to baseline, # significant time effect compared to post warm-up ($P < 0.05$).

Lower Posterior Leg

With respect to mean skin temperature of the lower posterior left leg, there was no effect of condition [$F(3, 27) = .890$, $P = 0.459$, $\eta p^2 = .090$]. There was a time effect [$F(2, 18) = 23.671$, $P = 0.001$, $\eta p^2 = .725$]. Pairwise comparisons showed that mean skin temperature was higher at post run compared to baseline and post warm-up ($P = 0.002$ and $P = 0.001$, respectively). There was no interaction effect [$F(6, 54) = .742$ $P = 0.618$, $\eta p^2 = .076$] (**Figure 8.6**).

With respect to mean temperature of the lower posterior right leg, there was no effect of condition [$F(3, 27) = .537$, $P = 0.661$, $\eta p^2 = .056$]. There was a time effect [$F(2, 18) = 24.501$, $P =$

0.001, ηp^2 = .731]. Pairwise comparisons showed that mean skin temperature was higher at post run compared to baseline and post warm-up (P = 0.001 and P = 0.001, respectively). There was no interaction effect [F(6, 54) = .737, P = 0.622, ηp^2 = .076] (**Figure 8.6**).

Upper Posterior Leg

With respect to mean skin temperature of the upper posterior left leg, there was no effect of condition [F(3, 27) = .406, P = 0.750, ηp^2 = .043]. There was a time effect [F(2, 18) = 46.596, P = 0.001, ηp^2 = .838]. Pairwise comparisons showed that mean skin temperature was higher at post run compared to baseline and post warm-up (P = 0.001 and P = 0.001, respectively). There was no interaction effect [F(6, 54) = .697 P = 0.653, ηp^2 = .072] (**Figure 8.6**).

With respect to mean temperature of the upper posterior right leg, there was no effect of condition [F(3, 27) = .548, P = 0.654, ηp^2 = .057]. There was a time effect [F(2, 18) = 42.592, P = 0.001, ηp^2 = .826]. Pairwise comparisons showed that mean skin temperature was higher at post run compared to baseline and post warm-up (P = 0.001 and P = 0.001, respectively). There was no interaction effect [F(6, 54) = .991 P = 0.441, ηp^2 = .099] (**Figure 8.6**).

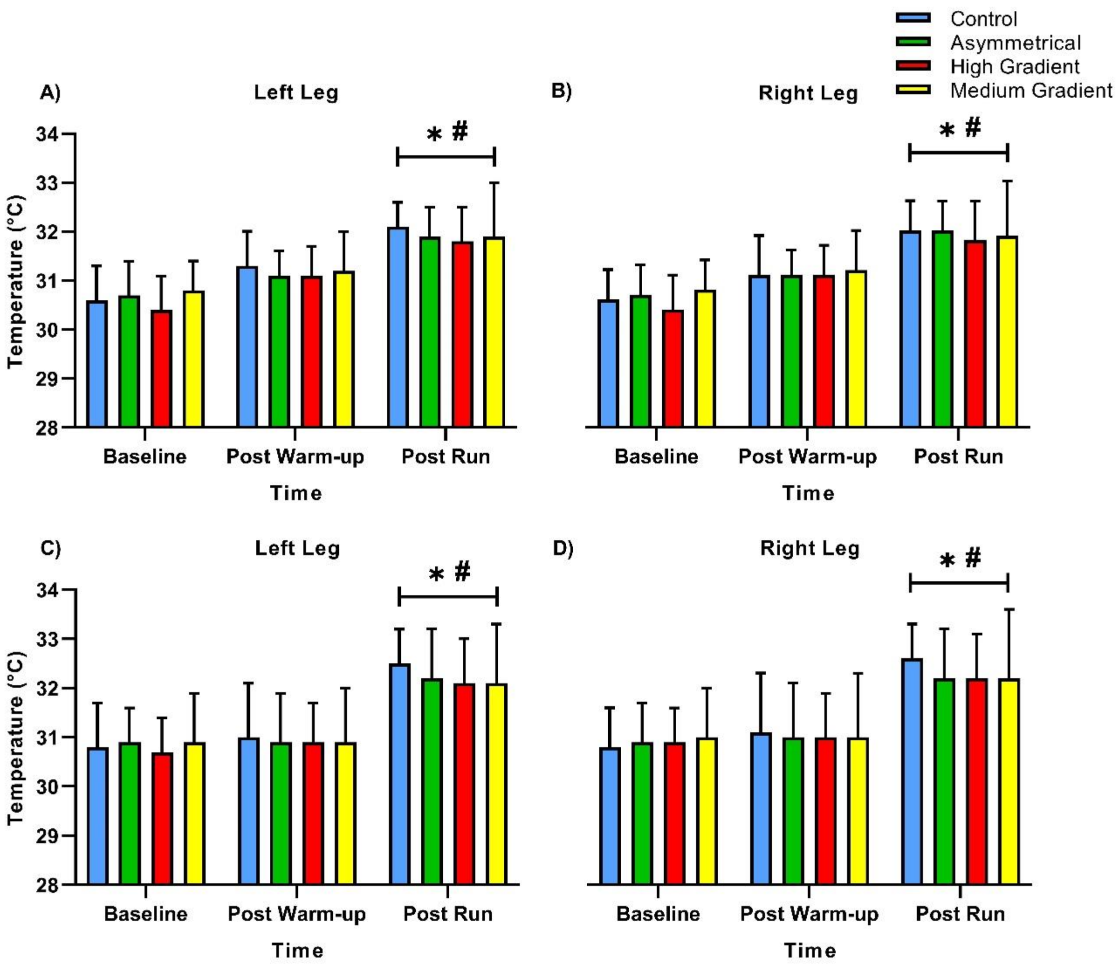


Figure 8.6. Mean skin temperature for the lower posterior left (A) and right (B) legs and for the upper posterior left (C) and right (D) legs at baseline, post warm-up and post the 30-minute run in the control, asymmetrical, high gradient and medium gradient garment conditions (mean ± standard deviation). * significant time effect compared to baseline, # significant time effect compared to post warm-up (P < 0.05).

Comfort Questionnaire

Material Comfort

With respect to material comfort, there was an effect of condition [$F(3, 27) = 4.729$, $P = 0.009$, $\eta p^2 = .344$]. Pairwise comparisons showed that material comfort was lower in the medium gradient garment condition compared to the control garment condition ($P = 0.016$). A time effect was evident when baseline and post run timepoints were compared [$F(1, 9) = 7.365$, $P = 0.024$, $\eta p^2 = .450$]. There was no interaction effect [$F(3, 27) = 0.996$, $P = 0.383$, $\eta p^2 = .100$] (**Figure 8.7**).

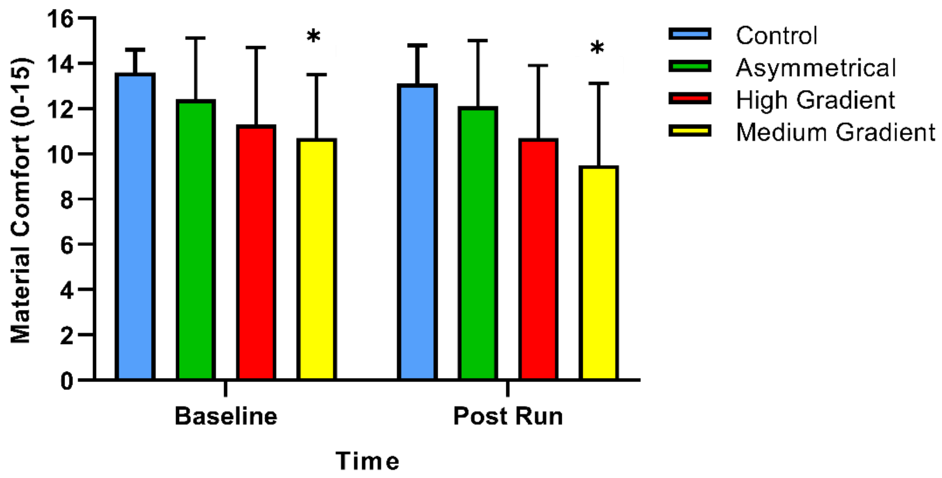


Figure 8.7. Material comfort in the control, asymmetrical, high gradient and medium gradient garment conditions at baseline and post run (mean ± standard deviation), 0 = most uncomfortable imaginable, and 15 = most comfortable imaginable. * significant condition effect compared to the control garment condition ($P < 0.05$).

General Comfort Left Leg

With respect to general comfort of the left leg, there was an effect of condition [$F(3, 27) = 13.879$, $P = 0.001$ $\eta p^2 = .607$] . Pairwise comparisons showed that general comfort was lower in the medium gradient garment condition compared to the control and asymmetrical garment conditions (both $P = 0.004$). A time effect was evident when baseline and post run timepoints were compared. [$F(1, 9) = 8.859$, $P = 0.016$, $\eta p^2 = .496$]. There was no interaction effect [$F(3, 27) = 0.431$, $P = 0.733$, $\eta p^2 = .046$] (**Figure 8.8**).

General Comfort Right Leg

With respect to general comfort of the right leg, there was an effect of condition [$F(3, 27) = 11.501$, $P = 0.001$, $\eta p^2 = .561$]. Pairwise comparisons showed that general comfort was lower in the medium gradient garment condition compared to the control and asymmetrical garment conditions ($P = 0.005$ and 0.029, respectively). A time effect was evident when baseline and post run timepoints were compared [$F(1, 9) = 7.376$, $P = 0.024$, $\eta p^2 = .450$]. There was no interaction effect [$F(3, 27) = 0.555$, $P = 0.649$, $\eta p^2 = .058$] (**Figure 8.8**).

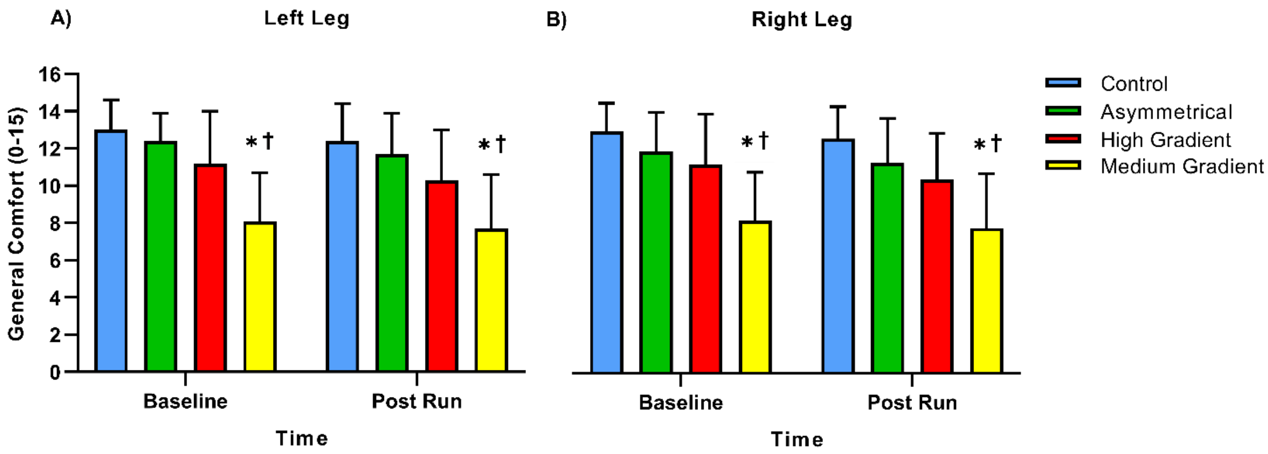


Figure 8.8. General comfort for the left (A) and right (B) legs the in the control, asymmetrical, high gradient and medium gradient garment conditions at baseline and post run (mean ± standard deviation), 0 = most uncomfortable imaginable, and 15 = most comfortable imaginable. * significant condition effect compared to the control garment condition, † significant condition effect compared to the asymmetrical garment condition, ($P < 0.05$).

Compression Comfort Left Leg

With respect to compression comfort of the left leg, there was an effect of condition [$F(1.830, 16.466) = 4.704$, $P = 0.027$, $\eta p^2 = .343$]. However, pairwise comparisons showed no significant differences between conditions, with the largest difference occurring between the control and medium gradient garment conditions (mean difference = 3.1, $P = 0.171$). There was no time effect when baseline and post run timepoints were compared [$F(1, 9) = 0.883$, $P = 0.372$, $\eta p^2 = .089$]. There was no interaction effect [$F(3, 27) = 2.608$, $P = 0.072$, $\eta p^2 = .225$] (**Figure 8.9**).

Compression Comfort Right Leg

With respect to compression comfort of the right leg, there was an effect of condition [$F(3, 27) = 4.439$, $P = 0.012$, $\eta p^2 = .330$]. However, pairwise comparisons showed no significant differences between conditions, with the largest difference occurring between the control and medium gradient garment conditions (mean difference = 2.9, $P = 0.171$). There was no time effect when baseline and post run timepoints were compared [$F(1, 9) = 0.217$, $P = 0.652$, $\eta p^2 = .024$]. There was no interaction effect [$F(3, 27) = 2.491$, $P = 0.082$, $\eta p^2 = .217$] (**Figure 8.9**).

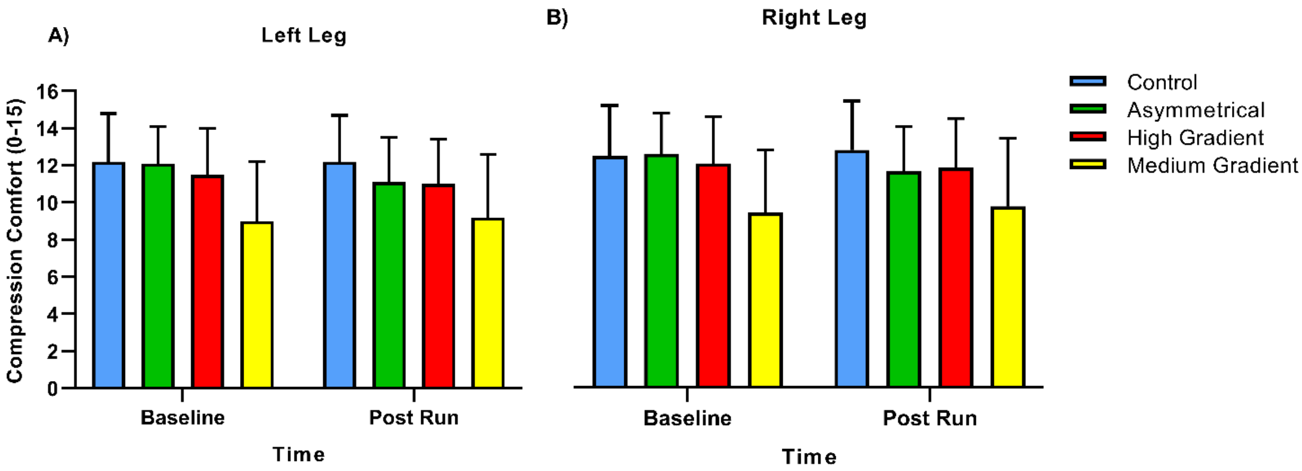


Figure 8.9. Compression comfort for the left (A) and right (B) legs the in the control, asymmetrical, high gradient and medium gradient garment conditions at baseline and post run (mean ± standard deviation), 0 = most uncomfortable imaginable, and 15 = most comfortable imaginable.

Temperature Comfort

With respect to temperature comfort, there was an effect of condition [$F(3, 27) = 4.372$, $P = 0.012$, $\eta p^2 = .327$]. However, pairwise comparisons showed no significant differences between conditions with the largest difference occurring between the control and medium gradient garment conditions (mean difference = 2.5, $P = 0.066$). A time effect was evident when baseline and post run timepoints were compared [$F(1, 9) = 30.297$, $P = 0.001$, $\eta p^2 = .771$]. There was no interaction effect [$F(3, 27) = 0.058$, $P = 0.981$, $\eta p^2 = .006$] (**Figure 8.10**).

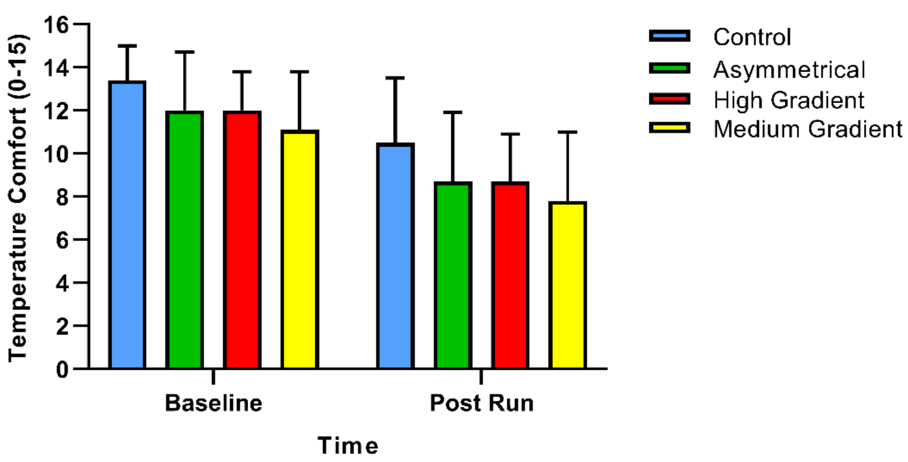


Figure 8.10. Temperature comfort in the control, asymmetrical, high gradient and medium gradient garment conditions at baseline and post run (mean ± standard deviation), 0 = most uncomfortable imaginable, and 15 = most comfortable imaginable.

Breathability Comfort

With respect to breathability comfort, there was no effect of condition [$F(3, 27) = 3.064$, $P = 0.083$, $\eta p^2 = .254$]. A time effect was evident when baseline and post run timepoints were compared [$F(1, 9) = 19.399$, $P = 0.002$, $\eta p^2 = .683$]. There was no interaction effect [$F(3, 27) = 1.255$, $P = 0.310$, $\eta p^2 = .122$] (**Figure 8.11**).

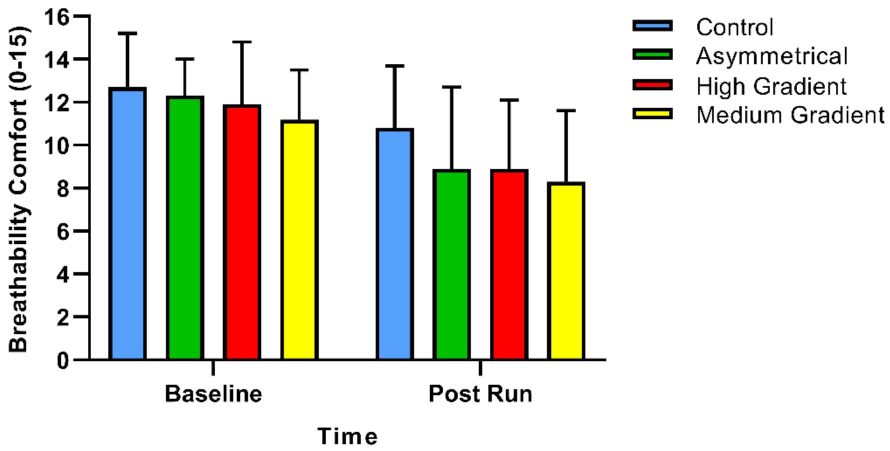


Figure 8.11. Breathability comfort in the control, asymmetrical, high gradient and medium gradient garment conditions at baseline and post run (mean ± standard deviation), 0 = most uncomfortable imaginable, and 15 = most comfortable imaginable.

Compression and General Comfort (Asymmetrical Garment)

There was no difference of perceived general comfort between the left and right legs in the asymmetrical garment condition at baseline ($t (9) = 0.812$, $P = 0.438$), and at post run ($t (9) = 0.585$, $P = 0.573$) (**Figure 8.12**). There was no difference of perceived compression comfort between the left and right legs in the asymmetrical garment condition at baseline ($t (9) = 0.090$, $P = 0.930$) and at post at run ($t (9) = -0.274$, $P = 0.791$) (**Figure 8.13**).

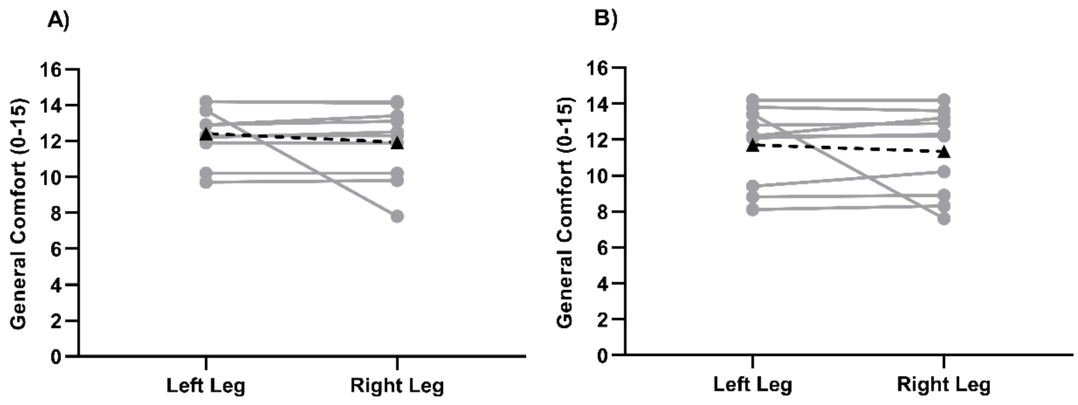


Figure 8.12. Individual participant data for perceived general comfort in the asymmetrical garment for the left (A) and right (B) legs at baseline and at post 30-minute run. The black data point and dashed line represents the group mean.

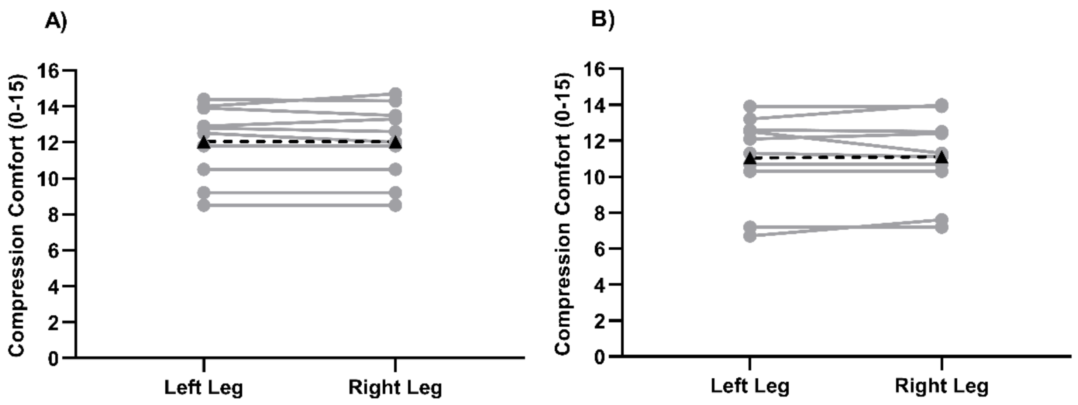


Figure 8.13. Individual participant data for perceived compression comfort in the asymmetrical garment for the left (A) and right (B) legs at baseline and at post 30-minute run. The black data point and dashed line represents the group mean.

Rating of Perceived Exertion

With respect to RPE, there was no effect of condition [F(3, 27) = 1.874, *P* = 0.158, ηp2 = .172]. A time effect was evident as participants RPE increased from baseline to post run [F(6, 54) = 104.394, *P* = 0.001, ηp2 = .921]. There was no interaction effect [F(18, 162) = 1.198, *P* = 0.268, ηp2 = .117] (**Table 8.6**).

Table 8.6. RPE in the control, asymmetrical, high gradient and medium gradient garment conditions at rest, 5, 10, 15, 20, 25 and 30 min during the run (mean ± standard deviation).

	Control	Asymmetrical	High Gradient	Medium Gradient
Rest	6 ± 0	6 ± 0	6 ± 0	6 ± 0
5 min	9.6 ± 1.4	9.6 ± 1.5	9.4 ± 1.4	9.4 ± 1.5
10 min	10.3 ± 1.2	10.3 ± 1.1	10.3 ± 1.4	10.1 ±1.2
15 min	11.3 ± 0.7	10.6 ± 0.7	11.0 ±1.1	11.0 ± 0.8
20 min	11.8 ± 0.9	11.1 ± 0.9	11.2 ± 0.9	11.3 ± 0.7
25 min	11.9 ± 0.7	11.4 ± 1.0	11.7 ± 0.9	11.7 ± 0.7
30 min	11.9 ± 0.9	11.7 ± 1.2	12.0 ± 1.2	11.9 ± 0.7

Thermal Sensation

With respect to thermal sensation, there was no effect of condition [$F(3, 27) = .311$, $P = 0.818$, $\eta p^2 = .033$]. A time effect was evident as participants thermal sensation increased from baseline to post run [$F(6, 54) = 89.706$, $P = 0.001$, $\eta p^2 = .909$]. There was no interaction effect [$F(18, 162) = 1.427$, $P = 0.125$, $\eta p^2 = .137$] (**Table 8.7**).

Table 8.7. Thermal Sensation in the control, asymmetrical, high gradient and medium gradient garment conditions at rest, 5, 10, 15, 20, 25 and 30 min during the run (mean ± standard deviation).

	Control	Asymmetrical	High Gradient	Medium Gradient
Rest	3.8 ± 0.7	3.7 ± 0.5	3.9 ± 0.3	3.6 ± 0.6
5 min	4.5 ± 0.6	4.4 ± 0.5	4.6 ± 0.5	4.1 ± 0.6
10 min	5.1 ± 0.6	4.9 ± 0.3	5.0 ± 0.3	5.0 ± 0.7
15 min	5.6 ± 0.6	5.4 ± 0.5	5.5 ± 0.6	5.5 ± 0.6
20 min	5.9 ± 0.8	5.7 ± 0.5	5.6 ± 0.6	5.8 ± 0.5
25 min	6.0 ± 0.8	5.8 ± 0.6	5.9 ± 0.5	6.1 ± 0.5
30 min	6.0 ± 0.8	5.9 ± 0.6	6.0 ± 0.6	6.2 ± 0.5

8.5 Discussion and Conclusion

This study aimed to examine the effect of wearing made-to-measure compression garments, with different pressure profiles, on thermal responses and comfort perception before and after exercise. The key findings of this study were that skin temperature and perceived thermal sensation were not affected by the variable pressure profiles elicited by the four different made-to-measure compression garments, before and after submaximal running exercise. Also, the results demonstrate that the compression garment that elicited a high peak pressure and the shallowest pressure gradient significantly reduced the participants perception of material comfort and general comfort.

In the current study, maximum and mean skin temperature of all leg segments were not different when the four compression garment conditions were compared. Goh and colleagues (2011) found no differences in skin temperature, measured using skin thermistors, over the pectoralis major, biceps brachii, rectus femoris and gastrocnemius between control (running shorts) and compression garment conditions during rest, submaximal running, maximal running and post run, at 32°C. Conversely, skin temperatures over the rectus femoris and gastrocnemius were higher in the compression garment condition than the control condition, at 10°C, which was likely due to the insulative properties of the compression garment in colder temperatures. Barwood and colleagues (2013) measured skin temperature, using skin thermistors, at eight anatomical sites on the body during a 15-minute submaximal run and during a 5 km time trial, at 35°C. Their study found that there were no differences in skin temperature, for seven of the examined locations, between control (loose shorts), sham garment (oversized compression garment) and correctly sized compression garment conditions. However, during the time trial, quadriceps skin temperature was significantly higher in the sham garment and correctly sized compression garment conditions than the control condition. The difference in quadriceps temperature in the garment conditions was likely caused by a radiant heat load applied prior to exercise and the quadriceps site was most exposed to the radiant heat. Furthermore, the authors suggested that the black colouration of the compression garments may have influenced the skin temperature during the radiant heat load exposure. Participant thermal sensation was also not different between conditions. The findings of the current study were consistent with the findings of Barwood and colleagues (2013) as in the current study no differences in maximum or mean skin temperature for any of the leg segments was observed between the four compression garment conditions. Also, thermal sensation was not different between the four compression garment conditions. However, given that the current study did not include a ‘no garment’ trial it is not possible to comment on the thermoregulatory effects of wearing the compression garments compared with their absence.

In the current study, skin temperature typically increased from baseline to post run. The management of both core and skin temperature, particularly during exercise in the heat, is fundamental for exercise performance (Kenefick & Sawka, 2007). Therefore, it is vital that when wearing compression garments during exercise, such clothing should not inhibit heat transfer from the body, thereby instigating excessive heat storage during exercise. Priego Quesada and colleagues (2015) found that when wearing a lower body compression garment, mean skin temperature change from baseline to post exercise was 0.76°C, 0.30°C, 1.28°C and 0.55°C for the tibialis anterior, gastrocnemius, vastus lateralis and semitendinosus segments respectively, as measured by infrared thermal imaging. The temperature changes in the current study were larger as the mean skin temperature change from baseline to post run ranged between 1.4 – 2.0°C, 1.1 – 1.5°C, 1.6 – 1.8°C and 1.2 – 1.7°C for the lower anterior and posterior, and the upper anterior and posterior leg segments respectively, in all four compression garment conditions. However, the mean baseline skin temperatures of all leg segments were lower in the current study (30.5 °C) compared to that of Priego Quesada and colleagues (2015) (~31.5 °C). Also, given that baseline skin temperature is typically regulated by the ambient temperature (Goh et al., 2010), it is likely that this difference is due to the lower ambient temperature in the current study (20.5 °C) compared to that of Priego Quesada and colleagues (2015) (23.7°C). In the current study, absolute mean temperature at post run in all garment conditions was not different and ranged between 31.4 and 32.6°C for all leg segments, which was similar to those found by Priego Quesada and colleagues (2015). It has been suggested that a skin temperature greater than 35°C can negatively influence aerobic exercise performance and increase cardiovascular strain (Sawka et al., 2012). Also, it has been shown that when the skin temperature is elevated above 35°C, exercise such as time to exhaustion and time trial performance is negatively affected, despite core temperatures below 40°C at the end of exercise (critical core temperature theory) (González-Alonso et al., 1999; MacDougall et al., 1974; Tatterson et al., 2000). The made-to-measure compression garments used in the current study, which elicited different pressure profiles, did not seem to negatively influence exercise performance as mean skin temperature did not elevate above 32.6°C during submaximal running exercise at 2.5 ± 0.3 m/s. However, the running intensity used in the current study was low, and therefore the metabolic heat production during exercise may have also been low. Given that higher exercise intensities typically increase metabolic heat production, it would be beneficial to examine if wearing made-to-measure compression garments elicit the same responses during strenuous exercise and in hotter environments, which will elicit greater thermoregulatory strain than that experienced in the current study.

A key finding from the current study was that the pressure profile elicited by a compression garment can affect the perceived comfort of the wearer. The study showed that general comfort was greater in the control (baseline: 13 ± 1.5, post-run: 12.5 ± 1.8) and asymmetrical (baseline: 12.2 ± 1.8, post-run: 11.5 ± 2.2) garments compared to the medium gradient (baseline: 8.2 ± 2.5, post-run: 7.7 ± 2.8) garment. There was no difference of general comfort between the high gradient (baseline: 11.2 ± 2.6, post-run: 10.3 ± 2.5) garment compared to the control, asymmetrical and medium gradient garments. Given that there was no difference of general comfort found between the control, asymmetrical and high gradient garments, and that the peak pressure at the ankle was similar between the high gradient and medium gradient garments, the higher pressure across the length of the leg experienced in the medium gradient garment likely contributed to the greater discomfort rather than the peak pressure at the ankle. These results, that show greater comfort in the control garment than the medium gradient garment, conflict with the findings of Lucas-Cuevas and colleagues (2015) who found no differences of general comfort between non-compression (placebo) and compressive garments. A factor which may explain these observed differences between studies is the elicited pressures of the garments used. Although the peak pressure was similar between studies, Lucas-Cuevas and colleagues (2015) relied on manufacturer reported pressure values and did not quantify the actual pressure of their garment. Given that manufacturer reported pressure values may overestimate the actual pressure elicited by the garment (Hill et al., 2015), it is possible that the compression garment used by Lucas-Cuevas and colleagues (2015) did not elicit the high pressures that the current study's results suggest may increase wearer discomfort. Furthermore, the type of garment used differed between studies with Lucas-Cuevas and colleagues (2015) opting for below-knee stockings compared to the ankle to hip tights used in the current study. The different body coverage of the compression garments may have contributed to the conflicting comfort results.

The current study showed that the compression garment which elicited the highest overall pressure across the whole leg was rated as the most uncomfortable which is consistent with the results found by Ali and colleagues (2010). Surprisingly, few studies have investigated wearer comfort when wearing compression garments (Ali et al., 2010; Lien et al., 2014; Lucas-Cuevas et al., 2015; Lucas-Cuevas et al., 2017). The comfort of a compression garment is an important factor which may influence exercise performance. If a compression garment is deemed uncomfortable by the wearer, their desire to wear the garment is likely to be reduced, and if they do wear it negative emotions may result (Lucas-Cuevas et al., 2015). Furthermore, discomfort during exercise could lead to changes in movement patterns which may be less efficient, and such changes could potentially induce fatigue and ultimately influence performance (Lucas-Cuevas et al., 2015). In the current study, there was no evidence to suggest that greater discomfort in the medium gradient garment influenced running performance as RPE was not different between garment conditions. As comfort may influence the use of and enthusiasm for compression garments by athletes, garments should have an optimal balance between elicited pressures that are high enough to produce favourable physiological adaptations, but have pressures low enough that they ensure wearer comfort.

The prospect of a within garment control has been developed and applied in previous research (Perrey et al., 2008; Trenell et al., 2006). However, in these studies a compression garment was applied to one leg and the other leg had no garment applied, thus, participant blinding was not possible. In the current study, the asymmetrical compression garment was applied to both legs using the same garment whereby, control garment pressures were elicited on the left leg and high gradient garment pressures were elicited on the right leg. The comfort questionnaire revealed that 90% of participants did not perceive compression differences between left and right legs, and 100% of participants perceived the same general comfort between legs even though the elicited peak pressure on the right leg was twice as high than that on the left leg (right: 26 ± 3 vs. left: 13 ± 2 mmHg). The between leg compression comfort results found for the asymmetrical garment disagree with the results of Lien and colleagues (2014) who found that 61% of participants perceived that a recommended fit compression garment elicited a higher level of pressure compared to an oversized fit garment. However, unlike the current study the pressure differences between recommended fitted and oversized fitted garments are unknown as Lien and colleagues (2014) did not report the pressures elicited by their compression garments. The results of the current study show that a within garment control can be created that successfully ‘blinds’ the majority of participants (90%) to the pressures exerted by the garment they are wearing.

The pressure elicited by the control garment and the left leg of the asymmetrical garment was below that of UK clinical compression standards (< 14 mmHg). Although the elicited pressure of these garments was below UK clinical compression standards it cannot be assumed that the pressure did not influence physiological responses. Although high levels of compression typically increase muscle oxygenation and haemodynamics to a greater extent compared to low levels of compression (Dermont et al., 2015; Lee et al., 2020). The low elicited pressure of the control garment used in the current study may still have the potential to influence physiological responses. As a result, it would be beneficial for future research to determine whether garment elicited pressures that are below UK clinical compression standards influence physiological mechanisms such as blood flow and haemodynamics.

Limitations

A no compression garment condition was not used in this study which is a limitation that must be acknowledged. The study used an approach whereby a control garment eliciting pressures below UK clinical compression standards (< 14 mmHg) was used. However, regardless of elicited pressure, wearing compression garments is likely to inhibit heat exchange between the body and the environment compared with wearing no garment (MacRae et al., 2011). However, as the current study did not use a no garment condition it is impossible to evidence such effect. Therefore, for future research it would prove beneficial to investigate temperature differences between wearing and not wearing a compression garment before, during and after exercise.

In conclusion, the current study demonstrated that the variable pressure profile of four different made-to-measure compression garments had no effect on skin temperature, as the mean skin temperature at post run ranged between 31.4 – 31.9°C, 31.8 – 32.1°C, 32.0 – 32.4°C and 32.1 – 32.6 for the lower anterior and posterior, and the upper anterior and posterior leg segments respectively, in all four compression garment conditions. Participant perception of comfort when wearing made-to-measure compression garments was affected by the pressure profile elicited by the garments, with a high peak pressure and a shallow pressure gradient significantly reducing comfort. The medium gradient garment elicited the highest pressures across the length of the leg and was rated as most uncomfortable at baseline compared to the control garment (8.1 ± 2.6 vs. 13.0 ± 1.6) as well as at post run (7.7 ± 2.9 vs. 12.4 ± 2.0). Furthermore, the results suggest that a blinded within participant control garment can be developed which may have utility to examine the efficacy of wearing compression garments for exercise performance and recovery.

Chapter 9: The effect of wearing made-to-measure compression garments on submaximal running biomechanics.

9.1 Rationale

The previous chapter examined the effect of wearing made-to-measure compression garments on thermoregulation and comfort perception before and after running. The results showed that the pressure profile of made-to-measure compression garments had no effect on skin temperature and thermal sensation before and after running exercise. Furthermore, the compression garments which elicited higher pressures were generally perceived to provide greater discomfort. A small number of compression garments studies have investigated the effect of wearing compression garments on running kinematics and kinetics (Borràs et al., 2011; Stickford et al., 2015; Varela-Sanz et al., 2011). However, these studies only measure scalar variables of running such as stride length, stride frequency and stride duration. Currently, no study has examined the effect of wearing made-to-measure compression garments on temporal waveform kinematic and kinetic biomechanical variables during running. Moreover, given the compressive characteristics of compression garments over joints structures, compression garments may alter running gait. Therefore, this chapter aimed to examine the effect of wearing made-to-measure compression garments, with different pressure profiles, on running kinematics and kinetics.

9.2 Introduction

The use of compression garments has become prevalent among athletes as an ergogenic aid for exercise performance (Mizuno et al., 2017). Compression garments are defined as elasticated clothing that provides an external pressure onto the body, which compresses the skin and underlying tissues (MacRae et al., 2011). Many compression garments are designed to incorporate graduated compression with the pressure decreasing from distal to proximal to aid haemodynamics (Agu et al., 1999). The use of compression garments within sport has arisen from their effective application in clinical practice where they are used to treat deep vein thrombosis and other venous insufficiencies (Ibegbuna et al., 2003; Scurr et al., 2001).

Many physiological mechanisms have been reported with the use of compression garments which may benefit exercise performance including: reduced heart rate (Driller & Halson, 2013), reduced muscle oscillation (Broatch et al., 2020; Borràs et al., 2011), reduced muscle activation (Hsu et al., 2016), improved muscle blood flow (Broatch et al., 2017), improved exercise to exhaustion time (Kemmler et al., 2009) and enhanced lactate clearance following exercise (Rimaud et al., 2010; Chatard et al., 2004). However, others have found no effect of wearing such garments during exercise on heart rate (MacRae et al., 2012), muscle blood flow (Venckunas et al., 2014), exercise to exhaustion time (Sperlich et al., 2010) and lactate clearance (Pruscino et al., 2013). The inconsistent findings between studies may be a result of substantial differences in the study design, type of compression garment, the study population and the type of exercise performed (MacRae et al., 2011). The elicited pressure of the compression garments used between studies may also contribute to such inconsistencies, and a review by Beliard and colleagues (2014) demonstrated that measured pressure in the reviewed studies ranged from 1.1 - 34.3 mmHg at the ankle, and from 8.0 - 27.0 mmHg at the calf. Therefore, it would be useful to determine if specific pressures and pressure gradients influence exercise performance.

The published literature suggests that wearing compression garments, during maximal exercise, may not influence maximal oxygen consumption ($\dot{V}O_{2max}$) (Rider et al., 2014; Sperlich et al., 2010; Scanlan et al., 2008). However, some studies have reported that compression garments may improve the economy of oxygen use during running exercise (Bringard et al., 2006). Running economy is defined as the energy required for a standardised velocity of submaximal running and is established by measuring the steady state oxygen consumption ($\dot{V}O_2$) as well as the respiratory exchange ratio (Saunders et al., 2004). Therefore, compression garments may not enhance the uptake of oxygen, but may enable the wearer to take greater advantage of that which is available. There is evidence that suggest that running economy may provide a better prediction of exercise performance as compared to $\dot{V}O_{2max}$ (Lucía et al., 2002) and therefore this may be of more interest when investigating the use of compression garments.

There are many factors which may influence running economy such as; sex (Mendonca et al., 2020), age (Krahenbuhl & Pangrazi, 1983), body weight (Bergh et al., 1991), muscle fiber composition

(Barnes & Kilding, 2015), core temperature, (Morgan & Craib, 1992), heart rate and ventilation (Saunders et al., 2004). Furthermore, it has been reported that biomechanical factors may also substantially influence running economy. Biomechanical factors that are associated with improved running economy are: reduced vertical oscillation (Moore, 2016), minimal change in running velocity during ground contact (Kaneko, 1990), longer stride length (Cavanagh & Williams, 1982), longer ground contact time (Di Michele & Merni, 2014), increased swing time (Williams & Cavanagh, 1987), smaller ground reaction forces (Anderson, 1996), reduced leg extension at the toe-off phase of the gait cycle (Moore et al., 2012), greater knee flexion and ankle dorsi flexion during the stance phase of the gait cycle (Williams & Cavanagh, 1987; Williams, Cavanagh & Ziff 1987), reduced peak hip flexion during braking phase of the gait cycle (Sinclair et al., 2013), greater leg stiffness (Dalleau et al., 1998) and slight forward lean (Anderson, 1996). However, for running performance outcomes, disagreement exists in the published literature. Some studies have shown that wearing compression garments improves run to exhaustion time (Armstrong et al., 2015; Kemmler et al., 2009), whereas, others have found no effect (Dascombe et al., 2011; Sperlich et al., 2010). Interestingly, although Kemmler and colleagues (2009) and Dascombe and colleagues (2011) found conflicting run to exhaustion results, both found that compression garments did not influence $\dot{V}O_{2max}$. Therefore, the longer run to exhaustion time found by Kemmler and colleagues (2009) may be a result of enhanced running economy when wearing the compression garment.

A study by Bringard and colleagues (2006) was one of the first to report that wearing compression garments improved running economy compared to wearing loose shorts. However, mechanisms to explain such improvement remains unclear. Wearing compression garments may alter running biomechanics (Kerhervé et al., 2017), and such biomechanical alterations caused by wearing compression garments (i.e., reduced vertical oscillation, longer stride length and greater leg stiffness) may ultimately improve running economy. As a result, recent studies have examined if wearing compression garments alter running biomechanics and subsequently improves running economy (Stickford et al., 2015; Varela-Sanz et al., 2011). Varela-Sanz and colleagues (2011) employed two independent methods. Firstly, they examined the effect of wearing compression garments on running economy at submaximal intensities. Secondly, they examined the effect of wearing compression garments on running time to exhaustion. To examine running economy participants performed 4 consecutive runs on a treadmill, with and without compression socks (15-22 mmHg), for 6 min at a recent half-marathon pace (14.8 ± 2.2 $km \cdot h^{-1}$), with 2-minute rest intervals between runs. Oxygen uptake was measured breath-by-breath during each run to examine running economy. For the second method, participants were randomly divided into 2 groups; compression socks group and control group. Participants performed a run to exhaustion on a treadmill with a gradient of 1% and at a speed of 105% of each participants' recent 10km run time (17 ± 2 $km \cdot h^{-1}$). During the run to exhaustion, biomechanical variables of ground contact time, flight time, flight height, power generated, stride length and stride frequency were measured. The results showed no effect of wearing compression socks on running economy at submaximal intensities ($P > 0.05$ $d = 0.05$). For the run to exhaustion, the results showed no effects for run duration, biomechanical variables and running economy between the compression and control groups ($P > 0.05$). However, although not statistically different, the compression socks group ran for 13% longer ($d = 0.32$) and had an 8% better running economy ($d = 0.90$) compared to the control group, for the run to exhaustion test. Stickford and colleagues (2015) also examined the effect of wearing a compression garment on running economy and kinematics at submaximal running intensities. Participants performed 2 separate running economy tests on a treadmill with and without wearing compression calf sleeves. Participants ran at 3 constant submaximal speeds of 14 $km \cdot h^{-1}$, 16 $km \cdot h^{-1}$, and 18 $km \cdot h^{-1}$ for 4-min at each speed. During each speed, running economy and biomechanical variables of ground contact time, swing time, stride length and stride frequency were measured. The results showed no effect of wearing compression calf sleeves on running economy at any of the submaximal speeds ($P > 0.05$). Furthermore, the results showed no effects for any of the kinematics variables between compression and control conditions ($P > 0.05$). Typically, a relatively small number of biomechanical scalar (spatial-temporal) variables have been examined when wearing compression garments during running such as; stride length, stride frequency, ground contact time and swing time using accelerometery (Lucas-Cuevas et al., 2015; Stickford et al., 2015). However, it may prove beneficial to examine the effect of compression garments on waveform biomechanical variables such as: ground reaction forces, joint angles, joint powers and joint moments, which have not previously been examined.

In some alternative biomechanical investigations of gait such as barefoot running, discrete outcome variables of ground reaction forces, joint angles, joint powers and joint moments undergo traditional biomechanical analysis methods using one time point of a waveform (i.e., peak knee angle), together with a statistical hypothesis test, such as a t-test or the analysis of variance (ANOVA) (Phinyomark et al., 2014, 2015). However, such methods cannot capture the complexity of these relationships between interventions (Phinyomark et al., 2018), and will often show no differences between interventions as throughout the full gait cycle significant group differences could be missed at other time points. In response to these shortcomings, advanced multivariate analysis and machine learning methods such as principal component analysis (PCA) have been employed to identify complex associations between interventions using discrete variable waveform data rather than a single time point (Bisele et al., 2017; Leporace et al., 2012; Phinyomark et al., 2014).

Some limitations exist in the published research that examines the use of compression garments on biomechanics and running economy. Firstly, in these studies the amount of compression elicited by the garments used is not measured and studies typically report manufacturer estimated pressure values (Lucas-Cuevas et al., 2015; Stickford et al., 2015; Varela-Sanz et al., 2011). However, compression garment manufacturers typically measure elicited pressures in vivo using wooden leg models which may not reflect the pressures elicited on a human leg (Partsch et al., 2006). Furthermore, Hill and colleagues (2015) found that in three commercially available compression garments, elicited pressures at the calf and quadricep were substantially lower compared to published recommendations (Watanuki & Murata, 1994). As such, if the amount of compression is not measured, it is difficult to be certain on the pressure elicited by the garment and whether the pressure is sufficient to influence biomechanics or physiology during exercise. Secondly, the type of compression garment used may heavily contribute to the reported findings. Typically, the published research that has examined the use of compression garments on biomechanics and running economy has used compression shorts, socks and calf sleeves (Borràs et al., 2011; Lucas-Cuevas et al., 2015; Stickford et al., 2015; Varela-Sanz et al., 2011).

However, the effect of full leg (ankle to hip) compression tights on these variables have had little investigation. Interestingly, Born and colleagues (2014) found that wearing compression tights which elicited pressures of 20.2 ± 4.3, 20.2 ± 4.9, 18.2 ± 4.1, 19.5 ± 5.6 and 19.9 ± 5.6 (all mmHg) at the gluteus maximus, rectus femoris, vastus lateralis, biceps femoris and gastrocnemius, respectively, reduced hip flexion ($P = 0.01$) and increased step length ($P = 0.01$) during maximal 30 m sprints. Given that tights provide compression over the knee and hip joints, there is the possibility of movement restriction at multiple joints as compared to the socks and also that there would be a substantially larger volume of the leg acted on by the compressive properties of the garments. Therefore, it may be beneficial to examine the effect of compression tights on running biomechanics. Finally, the majority of the published literature use commercially available compression garments that are typically available in generic sizing categories (i.e., extra-small, small, medium, large and extra-large) which are developed by the compression garment manufacturer as an individuals' body geometry is not known (MacRae et al., 2011). However, it has been shown that when wearing generically sized compression garments the measured pressures may vary between participants even if participants fit within the same sizing category (Brophy-Williams et al., 2015; Hill et al., 2015). To undertake a research study with sufficient reliability and validity, the intervention experienced by the participants must be the same. However, in the case of compression garment research, the use of generically sized compression garments may lead to participants experiencing large differences of elicited pressure, within the same intervention. As such, it may be beneficial to use made-to-measure compression garments which are specifically fitted to each participants' body geometry and may allow for a more consistent fit for a study population. Made-to-measure compression garments have recently been used to examine their influence on recovery from exercise (Brown et al., 2020, 2021). However, to the authors knowledge, no study has examined the effect of made-to-measure compression tights on kinematics and kinetics during running. Therefore, the aim of this study was to examine the effect of wearing made-to-measure compression garments, with different pressure profiles, on submaximal running kinetics and kinematics.

9.3 Methodology

9.3.1 Participants

Nine male, recreational runners (age 22.9 ± 2.1 years, stature 182.0 ± 5.1 cm, body mass 76.4 ± 5.6 kg) volunteered and provided informed consent to participate in the study. All participants completed a health screen questionnaire before involvement in the study, to ensure they had no medical or other conditions that would have prevented them from taking part. Participants were instructed to refrain from strenuous exercise and alcohol consumption 24 hours prior to experimental trials and to avoid caffeine consumption on the day of a trial whilst attending the laboratory at least 3 hours postprandial. The study was approved by a University Ethics Committee, (Nottingham Trent University Ethical Committee Application for Human Biological Investigation reference number: 560).

9.3.2 Experimental Design

Participants visited the laboratory on five occasions. The first visit was a familiarisation trial, which consisted of a baseline 3D scan that was subsequently used to support the manufacture of the made-to-measure compression garments for each participant. Also, during the familiarisation visit, participants performed a 30-minute run to establish a self-selected comfortable running speed for subsequent experimental trials. The subsequent four experimental trials consisted of a 5-minute warm up run, followed by a 30-minute run whilst wearing a randomly assigned made-to-measure lower body garment. During the 30-minute run, kinematics, kinetics, heart rate and rating of perceived exertion (RPE) were recorded. Prior to the 30-minute run, the pressure profile, defined as the peak pressure and pressure gradient from the distal to the proximal end of both legs, was measured for the compression garments. A different made-to-measure compression garment was worn for each experimental trial. The compression garment conditions were: 1) control, 2) asymmetrical, 3) high gradient, and 4) medium gradient (see detailed description below). Experimental trials were performed at a similar time of day and were separated by a minimum of 48 hours. All experimental trials were performed in similar environmental conditions 20.5 ± 0.8°C and 36.7 ± 5.3% relative humidity.

9.3.3 Compression Garments and 3D Scan

A detailed description of the Artec Eva 3D scanner, scanning procedure and compression garments is provided in the General Methodology (*Section 3.5.6* and *Section 3.5.7*).

Briefly, this study used made-to-measure, full leg compression tights (Kurio 3D Compression Ltd, Nottingham, UK). An Artec Eva 3D scanner (Artec Group, Luxembourg, Luxembourg) was used to capture a lower-body 3D scan performed during the familiarisation trial and used by the company to support the manufacture of the compression garments. For each trial, the compression garment worn elicited a different pressure profile. For this study, the pressure classifications used to inform the design of the compression garment interventions corresponded to UK clinical compression standards (BS-6612; 1985): Class one (14 – 17 mmHg), two (18 – 24 mmHg) and three (25 – 35 mmHg). The made-to-measure compression garments conditions were: 1) control garment, which was designed to elicit pressure below clinical standards (< 14 mmHg); 2) high gradient garment which was designed to elicit pressure within clinical standards (14 – 35 mmHg) and to include a steep pressure gradient; 3) asymmetrical garment which was designed to elicit control garment conditions in the left leg and high gradient garment conditions in the right leg; and 4) medium gradient garment which was designed to elicit pressure within clinical standards (14 – 35 mmHg) and to include a shallower pressure gradient than the high gradient garment.

9.3.4 Pressure Profile Assessment

A detailed description the of pressure monitoring device and the measurement procedure is provided in the General Methodology (*Section 3.5.2*).

Briefly, the pressure profiles of the compression garments were assessed using a Kikuhime pressure-monitoring device (MediGroup, Melbourne, Australia). Pressure elicited by the garments was measured at multiple sites on the mid-line of the posterior surface of each leg. The location of the pressure sensor measurement sites was acquired simultaneously with pressure measurements using a thirteen-camera 3D motion capture system (Qualisys AB, Göteborg, Sweden) sampling at 100 Hz. Eight reflective markers were applied to the legs, using bi-adhesive tape, to represent the line of the leg. Four markers were placed on each leg at the following landmarks: 1) the lateral malleolus (ankle); 2) the lateral femoral condyle (knee); 3) the greater trochanter; and 4) the iliac crest. The anatomical marker locations and marker placement was performed by a trained anthropometrist (ISAK level 1). The sensor of the pressure monitoring device was placed between the garment and skin interface starting from 5 cm proximal to the ankle malleolus and pulled up the posterior surface of each leg at approximately 5 cm increments. To obtain a precise location for the pressure measurements, a reflective wand marker was placed briefly on the pressure measurement site before reading the pressure. The modelled peak pressure at the ankle and pressure gradient of each compression garment for the left and right legs are displayed in **Table 9.1**. Scatter plots of the pooled pressure profile data for each garment are presented in **Appendix 7**.

Table 9.1. Peak pressure at the ankle and pressure gradient from the ankle to the gluteal fold for the left and right legs in the control, asymmetrical, high gradient and medium gradient compression garment conditions (mean ± standard deviation).

	Control		**Asymmetrical**		**High Gradient**		**Medium Gradient**	
	Peak Pressure	Pressure Gradient	Peak Pressure	Pressure Gradient	Peak Pressure	Pressure Gradient	Peak Pressure	Pressure Gradient
Left Leg (mmHg)	13.5 ± 2.3	-8.9 ± 3.5	12.7 ± 2.5	-7.5 ± 3.9	27.7 ± 2.2	-25.0 ± 4.1	25.8 ± 2.4	-18.1 ± 5.0
Right Leg (mmHg)	12.9 ± 2.6	-7.4 ± 3.0	26.3 ± 3.4	-21.9 ± 3.2	27.5 ± 1.6	-22.3 ± 3.6	26.3 ± 3.5	-16.6 ± 4.9

9.3.5 Data Acquisition

A detailed description of the kinematics and kinetics data acquisition procedure is provided in the General Methodology (*Section 3.5.4 and Section 3.5.5*).

Kinematic data were captured at 100 Hz using a thirteen-camera motion capture system, (Oqus, Qualisys, Gothenburg, SE). To define segments, a full body marker set was used (**Figure 9.1**) and 14 mm reflective markers were applied using bi-adhesive tape to the participants' head, upper limbs, trunk (Leardini et al., 1999), and lower limbs (Cappozzo et al., 1995). In addition, four tracking clusters were placed on the lateral aspect of each shank and thigh. Following marker placement, a static trial was captured with the participant standing in the anatomical position, which was subsequently used for segment definition.

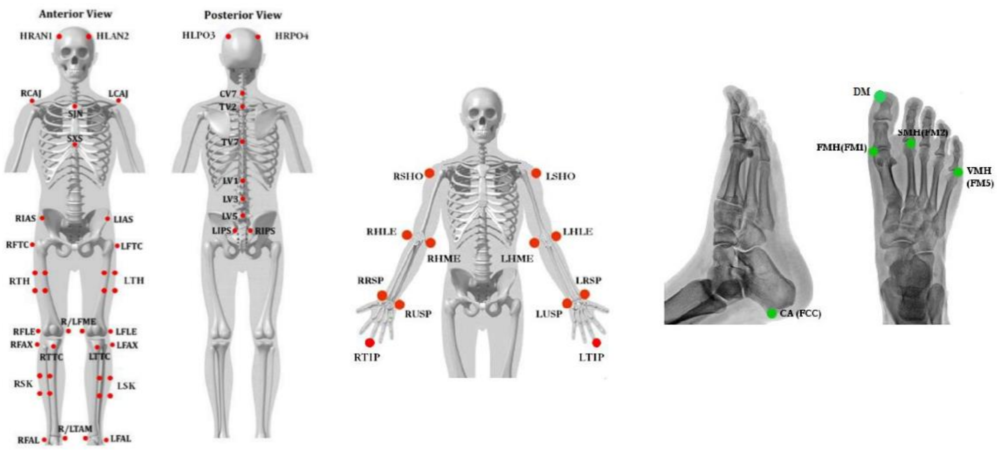


Figure 9.1. Marker model adopted in the study to represent body segments.

For the 30-minute run, participants ran on a AMTI instrumented treadmill (AMTI, Watertown, MA, USA). The instrumented treadmill consisted of two, inline, synchronized treadmill belts with an underlying strain gauge force platform under each belt. The strain gauge force platforms were used to obtain ground reaction force (GRF) data which was measured at 1000 Hz. Kinematic and kinetic data were recorded simultaneously for the last 30 seconds of each 5-minute interval during the 30-minute run. Participants were instructed to run at a self-selected comfortable running speed which reflected a rating of perceived exertion (RPE) of 11 or 12, an intensity less than “somewhat hard” (13) (Borg, 1982). The running speed was determined during the familiarisation trial and once the participant selected their running speed, it remained identical for all experimental trials. The running speed during the study was 2.5 ± 0.3 m/s (mean ± standard deviation).

9.3.6 Data Processing

From each 30-second data capture, a minimum of eight consecutive gait cycles were selected for analysis. A gait cycle started at the right foot heel strike on the force platform and ended at the consecutive heel strike of the same foot. Raw marker trajectories were labelled as anatomical landmarks using Qualisys software (Qualisys Track Manager version 2019.3, Gothenburg, Sweden). The labelled trajectories and raw force data were exported as .c3d files and processed using Visual 3D (C Motion, Inc., Germantown, MD, USA). Kinematic and GRF data were filtered using a 4th order Butterworth bidirectional low pass filter with 6 Hz and 25 Hz cut-off frequencies. All data were normalised to 100% of the gait cycle and interpolated using a cubic-spline algorithm to give kinematics at each percentile of the gait cycle. Gait events of foot ground contact and foot ground departure for the left the right leg were defined using an event detection algorithm (Stanhope et al., 1990). A cardan sequence was applied to define the order of rotations to calculate joint kinematics (i.e., flexion-extension, abduction-adduction, internal-external rotation). Joint powers (W.kg^{-1}), joint moments (N.m.kg^{-1}), joint angles (°) and joint angular velocities (°/s) were calculated for the left and right ankle, knee and hip joints, in the vertical anatomical plane. Vertical, anterior/posterior, and medial/lateral GRF's were calculated from the net GRF using the sum of the front and rear force platforms on the instrumented treadmill and normalised to the participants body weight (BW) (**Table 9.2**). Stride frequency (strides/min), stride length (metres), stride duration (seconds), swing time (seconds) and stance time (seconds) were also measured (**Table 9.3**). All variables were calculated for the left and right legs using Visual 3D. The processed joint powers, joint moments, joint angles, joint angular velocities, GRF's, stride frequency, stride length, stride duration, swing time and stance time data were exported to separate Excel files which included: 1) temporal waveform variable data for the left leg, 2) temporal waveform variable data for the right leg, 3) spatial-temporal scalar data for both left and right legs. In the temporal waveform variable Excel files, each column represented a variable, whilst each row represented a data point in time, normalised to 101 data points for 100% of the gait cycle. The Excel spreadsheets containing the variable signals were imported into MATLAB R2020a (MathWorks Inc., MA, USA) for analysis.

Table 9.2. Temporal waveform biomechanical variables examined in the study.

No.	Temporal Waveform Variables	Measurement Units
1	Ground Reaction Force (Anterior-posterior)	Newtons (BW)
2	Ground Reaction Force (Medio-lateral)	Newtons (BW)
3	Ground Reaction Force (Vertical)	Newtons (BW)
4	Hip Power (Sagittal)	Watts/Kilogram ($W.kg^{-1}$)
5	Hip Moment (Sagittal)	Newton Metres/Kilogram ($N.m.kg^{-1}$)
6	Hip Angle (Sagittal)	Degrees (˚)
7	Hip Angular Velocity (Sagittal)	Degrees/Second (˚/sec)
8	Knee Power (Sagittal)	Watts/Kilogram ($W.kg^{-1}$)
9	Knee Moment (Sagittal)	Newton Metres/Kilogram ($N.m.kg^{-1}$)
10	Knee Angle (Sagittal)	Degrees (˚)
11	Knee Angular Velocity (Sagittal)	Degrees/Second (˚/sec)
12	Ankle Power (Sagittal)	Watts/Kilogram ($W.kg^{-1}$)
13	Ankle Moment (Sagittal)	Newton Metres/Kilogram ($N.m.kg^{-1}$)
14	Ankle Angle (Sagittal)	Degrees (˚)
15	Ankle Angular Velocity (Sagittal)	Degrees/Second (˚/sec)

Table 9.3. Spatial-temporal scalar biomechanical variables examined in the study.

No.	Scalar Kinematic Variables	Measurement Units
1	Stride Frequency	Strides/Minute (strides/min)
2	Stride Length	Metres (m)
3	Stride Duration	Seconds (sec)
4	Swing Time	Seconds (sec)
5	Stance Time	Seconds (sec)

9.3.7 Heart Rate and Rating of Perceived Exertion

Heart rate was measured using a chest mounted heart rate monitor (Polar S610i, Polar Electro OY, Kembele, Finland) and was recorded at rest and at six, five-minute intervals during the 30-minute run. Rating of perceived exertion was assessed using a visual 6 (no exertion) – 20 (maximal exertion) scale (Borg, 1982). Rating of perceived exertion was recorded at rest and at six, five-minute intervals during the 30-minute run. Participants verbally stated their rating of perceived exertion from a scale positioned in their view.

9.3.8 Statistical Analysis

Linear regression was used to determine the peak pressure at the ankle and the pressure gradient of the left and right legs under each compression garment condition. Principal component analysis (PCA) was conducted to examine differences of running kinematic and kinetic variables of GRF, joint power, joint moment, joint angle and joint angular velocity between compression garment conditions during the 30-minute run. Principal component analysis was adopted in this study as it is an unsupervised algorithm which performs data reduction of input variables in large data sets such as that of the current study. Furthermore, PCA selects features within the data that hold the greatest variance (selection of only important data), which is ultimately used to determine the variation (differences) between variables and experimental conditions. When conducting PCA, the data is presented in a new coordinate system which captures the maximum variance of a data set (Badesa et al., 2014; Dillmann et al., 2014). Principal component analysis is conducted using covariance or correlation matrices. However, given that the correlation matrix is typically used when the variables have different measurement units, this approach was used in the current study and the waveform data that were used for PCA were normalised to units.

For the PCA, differences between conditions are represented using scatter plots to highlight any clustering of the data. Where clusters are separated based on condition, it can indicate an effect of the condition. In contrast, the absence of clustering by condition indicates no difference between conditions. Eigen spectra of PCA, in the form of bar figures were also produced and show the weighing of variables towards each principal component. The magnitude of eigen spectra demonstrates the contribution of a variable to the classification between conditions. The principal components (PC) were ordered by decreasing variance such that the majority of variation in the data was explained by the first. The first four PC's were selected for graphical evaluation of any clustering. Fifteen temporal running gait waveform variables were examined for the left and right legs. The PCA was used to establish differences between: 1) compression garment conditions, 2) left and right legs, and 3) time points (5 to 30 min).

A two-way repeated measures analysis of variance (ANOVA) was conducted to compare differences between garment conditions for spatial-temporal scalar variables of stride length, stride frequency, stride duration, swing time and stance time for the left and the right legs. Significant effects were further analysed using a Bonferroni post-hoc test. Effect sizes were calculated as partial eta squared (ηp^2) and interpreted as 0.01 = small, 0.06 = medium and 0.14 = large (Cohen, 1988). A significance level of $P < 0.05$ was applied throughout.

9.4 Results

Principal Component Analysis (PCA)

The PCA outcomes are shown for the first four PC's, where each view represents two dimensions with a different PC representing each dimension. The PCA was used to determine differences between garment conditions (control, asymmetrical, high gradient and medium gradient), legs (left and right) and time points (5, 10, 15, 20, 25 and 30 min). The PCA outcomes for the discrimination between conditions for all nine participants are illustrated in **Figure 9.2**, **Figure 9.4**, **Figure 9.6** and **Figure 9.8**. There was no consistent obvious classification evident from clustering of data points for compression garment conditions, left and right legs or time points. Some PC pairs did display clustering and warrant further description (see below).

PC1 x PC2

The PCA outcomes between PC1 and PC2 demonstrated a clustering of one cloud in the horizontal axis (PC1) but some data for the high gradient and asymmetrical garments clustered to the right of the cloud (see data inside black oval, **Figure 9.2**). The Eigen spectrum of PC1 for the temporal waveforms highlighted variables of vertical GRF and anterior-posterior GRF (numbers 1 and 3) contributed to the greatest variance (**Figure 9.10**). However, not all data within a garment condition clustered together, rather smaller clusters within a garment condition were visible. As such, it is not possible to infer a strong condition specific effect. When data points were labelled according to their participant there was no clear clustering of data to indicate individual participant differences (**Figure 9.3**). There was no clustering in the vertical axis (PC2). Therefore, in general, there was no clustering associated with garment conditions, legs or time points.

PC1 x PC3

The PCA outcomes between PC1 and PC3 demonstrated a clustering of one cloud in the horizontal axis (PC1) but some data for the high gradient and asymmetrical garments clustered to the right of the cloud (see data inside black oval, **Figure 9.4**). The Eigen spectrum of PC1 for the temporal waveforms highlighted variables of vertical GRF and anterior-posterior GRF (numbers 1 and 3) contributed to the greatest variance (**Figure 9.10**). However, not all data within a garment condition clustered together, rather smaller clusters within a garment condition were visible. As such, it is not possible to infer a strong condition specific effect. When data points were labelled according to their participant (**Figure 9.5**), there was no clear clustering of data to indicate individual participant differences. There was no clustering in the vertical axis (PC3). Therefore, in general, there was no clustering associated with garment conditions, legs or time points.

PC2 x PC3

The PCA outcomes between PC2 and PC3 demonstrated clustering of two separate clouds in the vertical axis (PC3) (**Figure 9.6**). The Eigen spectrum of PC3 for the temporal waveforms highlighted variables of ankle, knee and hip joint angular velocity (numbers 7, 11 and 15) contributed to the greatest variance (**Figure 9.10**). However, within the two separate clouds, there were no garment condition clusters. As such, it is not possible to infer a strong condition specific effect. When data points were labelled according to their participant (**Figure 9.7**), there was no clear clustering of data to indicate individual participant differences. There was no clustering in the horizontal axis (PC2). Therefore, in general, there was no clustering associated with garment conditions, legs or time points.

PC2 x PC4

The PCA outcomes between PC2 and PC4 showed no clustering in the horizontal axis (PC2) or the vertical axis (PC4) (**Figure 9.8**). When data points were labelled according to their participant, there was also no clustering of data to indicate individual participant differences (**Figure 9.9**). Overall, there was no clustering associated with garment conditions, legs or time points.

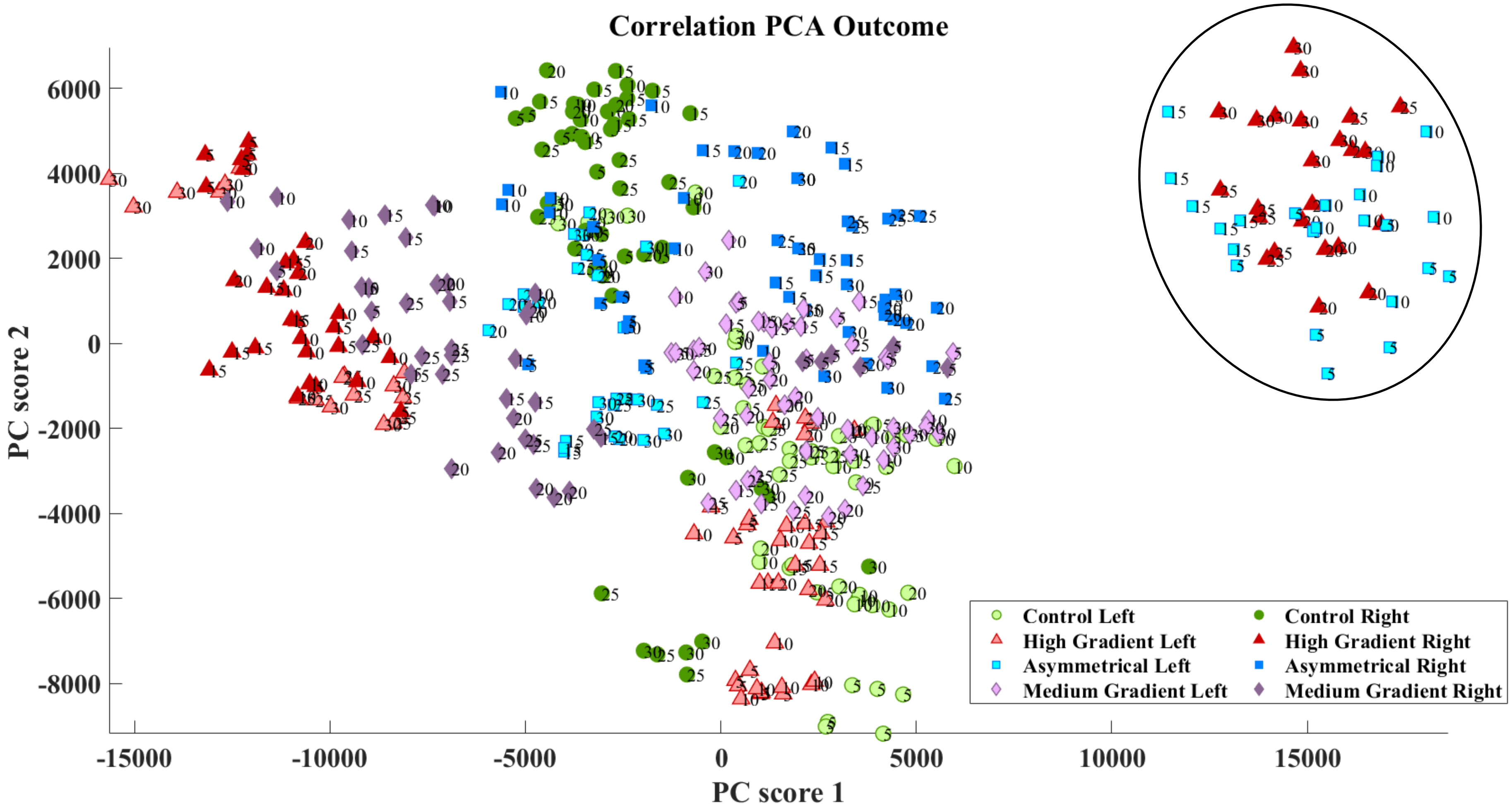


Figure 9.2. PCA outcome comparing between garment conditions, left and right legs and time points using temporal waveforms. The number to the right of each data point represents an individual time point (5-30 min). The black oval represents possible clustered data.

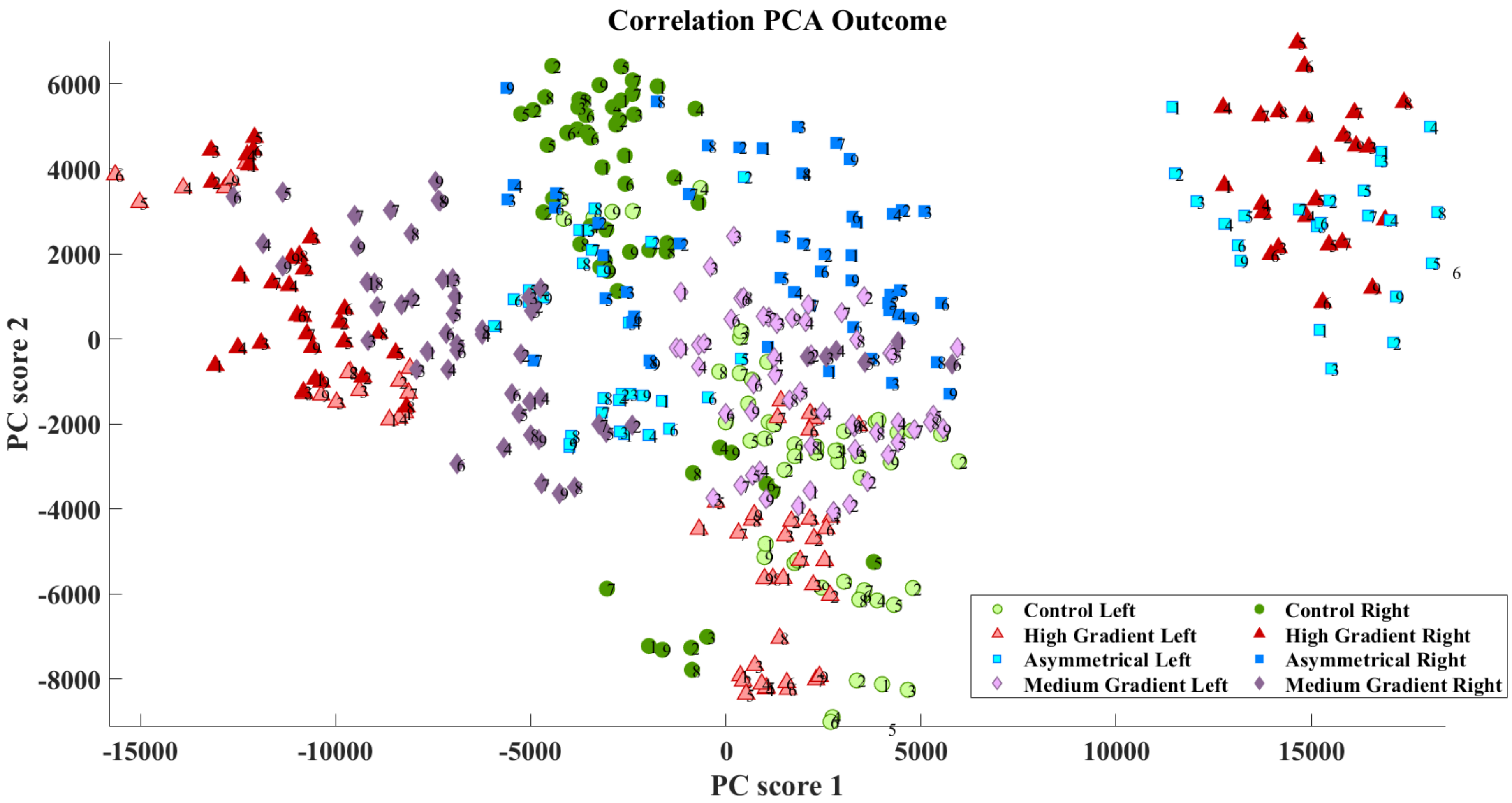


Figure 9.3. PCA outcome comparing between garment conditions, left and right legs and individual participants using temporal waveforms. The number to the right of each data point represents an individual participant (1-9).

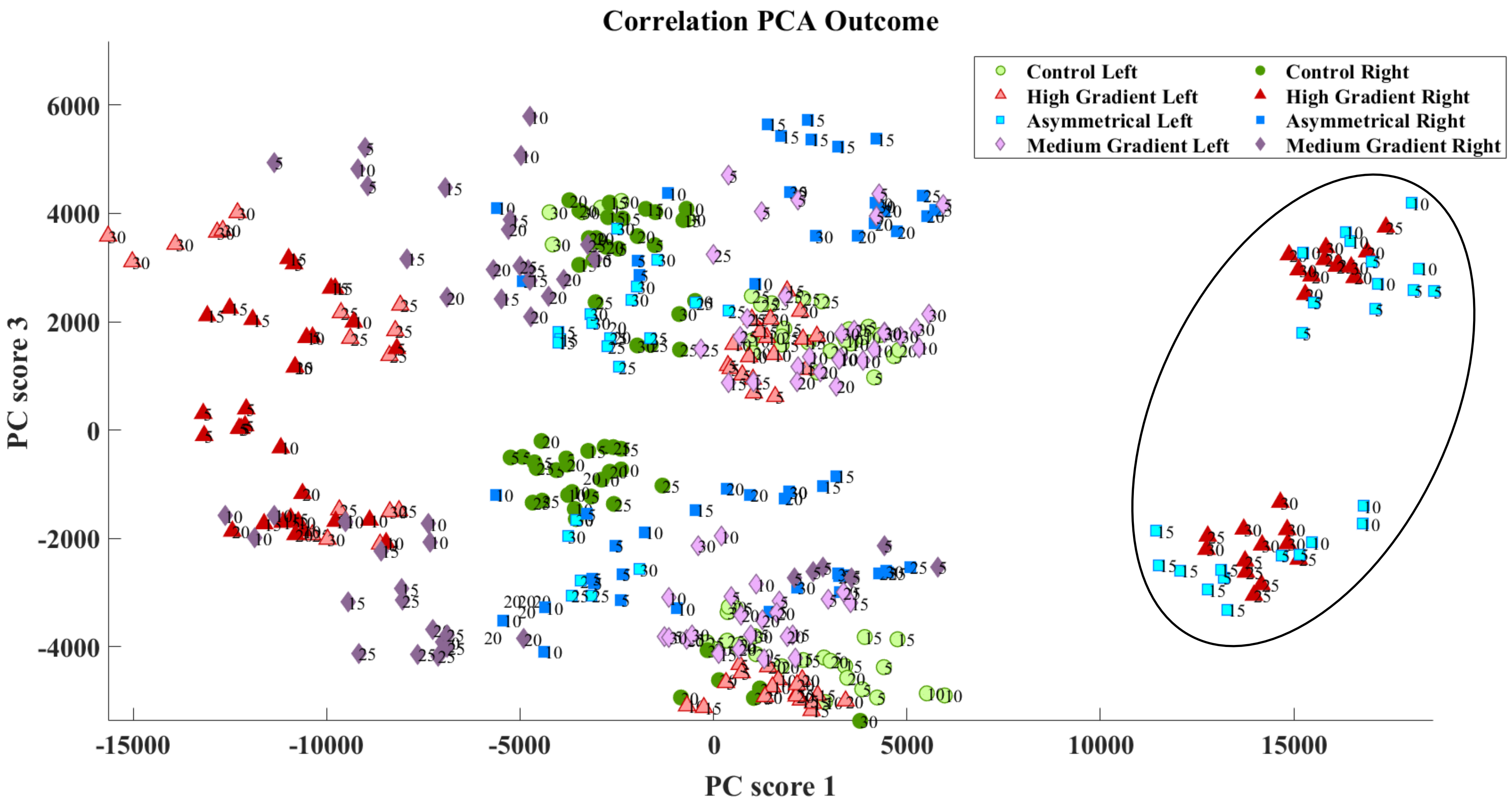


Figure 9.4. PCA outcome comparing between garment conditions, left and right legs and time points using temporal waveforms. The number to the right of each data point represents an individual time point (5-30 min). The black oval represents possible clustered data.

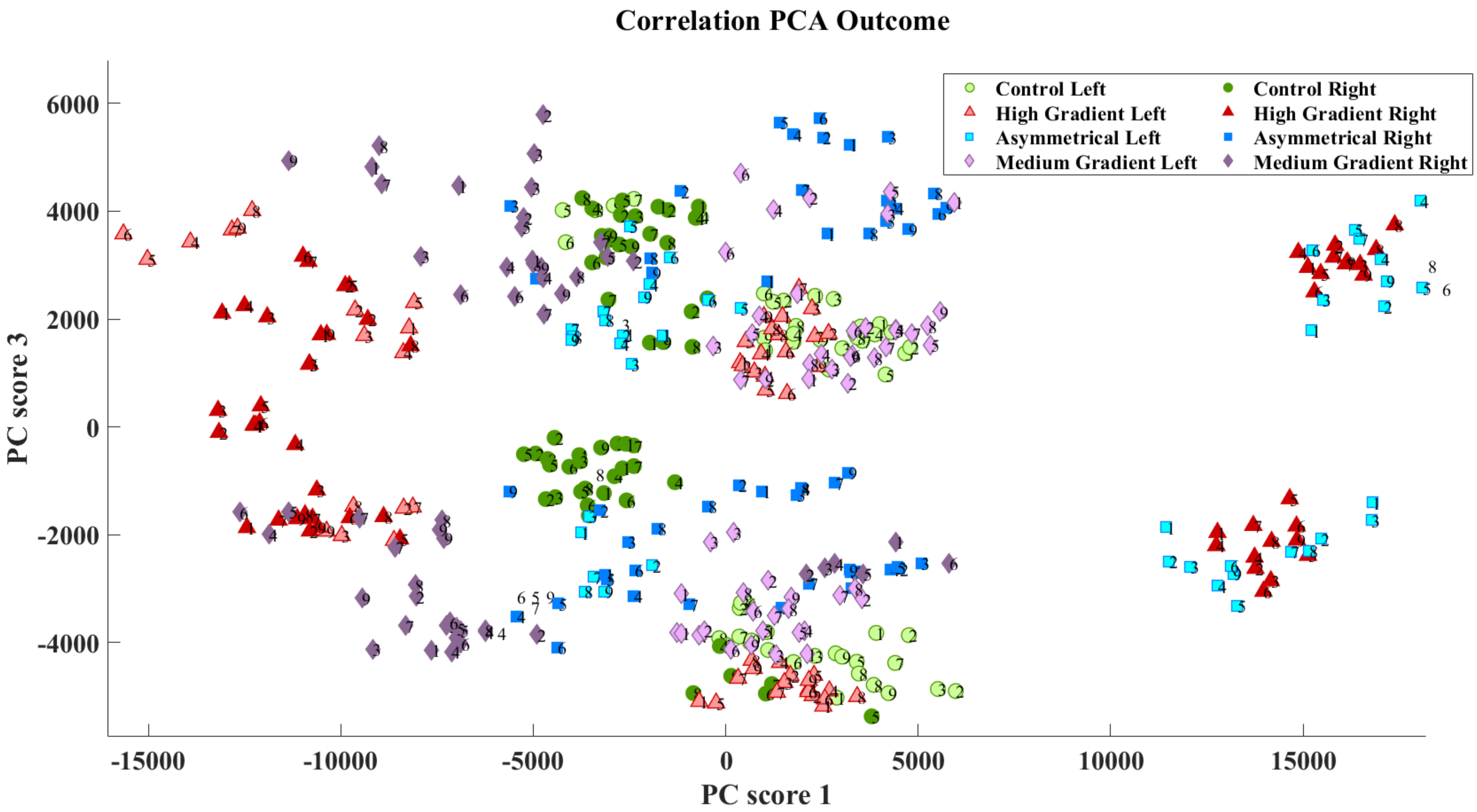


Figure 9.5. PCA outcome comparing between garment conditions, left and right legs and individual participants using temporal waveforms. The number to the right of each data point represents an individual participant (1-9).

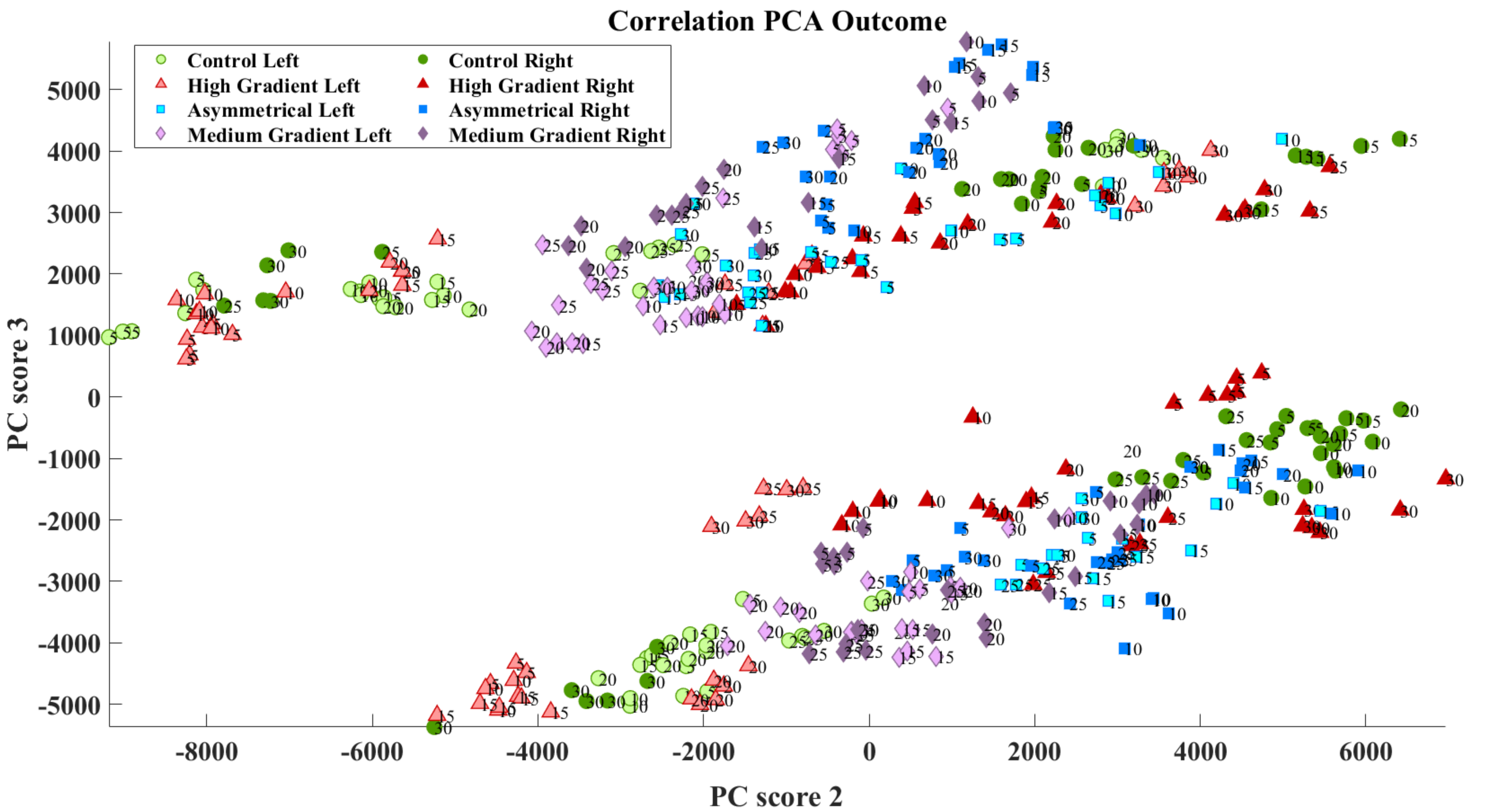


Figure 9.6. PCA outcome comparing between garment conditions, left and right legs and time points using temporal waveforms. The number to the right of each data point represents an individual time point (5-30 min).

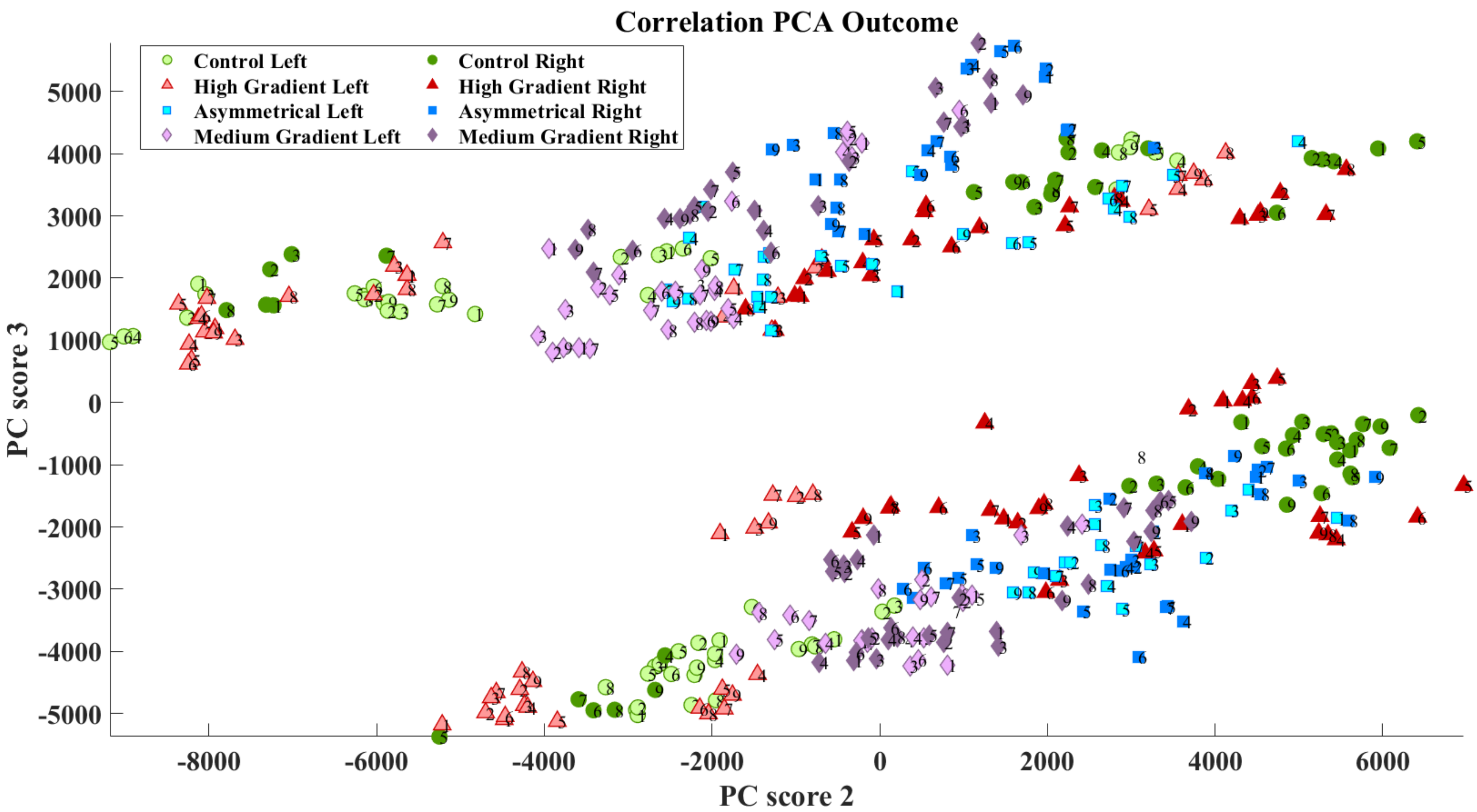


Figure 9.7. PCA outcome comparing between garment conditions, left and right legs and individual participants using temporal waveforms. The number to the right of each data point represents an individual participant (1-9).

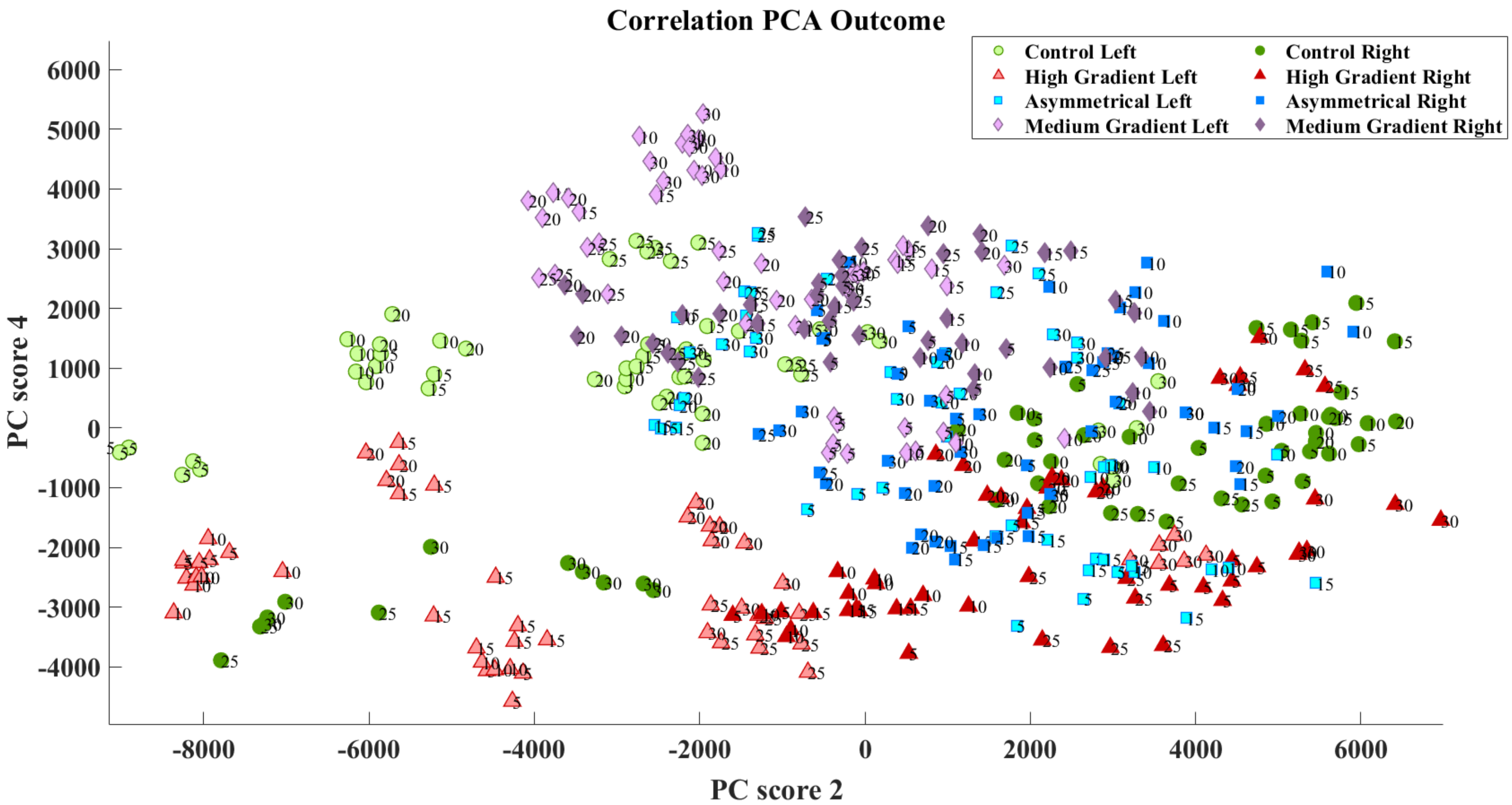


Figure 9.8. PCA outcome comparing between garment conditions, left and right legs and time points using temporal waveforms. The number to the right of each data point represents an individual time point (5-30 min).

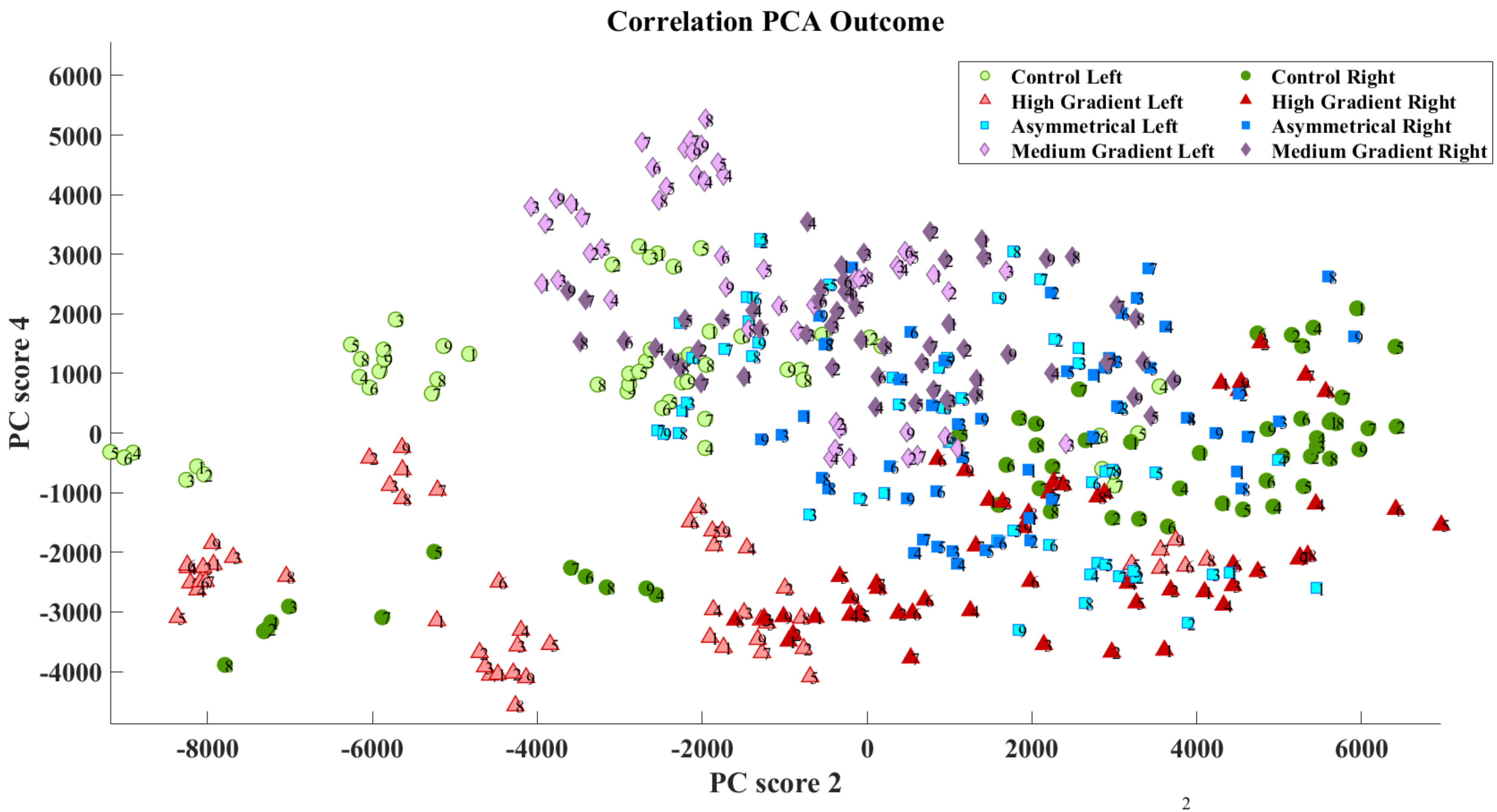


Figure 9.9. PCA outcome comparing between garment conditions, left and right legs and individual participants using temporal waveforms. The number to the right of each data point represents an individual participant (1-9).

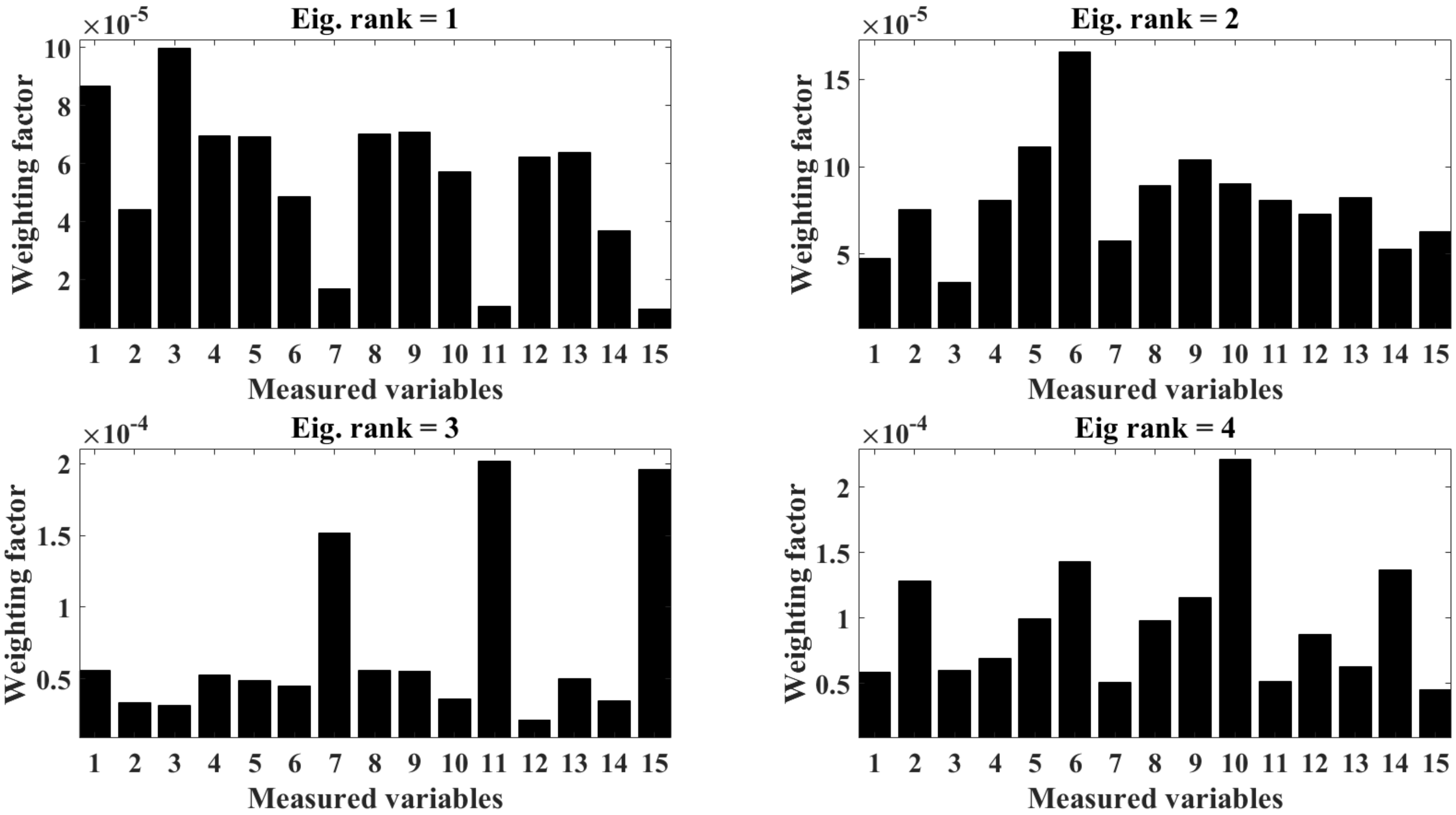


Figure 9.10. Eigen spectra for the PCA outcomes which identifies the variables (1-15) which cause the greatest variance within the data. Variables with large weighting of the variance display a larger value on the bar figures.

Spatial-Temporal Scalar Running Data

A two-way repeated measures ANOVA revealed that there were no condition, time or interaction effects for stride frequency, stride length, stride duration, swing time and stance time between the control, asymmetrical, high gradient and medium gradient garment conditions during the 30-minute run ($P > 0.05$), (**Table 9.4** and **Table 9.5**)

Table 9.4. Pooled spatial-temporal scalar running data of stride frequency, stride length, stride duration, swing time and stance time in each compression garment condition for the *left leg* during the 30-minute run (mean ± standard deviation).

	Control	Asymmetrical	High Gradient	Medium Gradient
Stride Frequency (strides/min)	80.59 ± 3.92	80.19 ± 3.79	80.09 ± 3.88	81.14 ± 3.92
Stride Length (m)	1.86 ± 0.27	1.87 ± 0.27	1.87 ± 0.27	1.85 ± 0.27
Stride Duration (sec)	0.75 ± 0.04	0.75 ± 0.04	0.75 ± 0.04	0.74 ± 0.04
Swing Time (sec)	0.47 ± 0.04	0.48 ± 0.04	0.48 ± 0.04	0.47 ± 0.05
Stance Time (sec)	0.27 ± 0.02	0.27 ± 0.03	0.27 ± 0.03	0.27 ± 0.02

Table 9.5. Pooled spatial-temporal scalar running data of stride frequency, stride length, stride duration, swing time and stance time in each compression garment condition for the *right leg* during the 30-minute run (mean ± standard deviation).

	Control	Asymmetrical	High Gradient	Medium Gradient
Stride Frequency (strides/min)	80.60 ± 3.97	80.19 ± 3.76	80.04 ± 3.91	81.11 ± 3.92
Stride Length (m)	1.86 ± 0.27	1.87 ± 0.27	1.87 ± 0.27	1.85 ± 0.27
Stride Duration (sec)	0.75 ± 0.04	0.75 ± 0.04	0.75 ± 0.04	0.74 ± 0.04
Swing Time (sec)	0.47 ± 0.04	0.47 ± 0.04	0.48 ± 0.04	0.47 ± 0.05
Stance Time (sec)	0.27 ± 0.02	0.27 ± 0.02	0.27 ± 0.02	0.27 ± 0.03

Heart Rate

A two-way repeated measures ANOVA revealed an effect of condition for heart rate ([$F(3, 24) = 6.076$, $P = 0.003$, $\eta p^2 = .432$]. Pairwise comparisons showed that heart rate was greater in the control garment (136 ± 32 bpm) compared to the medium gradient garment (130 ± 31 bpm, $P = 0.011$). Heart rate was also greater in the control garment compared to the high gradient garment (131 ± 30 bpm, $P = 0.046$). A time effect was evident as participants heart rate increased from baseline during the 30 minute-run [$F(6, 48) = 441.041$, $P = 0.001$, $\eta p^2 = .982$]. There was no interaction effect [$F(18, 144) = .529$, $P = 0.940$, $\eta p^2 = .062$], (**Table 9.6**)

Rating of Perceived Exertion

For RPE, there was no effect of condition [$F(3, 24) = 1.683$, $P = 0.197$, $\eta p^2 = .174$]. A time effect was evident as participants RPE increased from baseline to post run [$F(6, 48) = 88.188$, $P = 0.001$, $\eta p^2 = .917$]. There was no interaction effect [$F(18, 144) = 1.187$, $P = 0.279$, $\eta p^2 = .129$], (**Table 9.7**).

Table 9.6. Heart rate (bpm) at rest and at each 5-minute interval during the 30-minute run in each garment condition (mean ± standard deviation).

	Control	**Asymmetrical**	**High Gradient**	**Medium Gradient**
Baseline	73 ± 17	69 ± 11	65 ± 13	65 ± 9
5 min	138 ± 17	137 ± 14	136 ± 15	134 ± 18
10 min	144 ± 20	141 ± 15	140 ± 17	138 ± 18
15 min	146 ± 20	144 ± 16	142 ± 17	140 ± 18
20 min	150 ± 20	144 ± 13	144 ± 17	142 ± 18
25 min	151 ± 20	146 ± 16	146 ± 17	144 ± 19
30 min	153 ± 20	149 ± 18	147 ± 20	144 ± 18

Table 9.7. Rating of perceived exertion (RPE) at rest and at each 5-minute interval during the 30-minute run in each garment condition (mean ± standard deviation).

	Control	**Asymmetrical**	**High Gradient**	**Medium Gradient**
Baseline	6 ± 0	6 ± 0	6 ± 0	6 ± 0
5 min	10 ± 2	10 ± 2	9 ± 2	9 ± 2
10 min	10 ± 1	10 ± 1	10 ± 1	10 ± 1
15 min	11 ± 1	11 ± 1	11 ± 1	11 ± 1
20 min	12 ± 1	11 ± 1	11 ± 1	11 ± 1
25 min	12 ± 1	11 ± 1	12 ± 1	12 ± 1
30 min	12 ± 1	12 ± 1	12 ± 1	12 ± 1

9.5 Discussion and Conclusion

This study aimed to examine the effect of wearing made-to-measure compression garments, with different pressure profiles, on submaximal running kinetics and kinematics. The main findings were that PCA did not highlight any consistent clustering of temporal waveform kinematic and kinetic data by garment conditions, legs or time points. This indicates that the pressure profile elicited by the made-to-measure compression garments had no effect on running kinematics and kinetics. Furthermore, no differences were revealed between compression garment conditions for spatial-temporal scalar biomechanical variables.

This study is the first to employ PCA to investigate the effect of wearing made-to-measure compression garments on kinematic and kinetic waveforms of running gait. Furthermore, this study has found that the compression garment pressure profiles utilised in this study have no effect on waveform biomechanical variables of GRF's, joint angles, joint powers, joint moments and joint angular velocities during running. In the published literature, the effects of wearing compression garments on spatial-temporal variables has been examined during running exercise. Both Stickford and colleagues (2015) and Varela-Sanz and colleagues (2011) found that ground contact time, swing time, stride frequency and stride length were not influenced by the use of compression garments during running exercise. Such results are consistent with those found in the current study as spatial-temporal variables of stride length, stride frequency, stride duration, swing time and stance time during running were not influenced using compression garments.

Interestingly, the current study indicated that mean heart rate was lower when wearing the medium gradient garment (130 ± 31 bpm) and high gradient garment (131 ± 30 bpm) compared to the control garment (136 ± 32 bpm) when running at 2.5 ± 0.3 m/s (9 ± 1.1 $km{\cdot}h^{-1}$). The reduction of heart rate when wearing compression garments is consistent with the published literature. Lovell and colleagues (2011) found that during two separate active recovery runs at 6 $km{\cdot}h^{-1}$, heart rate was lower by four and five beats per minute when wearing compression garments (tights) compared to regular running shorts. However, these results were not replicated when running at the faster velocity of 10 $km{\cdot}h^{-1}$. Mizuno and colleagues (2017) found that during a 120-minute uphill running protocol at 60%

VO_{2max} (running velocity of 6.6 ± 0.5 km·h^{-1}), heart rate was lower when wearing the 'medium pressured' compression tights (MED) eliciting high graduated pressure (calf: 17.9 ± 3.8 mmHg, and thigh: 16.1 ± 2.0 mmHg) compared to the 'low pressured' control compression tights (CON) eliciting minimal pressure (calf: 3.0 ± 1.6 mmHg, and thigh: 4.4 ± 1.2 mmHg). Mean heart rate was lower in the MED trial (0 – 60 min: 158 ± 4 bpm, 60 – 120 min: 167 ± 4 bpm) compared with the CON trial (0 – 60 min: 164 ± 4 bpm, 60–120 min: 177 ± 4 bpm) in both the first and second half of the run respectively. Conversely, a study by Bringard and colleagues (2006) that used faster running speeds showed no effect of wearing compression garments on heart rate, when wearing compression tights as compared to conventional running shorts (control) when running at velocities of 10, 12, 14, and 16 km·h^{-1}. Given that studies which have used running velocities below 10 km·h^{-1} have shown a reduction in heart rate when wearing compression garments and others have shown no differences when the running speed was 10 km·h^{-1} and above, there may be a speed related response associated with such reductions in heart rate.

The current study also highlighted a potential dose response between the elicited pressure and reduction of heart rate. The medium gradient garment elicited the highest pressures across the whole leg and revealed the largest reduction of heart rate. This was followed by the high gradient garment which provided similar peak pressure to the medium gradient garment but a steeper pressure gradient, thus, lower overall elicited pressure. Finally for the asymmetrical garment, where the pressure profile on the right leg was identical to the high gradient garment and the pressure profile on the left leg was identical to the control garment (essentially half the lower body experienced graduated compression), there was a 3 bpm lower heart rate compared to the control garment, although this was not statistically significant. Previous research has also found a dose response when wearing compression garments for other variables. Dermont and colleagues (2015) found that when wearing 15 differently pressured compressive calf sleeves, there was positive linear relationship between calf tissue oxygen saturation and increased garment pressure. The largest increase of tissue oxygen saturation occurred when wearing garments which elicited pressure at the calf of 36.5 – 39.5 mmHg (above UK clinical compression standards). The results of the current study suggest that a greater sum of pressure acting along the legs was associated with a beneficial reduction of heart rate during running exercise. A particular mention is warranted regarding the benefits of graduation, since in this study we have found that for a shallower pressure gradient (describing the pressure reduction from the distal to proximal ends of the leg), there was a beneficial reduction in heart rate. However, future research is required to independently investigate the relationship between net pressure acting on the legs and the effect of a pressure gradient which has been a founding principal of compression garments to help overcome hydrostatic pressure.

Compression garments provide a mechanical pressure on the body, thereby compressing and perhaps stabilizing underlying tissues (MacRae et al., 2011). It has been purposed that the compression over joints may restrict range of motion (Borràs et al., 2011). Indeed, Doan and colleagues (2003) found a decreased hip flexion angle during sprinting and a lower squat depth during a vertical jump exercise. These results are supported by Bernhardt & Anderson (2005) who found a decreased range of motion during vertical jump exercise. In the current study, range of motion, in terms of ankle, knee and hip joint angles, were not different between garment conditions. Therefore, our results suggest that the lower heart rate found when wearing the high gradient and medium gradient compression garments may be caused by improved cardiovascular responses rather than changes to running biomechanics. The reduction of heart rate when wearing compression garments is purposed to be caused by enhanced central haemodynamic responses and increased blood flow leading to increased venous return (Lee et al., 2020). However, it is possible that at higher running velocities, the work required by the heart to perform vigorous exercise outweighs any beneficial physiological effects promoted by compression garments. MacRae and colleagues (2011) highlighted that a potential factor for lower heart rate when wearing compression garments during exercise was augmented stroke volume associated with increased venous return. Therefore, considering that venous return would be augmented depending on exercise intensity, the influence of compression garments on haemodynamic responses may be trivial during intensive exercise (Mizuno et al., 2017).

Limitations

In the current study kinematic and GRF data were filtered using a 4th order Butterworth bidirectional low pass filter with 6 Hz and 25 Hz cut-off frequencies. The cut-off frequencies were identified using a residual analysis method. However, Kristianslund and colleagues (2012) demonstrated that joint moments are particularly affected by the cut-off frequency used and they found significantly different knee and hip joint moments when using 10 and 15 Hz cut-off frequencies. The authors suggested that caution is needed when identifying cut-off frequencies for joint moment data. Therefore, in the current study we must acknowledge that the cut-off frequency for the kinematics data may be too low for joint moment data and as a result, artefacts within the data may be present.

In conclusion, the current study demonstrated that made-to-measure compression garments, which elicited different pressure profiles, had no effect on running kinematics on kinetics. However, heart rate was reduced by 5 and 6 bpm when wearing a high gradient and medium gradient compression garment respectively, compared to a control garment, which may be the result of enhanced haemodynamics.

Chapter 10: General Discussion and Conclusions

10.1 Summary

Over the past two decades, the use of sports compression garments has become prevalent among athletes in various sporting disciplines as this type of clothing is seen as a potential ergogenic aid, which may improve exercise performance (Mizuno et al., 2017), and also may enhance the process of recovery (MacRae et al., 2011). Typically, research studies have used standard sized garments (i.e., small, medium and large) when examining the effect and efficacy of compression garments on exercise performance and recovery (MacRae et al., 2011). However, it has been shown that the use of standard sized compression garments may not provide appropriate pressures and may elicit different pressures between individuals, even if individuals fit within the same sizing category (Brophy-Williams et al., 2015; Hill et al., 2015). Another key problem with previous research work is that often studies do not directly measure the pressures exerted by the garments they are examining. Consequently, there is a great deal of equivocality in the current research literature as to whether compression garments can or cannot improve exercise performance and / or enhance the process of recovery. And, perhaps, it is not surprising that this is the case, given the points noted above. Therefore, the development and application of made-to-measure compression garments with prescribed pressure profiles (appropriately established and confirmed), and optimal fitting, may have substantial utility within research and ultimately within sport. Furthermore, the effect of wearing compression garments on running biomechanics and thermal responses has received limited investigation and no study has examined the use of made-to-measure compression garments within such areas.

Therefore, the work within this PhD thesis aimed: 1) to develop a novel methodology of measuring the elicited pressures of sports compression garments and to examine if the aspect of the leg pressure measurements are made on influences pressure profiles (peak pressure and pressure gradient); 2) to examine if it was possible to make made-to-measure compression garments that elicit pressures that fit within and below UK clinical compression standards and provide the same fit between participants; 3) to examine the reliability (test-retest, intra- and inter-day) and validity of a 3D scanning system for measuring leg volume (this 3D scanning approach was also used to support the manufacture of the made-to-measure compression garments); 4) to develop a methodology of extracting temperature data from thermal images (thermograms) and to examine the sensitivity of skin temperature outputs to changes of the thermogram segment region of interest border zone and segment region of interest size; and 5) to examine the effect of wearing made-to-measure compression garments on running biomechanics, thermal responses and comfort perception.

The main findings of the thesis are summarised below:

- A novel methodology of measuring compression garment pressures using multiple pressure measurements (11 ± 1) on the same aspect of the leg (posterior) was developed. Pressure values recorded on the posterior and anterior aspect of the whole leg length typically elicited higher pressures compared to values recorded on the medial and lateral aspect of the leg. The variation of pressure along the whole length of the leg was smallest when measurements were made on the posterior aspect of the leg which is likely due to the consistent tissue structure and curvature found here. When pressure values of the novel method (posterior aspect) were compared to an established method typically used in the published research literature, the results showed that the peak pressure at the ankle was higher when using the novel method (27.5 ± 2.2 mmHg) compared to the established method (19.8 ± 3.0 mmHg), when pressures were measured over the whole length of the leg , and the pressure gradient was also steeper using the novel method (-21.7 ± 2.9 mmHg) compared to the established method (-11.2 ± 4.5 mmHg). The novel method includes more pressure measurements (11 ± 1) compared to the established method (6) and provides a more informative and better reflection of the pressure profile elicited by a compression garment. Therefore, it is recommended that pressure measurements should be made on the posterior aspect of a leg using the novel methodology developed in this thesis (Chapter 4).
- Made-to-measure compression garments can be made, using 3D scanned geometry of the participants' lower body, to elicit prescribed pressures within and below UK clinical compression standards and elicit equivalent pressure profiles (peak pressure and pressure

gradient) between different participants. This was demonstrated as the high gradient garment elicited peak pressure of 27.7 ± 2.2 mmHg, and 27.5 ± 1.6 mmHg for the left and right legs respectively (within clinical standards). The corresponding values for the control garment were 13.5 ± 2.3 mmHg, and 12.9 ± 2.6 for the left and right legs respectively (below clinical standards), (Chapter 5).

- The use of three-dimensional scanning to measure leg volume had excellent test-retest reliability and the mean systematic bias and limits of agreement between duplicate leg volume measurements were 1% and 4% for the lower leg, and ±1% and 4% for the upper leg respectively. The corresponding values for the water displacement method were 1% and 6% for the lower leg, and 1% and 5% for the upper leg respectively. Therefore, 3D scanning may be a useful, non-invasive method of measuring leg volume (Chapter 6).
- A novel methodology was developed to standardise the selection of regions of interest on thermograms to subsequently extract skin temperature data, using reference markers placed on the body. In this methodology, reductions to the segment border zone and segment size (length) were performed to examine: 1) the effect of the 'cold' border zone on skin temperature outputs; and 2) the effect of reducing the segment region of interest size (length) on skin temperature outputs. This approach highlighted that the 'cold' border which surrounds the imaged object (leg) reduced mean skin temperature by up to 0.24°C when included within the analysis, which may influence the accuracy of the skin temperature measurements. This evidences the importance of border removal when selecting regions of interest, which is not currently considered in the published research literature. When changes to the segment size (length) were performed, skin temperature was influenced by the underlying tissues with bone typically causing reductions in skin temperature (Chapter 7). This novel method should be used in future research to standardise segment regions of interest, as well as to determine the appropriate border removal for accurate skin temperature measurement, when using infrared thermal imaging.

- The elicited pressure profile of made-to-measure compression garments had no effect on skin temperature and thermal sensation before and after running exercise. Also, participant perceived comfort, was lower when wearing the medium gradient made-to-measure compression garment which elicited a high peak pressure (left leg: 25.8 ± 2.4 mmHg, and right leg: 26.3 ± 3.5 mmHg) and a shallow pressure gradient (left leg: -18.1 ± 5.0 mmHg, and right leg: -16.6 ± 4.9 mmHg). Furthermore, a within participant control garment with high pressures on the right leg and low pressures on the left leg was developed (Chapter 8). The results of the study showed that the within participant control garment successfully 'blinded' the majority of participants (90%) to the pressures exerted by the garment they were wearing.
- The elicited pressure profile of made-to-measure compression garments had no effect on running kinematics and kinetics which was established using principal component analysis. Interestingly, the medium gradient garment (peak pressure left leg: 25.8 ± 2.4 mmHg, and right leg: 26.3 ± 3.5 mmHg; pressure gradient left leg: -18.1 ± 5.0 mmHg, and right leg: -16.6 ± 4.9 mmHg) and the high gradient garment (peak pressure left leg: 27.7 ± 2.2 mmHg, and right leg: 27.5 ± 1.6 mmHg; pressure gradient left leg: -25.0 ± 4.1 mmHg, and right leg: -22.3 ± 3.6 mmHg) reduced mean heart rate during the 30-minute run by 6 and 5 beats per minute respectively, compared to the control garment (peak pressure left leg: 13.5 ± 2.3 mmHg, and right leg: 12.9 ± 2.6 mmHg; pressure gradient left leg: -8.9 ± 3.5 mmHg, and right leg: -7.4 ± 3.0 mmHg) (Chapter 9).

10.2 Overview and Discussion of Experimental Chapter Results

Novel Pressure Measurement Method

In the first study of this thesis, presented in Chapter 4, the aim was to develop a novel method to assess pressure profiles (peak pressure and pressure gradient) in sports compression garments, and to establish if differences in pressure values were evident when measurements were made on different aspects of the leg. Accurately measuring and reporting compression garment elicited pressures in research studies is imperative to ensure findings can be meaningfully compared, and to ensure the benefits (or otherwise) of wearing compression garments on exercise performance and / or recovery can be established. Establishing the efficacy of compression garments eliciting particular pressures will also ensure the prescription of pressures for given sporting situations will be appropriate, and will also offer the potential of understanding the mechanisms underpinning any benefits. Although the measurement and reporting of compression garment pressures is becoming more common, many studies have not measured the elicited pressures (Kraemer et al., 2010; Pereira et al., 2014; Perrey et al., 2008; Shimokochi et al., 2017; Winke & Williamson, 2017). A method to measure the pressure profile elicited by a compression garment was adopted by Brophy-Williams and colleagues (2014). This method records three pressure measurements on the medial lower leg, and three pressure measurements on the anterior upper leg using a pressure monitoring device. However, these locations, particularly at the lower leg, require pressure measurements over hard tissues such as bone, which cause inflated pressures (McManus et al., 2020). Furthermore, it may be argued that six pressure measurements across the whole length of the leg may not be optimal to accurately reflect the pressure profile (peak pressure and pressure gradient) of the garment. The results of this study showed that peak pressure was typically higher when measurements were made on the posterior (18.3 to 27.5 mmHg) and anterior (16.6 to 27.6 mmHg) aspects of the upper, lower and whole leg, compared to the lateral (12.4 to 21.2 mmHg) and medial (12.2 to 23.0 mmHg) aspects. The pressure gradient was also steeper when measurements were made on the posterior (-21.7 to -26.9 mmHg) and anterior (-22.1 to -23.2 mmHg) aspects of the upper, lower and whole leg, compared to the lateral (-11.0 to -15.3 mmHg) and medial (-13.9 to -19.3 mmHg) aspects. The RMSD was lowest when pressure measurements were made on the posterior aspect of the upper, lower and whole leg (1.2 to 1.8 mmHg), compared to the anterior, lateral, and medial aspects (1.2 to 3.7 mmHg). When the novel method of measuring pressure from the current study (posterior aspect) was compared with the established method, peak pressure was higher (posterior vs. established: 27.5, 28.3, 18.3 mmHg vs. 19.8, 19.0, 15.6 mmHg, for the whole, lower and upper legs respectively) and the pressure gradient was steeper (posterior vs. established: -21.7, -26.2, -26.9 mmHg vs. -11.2, -6.5, -16.1 mmHg for the whole, lower and upper legs respectively) when using the novel method. The RMSD was similar between the novel (posterior aspect) and established method for the whole leg (1.8 ± 0.4 mmHg vs. 1.6 ± 0.5 mmHg) and for the lower leg (1.4 ± 0.6 mmHg vs. 1.4 ± 0.9 mmHg). These findings highlight that the aspect of the leg on which pressure measurements are taken influences the magnitude of the values recorded. The variability of pressure values (established using an RMSD analysis) showed that the posterior aspect of the leg provided the smallest RMSD. This is desirable and is almost certainly due to the consistent tissue structures and obtuse curvature found on this aspect, which may have less influence on the pressure values compared to the anterior aspect of the leg where tissue structures and characteristics are less consistent.

There is also practical relevance to measuring pressures over muscular tissues found on the posterior aspect of the leg. The mechanisms purposed by compression garments typically include changes to muscle (i.e., reduced muscle oscillation during exercise) therefore it would seem appropriate to measure over muscular tissues. As a result of the smaller variability in pressure values and the practical relevance of pressure measurements made over the posterior leg, we purpose using the posterior of the lower and upper leg for making pressure measurements in sports compression garments. When comparing the novel method to the established, using the same aspects of the leg (medial lower leg and anterior upper leg), the peak pressures were higher and pressure gradients were steeper in the novel method for the lower leg whereas they were not different between methods for the upper leg. There may be two main factors which contribute to the differences in peak pressure and pressure gradient observed in the lower leg: 1) although the pressure measurements were made on the same aspect of the leg, the exact location of pressure measurements differed between methods; therefore, it is possible that measurements were made over slightly different tissue structures and that the curvature was not the same; and 2) more pressure measurements were made using the novel method (5-6) compared to the established method on the lower leg (3). Given that, 1) the novel method includes a greater number of pressure measurements compared to the established method, which provides a more detailed and better reflection of the garment pressure profile, and 2) that measurements made on the posterior leg provide the smallest variability in pressure values, we purpose using the novel method (posterior aspect) to measure pressure profiles in sports compression garments in the future.

Made-to-Measure Compression Garments with Customised Pressure Profiles

In the second study of this thesis, presented in Chapter 5, the aims were: 1) to make made-to-measure compression garments that elicit pressures within and below clinical standards, and 2) examine whether peak pressures and pressure gradients can be replicated within and between participants' legs, and between separate compression garment conditions. The results of Chapter 5 showed that made-to-measure compression garments, manufactured using 3D scanned geometry of the participants' lower body, can be developed to elicit prescribed pressure profiles which are the same between participants. The control garment was designed to elicit pressure below clinical standards (< 14 mmHg) with no pressure gradient. The high gradient garment was designed to elicit pressure within clinical standards (14–35 mmHg) and to include a linear pressure gradient from distal to proximal (graduated compression). The asymmetrical garment was designed to elicit control garment conditions in the left leg and high gradient garment conditions in the right leg. Linear regression showed that peak pressure at the ankle in the left and right leg were: control garment, 13.5 ± 2.3 and 12.9 ± 2.6; asymmetrical garment, 12.7 ± 2.5 and 26.3 ± 3.4; high gradient garment, 27.7 ± 2.2 and 27.5 ± 1.6 (all mmHg, mean ± standard deviation). Pressure reduction from the ankle to the gluteal fold in the left and right leg were: control garment, 8.9 ± 3.5 and 7.4 ± 3.0; asymmetrical garment, 7.8 ± 3.9 and 21.9 ± 3.2; high gradient garment, 25.0 ± 4.1 and 22.3 ± 3.6 (all mmHg, mean ± standard deviation). Furthermore, the root mean squared differences between predicted and actual pressures in the left and right leg, respectively, were: control garment, 2.1 and 2.1; asymmetrical garment, 2.0 and 2.5; high gradient garment, 2.1 and 2.1 (all mmHg). The published literature investigating the effect of wearing compression garments on exercise performance and recovery typically use commercially available, standard sized compression garments (Atkins et al., 2020; Brophy-Williams et al., 2018; Davies et al., 2009; Higgins et al., 2009; Hill et al., 2014; Kim et al., 2017). However, it has been shown that by wearing standard sized compression garments (small, medium and large), the elicited pressures vary between individuals even if individuals fit within the same sizing category. The differences in pressure found between individuals is caused by differences of body morphology which cannot be corrected for when using standard sized compression garments (Brophy-Williams et al., 2015; Hill et al., 2015). Made-to-measure compression garments overcome this issue as garments are fitted according to each participants' precise body geometry. Given that made-to-measure compression garments can be developed to provide the same fit between participants, future research should aim to use made-to-measure compression garments. Although made-to-measure compression garments are commercially available (Kurio 3D Compression; Isobar Compression) some researchers may not have access to such garments. However, if standard sized compression garments need to be used, the measurement and reporting of garment elicited pressure profiles for each participant is essential. Accurately quantifying pressure profiles ensures the pressures exerted by a compression garment are precisely known and also means that any performance improvements or enhanced recovery responses can be linked to specific garment pressure characteristics. Accurately quantifying pressure profiles also ensures identification of differences in pressure values between participants and potential individual responses to wearing compression garments can be identified.

The Reliability and Validity of a 3D Scanner to Measure Leg Volume

In the third study of this thesis, presented in Chapter 6, the aims of the study were: 1) to examine the reliability (test-retest, intra-day and inter-day) of a structured light 3D scanning system (Artec Leo) and water displacement method for measuring leg volume; and 2) to examine the measurement validity of a structured light 3D scanning system (Artec Leo) for measuring leg volume compared to a water displacement method. The 3D scanner was predominantly used within the experimental studies of this thesis to measure lower body geometry to subsequently support the manufacture of the made-to-measure compression garments. However, 3D scanning technology has other applications such as measuring limb volume which may have utility in both medical and sporting practice (McKinnon et al., 2007; Seminati et al., 2017). The results revealed that test-retest reliability for the lower leg was better for the 3D scanner method compared to the water displacement method. This was evidenced by smaller systematic bias and narrower limits of agreement for the 3D scanner method (±1%, and 4% respectively) compared to the water displacement method (1-2%, and 5-7% respectively). The test-retest reliability for the upper leg was also better for the 3D scanner method compared to the water displacement method. This was evidenced by smaller systematic bias and narrower limits of agreement for the 3D scanner method (±1%, and 3-5% respectively) compared to the water displacement method (1%, and 4-6% respectively). The test-retest reliability results suggest that both the 3D scanner and water displacement methods may be used to measure lymphedema, in clinical practice, as the measurement systematic bias and limits of agreement were less than the 10% volume change threshold typically used to identify lymphedema (Armer & Stewart, 2005; Asim et al., 2012; Johansson et al., 2001). However, both methods might not be adequate for determining leg volume changes following eccentric exercise as although the systematic bias was below the 3% threshold, the limits of agreement were greater than the ~3% volume change previously reported following eccentric exercise (Whitehead et al., 1998, 2001). However, the 3D scanner method showed promising results and with a 1–2% improvement of the limits of agreement for test-retest reliability, the 3D scanner may be used for measuring leg volume changes following exercise induced muscle damage. Therefore, future research is required to examine if the 3D scanner measurement could be made more reliable such as reducing the postural sway when scanning a participant to minimise measurement error to extend its application to sporting environments. Overall, the structured light 3D scanner (Artec Leo) provided better reliability than the water displacement method and was shown to be a valid method for measuring upper leg volume compared to the water displacement method. Given that the 3D scanner is also non-invasive, contactless and quick to perform, the methodology would appear to have many characteristics that would make it attractive for use within clinical practice. However, further research is required to examine its efficacy for many sporting applications. To the authors knowledge, this is the first study to examine the test-retest reliability, intra-day reliability, inter-day reliability and validity, using a structured light 3D scanner on healthy participants.

The Effect of Thermogram Border and Region of Interest Size on Skin Temperature

The fourth and fifth study of this thesis were presented in Chapter 7. The aims of chapter 7 were: 1) to develop a methodology to standardise the selection of regions of interest on thermograms, and 2) to examine the effect of the thermogram border zone and segment region of interest size on skin temperature outputs (Chapter 7). The key findings of Chapter 7 revealed that the mean and maximum skin temperature outputs had no to small sensitivity to thermogram border (defined as the cooler boundary around the imaged object, i.e., human) removal and to the reductions of the region of interest size (length) for anterior and posterior leg segments, pre- and post-exercise. However, although temperature change had no and small sensitivity to the border removal, the initial 2% of border removal of the segments increased mean temperature between 0.14 – 0.24°C for the anterior and posterior leg segments, at pre run. The corresponding mean temperature increase at post run ranged between 0.16 –

0.24°C. Following 4% of border removal, the mean temperature outputs plateaued. Although the influence of including the colder thermogram border in the region of interest may seem trivial, the detection of injury or disease relies on small skin temperature differences between limbs, and differences above 0.65°C are associated with pathology (Sands et al., 2011). Therefore, the inclusion of the ‘cooler’ thermogram border may have implications for injury screening and potentially lead to misdiagnosis. As a result, this study developed a method which allows the removal of the border which will ultimately aid accurate quantification of skin temperature. A review of thermal imaging has suggested the use of automated methods to select regions of interest to improve reliability and efficiency and allow accurate comparisons of regions of interest between studies (Fernández-Cuevas et al., 2015). This study developed a novel automated region of interest selection tool whereby the segment region of interest is selected, and the temperature data is extracted for analysis using reference markers placed onto specific landmarks on the body, which allows standardised regions of interest both within and between participants. Another benefit of this technique is that the regions of interest follow the curvature of the body which ensures that only temperatures of the participant are measured, and unwanted temperature data such as the background is not selected which is a common issue with standard shapes used to select regions of interest using manufacturer thermal imaging software (Duarte et al., 2014). The results of this study may have a significant impact on future research as researchers will be able to examine the impact of including the thermogram border on mean skin temperature outputs and will be able to calculate how much of the border should be removed for accurate temperature measurements, which has not been previously considered.

Effects of Wearing Made-to-Measure Compression Garments on Thermal Responses

The aim of Chapter 8 was to examine the effect of wearing made-to-measure compression garments, with different pressure profiles, on thermal responses and comfort perception before and after running exercise. The automated method developed to standardise the selection of regions of interest in Chapter 7 was subsequently applied in the study presented in Chapter 8. Furthermore, the sensitivity analysis results presented in Chapter 7 suggested that 4% of pixel removal from the region of interest border was appropriate, and this threshold was applied in Chapter 8 and standardised for all thermograms. A border removal of less than 4% would likely include the ‘cooler’ border which was shown to reduce mean skin temperature if included within the region of interest, in Chapter 7. A border removal of greater than 4% may exclude required temperature data. For each segment region of interest, all the area between the distal and proximal reference markers (100%) was used for temperature extraction for the anterior and posterior leg segments. The main findings of Chapter 8 were that skin temperature increased from baseline to post run for each segment of the legs. For all the anterior and posterior left leg segments, the mean skin temperature increase from baseline to post run ranged between 4% and 6% for all compression garment conditions, which corresponded to a ~2°C increase. The same response was demonstrated for anterior and posterior right leg segments as the mean skin temperature increase from baseline to post run ranged between 4% and 6% for all compression garment conditions. However, there were no differences in mean or maximum skin temperature at baseline, post warm-up or post 30-minute run between the four compression garment conditions. The results of this study are consistent with those found by Goh and colleagues (2011) who showed that there were no differences in mean thigh and calf skin temperatures when wearing compression tights compared to loose running shorts (control), during 20-min of submaximal running and a subsequent run to exhaustion in temperatures of 32°C. Conversely, Priego Quesada and colleagues (2015) showed that skin temperature change over the vastus lateralis, abductor, tibialis anterior, ankle anterior, semitendinosus and gastrocnemius, from baseline to post 20-minute run, was greater when wearing knee-high compression socks compared to a no compression control condition in temperatures of 23.7°C. However, given that the current study did not include a ‘no garment’ trial it is not possible to comment on the thermoregulatory effects of wearing the compression garments compared with their absence. Comparisons between studies are made more difficult given that different types of compression garments are also used (tights, socks and shorts). It is likely that the garment material composition may influence heat transfer and subsequent skin temperature (Holmér, 1985). The current study used compression tights with a material composition of 22% Elastane and 78% Nylon, whereas, Priego Quesada and colleagues (2015) used compression socks with a material composition of 15% Elastane and 85% Nylon. The difference of material composition and type of garment used may explain the observed differences, but further research is required in different environmental temperatures to explore the effect of compression garment material composition and garment type on skin temperature and thermoregulation. It has been suggested that a skin temperature greater than 35°C can negatively influence aerobic performance and increase cardiovascular strain (Sawka et al., 2012). In the current study, mean skin temperature at post 30-minute run, in all garment conditions ranged between 31.4 and 32.6 °C for all leg segment locations. However, the running intensity was low, and so metabolic heat production may have also been low, ultimately limiting the thermal strain experienced by participants. As a result, whether the responses seen in Chapter 8 would also be evident in hotter environments (>30°C) and at higher exercise intensity remains unknown. However, based on the findings in Chapter 8, where environmental temperatures were 20.5°C, wearing made-to-measure compression garments did not elevate skin temperature to levels that are suggested to be harmful to exercise performance (>35°C), and the pressure profile elicited by the compression garment did not seem to influence thermoregulation.

Effects of Wearing Made-to-Measure Compression Garments on Biomechanics

The final study of this thesis was presented in Chapter 9. The study aimed to examine the effect of wearing made-to-measure compression garments, with different pressure profiles, on running kinetics and kinematics. The main findings of this study were that the principal component analysis (PCA) did not define differences of running kinematics and kinetics between the control, asymmetrical, high gradient and medium gradient compression garments during a 30-minute run at 2.5 ± 0.3 m/s (9.0 ± 1.1 $km{\cdot}h^{-1}$). The PCA plots which displayed principal components 1, 2, 3 and 4 showed that temporal waveform biomechanics data did not cluster consistently between garment conditions (control, asymmetrical, high gradient and medium gradient), legs (left and right) and time points (5, 10, 15, 20, 25 and 30 min). The scalar variable data (stride frequency, stride length, stride duration, swing time and stance time) was compared using a two-way repeated measures ANOVA which found no difference between compression garments, legs or time points. The published literature typically measure scalar kinematic variables such as stride length, stride frequency, ground contact time and swing time (Born et al., 2014; Borràs, Balius, & Drobnic, 2011; Varela-Sanz et al., 2011). However, no study has explored the influence of wearing made-to-measure compression garments on waveform variables such as ground reaction force, joint angles, joint moments, joint powers and joint angular velocities during running. This study showed that wearing made-to-measure compression garments had no effect on waveform kinematics and kinetics regardless of the pressure profile of the compression garment, which adds new knowledge to the existing literature. Furthermore, the finding of no effect of wearing made-to-measure compression garments on scalar kinematic variables is consistent with the results of the published literature. Both Stickford and colleagues (2015) and Varela-Sanz and colleagues (2011) found no effect of wearing compression garments, in the form of calf sleeves and knee high socks, on scalar kinematics during running exercise. The current study used compression tights rather than socks or calf sleeves, which adds an additional garment type which may not influence running kinematics and kinetics.

Interestingly, the current study found that mean heart rate during the 30-minute run was lower when wearing the medium gradient garment (130 ± 31 bpm) and high gradient garment (131 ± 30 bpm) compared to the control garment (136 ± 32 bpm). These findings are consistent with those of Varela-Sanz and collagues (2011) who showed that although no differences were observed for scalar kinematic variables during a run to exhaustion, participants who wore knee high compression socks reached a lower percentage of their maximum heart rate compared to participants who did not wear compression socks (P = 0.01; d = 1.82). In the current study, the pressure gradient was steepest in the high gradient garment (right leg: -22.3 ± 3.6 mmHg, and left leg: -25.0 ± 4.1 mmHg) and shallower in the medium gradient garment (right leg: -18.1 ± 5.0 mmHg, and left leg: -16.6 ± 4.9 mmHg). The peak pressure located at the ankle was similar between the high gradient garment (right leg: 27.5 ± 1.6 mmHg, and left leg: 27.7 ± 2.2 mmHg) and medium gradient garment (right leg: 26.3 ± 3.5 mmHg, and left leg: 25.8 ± 2.4 mmHg). Given that there was no difference of mean heart rate between the high gradient and medium gradient compression garments, it would seem that the steepness of the pressure gradient between high and medium gradients may not influence heart rate. However, given that the peak pressure at the ankle was similar between both garments and only a one beat per minute difference of heart rate was found, it is likely that the elicited pressures had a substantial role in the reduction of heart rate evidenced in this study. Furthermore, no differences of kinematics and kinetics were found between the four compression garments. Therefore, it is likely that the reduction of heart rate may be caused by other purposed mechanisms of wearing compression garments such as graduated compression, improved haemodynamics, increased blood flow and venous return rather than a more economical running technique. However, further research is warranted to establish such effects.

10.3 Summary of Results

The studies presented within this thesis provide new knowledge for the use of made-to-measure compression garments during exercise and have developed novel methodologies within compression garment research. Overall, the findings showed that a novel method of measuring pressure profiles using the posterior aspect of the leg and multiple pressure measurements (~11) is optimal. This is due to the consistent tissue structures found on the posterior aspect of the leg which minimises the variability in pressure values, and by recording multiple pressure measurements, this provides a better reflection of the pressure profile of the compression garment. This method was adopted in Chapter 5 and this study showed that made-to-measure compression garments can be made to elicit prescribed peak pressures and pressure gradients, within and below clinical standards, which are the same between participants. The application of 3D scanning used in the work presented in this thesis to support the manufacture of the made-to-measure compression garments may also be used to reliably measure leg volume, which may have clinical and sporting applications to examine changes in leg volume. When worn during submaximal running (2.5 m/s) in 20.5°C environmental temperatures, the pressure profile (peak pressure and pressure gradient) of made-to-measure compression garments does not influence skin temperature and although skin temperature increased from pre run to post run, it did not elevate to temperatures associated with performance decrements (>35°C). Finally, the pressure profile of made-to-measure compression garments do not influence running biomechanics (kinematics and kinetics) but compression garments with higher peak pressure at the ankle (26 - 28 mmHg) may provide cardiovascular benefits as evidence by a reduced heart rate compared to compression garments with lower peak pressures (~13 mmHg). Overall, the findings within this thesis support the use of made-to-measure compression garments during submaximal running. The reduction of heart rate found highlights the potential ergogenic aid of wearing such garments.

10.4 Limitations

No Compression Garment Condition

A number of limitations within the present work must be acknowledged. In Chapters 8 and 9, there was no condition which involved wearing no compression garment; rather, a control garment was used, which elicited pressures below clinical compression standards (<14 mmHg). However, with thermoregulation, the skin offers optimal heat transfer, and clothing such as compression garments may create an insulative layer next to the body which may impede sweat evaporation and ultimately limit optimal heat transfer. Therefore, it would have been useful to compare skin temperature differences when wearing a compression garment with those when no garment was worn to establish if compression garments prevent optimal heat transfer. Furthermore, the same approach would have been beneficial when examining running kinematics and kinetics (Chapter 9) as it is unknown if wearing the control compression garment would have influenced such variables compared to wearing no garment. Although, the control garment was used to offset any placebo effects, which is a significant issue that has been highlighted within the published research literature (MacRae et al., 2011), in hindsight a no compression condition would have been beneficial in some of the studies described in this thesis. Furthermore, although the control garment elicited peak pressure at the ankle which was below clinical compression standards, there is no evidence to suggest that these pressures do not have any physiological or biomechanical effects. Pressures of ~14 mmHg have been used within experimental compression garments previously (Faulkner et al., 2013; Govus et al., 2018) and although no benefits were found for strength recovery, muscle soreness, blood creatine kinase and lactate concentrations and 400m running performance, small effects may still be possible. Future research is required to establish whether compression garments influence thermoregulation and running biomechanics compared to wearing no garment, and future research must examine if pressure thresholds exist that influence physiological responses and mechanisms.

Running Economy

It has been suggested that wearing compression garments may improve running economy (Bringard et al., 2006). However, the mechanisms behind such a phenomenon remain unknown. Running biomechanics are a factor which may be influenced by wearing compression garments and a change in biomechanics can improve running economy through factors such as, reduced vertical oscillation (Moore, 2016), minimal change in running velocity during ground contact (Kaneko, 1990) and reduced leg extension at the toe-off phase of the gait cycle (Moore et al., 2012). Chapter 9 investigated whether running biomechanics were influenced by wearing made-to-measure compression garments which elicited different pressure profiles (peak pressure and pressure gradient). However, in Chapter 9 running economy was not directly measured, thus, any physiological or biomechanical changes observed by wearing made-to-measure compression garments cannot be directly linked to an improved running economy. Although running biomechanics were not influenced by wearing compression garments, when wearing the high gradient garment and the medium gradient garment, mean heart rate was reduced by 5 and 6 bpm compared to the control garment during the 30-minute run. Although a lower heart rate may relate to an improved running economy, this could not be confirmed as running economy was not measured via oxygen uptake.

10.5 Future Research

Limited published research has examined the effect of wearing made-to-measure compression garments on recovery from exercise (Brown et al., 2020; Brown et al., 2021) and to the authors knowledge no research has examined the effect of wearing such garments on exercise performance. To advance the knowledge regarding the use of made-to-measure compression garments within sport, the following suggestions are recommended for future research:

- Examine the effect of wearing made-to-measure compression garments compared to standard sized compression garments on running performance. This would be useful to determine whether the improved fit of made-to-measure compression garments, demonstrated in this thesis, elicit any different physiological or biomechanical responses during exercise compared to standard sized garments.
- Given that heart rate was reduced during submaximal running when wearing made-to-measure compression garments (Chapter 9), it would be beneficial for future research to examine the underlying physiological mechanisms (i.e., altered cardiac output) behind this effect and to determine whether the response is exercise intensity specific.

- Although the work within this thesis focused on running exercise, compression garments may also improve recovery from exercise. However, there is no evidence to suggest a specific beneficial peak pressure and pressure gradient to aid recovery. Therefore, it would be beneficial for future research to use made-to-measure compression garments with different elicited pressure profiles to examine their efficacy on recovery following exercise and to establish the specific peak pressures and pressure gradients likely to produce such improvements. This would ultimately aid the prescription of specific garment pressures likely to aid recovery following exercise.
- The work within this thesis has attempted to assist with the standardisation of future compression garment research through developing made-to-measure compression garments which provide a consistent fit between participants, as well as developing a novel methodology for measuring pressures elicited by compression garments. The author would argue that future research should use these methodologies as they will allow and ensure more effective comparison of research study findings.

10.6 Conclusion

The novel findings from this series of investigations have enabled an improved understanding of the use of made-to-measure sports compression garments during running exercise. The results suggest that compression garments do not change running biomechanics but may provide a cardiovascular benefit during submaximal exercise, as evidenced by a reduction of heart rate. Furthermore, the novel methodologies of measuring garment pressures and using made-to-measure compression garments will prove beneficial for future research to help standardise studies and allow effective comparisons of study findings.

Chapter 11: References

Abate, M., Di Carlo, L., Di Donato, L., Romani, G. L., & Merla, A. (2013). Comparison of cutaneous termic response to a standardised warm up in trained and untrained individuals. *Journal of Sports Medicine and Physical Fitness*, *53*(2), 209–215.

Adams, W. C., & Bernauer, E. M. (1968). The Effect of Selected Pace Variations on the Oxygen Requirement of Running a 4:37 Mile. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *39*(4), 837–846. https://doi.org/10.1080/10671188.1968.10613428

Agu, O., Hamilton, G., & Baker, D. (1999). Graduated compression stockings in the prevention of venous thromboembolism. *British Journal of Surgery*, *86*(8), 992–1004. https://doi.org/10.1046/j.1365-2168.1999.01195.x

Ali, A., Creasy, R. H., & Edge, J. A. (2010a). Physiological effects of wearing graduated compression stockings during running. *European Journal of Applied Physiology*, *109*(6), 1017–1025. https://doi.org/10.1007/s00421-010-1447-1

Ali, A., Creasy, R. H., & Edge, J. A. (2010b). Physiological effects of wearing graduated compression stockings during running. *European Journal of Applied Physiology*, *109*(6), 1017–1025. https://doi.org/10.1007/s00421-010-1447-1

Ali, A., Creasy, R. H., & Edge, J. A. (2011). The effect of graduated compression stockings on running performance. *Journal of Strength and Conditioning Research*, *25*(5), 1385–1392. https://doi.org/10.1519/JSC.0b013e3181d6848e

Ammer, K. (2008). The Glamorgan protocol for recording and evaluation of thermal images of the human body. *Thermology International*, *18*(4), 125–144.

Amsler, F., & Blättler, W. (2008). Compression Therapy for Occupational Leg Symptoms and Chronic Venous Disorders - a Meta-analysis of Randomised Controlled Trials. *European Journal of Vascular and Endovascular Surgery*, *35*(3), 366–372. https://doi.org/10.1016/j.ejvs.2007.09.021

Anderson, T. (1996). Biomechanics and running economy. *Sports Medicine (Auckland, N.Z.)*, *22*(2), 76–89. https://doi.org/10.2165/00007256-199622020-00003

Angelhed, J.-E., Strid, L., Bergelin, E., & Fagerberg, B. (2008). Measurement of lower-leg volume change by quantitative computed tomography. *Acta Radiologica (Stockholm, Sweden : 1987)*, *49*(9), 1024–1030. https://doi.org/10.1080/02841850802427879

Areces, F., Salinero, J. J., Abian-Vicen, J., González-MILLÁN, C., Ruiz-Vicente, D., Lara, B., Lledó, M., & Del Coso, J. (2015). The use of compression stockings during a marathon competition to reduce exercise-induced muscle damage: Are they really useful? *Journal of Orthopaedic and Sports Physical Therapy*, *45*(6), 462–470. https://doi.org/10.2519/jospt.2015.5863

Armer, J. M., & Stewart, B. R. (2005). A comparison of four diagnostic criteria for lymphedema in a post-breast cancer population. *Lymphatic Research and Biology*, *3*(4), 208–217. https://doi.org/10.1089/lrb.2005.3.208

Armstrong, S. A., Till, E. S., Maloney, S. R., & Harris, G. A. (2015a). Compression socks and functional recovery following marathon running: A randomized controlled trial. *Journal of Strength and Conditioning Research*, *29*(2), 528–533. https://doi.org/10.1519/JSC.0000000000000649

Armstrong, S. A., Till, E. S., Maloney, S. R., & Harris, G. A. (2015b). Compression socks and functional recovery following marathon running: A randomized controlled trial. *Journal of Strength and Conditioning Research*, *29*(2), 528–533. https://doi.org/10.1519/JSC.0000000000000649

Asim, M., Cham, A., Banerjee, S., Nancekivell, R., Dutu, G., McBride, C., Cavanagh, S., Lawrenson, R., & Campbell, I. (2012). Difficulties with defining lymphoedema after axillary dissection for breast cancer. *The New Zealand Medical Journal*, *125*(1351), 29–39.

Atkins, R., Lam, W. K., Scanlan, A. T., Beaven, C. M., & Driller, M. (2020). Lower-body compression garments worn following exercise improves perceived recovery but not subsequent performance in basketball athletes. *Journal of Sports Sciences*, *38*(9), 961–969. https://doi.org/10.1080/02640414.2020.1737387

Bach, A. J. E., Stewart, I. B., Disher, A. E., & Costello, J. T. (2015). A comparison between conductive and infrared devices for measuring mean skin temperature at rest, during exercise in the heat, and recovery. *PLoS ONE*, *10*(2), 1–13. https://doi.org/10.1371/journal.pone.0117907

Badesa, F. J., Morales, R., Garcia-Aracil, N., Sabater, J. M., Casals, A., & Zollo, L. (2014). Auto-adaptive robot-aided therapy using machine learning techniques. *Computer Methods and Programs in Biomedicine*, *116*(2), 123–130. https://doi.org/10.1016/j.cmpb.2013.09.011

Ballmann, C., Hotchkiss, H., Marshall, M., & Rogers, R. (2019). The Effect of Wearing a Lower Body Compression Garment on Anaerobic Exercise Performance in Division I NCAA Basketball Players. *Sports*, *7*(6), 144. https://doi.org/10.3390/sports7060144

Barker, L., Mendoza, D., & Mercer, J. A. (2018). Exploring the Use of 3D Scanning to Determine Whole-Body Volume While Wearing a Triathlon Wetsuit. *Journal of Functional Morphology and Kinesiology*, *3*(2), 20–24. https://doi.org/10.3390/jfmk3020024

Barnes, K. R., & Kilding, A. E. (2015). Running economy: measurement, norms, and determining factors. *Sports Medicine - Open*, *1*(1), 1–15. https://doi.org/10.1186/s40798-015-0007-y

Barnes, R. B. (1963). Thermography of the human body. *Science*, *140*(3569), 870–877. https://doi.org/10.1126/science.140.3569.870

Bartuzi, P., Roman-Liu, D., & Wiśniewski, T. (2012). The influence of fatigue on muscle temperature. *International Journal of Occupational Safety and Ergonomics*, *18*(2), 233–243. https://doi.org/10.1080/10803548.2012.11076931

Barwood, M. J., Corbett, J., Feeney, J., Hannaford, P., Henderson, D., Jones, I., & Kirke, J. (2013). Compression Garments: No enhancement of high-intensity exercise in hot radiant conditions. *International Journal of Sports Physiology and Performance*, *8*(5), 527–535. https://doi.org/10.1123/ijspp.8.5.527

Beliard, S., Chauveau, M., Moscatiello, T., Cros, F., Ecarnot, F., & Becker, F. (2014). Compression garments and exercise: No influence of pressure applied. *Journal of Sports Science and Medicine*, *14*(1), 75–83.

Bergh, U., Sjödin, B., Forsberg, A., & Svedenhag, J. (1991). The relationship between body mass and oxygen uptake during running in humans. *Medicine and Science in Sports and Exercise*, *23*(2), 205–211.

Bernard, V., Staffa, E., Mornstein, V., & Bourek, A. (2013). Infrared camera assessment of skin surface temperature - Effect of emissivity. *Physica Medica*, *29*(6), 583–591. https://doi.org/10.1016/j.ejmp.2012.09.003

Bernhardt, T., & Anderson, G. S. (2005). Influence of moderate prophylactic compression on sport performance. *Journal of Strength and Conditioning Research*, *19*(2), 292–297. https://doi.org/10.1519/1533-4287(2005)19[292:IOMPCO]2.0.CO;2

Berry, M. J., & McMurray, R. G. (1987). Effects of graduated compression stockings on blood lactate following an exhaustive bout of exercise. *American Journal of Physical Medicine*, *66*(3), 121–132.

Bieuzen, F., Brisswalter, J., Easthope, C., Vercruyssen, F., Bernard, T., & Hausswirth, C. (2014). Effect of wearing compression stockings on recovery after mild exercise-induced muscle damage. *International Journal of Sports Physiology and Performance*, *9*(2), 256–264. https://doi.org/10.1123/IJSPP.2013-0126

Bisele, M., Bencsik, M., Lewis, M. G. C., & Barnett, C. T. (2017). Optimisation of a machine learning algorithm in human locomotion using principal component and discriminant function analyses. *PLoS ONE*, *12*(9), 1–19. https://doi.org/10.1371/journal.pone.0183990

Bishop, D., & Edge, J. (2006). Determinants of repeated-sprint ability in females matched for single-sprint performance. *European Journal of Applied Physiology*, *97*(4), 373–379. https://doi.org/10.1007/s00421-006-0182-0

Bishop, D., Girard, O., & Mendez-Villanueva, A. (2011). Repeated-sprint ability part II: Recommendations for training. *Sports Medicine*, *41*(9), 741–756. https://doi.org/10.2165/11590560-000000000-00000

Bland, J. M., & Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet (London, England)*, *1*(8476), 307–310.

Boland, R., & Adams, R. (1996). Development and evaluation of a precision forearm and hand volumeter and measuring cylinder. *Journal of Hand Therapy : Official Journal of the American Society of Hand Therapists*, *9*(4), 349–358. https://doi.org/10.1016/s0894-1130(96)80041-x

Borg, G. (1982). Psychophysical bases of perceived exertion. *Medicine & Science in Sports & Exercise*, *14*(5). https://journals.lww.com/acsm-msse/Fulltext/1982/05000/Psychophysical_bases_of_perceived_exertion.12.aspx

Born, D. P., Holmberg, H. C., Goernert, F., & Sperlich, B. (2014). A novel compression garment with adhesive silicone stripes improves repeated sprint performance - a multi-experimental approach on the underlying mechanisms. *BMC Sports Science, Medicine and Rehabilitation*, *6*(21). https://doi.org/10.1186/2052-1847-6-21

Born, D. P., Sperlich, B., & Holmberg, H. C. (2013). Bringing light into the dark: Effects of compression clothing on performance and recovery. *International Journal of Sports Physiology and Performance*, *8*(1), 4–18. https://doi.org/10.1123/ijspp.8.1.4

Borràs, X., Balius, X., & Drobnic, F. (2011). Effect of lower body compression garment in running mechanics. *Portuguese Journal of Sport Sciences*, *11*(2), 593–596.

Borràs, X., Balius, X., Drobnic, F., Til, L., & Turmo, A. (2011). Effects of lower body compression garment in muscle oscillation and tissular injury during intense exercise. *Portuguese Journal of Sport Sciences*, *11*, 685–688.

Brijker, Heijdra, Elshout, V. Den, Bosch, & Folgering. (2000). Volumetric measurements of peripheral oedema in clinical conditions. *Clinical Physiology*, *20*(1), 56–61. https://doi.org/https://doi.org/10.1046/j.1365-2281.2000.00224.x

Bringard, A., Perrey, S., & Belluye, N. (2006a). Aerobic energy cost and sensation responses during submaximal running exercise - Positive effects of wearing compression tights. *International Journal of Sports Medicine*, *27*(5), 373–378. https://doi.org/10.1055/s-2005-865718

Bringard, A., Perrey, S., & Belluye, N. (2006b). Aerobic energy cost and sensation responses during submaximal running exercise - Positive effects of wearing compression tights. *International Journal of Sports Medicine*, *27*(5), 373–378. https://doi.org/10.1055/s-2005-865718

Broatch, J, Bishop, D., & Halson, S. (2017). Lower-limb sports compression garments improve exercise performance and muscle blood flow during repeated-sprint cycling. *International Journal of Sports Physiology and Performance*, *13*(7), 882–890.

Broatch, James, Brophy-williams, N., Phillips, E., Bryan, S., Halson, S., Barnes, S., & Bishop, D. (2020). Compression Garments Reduce Muscle Movement and Activation during Submaximal Running. *Medicine & Science in Sports & Exercise*, *52*(3), 685–695. https://doi.org/10.1249/MSS.0000000000002182

Brophy-Williams, N., Driller, M. W., Halson, S. L., Fell, J. W., & Shing, C. M. (2014). Evaluating the Kikuhime pressure monitor for use with sports compression clothing. *Sports Engineering*, *17*(1), 55–60. https://doi.org/10.1007/s12283-013-0125-z

Brophy-Williams, Ned, Driller, M. W., Kitic, C. M., Fell, J. W., & Halson, S. L. (2017). Effect of compression socks worn between repeated maximal running bouts. *International Journal of Sports Physiology and Performance*, *12*(5), 621–627. https://doi.org/10.1123/ijspp.2016-0162

Brophy-Williams, Ned, Driller, M. W., Kitic, C. M., Fell, J. W., & Halson, S. L. (2018). Wearing compression socks during exercise aids subsequent performance. *Journal of Science and Medicine in Sport*, *22*(1), 123–127. https://doi.org/10.1016/j.jsams.2018.06.010

Brophy-Williams, Ned, Driller, M. W., Kitic, C. M., Fell, J. W., & Halson, S. L. (2019). Wearing compression socks during exercise aids subsequent performance. *Journal of Science and Medicine in Sport*, *22*(1), 123–127. https://doi.org/10.1016/j.jsams.2018.06.010

Brophy-Williams, Ned, Driller, M. W., Shing, C. M., Fell, J. W., & Halson, S. L. (2015). Confounding compression: the effects of posture, sizing and garment type on measured interface pressure in sports compression clothing. *Journal of Sports Sciences*, *33*(13), 1403–1410. https://doi.org/10.1080/02640414.2014.990489

Brown, F. C. W., Hill, J. A., van Someren, K., Howatson, G., & Pedlar, C. R. (2021). The effect of custom-fitted compression garments worn overnight for recovery from judo training in elite athletes. *European Journal of Sport Science*, 1–9. https://doi.org/10.1080/17461391.2021.1891294

Brown, F., Gissane, C., Howatson, G., van Someren, K., Pedlar, C., & Hill, J. (2017). Compression Garments and Recovery from Exercise: A Meta-Analysis. *Sports Medicine*, *47*(11), 2245–2267. https://doi.org/10.1007/s40279-017-0728-9

Brown, F., Jeffries, O., Gissane, C., Howatson, G., van Someren, K., Pedlar, C., Myers, T., & Hill, J. A. (2020a). Custom-Fitted Compression Garments Enhance Recovery From Muscle Damage in Rugby Players. *Journal of Strength and Conditioning Research*, *Publish Ah*(July). https://doi.org/10.1519/jsc.0000000000003408

Brown, F., Jeffries, O., Gissane, C., Howatson, G., van Someren, K., Pedlar, C., Myers, T., & Hill, J. A. (2020b). Custom-Fitted Compression Garments Enhance Recovery From Muscle Damage in Rugby Players. *Journal of Strength and Conditioning Research*, *34*, 1. https://doi.org/10.1519/jsc.0000000000003408

Brownlie, L., Mekjavc, I., & Banister, E. (1987). Thermoregulation in Athletic Racing Apparel. *The Annals of Physiological Anthropology*, *6*(3), 145–155. https://doi.org/10.2114/ahs1983.6.145

Buffa, R., Mereu, E., Lussu, P., Succa, V., Pisanu, T., Buffa, F., & Marini, E. (2015). A new, effective and low-cost three-dimensional approach for the estimation of upper-limb volume. *Sensors*, *15*(6), 12342–12357. https://doi.org/10.3390/s150612342

Burden, R. J., & Glaister, M. (2012). The Effects of Ionized and Nonionized Compression Garments on Sprint and Endurance Cycling. *The Journal of Strength & Conditioning Research*, *26*(10). https://journals.lww.com/nsca-jscr/Fulltext/2012/10000/The_Effects_of_Ionized_and_Nonionized_Compression.30.aspx

Burgdorf, W. H. C., Muscarella, V. A., & Hoenig, L. J. (2015). Conrad Jobst: Great inventor and stocking maker. *JAMA Dermatology*, *151*(11), 1243.

https://doi.org/10.1001/jamadermatol.2014.3905

Burke, M., Murphy, B., & Geraghty, D. (2014). Measurement of sub-bandage pressure during venous compression therapy using flexible force sensors. *IEEE SENSORS 2014 Proceedings*, 1623–1626.

Cau, N., Galli, M., Cimolin, V., Aranci, M., Caraceni, A., & Balzarini, A. (2016). Comparative study between circumferential method and laser scanner 3D method for the evaluation of arm volume in healthy subjects. *Journal of Vascular Surgery: Venous and Lymphatic Disorders*, *4*(1), 64–72. https://doi.org/10.1016/j.jvsv.2015.05.005

Cavanagh, P. R., & Williams, K. R. (1982). The effect of stride length variation on oxygen uptake during distance running. *Medicine and Science in Sports and Exercise*, *14*(1), 30–35. https://doi.org/10.1249/00005768-198201000-00006

Cerqueira, M. S., Santos Borges, L., dos Santos Rocha, J. A., Brito Andrade, H., Silva PirÔpo, U., Lupato Conrado, L. A., & Pereira, R. (2015). Twelve hours of a compression sleeve is not enough to improve the muscle recovery of an exercise-damaged upper arm. *Apunts Medicina de l'Esport*, *50*(185), 23–28. https://doi.org/10.1016/j.apunts.2014.07.003

Chapman, D., Newton, M., Sacco, P., & Nosaka, K. (2006). Greater muscle damage induced by fast versus slow velocity eccentric exercise. *International Journal of Sports Medicine*, *27*(8), 591–598. https://doi.org/10.1055/s-2005-865920

Chatard, J. C., Atlaoui, D., Farjanel, J., Louisy, F., Rastel, D., & Guézennec, C. Y. (2004). Elastic stockings, performance and leg pain recovery in 63-year-old sportsmen. *European Journal of Applied Physiology*, *93*(3), 347–352. https://doi.org/10.1007/s00421-004-1163-9

Cheung, K., Hume, P., & Maxwell, L. (2003). Delayed onset muscle soreness : treatment strategies and performance factors. *Sports Medicine*, *33*(2), 145–164. https://doi.org/10.2165/00007256-200333020-00005

Chohan, A., Haworth, L., Sumner, S., Olivier, M., Birdsall, D., & Whitaker, J. (2019). Examination of the effects of a new compression garment on skin tissue oxygenation in healthy volunteers. *Journal of Wound Care*, *28*(7), 429–435. https://doi.org/10.12968/jowc.2019.28.7.429

Christopoulos, D., Nicolaides, A. N., Belcaro, G., & Duffy, P. (1990). The Effect of Elastic Compression on Calf Muscle Pump Function. *Phlebology*, *5*(1), 13–19. https://doi.org/10.1177/026835559000500105

Chromy, A., Zalud, L., Dobsak, P., Suskevic, I., & Mrkvicova, V. (2015). Limb volume measurements: comparison of accuracy and decisive parameters of the most used present methods. *SpringerPlus*, *4*(1), 1–15. https://doi.org/10.1186/s40064-015-1468-7

Chudecka, M., & Lubkowska, A. (2015). Thermal maps of young women and men. *Infrared Physics and Technology*, *69*, 81–87. https://doi.org/10.1016/j.infrared.2015.01.012

Chudecka, M., Lubkowska, A., Leźnicka, K., & Krupecki, K. (2015). The use of thermal imaging in the evaluation of the symmetry of muscle activity in various types of exercises (Symmetrical and Asymmetrical). *Journal of Human Kinetics*, *49*(1), 141–147. https://doi.org/10.1515/hukin-2015-0116

Clarkson, P. M., & Hubal, M. J. (2002). Exercise-Induced Muscle Damage in Humans. *American Journal of Physical Medicine & Rehabilitation*, *81*(11). https://journals.lww.com/ajpmr/Fulltext/2002/11001/Exercise_Induced_Muscle_Damage_in_Humans.7.aspx

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (Second Edi). Routledge Academic.

Corana, A., Marchesi, M., Martini, C., & Ridella, S. (1987). Minimizing Multimodal Functions of

Continuous Variables with the "Simulated Annealing" Algorithm. *ACM Transactions on Mathematical Software (TOMS)*, *13*(3), 262–280. https://doi.org/10.1145/29380.29864

Corbett, J., Barwood, M. J., & Tipton, M. J. (2015). Physiological cost and thermal envelope: A novel approach to cycle garment evaluation during a representative protocol. *Scandinavian Journal of Medicine and Science in Sports*, *25*(2), 152–158. https://doi.org/10.1111/sms.12176

Costa, C. M. A., Moreira, D. G., Sillero-Quintana, M., Brito, C. J., de Azambuja Pussieldi, G., de Andrade Fernandes, A., Cano, S. P., & Bouzas Marins, J. C. (2018). Daily rhythm of skin temperature of women evaluated by infrared thermal imaging. *Journal of Thermal Biology*, *72*, 1–9. https://doi.org/10.1016/j.jtherbio.2017.12.002

Costello, J., Stewart, I. B., Selfe, J., Kärki, A. I., & Donnelly, A. E. (2013). Use of thermal imaging in sports medicine research: A short report. *International SportMed Journal*, *14*(2), 94–98.

Costello, J. T., Donnelly, A. E., Karki, A., & Selfe, J. (2014). Effects of whole body cryotherapy and cold water immersion on knee skin temperature. *International Journal of Sports Medicine*, *35*(1), 35–40. https://doi.org/10.1055/s-0033-1343410

Costello, Joseph T., McInerney, C. D., Bleakley, C. M., Selfe, J., & Donnelly, A. E. (2012). The use of thermal imaging in assessing skin temperature following cryotherapy: A review. *Journal of Thermal Biology*, *37*(2), 103–110. https://doi.org/10.1016/j.jtherbio.2011.11.008

Coza, A., Dunn, J. F., Anderson, B., & Nigg, B. M. (2012). Effects of Compression on Muscle Tissue Oxygenation at the Onset of Exercise. *The Journal of Strength & Conditioning Research*, *26*(6). https://journals.lww.com/nsca-jscr/Fulltext/2012/06000/Effects_of_Compression_on_Muscle_Tissue.24.aspx

Cronin, J. B., Oliver, M., & Mcnair, P. J. (2004). *Muscle stiffness and injury effects of whole body vibration*. *5*, 68–74. https://doi.org/10.1016/j.ptsp.2004.01.004

da Silva, C. A., Helal, L., da Silva, R. P., Belli, K. C., Umpierre, D., & Stein, R. (2018). Association of Lower Limb Compression Garments During High-Intensity Exercise with Performance and Physiological Responses: A Systematic Review and Meta-analysis. *Sports Medicine*, *48*(8), 1859–1873. https://doi.org/10.1007/s40279-018-0927-z

da Silva, W., Machado, Á. S., Souza, M. A., Kunzler, M. R., Priego-Quesada, J. I., & Carpes, F. P. (2018). Can exercise-induced muscle damage be related to changes in skin temperature? *Physiological Measurement*, *39*(10), 104007. https://doi.org/10.1088/1361-6579/aae6df

Dalleau, G., Belli, A., Bourdin, M., & Lacour, J. R. (1998). The spring-mass model and the energy cost of treadmill running. *European Journal of Applied Physiology and Occupational Physiology*, *77*(3), 257–263. https://doi.org/10.1007/s004210050330

Dandrieux, P. E., Thouze, A., & Rossi, J. (2020). Acute effect of thigh compression garment on muscle oscillations during running: impact of speed and slope. *Computer Methods in Biomechanics and Biomedical Engineering*, *23*(sup1), S66–S68. https://doi.org/10.1080/10255842.2020.1812161

Daniels, J. (1985). A physiologist's view of running economy. *Medicine and Science in Sports and Exercise*, *17*(3), 332–338.

Daniels, J., & Daniels, N. (1992). Running economy of elite male and elite female runners. *Medicine and Science in Sports and Exercise*, *24*(4), 483–489.

Dascombe, B. J., Hoare, T. K., Sear, J. A., Reaburn, P. R., & Scanlan, A. T. (2011a). 5. *International Journal of Sports Physiology and Performance*, *6*(2), 160–173. https://doi.org/10.1123/ijspp.6.2.160

Dascombe, B. J., Hoare, T. K., Sear, J. A., Reaburn, P. R., & Scanlan, A. T. (2011b). The effects of wearing undersized lower-body compression garments on endurance running performance.

International Journal of Sports Physiology and Performance, *6*(2), 160–173. https://doi.org/10.1123/ijspp.6.2.160

Davies, R. C., Rowlands, A. V., & Eston, R. G. (2009). Effect of exercise-induced muscle damage on ventilatory and perceived exertion responses to moderate and severe intensity cycle exercise. *European Journal of Applied Physiology*, *107*(1), 11–19. https://doi.org/10.1007/s00421-009-1094-6

Davies, V., Thompson, K. G., & Cooper, S.-M. (2009a). The Effects of Compression Garments on Recovery. *The Journal of Strength & Conditioning Research*, *23*(6). https://journals.lww.com/nsca-jscr/Fulltext/2009/09000/The_Effects_of_Compression_Garments_on_Recovery.23.aspx

Davies, V., Thompson, K. G., & Cooper, S. M. (2009b). The effects of compression garments on recovery. *Journal of Strength and Conditioning Research*, *23*(6), 1786–1794. https://doi.org/10.1519/JSC.0b013e3181b42589

de Glanville, K., & Hamlin, M. (2012). Positive effect of lower body compression garments on subsequent 40-km cycling time trial performance. *Journal of Strength and Conditioning Research*, *26*(2), 480–486.

Del Coso, J., Areces, F., Salinero, J. J., González-Millán, C., Abián-Vicén, J., Soriano, L., Ruiz, D., Gallo, C., Lara, B., & Calleja-Gonzalez, J. (2014). Compression stockings do not improve muscular performance during a half-ironman triathlon race. *European Journal of Applied Physiology*, *114*(3), 587–595. https://doi.org/10.1007/s00421-013-2789-2

Deltombe, T., Jamart, J., Recloux, S., Legrand, C., Vandenbroeck, N., Theys, S., & Hanson, P. (2007). Reliability and limits of agreement of circumferential, water displacement, and optoelectronic volumetry in the measurement of upper limb lymphedema. *Lymphology*, *40*(1), 26–34.

Dermont, T., Morizot, L., Bouhaddi, M., & Ménétrier, A. (2015). Changes in Tissue Oxygen Saturation in Response to Different Calf Compression Sleeves. *Journal of Sports Medicine*, *2015*, 1–5. https://doi.org/10.1155/2015/857904

Devoogdt, N., Cavaggion, C., Van der Gucht, E., Dams, L., De Groef, A., Meeus, M., Van Hemelrijck, R., Heynen, A., Thomis, S., & Orhan, C. (2019). Reliability, Validity, and Feasibility of Water Displacement Method, Figure-of-Eight Method, and Circumference Measurements in Determination of Ankle and Foot Edema. *Lymphatic Research and Biology*, *17*(5), 531–536. https://doi.org/10.1089/lrb.2018.0045

Di Michele, R., & Merni, F. (2014). The concurrent effects of strike pattern and ground-contact time on running economy. *Journal of Science and Medicine in Sport*, *17*(4), 414–418. https://doi.org/10.1016/j.jsams.2013.05.012

Di Salvo, V., Baron, R., Tschan, H., Calderon Montero, F. J., Bachl, N., & Pigozzi, F. (2007). Performance characteristics according to playing position in elite soccer. *International Journal of Sports Medicine*, *28*(3), 222–227. https://doi.org/10.1055/s-2006-924294

Dillmann, U., Holzhoffer, C., Johann, Y., Bechtel, S., Gräber, S., Massing, C., Spiegel, J., Behnke, S., Bürmann, J., & Louis, A. K. (2014). Principal Component Analysis of gait in Parkinson's disease: relevance of gait velocity. *Gait & Posture*, *39*(3), 882–887. https://doi.org/10.1016/j.gaitpost.2013.11.021

Doan, B. K., Kwon, Y. H., Newton, R. U., Shim, J., Popper, E. M., Rogers, R. A., Bolt, L. R., Robertson, M., & Kraemer, W. J. (2003). Evaluation of a lower-body compression garment. *Journal of Sports Sciences*, *21*(8), 601–610. https://doi.org/10.1080/0264041031000101971

Doan, B. K., Kwon, Y., Newton, R. U., Shim, J., Popper, E. V. A. M., Rogers, R. A., Bolt, L. R., Robertson, M., & J, K. W. (2003). Evaluation of a lower-body compression garment. *Journal of*

Sport Sciences, 21(8), 601–610. https://doi.org/10.1080/0264041031000101971

Doan, B., Kwon, Y., Newton, R., Shim, J., Popper, E. V. A., Rogers, R., Bolt, L., Robertson, M., & Kraemer, W. (2011). *Evaluation of a lower-body compression garment Evaluation of a lower-body compression garment*. *August 2013*, 37–41. https://doi.org/10.1080/0264041031000101971

Driller, M. W., & Halson, S. L. (2013). The effects of wearing lower body compression garments during a cycling performance test. *International Journal of Sports Physiology and Performance*, *8*(3), 300–306. https://doi.org/10.1123/ijspp.8.3.300

Driller, M. W., & Halson, S. L. (2013). The effects of lower-body compression garments on recovery between exercise bouts in highly-trained cyclists. Journal of Science and Cycling, 2(1), 45-50. Retrieved from https://www.jsc-journal.com/index.php/JSC/article/view/30

Drzazga, Z., Binek, M., Pokora, I., & Sadowska-Krępa, E. (2018). A preliminary study on infrared thermal imaging of cross-country skiers and swimmers subjected to endurance exercise. *Journal of Thermal Analysis and Calorimetry*, *134*(1), 701–710. https://doi.org/10.1007/s10973-018-7311-y

Duarte, A., Carrão, L., Espanha, M., Viana, T., Freitas, D., Bártolo, P., Faria, P., & Almeida, H. A. (2014). Segmentation Algorithms for Thermal Images. *Procedia Technology*, *16*, 1560–1569. https://doi.org/10.1016/j.protcy.2014.10.178

Duffield, R., Cannon, J., & King, M. (2010). The effects of compression garments on recovery of muscle performance following high-intensity sprint and plyometric exercise. *Journal of Science and Medicine in Sport*, *13*(1), 136–140. https://doi.org/10.1016/j.jsams.2008.10.006

Duffield, R., Edge, J., Merrells, R., Hawke, E., Barnes, M., Simcock, D., & Gill, N. (2008). The effects of compression garments on intermittent exercise performance and recovery on consecutive days. *International Journal of Sports Physiology and Performance*, *3*(4), 454–468. https://doi.org/10.1123/ijspp.3.4.454

Duffield, R., & Portus, M. (2007a). Comparison of three types of full-body compression garments on throwing and repeat-sprint performance in cricket players. *British Journal of Sports Medicine*, *41*(7), 409–414. https://doi.org/10.1136/bjsm.2006.033753

Duffield, R., & Portus, M. (2007b). Comparison of three types of full-body compression garments on throwing and repeat-sprint performance in cricket players. *British Journal of Sports Medicine*, *41*(7), 409–414. https://doi.org/10.1136/bjsm.2006.033753

Duffield, R., & Portus, M. (2007c). Comparison of three types of full-body compression garments on throwing and repeat-sprint performance in cricket players. *British Journal of Sports Medicine*, *41*(7), 409–414; discussion 414. https://doi.org/10.1136/bjsm.2006.033753

Eberhardt, R. T., & Raffetto, J. D. (2014). Chronic venous insufficiency. *Circulation*, *130*(4), 333–346. https://doi.org/10.1161/CIRCULATIONAHA.113.006898

Engelberger, R. P., Indermühle, A., Baumann, F., Fahrni, J., Diehm, N., Kucher, N., Egermann, U., Laederach, K., Baumgartner, I., & Willenberg, T. (2014). Diurnal changes of lower leg volume in obese and non-obese subjects. *International Journal of Obesity*, *38*(6), 801–805. https://doi.org/10.1038/ijo.2013.178

Fallowfield, J., & Wilkinson, D. (1999). *Improving Sports Performance in Middle and Long Distance Running: A Scientific Approach to Race Preparation*. Wiley.

Faulkner, J. A., Gleadon, D., McLaren, J., & Jakeman, J. R. (2013). Effect of lower-limb compression clothing on 400-m sprint performance. *Journal of Strength and Conditioning Research*, *27*(3), 669–676. https://doi.org/10.1519/JSC.0b013e31825c2f50

Felty, C. L., & Rooke, T. W. (2005). Compression therapy for chronic venous insufficiency. *Seminars* *in Vascular Surgery*, *18*(1 SPEC. ISS.), 36–40. https://doi.org/10.1053/j.semvascsurg.2004.12.010

Ferguson-Pell, M., Hagisawa, S., & Bain, D. (2000). Evaluation of a sensor for low interface pressure applications. *Medical Engineering and Physics*, *22*(9), 657–663. https://doi.org/10.1016/S1350-4533(00)00080-1

Fernández-Cuevas, I., Bouzas Marins, J. C., Arnáiz Lastras, J., Gómez Carmona, P. M., Piñonosa Cano, S., García-Concepción, M. Á., & Sillero-Quintana, M. (2015). Classification of factors influencing the use of infrared thermography in humans: A review. *Infrared Physics and Technology*, *71*(March), 28–55. https://doi.org/10.1016/j.infrared.2015.02.007

Fernie, G. R., & Holliday, P. J. (1982). Volume fluctuations in the residual limbs of lower limb amputees. *Archives of Physical Medicine and Rehabilitation*, *63*(4), 162–165.

Flaud, P., Bassez, S., & Counord, J.-L. (2010). Comparative in vitro study of three interface pressure sensors used to evaluate medical compression hosiery. *Dermatologic Surgery : Official Publication for American Society for Dermatologic Surgery [et Al.]*, *36*(12), 1930–1940. https://doi.org/10.1111/j.1524-4725.2010.01767.x

Formenti, D., Ludwig, N., Gargano, M., Gondola, M., Dellerma, N., Caumo, A., & Alberti, G. (2013). Thermal imaging of exercise-associated skin temperature changes in trained and untrained female subjects. *Annals of Biomedical Engineering*, *41*(4), 863–871. https://doi.org/10.1007/s10439-012-0718-x

Fournet, D., Ross, L., Voelcker, T., Redortier, B., & Havenith, G. (2013). Body mapping of thermoregulatory and perceptual responses of males and females running in the cold. *Journal of Thermal Biology*, *38*(6), 339–344. https://doi.org/10.1016/j.jtherbio.2013.04.005

Franke, T. P. C., Backx, F. J. G., & Huisstede, B. M. A. (2021). Lower extremity compression garments use by athletes: why, how often, and perceived benefit. *BMC Sports Science, Medicine and Rehabilitation*, *13*(1), 1–14. https://doi.org/10.1186/s13102-020-00230-8

French, D. N., Thompson, K. G., Garland, S. W., Barnes, C. A., Portas, M. D., Hood, P. E., & Wilkes, G. (2008). The effects of contrast bathing and compression therapy on muscular performance. *Medicine and Science in Sports and Exercise*, *40*(7), 1297–1306. https://doi.org/10.1249/MSS.0b013e31816b10d5

Gavin, T. (2003). Clothing and Thermoregulation During Exercise. *Sports Medicine*, *33*(13), 941–947. https://doi.org/10.1159/000072236

Gavin, T. P. (2003). Clothing and Thermoregulation During Exercise. *Sports Medicine*, *33*(13), 941–947. https://doi.org/10.2165/00007256-200333130-00001

Goh, S. S., Laursen, P. B., Dascombe, B., & Nosaka, K. (2011). Effect of lower body compression garments on submaximal and maximal running performance in cold (10°C) and hot (32°C) environments. *European Journal of Applied Physiology*, *111*(5), 819–826. https://doi.org/10.1007/s00421-010-1705-2

González-Alonso, J, Teller, C., Andersen, S. L., Jensen, F. B., Hyldig, T., & Nielsen, B. (1999). Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, *86*(3), 1032–1039. https://doi.org/10.1152/jappl.1999.86.3.1032

González-Alonso, José. (2012). Human thermoregulation and the cardiovascular system. *Experimental Physiology*, *97*(3), 340–346. https://doi.org/https://doi.org/10.1113/expphysiol.2011.058701

Govus, A. D., Andersson, E. P., Shannon, O. M., Provis, H., Karlsson, M., & McGawley, K. (2018). Commercially available compression garments or electrical stimulation do not enhance recovery following a sprint competition in elite cross-country skiers. *European Journal of Sport Science*, *18*(10), 1299–1308. https://doi.org/10.1080/17461391.2018.1484521

Hamlin, M., Mitchell, C., Ward, F., Draper, N., Shearman, J., & Kimber, N. (2012). Effect of compression garments on short term recovery of repeated sprint and 3-km running performance in rugby union players. *Journal of Strength and Conditioning Research*, *26*(11), 2975–2982.

Harrison, J. A., Nixon, M. A., Fright, W. R., & Snape, L. (2004). Use of hand-held laser scanning in the assessment of facial swelling: a preliminary study. *British Journal of Oral and Maxillofacial Surgery*, *42*(1), 8–17. https://doi.org/https://doi.org/10.1016/S0266-4356(03)00192-X

Hebeda, C. L., de Boer, E. M., Verburgh, C. A., Krijnen, R. M. A., Nieboer, C., & Bezemer, P. D. (1993). Lower Limb Volume Measurements: Standardization and Reproducibility of an Adapted Optical Leg Volume Meter. *Phlebology*, *8*(4), 162–166. https://doi.org/10.1177/026835559300800407

Heiss, R., Hotfiel, T., Kellermann, M., May, M. S., Wuest, W., Janka, R., Nagel, A. M., Uder, M., & Hammon, M. (2018). Effect of compression garments on the development of edema and soreness in delayed-onset muscle soreness (DOMS). *Journal of Sports Science and Medicine*, *17*(3), 392–401.

Higgins, T., Naughton, G. A., & Burgess, D. (2009). Effects of wearing compression garments on physiological and performance measures in a simulated game-specific circuit for netball. *Journal of Science and Medicine in Sport*, *12*(1), 223–226. https://doi.org/10.1016/j.jsams.2007.08.018

Hildebrandt, C., Raschner, C., & Ammer, K. (2010). An overview of recent application of medical infrared thermography in sports medicine in Austria. *Sensors*, *10*(5), 4700–4715. https://doi.org/10.3390/s100504700

Hill, J. A., Howatson, G., Someren, K. A., Davidson, S., & Pedlar, C. R. (2015). The variation in pressures exerted by commercially available compression garments. *Sports Engineering*, *18*(2), 115–121. https://doi.org/10.1007/s12283-015-0170-x

Hill, J. A., Howatson, G., van Someren, K. A., Davidson, S., & Pedlar, C. R. (2015a). Pressures exerted by commercially available lower limb compression garments. *Sports Engineering*, *18*(2), 115–121. https://doi.org/10.1007/s12283-015-0170-x

Hill, J. A., Howatson, G., van Someren, K. A., Davidson, S., & Pedlar, C. R. (2015b). The variation in pressures exerted by commercially available compression garments. *Sports Engineering*, *18*(2), 115–121. https://doi.org/10.1007/s12283-015-0170-x

Hill, J. A., Howatson, G., van Someren, K. A., Davidson, S., & Pedlar, C. R. (2015c). The variation in pressures exerted by commercially available compression garments. *Sports Engineering*, *18*(2), 115–121. https://doi.org/10.1007/s12283-015-0170-x

Hill, J. A., Howatson, G., Van Someren, K. A., Walshe, I., & Pedlar, C. R. (2014). Influence of compression garments on recovery after marathon running. *Journal of Strength and Conditioning Research*, *28*(8), 2228–2235. https://doi.org/10.1519/JSC.0000000000000469

Hill, J., Howatson, G., Someren, K. van, Gaze, D., Legg, H., Lineham, J., & Pedlar, C. (n.d.). The Effects of Compression-Garment Pressure on Recovery After Strenuous Exercise. *International Journal of Sports Physiology and Performance*, *12*(8), 1078–1084. https://doi.org/10.1123/ijspp.2016-0380 10.1123/ijspp.2016-0380 10.1123/ijspp.2016-0380 10.1123/ijspp.2016-0380

Hill, J., Howatson, G., Van Someren, K., Gaze, D., Legg, H., Lineham, J., & Pedlar, C. (2017). The effects of compression-garment pressure on recovery after strenuous exercise. *International Journal of Sports Physiology and Performance*, *12*(8), 1078–1084. https://doi.org/10.1123/ijspp.2016-0380

Hill, J., Howatson, G., van Someren, K., Leeder, J., & Pedlar, C. (2014). Compression garments and recovery from exercise-induced muscle damage: a meta-analysis. *British Journal of Sports Medicine*, *48*(18), 1340–1346. https://doi.org/10.1136/bjsports-2013-092456

Holmér, I. (1985). Heat Exchange and Thermal Insulation Compared in Woolen and Nylon Garments During Wear Trials. *Textile Research Journal*, *55*(9), 511–518. https://doi.org/10.1177/004051758505500901

Houghton, L. A., Dawson, B., & Maloney, S. K. (2009). Effects of wearing compression garments on thermoregulation during simulated team sport activity in temperate environmental conditions. *Journal of Science and Medicine in Sport*, *12*(2), 303–309. https://doi.org/10.1016/j.jsams.2007.09.004

Howell, J. N., Chleboun, G., & Conatser, R. (1993). Muscle stiffness, strength loss, swelling and soreness following exercise-induced injury in humans. *The Journal of Physiology*, *464*(1), 183–196. https://doi.org/10.1113/jphysiol.1993.sp019629

Hsu, W. C., Tseng, L. W., Chen, F. C., Wang, L. C., Yang, W. W., Lin, Y. J., & Liu, C. (2016). Effects of compression garments on surface EMG and physiological responses during and after distance running. *Journal of Sport and Health Science*, *April*, 1–7. https://doi.org/10.1016/j.jshs.2017.01.001

Huang, J. (2006). Thermal parameters for assessing thermal properties of clothing. *Journal of Thermal Biology*, *31*(6), 461–466. https://doi.org/10.1016/j.jtherbio.2006.03.001

Ibegbuna, V., Delis, K. T., Nicolaides, A. N., & Aina, O. (2003). Effect of elastic compression stockings on venous hemodynamics during walking. *Journal of Vascular Surgery*, *37*(2), 420–425. https://doi.org/10.1067/mva.2003.104

ISO. (2008). *International Organization for Standardization. (2008). 18434-1:2008: Condition monitoring and diagnostics of machines—thermography—part 1: general procedures*. https://www.iso.org/standard/41648.html

Jakeman, J. R., Byrne, C., & Eston, R. G. (2010). Lower limb compression garment improves recovery from exercise-induced muscle damage in young, active females. *European Journal of Applied Physiology*, *109*(6), 1137–1144. https://doi.org/10.1007/s00421-010-1464-0

James, C. A., Richardson, A. J., Watt, P. W., & Maxwell, N. S. (2014). Reliability and validity of skin temperature measurement by telemetry thermistors and a thermal camera during exercise in the heat. *Journal of Thermal Biology*, *45*, 141–149. https://doi.org/10.1016/j.jtherbio.2014.08.010

Johansson, K., Ingvar, C., Albertsson, M., & Ekdahl, C. (2001). Arm Lymphoedema, Shoulder Mobility and Muscle Strength after Breast Cancer Treatment ? A Prospective 2-year Study. *Advances in Physiotherapy*, *3*(2), 55–66. https://doi.org/10.1080/14038190119371

Johnson, S. (2002). Compression hosiery in the prevention and treatment of venous leg ulcers. *World Wide Wounds*, *2002*(2), 70–75.

Joyner, M. J., & Coyle, E. F. (2008). Endurance exercise performance: the physiology of champions. *The Journal of Physiology*, *586*(1), 35–44. https://doi.org/10.1113/jphysiol.2007.143834

Kaneko, M. (1990). Mechanics and energetics in running with special reference to efficiency. *Journal of Biomechanics*, *23*, 57–63. https://doi.org/https://doi.org/10.1016/0021-9290(90)90041-Z

Kaulesar Sukul, D. M., den Hoed, P. T., Johannes, E. J., van Dolder, R., & Benda, E. (1993). Direct and indirect methods for the quantification of leg volume: comparison between water displacement volumetry, the disk model method and the frustum sign model method, using the correlation coefficient and the limits of agreement. *Journal of Biomedical Engineering*, *15*(6), 477–480. https://doi.org/10.1016/0141-5425(93)90062-4

Kemmler, W. K., Stengel, S. von, Köckritz, C., Mayhew, J., Wassermann, A., & Zapf, J. (2009). Effect of compression stockings on running performance in men runners. *Journal of Strength and Conditioning Research*, *23*(1), 101–105.

Kemmler, W., Stengel, S. von, Köckritz, C., Mayhew, J., Wassermann, A., & Zapf, J. (2009). Effect of Compression Stockings on Running Performance in Men Runners. *The Journal of Strength & Conditioning Research*, *23*(1). https://journals.lww.com/nsca-jscr/Fulltext/2009/01000/Effect_of_Compression_Stockings_on_Running.16.aspx

Kenefick, R. W., & Sawka, M. N. (2007). Heat Exhaustion and Dehydration as Causes of Marathon Collapse. *Sports Medicine*, *37*(4), 378–381. https://doi.org/10.2165/00007256-200737040-00027

Kennet, J., Hardaker, N., Hobbs, S., & Selfe, J. (2007). Cooling efficiency of 4 common cryotherapeutic agents. *Journal of Athletic Training*, *42*(3), 343–348.

Kerhervé, H. A., Samozino, P., Descombe, F., Pinay, M., Millet, G. Y., Pasqualini, M., & Rupp, T. (2017). Calf compression sleeves change biomechanics but not performance and physiological responses in trail running. *Frontiers in Physiology*, *8*(APR), 1–13. https://doi.org/10.3389/fphys.2017.00247

Kim, J., Kim, J., & Lee, J. (2017). Effect of compression garments on delayed-onset muscle soreness and blood inflammatory markers after eccentric exercise: A randomized controlled trial. *Journal of Exercise Rehabilitation*, *13*(5), 541–545. https://doi.org/10.12965/jer.1735088.554

Kraemer Flanagan, S., Comstock, B., Fragala, M., Earp, J., & Dunn-Lewis, C. et al., W. (2010). Whole Body Compression Garment On Markers Of Recovery After An Intense Whole Body Resistance Training Workout In Men. *Journal of Strength and Conditioning Research*, *34*(1), 804–814.

Kraemer, W., Flanagan, S., Comstock, B., Fragala, M., Earp, J., Dunn-Lewis, C., Ho, J.-Y., Thomas, G., Solomon-Hill, G., Penwell, Z., Powell, M., Wolf, M., Volek, J., Denegar, C., & Maresh, C. (2010). Effects of a whole body compression garment on markers of recovery after a heavy resistance workout in men and women. *Journal of Strength and Conditioning Research*, *24*(3), 804–814.

Kraemer, W. J., Bush, J. A., Newton, R. U., Duncan, N. D., Volek, J. S., Denegar, C. R., Canavan, P., Johnston, J., Putukian, M., & Sebastianelli, W. J. (1998). Influence of a compression garment on repetitive power output production before and after different types of muscle fatigue. *Sports Medicine, Training and Rehabilitation*, *8*(2), 163–184. https://doi.org/10.1080/15438629809512525

Kraemer, William J., Bush, J. A., Bauer, J. A., Triplett-McBride, N. T., Paxton, N. J., Clemson, A., Koziris, L. P., Mangino, L. C., Fry, A. C., & Newton, R. U. (1996). Influence of Compression Garments on Vertical Jump Performance in NCAA Division I Volleyball Players. *The Journal of Strength and Conditioning Research*, *10*(3), 180. https://doi.org/10.1519/1533-4287(1996)010<0180:iocgov>2.3.co;2

Kraemer, William J, Bush, J. A., Wickham, R. B., Denegar, C. R., Gomez, A. I., Gotshalk, L. A., Duncan, N. D., Jeff, V., Putukian, M., & Sebastianelli, W. (2001). *Influence of Compression Therapy on Symptoms Following Soft Tissue Injury from Maximal Eccentric Exercise*. *31*(6), 282–290.

Krahenbuhl, G. S., & Pangrazi, R. P. (1983). Characteristics associated with running performance in young boys. *Medicine and Science in Sports and Exercise*, *15*(6), 486–490.

Kremer, R. L., Wolfe, M. E., Brueckner, N. J., Viola, M. C., & Fisher, M. I. (2020). Validity and reliability of three-dimensional imaging to measure limb volume: A systematic review. *Physical Therapy Reviews*, *25*(1), 21–28. https://doi.org/10.1080/10833196.2019.1698160

Kristianslund, E., Krosshaug, T., & Van den Bogert, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. *Journal of Biomechanics*, *45*(4), 666–671. https://doi.org/10.1016/j.jbiomech.2011.12.011

Lawrence, D., & Kakkar, V. V. (1980). Graduated, static, external compression of the lower limb: a physiological assessment. *The British Journal of Surgery*, *67*(2), 119–121. https://doi.org/10.1002/bjs.1800670214

Lee, D. C. W., Ali, A., Sheridan, S., Chan, D. K. C., & Wong, S. H. S. (2020). Wearing Compression Garment Enhances Central Hemodynamics? A Systematic Review and Meta-Analysis. In *Journal of Strength and Conditioning Research: Vol. Publish Ah* (Issue November). https://doi.org/10.1519/jsc.0000000000003801

Lee, D. C. W., Sheridan, S., Ali, A., Sutanto, D., & Wong, S. H. S. (2021). Wearing compression tights post-exercise enhances recovery hemodynamics and subsequent cycling performance. *European Journal of Applied Physiology*, *121*(7), 2091–2100. https://doi.org/10.1007/s00421-021-04661-0

Lehman, S., & Stark, L. (1982). Three algorithms for interpreting models consisting of ordinary differential equations: Sensitivity coefficients, sensitivity functions, global optimization. *Bellman Prize in Mathematical Biosciences*, *62*, 107–122.

Leoz-Abaurrea, I., Tam, N., & Aguado-Jiménez, R. (2019). Heat dissipating upper body compression garment: Thermoregulatory, cardiovascular, and perceptual responses. *Journal of Sport and Health Science*, *8*(5), 450–456. https://doi.org/10.1016/j.jshs.2016.01.008

Leporace, G., Batista, L. A., Muniz, A. M., Zeitoune, G., Luciano, T., Metsavaht, L., & Nadal, J. (2012). Classification of gait kinematics of anterior cruciate ligament reconstructed subjects using principal component analysis and regressions modelling. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, *EMBS*, 6514–6517. https://doi.org/10.1109/EMBC.2012.6347486

Lewis, C. E., Antoine, J., Mueller, C., Talbot, W. A., Swaroop, R., & Edwards, W. S. (1976). Elastic compression in the prevention of venous stasis: A critical reevaluation. *The American Journal of Surgery*, *132*(6), 739–743. https://doi.org/https://doi.org/10.1016/0002-9610(76)90447-5

Lien, N., Steel, K., Graham, K., Penkala, S., Quinn, J., Dogramaci, S., & Moresi, M. (2014). What is the effect of compression garments on a novel kick accuracy task? *International Journal of Sports Science and Coaching*, *9*(2), 357–366. https://doi.org/10.1260/1747-9541.9.2.357

Liu, R., Guo, X., Lao, T. T., & Little, T. (2017). A critical review on compression textiles for compression therapy: Textile-based compression interventions for chronic venous insufficiency. *Textile Research Journal*, *87*(9), 1121–1141. https://doi.org/10.1177/0040517516646041

Liu, R., Lao, T. T., Kwok, Y. L., Li, Y., & Ying, M. T.-C. (2008). Effects of graduated compression stockings with different pressure profiles on lower-limb venous structures and haemodynamics. *Advances in Therapy*, *25*(5), 465–478. https://doi.org/10.1007/s12325-008-0058-2

Lovell, D. I., Mason, D. G., Delphinus, E. M., & McLellan, C. P. (2011). Do compression garments enhance the active recovery process after high-intensity running? *Journal of Strength and Conditioning Research*, *25*(12), 3264–3268. https://doi.org/10.1519/JSC.0b013e31821764f8

Lucas-Cuevas, A. G., Priego-Quesada, J. I., Aparicio, I., Giménez, J. V., Llana-Belloch, S., & Pérez-Soriano, P. (2015a). Effect of 3 Weeks Use of Compression Garments on Stride and Impact Shock during a Fatiguing Run. *International Journal of Sports Medicine*, *36*(10), 826–831. https://doi.org/10.1055/s-0035-1548813

Lucas-Cuevas, A. G., Priego-Quesada, J. I., Aparicio, I., Giménez, J. V, Llana-Belloch, S., & Pérez-Soriano, P. (2015b). Effect of 3 Weeks Use of Compression Garments on Stride and Impact Shock during a Fatiguing Run. *International Journal of Sports Medicine*, *36*(10), 826–831. https://doi.org/10.1055/s-0035-1548813

Lucas-Cuevas, Á. G., Priego Quesada, J. I., Giménez, J. V., Aparicio, I., Cortell-Tormo, J. M., & Pérez-

Soriano, P. (2017). Can Graduated Compressive Stockings Reduce Muscle Activity During Running? *Research Quarterly for Exercise and Sport*, *88*(2), 223–229. https://doi.org/10.1080/02701367.2017.1294726

Lucía, A., Hoyos, J., Pérez, M., Santalla, A., & Chicharro, J. L. (2002). Inverse relationship between VO2max and economy/efficiency in world-class cyclists. *Medicine and Science in Sports and Exercise*, *34*(12), 2079–2084. https://doi.org/10.1249/01.MSS.0000039306.92778.DF

MacDougall, J. D., Reddan, W. G., Layton, C. R., & Dempsey, J. A. (1974). Effects of metabolic hyperthermia on performance during heavy prolonged exercise. *Journal of Applied Physiology*, *36*(5), 538–544. https://doi.org/10.1152/jappl.1974.36.5.538

Macintyre, L., & Baird, M. (2006). Pressure garments for use in the treatment of hypertrophic scars—a review of the problems associated with their use. *Burns*, *32*(1), 10–15. https://doi.org/https://doi.org/10.1016/j.burns.2004.06.018

MacRae, B. A., Cotter, J. D., & Laing, R. M. (2011a). Compression garments and exercise: Garment considerations, physiology and performance. *Sports Medicine*, *41*(10), 815–843. https://doi.org/10.2165/11591420-000000000-00000

MacRae, B. A., Cotter, J. D., & Laing, R. M. (2011b). Compression garments and exercise: Garment considerations, physiology and performance. *Sports Medicine*, *41*(10), 815–843. https://doi.org/10.2165/11591420-000000000-00000

MacRae, B. A., Laing, R. M., Niven, B. E., & Cotter, J. D. (2012). Pressure and coverage effects of sporting compression garments on cardiovascular function, thermoregulatory function, and exercise performance. *European Journal of Applied Physiology*, *112*(5), 1783–1795. https://doi.org/10.1007/s00421-011-2146-2

Man, I. O. W., Glover, K., Nixon, P., Poyton, R., Terre, R., & Morrissey, M. C. (2004). Effect of body position on foot and ankle volume in healthy subjects. *Clinical Physiology and Functional Imaging*, *24*(6), 323–326. https://doi.org/10.1111/j.1475-097X.2004.00578.x

Maniar, N., Bach, A. J. E., Stewart, I. B., & Costello, J. T. (2015). The effect of using different regions of interest on local and mean skin temperature. *Journal of Thermal Biology*, *49–50*, 33–38. https://doi.org/10.1016/j.jtherbio.2015.01.008

Marins, J. C. B., De Andrade Fernandes, A., Moreira, D. G., Silva, F. S., Costa, C. M. A., Pimenta, E. M., & Sillero-Quintana, M. (2014). Thermographic profile of soccer players' lower limbs. *Revista Andaluza de Medicina Del Deporte*, *7*(1), 1–6. https://doi.org/10.1016/S1888-7546(14)70053-X

Marqués-Jiménez, D., Calleja-González, J., Arratibel, I., Delextrat, A., & Terrados, N. (2016). Are compression garments effective for the recovery of exercise-induced muscle damage? A systematic review with meta-analysis. *Physiology and Behavior*, *153*, 133–148. https://doi.org/10.1016/j.physbeh.2015.10.027

Martínez-Navarro, I., Aparicio, I., Priego-Quesada, J. I., Pérez-Soriano, P., Collado, E., Hernando, B., & Hernando, C. (2020). Effects of wearing a full body compression garment during recovery from an ultra-trail race. *European Journal of Sport Science*, *0*(0), 1–8. https://doi.org/10.1080/17461391.2020.1783369

McKinnon, J. G., Wong, V., Temple, W. J., Galbraith, C., Ferry, P., Clynch, G. S., & Clynch, C. (2007). Measurement of limb volume: Laser scanning versus volume displacement. *Journal of Surgical Oncology*, *96*(5), 381–388. https://doi.org/https://doi.org/10.1002/jso.20790

McManus, C., Venkatraman, P. D., & Sandercock, G. (2020a). The measurement of interface pressure applied by sports compression garments: A comparative study of two portable devices. *Measurement: Journal of the International Measurement Confederation*, *156*, 107592. https://doi.org/10.1016/j.measurement.2020.107592

McManus, C., Venkatraman, P. D., & Sandercock, G. (2020b). The measurement of interface pressure applied by sports compression garments: A comparative study of two portable devices. *Measurement*, *156*, 107592. https://doi.org/https://doi.org/10.1016/j.measurement.2020.107592

McNeely, M. L., Magee, D. J., Lees, A. W., Bagnall, K. M., Haykowsky, M., & Hanson, J. (2004). The addition of manual lymph drainage to compression therapy for breast cancer related lymphedema: A randomized controlled trial. *Breast Cancer Research and Treatment*, *86*(2), 95–106. https://doi.org/10.1023/B:BREA.0000032978.67677.9f

Megens, A. M., Harris, S. R., Kim-Sing, C., & McKenzie, D. C. (2001). Measurement of upper extremity volume in women after axillary dissection for breast cancer. *Archives of Physical Medicine and Rehabilitation*, *82*(12), 1639–1644. https://doi.org/10.1053/apmr.2001.26822

Meissner, M. H., Gloviczki, P., Bergan, J., Kistner, R. L., Morrison, N., Pannier, F., Pappas, P. J., Rabe, E., Raju, S., & Villavicencio, J. L. (2007). Primary chronic venous disorders. *Journal of Vascular Surgery, 46*(6 SUPPL.), 54–67. https://doi.org/10.1016/j.jvs.2007.08.038

Mendonca, G., Matos, P., & Correia, J. M. (2020). Running economy in recreational male and female runners with similar levels of cardiovascular fitness. *Journal of Applied Physiology*, *129*(3), 508–515. https://doi.org/10.1152/japplphysiol.00349.2020

Ménétrier, A., Mourot, L., Bouhaddi, M., Regnard, J., & Tordi, N. (2011). Compression sleeves increase tissue oxygen saturation but not running performance. *International Journal of Sports Medicine*, *32*(11), 864–868. https://doi.org/10.1055/s-0031-1283181

Merla, A., Mattei, P. A., Di Donato, L., & Romani, G. L. (2010). Thermal imaging of cutaneous temperature modifications in runners during graded exercise. *Annals of Biomedical Engineering*, *38*(1), 158–163. https://doi.org/10.1007/s10439-009-9809-8

Mestre, S., Veye, F., Perez-Martin, A., Behar, T., Triboulet, J., Berron, N., Demattei, C., & Quéré, I. (2014). Validation of lower limb segmental volumetry with hand-held, self-positioning three-dimensional laser scanner against water displacement. *Journal of Vascular Surgery: Venous and Lymphatic Disorders*, *2*(1), 39–45. https://doi.org/https://doi.org/10.1016/j.jvsv.2013.08.002

Mizuno, S., Morii, I., Tsuchiya, Y., & Goto, K. (2016). Wearing Compression Garment after Endurance Exercise Promotes Recovery of Exercise Performance. *International Journal of Sports Medicine*, *37*(11), 870–877. https://doi.org/10.1055/s-0042-106301

Mizuno, Sahiro, Arai, M., Todoko, F., Yamada, E., & Goto, K. (2017). Wearing lower-body compression garment with medium pressure impaired exerciseinduced performance decrement during prolonged running. *PLoS ONE*, *12*(5), 4–15. https://doi.org/10.1371/journal.pone.0178620

Modabber, A., Peters, F., Kniha, K., Goloborodko, E., Ghassemi, A., Lethaus, B., Hölzle, F., & Möhlhenrich, S. C. (2016). Evaluation of the accuracy of a mobile and a stationary system for three-dimensional facial scanning. *Journal of Cranio-Maxillo-Facial Surgery : Official Publication of the European Association for Cranio-Maxillo-Facial Surgery*, *44*(10), 1719–1724. https://doi.org/10.1016/j.jcms.2016.08.008

Moore, I. S. (2016). Is There an Economical Running Technique? A Review of Modifiable Biomechanical Factors Affecting Running Economy. *Sports Medicine*, *46*(6), 793–807. https://doi.org/10.1007/s40279-016-0474-4

Moore, I. S., Jones, A. M., & Dixon, S. J. (2012). Mechanisms for improved running economy in beginner runners. *Medicine and Science in Sports and Exercise*, *44*(9), 1756–1763. https://doi.org/10.1249/MSS.0b013e318255a727

Moreira, D. G., Costello, J. T., Brito, C. J., Adamczyk, J. G., Ammer, K., Bach, A. J. E., Costa, C. M. A., Eglin, C., Fernandes, A. A., Fernández-Cuevas, I., Ferreira, J. J. A., Formenti, D., Fournet, D., Havenith, G., Howell, K., Jung, A., Kenny, G. P., Kolosovas-Machuca, E. S., Maley, M. J., …

Sillero-Quintana, M. (2017). Thermographic imaging in sports and exercise medicine: A Delphi study and consensus statement on the measurement of human skin temperature. *Journal of Thermal Biology*, *69*, 155–162. https://doi.org/10.1016/j.jtherbio.2017.07.006

Moreira, D. G., Costello, J. T., Brito, C. J., & Sillero-Quintana, M. (2017). A checklist for measuring skin temperature with infrared thermography in sports and exercise medicine. *Thermology International*, *27*(4), 136–138.

Morgan, D., Baldini, F., Martin, P., & Kohrt, W. (1989). Ten kilometer performance and predicted velocity at V02max among well-trained male runners. *Medicine & Science in Sports & Exercise*, *21*(1). https://journals.lww.com/acsm-msse/Fulltext/1989/02000/Ten_kilometer_performance_and_predicted_velocity.14.aspx

Morgan, D. W., & Craib, M. (1992). Physiological aspects of running economy. *Medicine and Science in Sports and Exercise*, *24*(4), 456–461.

Mosti, G., Cavezzi, A., Partsch, H., Urso, S., & Campana, F. (2015). Adjustable Velcro® Compression Devices are More Effective than Inelastic Bandages in Reducing Venous Edema in the Initial Treatment Phase: A Randomized Controlled Trial. *European Journal of Vascular and Endovascular Surgery*, *50*(3), 368–374. https://doi.org/10.1016/j.ejvs.2015.05.014

Mota, G. R., Simim, M. A. de M., dos Santos, I. A., Sasaki, J. E., & Marocolo, M. (2020). Effects of Wearing Compression Stockings on Exercise Performance and Associated Indicators: A Systematic Review. *Journal of Sports Medicine*, *Volume 11*, 29–42. https://doi.org/10.2147/oajsm.s198809

Mündermann, A., Nigg, B. M., Stefanyshyn, D. J., & Humble, R. N. (2002). Development of a reliable method to assess footwear comfort during running. *Gait and Posture*, *16*(1), 38–45. https://doi.org/10.1016/S0966-6362(01)00197-7

Murawski, P., Jung, A., Ring, E. F. ., Zuber, J., Plassmann, P., & Kalicki, B. (2003). Image ThermaBase - a software program to capture and analyze thermographic images. *Thermology International*, *13*(1), 5–9.

Nandasiri, G. K., Shahidi, A. M., & Dias, T. (2020). Study of Three Interface Pressure Measurement Systems Used in the Treatment of Venous Disease. In *Sensors* (Vol. 20, Issue 20). https://doi.org/10.3390/s20205777

Nevill, A. M., & Atkinson, G. (1997). Assessing agreement between measurements recorded on a ratio scale in sports medicine and sports science. *British Journal of Sports Medicine*, *31*(4), 314 LP – 318. https://doi.org/10.1136/bjsm.31.4.314

Newham, D. J., Jones, D. A., & Clarkson, P. M. (1987). Repeated high-force eccentric exercise: effects on muscle pain and damage. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, *63*(4), 1381–1386. https://doi.org/10.1152/jappl.1987.63.4.1381

Nigg, B. M., & Wakeling, J. M. (2001). *Impact Forces and Muscle Tuning : A New Paradigm*. 37–41.

Oğlakcıoğlu, N., & Marmaralı, A. (2014). An approach for measuring pressure characteristics of medical compression stockings. *AATCC Journal of Research*, *1*(2), 20–27. https://doi.org/10.14504/ajr.1.2.3

Partsch, H, & Mosti, G. (2010). Comparison of three portable instruments to measure compression pressure. *International Angiology : A Journal of the International Union of Angiology*, *29*(5), 426–430. http://europepmc.org/abstract/MED/20924346

Partsch, Hugo. (2005). The Static Stiffness Index: A Simple Method to Assess the Elastic Property of Compression Material In Vivo. *Dermatologic Surgery*, *31*(6), 625–630. https://doi.org/https://doi.org/10.1111/j.1524-4725.2005.31604

Partsch, Hugo, Clark, M., Bassez, S., Benigni, J.-P., Becker, F., Blazek, V., Caprini, J., Cornu-Thénard, A., Hafner, J., Flour, M., Jünger, M., Moffatt, C., & Neumann, M. (2006). Measurement of lower leg compression in vivo: recommendations for the performance of measurements of interface pressure and stiffness: consensus statement. *Dermatologic Surgery : Official Publication for American Society for Dermatologic Surgery [et Al.]*, *32*(2), 224–232; discussion 233. https://doi.org/10.1111/j.1524-4725.2006.32039.x

Partsch, Hugo, Partsch, B., & Braun, W. (2006). Interface pressure and stiffness of ready made compression stockings : Comparison of in vivo and in vitro measurements. *Journal of Vascular Surgery*, *44*, 809–814. https://doi.org/10.1016/j.jvs.2006.06.024

Pasley, J. D., & O'Connor, P. J. (2008). High day-to-day reliability in lower leg volume measured by water displacement. *European Journal of Applied Physiology*, *103*(4), 393–398. https://doi.org/10.1007/s00421-008-0719-5

Pate, R. R., Macera, C. A., Bailey, S. P., Bartoli, W. P., & Powell, K. E. (1992). Physiological, anthropometric, and training correlates of running economy. *Medicine and Science in Sports and Exercise*, *24*(10), 1128–1133.

Payton, C., & Bartlett, R. (2007). *Biomechanical evaluation of movement in sport and exercise: the British Association of Sport and Exercise Sciences guide*. Routledge.

Pereira, M., Bottaro, M., Brown, L., Rocha-Junior, V., Martorelli, S., Neumann, M., & Carmo, J. (2014). The effects of graduated compression sleeves on muscle performance: A randomised controlled trial. *International Journal of Sports Science and Coaching*, *9*(5), 985–992. https://doi.org/10.1260/1747-9541.9.5.985

Perrey, S., Bringard, A., Racinais, S., Puchaux, K., Belluye, N., & Estivalet, M. (2008). Graduated Compression Stockings and Delayed Onset Muscle Soreness (P105). In *The Engineering of Sport* (Vol. 7, pp. 547–554). https://doi.org/10.1007/978-2-287-09411-8_64

Phinyomark, A., Hettinga, B. A., Osis, S., & Ferber, R. (2015). Do intermediate- and higher-order principal components contain useful information to detect subtle changes in lower extremity biomechanics during running? *Human Movement Science*, *44*, 91–101. https://doi.org/10.1016/j.humov.2015.08.018

Phinyomark, A., Hettinga, B. A., Osis, S. T., & Ferber, R. (2014). Gender and age-related differences in bilateral lower extremity mechanics during treadmill running. *PLoS ONE*, *9*(8). https://doi.org/10.1371/journal.pone.0105246

Phinyomark, A., Petri, G., Ibáñez-Marcelo, E., Osis, S. T., & Ferber, R. (2018). Analysis of Big Data in Gait Biomechanics: Current Trends and Future Directions. *Journal of Medical and Biological Engineering*, *38*(2), 244–260. https://doi.org/10.1007/s40846-017-0297-2

Priego Quesada, J. I., Lucas-Cuevas, A. G., Gil-Calvo, M., Giménez, J. V., Aparicio, I., Cibrián Ortiz de Anda, R. M., Salvador Palmer, R., Llana-Belloch, S., & Pérez-Soriano, P. (2015). Effects of graduated compression stockings on skin temperature after running. *Journal of Thermal Biology*, *52*, 130–136. https://doi.org/10.1016/j.jtherbio.2015.06.005

Priego Quesada, Jose I., Carpes, F. P., Bini, R. R., Salvador Palmer, R., Pérez-Soriano, P., & Cibrián Ortiz de Anda, R. M. (2015). Relationship between skin temperature and muscle activation during incremental cycle exercise. *Journal of Thermal Biology*, *48*, 28–35. https://doi.org/10.1016/j.jtherbio.2014.12.005

Priego Quesada, Jose Ignacio, Martínez Guillamón, N., De Anda, R. M. C. O., Psikuta, A., Annaheim, S., Rossi, R. M., Corberán Salvador, J. M., Pérez-Soriano, P., & Salvador Palmer, R. (2015). Effect of perspiration on skin temperature measurements by infrared thermography and contact thermometry during aerobic cycling. *Infrared Physics and Technology*, *72*, 68–76. https://doi.org/10.1016/j.infrared.2015.07.008

Pruscino, C. L., Halson, S., & Hargreaves, M. (2013). Effects of compression garments on recovery following intermittent exercise. *European Journal of Applied Physiology*, *113*(6), 1585–1596. https://doi.org/10.1007/s00421-012-2576-5

Rabe, E., Stücker, M., & Ottillinger, B. (2010). Water displacement leg volumetry in clinical studies - A discussion of error sources. *BMC Medical Research Methodology*, *10*(January). https://doi.org/10.1186/1471-2288-10-5

Raccuglia, M., Sales, B., Heyde, C., Havenith, G., & Hodder, S. (2018). Clothing comfort during physical exercise – Determining the critical factors. *Applied Ergonomics*, *73*(November 2017), 33–41. https://doi.org/10.1016/j.apergo.2018.05.014

Rauter, S., Vodicar, J., & Simenko, J. (2017). Body asymmetries in young male road cyclists. *International Journal of Morphology*, *35*(3), 907–912. https://doi.org/10.4067/S0717-95022017000300018

RibeiroCristina, Lima, S., Carreira, A., Masiero, D., & Chamlian, T. (2010). Inter-tester reliability assessment of the volumetric measurement of the hand in subjects without any changes in their upper extremities. *ACTA FISIATR*, *17*(1), 3–7.

Rider, B., Coughlin, A., Hew-Butler, T., & Goslin, B. (2014). Effect of compression stockings on physiological responses and running performance in division III collegiate cross-country runners during a maximal treadmill test. *Journal of Strength and Conditioning Research*, *28*(6), 1732–1738. https://doi.org/doi: 10.1519/JSC.0000000000000287

Ridner, S. H., Montgomery, L. D., Hepworth, J. T., Stewart, B. R., & Armer, J. M. (2007). Comparison of upper limb volume measurement techniques and arm symptoms between healthy volunteers and individuals with known lymphedema. *Lymphology*, *40*(1), 35–46.

Rimaud, D., Messonnier, L., Castells, J., Devillard, X., & Calmels, P. (2010). Effects of compression stockings during exercise and recovery on blood lactate kinetics. *European Journal of Applied Physiology*, *110*(2), 425–433. https://doi.org/10.1007/s00421-010-1503-x

Ring, E. F. J., & Ammer, K. (2000). The Technique of Infra red Imaging in Medicine. *Thermology International*, *10*(1), 7–14. https://doi.org/10.1088/978-0-7503-1143-4ch1

Ring, E. F. J., & Ammer, K. (2012). Infrared thermal imaging in medicine. *Physiological Measurement*, *33*(3). https://doi.org/10.1088/0967-3334/33/3/R33

Ring, E. F. J., & Ammer, K. (2015). The technique of infrared imaging in medicine. *Infrared Imaging: A Casebook in Clinical Medicine*, *February 2000*. https://doi.org/10.1088/978-0-7503-1143-4ch1

Ring, F. J., Ammer, K., Wiecek, B., Plassmann, P., Jones, C. D., Jung, A., & Murawski, P. (2007). Quality assurance of thermal imaging systems in medicine. *Thermology International*, *17*(7), 103–106.

Robertson, G., Caldwell, G. E., & Hamill, J. (2013). *Research Methods in Biomechanics* (2nd Editio, Issue November).

Rossignoli, I., Benito, P. J., & Herrero, A. J. (2015). Reliability of infrared thermography in skin temperature evaluation of wheelchair users. *Spinal Cord*, *53*(3), 243–248. https://doi.org/10.1038/sc.2014.212

Rugg, S., & Sternlicht, E. (2013). The effect of graduated compression tights, compared with running shorts, on counter movement jump performance before and after submaximal running. *Journal of Strength and Conditioning Research*, *27*(4), 1067–1073. https://doi.org/10.1519/JSC.0b013e3182610956

Sander, A. P., Hajer, N. M., Hemenway, K., & Miller, A. C. (2002). Upper-Extremity Volume Measurements in Women With Lymphedema: A Comparison of Measurements Obtained Via

Water Displacement With Geometrically Determined Volume. *Physical Therapy*, *82*(12), 1201–1212. https://doi.org/10.1093/ptj/82.12.1201

Sands, W., McNeal, J., & Stone, M. (2011). Thermal Imaging and Gymnastics Injuries: A Means of Screening and Identification. *Science of Gymnastics Journal*, *3*(2), 5.

Sarin, S., Scurr, J. H., & Coleridge Smith, P. D. (1992). Mechanism of action of external compression on venous function. *The British Journal of Surgery*, *79*(6), 499–502. https://doi.org/10.1002/bjs.1800790608

Saunders, P. U., Pyne, D. B., Telford, R. D., & Hawley, J. A. (2004). Factors Affecting Running Economy in Trained Distance Runners. *Sports Medicine*, *34*(7), 465–485.

Sawka, M. N., Cheuvront, S. N., & Kenefick, R. W. (2012). High skin temperature and hypohydration impair aerobic performance. *Experimental Physiology*, *97*(3), 327–332. https://doi.org/10.1113/expphysiol.2011.061002

Scanlan, A., Dascombe, B., Peter, R., & Osborne, M. (2008). The Effects of Wearing Lower-Body Compression Garments During Endurance Cycling. *International Journal of Sports Physiology and Performance*, *3*(4), 424–438.

Scanlan, A. T., Dascombe, B. J., Reaburn, P. R. J., & Osborne, M. (2008). The effects of wearing lower-body compression garments during endurance cycling. *International Journal of Sports Physiology and Performance*, *3*(4), 424–438. https://doi.org/10.1123/ijspp.3.4.424

Schober, P., & Schwarte, L. A. (2018). Correlation coefficients: Appropriate use and interpretation. *Anesthesia and Analgesia*, *126*(5), 1763–1768. https://doi.org/10.1213/ANE.0000000000002864

Schwartz, R. (2006). Guidelines for neuromusculoskeletal thermography. *Thermology International*, *16*(1), 5–9.

Scovil, C. Y., & Ronsky, J. L. (2006). Sensitivity of a Hill-based muscle model to perturbations in model parameters. *Journal of Biomechanics*, *39*(11), 2055–2063. https://doi.org/10.1016/j.jbiomech.2005.06.005

Scurr, J. H., Machin, S. J., Bailey-King, S., Mackie, I. J., McDonald, S., & Smith, P. D. (2001). Frequency and prevention of symptomless deep-vein thrombosis in long-haul flights: a randomised trial. *Lancet (London, England)*, *357*(9267), 1485–1489. https://doi.org/10.1016/S0140-6736(00)04645-6

Sear, J., Hoare, T., Scanlan, A., Abt, G., & Dascombe, B. (2010). The effects of whole-body compression garments on prolonged high-intensity intermittent exercise. *Journal of Strength and Conditioning Research*, *24*(7), 1901–1910.

Selfe, J., Hardaker, N., Thewlis, D., & Karki, A. (2006). An Accurate and Reliable Method of Thermal Data Analysis in Thermal Imaging of the Anterior Knee for Use in Cryotherapy Research. *Archives of Physical Medicine and Rehabilitation*, *87*(12), 1630–1635. https://doi.org/10.1016/j.apmr.2006.08.346

Seminati, E., Talamas, D. C., Young, M., Twiste, M., Dhokia, V., & Bilzon, J. L. J. (2017). Validity and reliability of a novel 3D scanner for assessment of the shape and volume of amputees' residual limb models. *PLoS ONE*, *12*(9), 1–16. https://doi.org/10.1371/journal.pone.0184498

Sharkey, A. R., King, S. W., Kuo, R. Y., Bickerton, S. B., Ramsden, A. J., & Furniss, D. (2018). Measuring Limb Volume: Accuracy and Reliability of Tape Measurement Versus Perometer Measurement. *Lymphatic Research and Biology*, *16*(2), 182–186. https://doi.org/10.1089/lrb.2017.0039

Sherman, R. A., Woerman, A. L., & Karstetter, K. W. (1996). Comparative effectiveness of videothermography, contact thermography, and infrared beam thermography for scanning relative skin temperature. *Journal of Rehabilitation Research and Development*, *33*(4), 377–386.

Shimokochi, Y., Kuwano, S., Yamaguchi, T., Abutani, H., & Shima, N. (2017). Effects of wearing a compression garment during night sleep on recovery from high-intensity eccentric-concentric quadriceps muscle fatigue. *Journal of Strength and Conditioning Research*, *31*(10), 2816–2824.

Silva, Y. A., Santos, B. H., Andrade, P. R., Santos, H. H., Moreira, D. G., Sillero-Quintana, M., & Ferreira, J. J. A. (2017). Skin temperature changes after exercise and cold water immersion. *Sport Sciences for Health*, *13*(1), 195–202. https://doi.org/10.1007/s11332-017-0353-x

Sinclair, J., Taylor, P. J., Edmundson, C. J., Brooks, D., & Hobbs, S. J. (2013). The influence of footwear kinetic, kinematic and electromyographical parameters on the energy requirements of steady state running. *Movement & Sport Sciences*, *80*, 39–49. https://doi.org/10.1051/sm/2012025

Skins Technology. (2021). *SKINS Compression UK*. https://www.skinscompression.com/uk/discover-skins-technology/

Spencer, M., Bishop, D., Dawson, B., & Goodman, C. (2005). Physiological and metabolic responses of repeated-sprint activities: Specific to field-based team sports. *Sports Medicine*, *35*(12), 1025–1044. https://doi.org/10.2165/00007256-200535120-00003

Sperlich, B., Haegele, M., Krüger, M., Schiffer, T., Holmberg, H. C., & Mester, J. (2011). Cardio-respiratory and metabolic responses to different levels of compression during submaximal exercise. *Phlebology*, *26*(3), 102–106. https://doi.org/10.1258/phleb.2010.010017

Sperlich, Billy, Born, D. P., Kaskinoro, K., Kalliokoski, K. K., & Laaksonen, M. S. (2013). Squeezing the Muscle: Compression Clothing and Muscle Metabolism during Recovery from High Intensity Exercise. *PLoS ONE*, *8*(4). https://doi.org/10.1371/journal.pone.0060923

Sperlich, Billy, Haegele, M., Achtzehn, S., Linville, J., Holmberg, H. C., & Mester, J. (2010). Different types of compression clothing do not increase sub-maximal and maximal endurance performance in well-trained athletes. *Journal of Sports Sciences*, *28*(6), 609–614. https://doi.org/10.1080/02640410903582768

Staley, M. J., & Richard, R. L. (1997). Use of pressure to treat hypertrophic burn scars. *Advances in Wound Care : The Journal for Prevention and Healing*, *10*(3), 44–46.

Stanhope, S. J., Kepple, T. M., McGuire, D. A., & Roman, N. L. (1990). Kinematic-based technique for event time determination during gait. *Medical and Biological Engineering and Computing*, *28*(4), 355–360. https://doi.org/10.1007/BF02446154

Stickford, A. S. L., Chapman, R. F., Johnston, J. D., & Stager, J. M. (2015). Lower-leg compression, running mechanics, and economy in trained distance runners. *International Journal of Sports Physiology and Performance*, *10*(1), 76–83. https://doi.org/10.1123/ijspp.2014-0003

Stolk, R., Van Der-Franken, C. P. M. W., Neumann, H. A. M., & Goldman, M. (2004). A method for measuring the dynamic behavior of medical compression hosiery during walking. *Dermatologic Surgery*, *30*(5), 729–736. https://doi.org/10.1111/j.1524-4725.2004.30203.x

Stout, N., Partsch, H., Szolnoky, G., Forner-Cordero, I., Mosti, G., Mortimer, P., Flour, M., Damstra, R., Piller, N., Geyer, M. J., Benigni, J.-P., Moffat, C., Cornu-Thenard, A., Schingale, F., Clark, M., & Chauveau, M. (2012). Chronic edema of the lower extremities: international consensus recommendations for compression therapy clinical research trials. *International Angiology : A Journal of the International Union of Angiology*, *31*(4), 316–329.

Struhár, I., Kumstát, M., & Králová, D. M. (2018). Effect of Compression Garments on Physiological Responses after Uphill Running. *Journal of Human Kinetics*, *61*(1), 119–129. https://doi.org/10.1515/hukin-2017-0136

Tachi, M., Kouzaki, M., Kanehisa, H., & Fukunaga, T. (2004). The influence of circulatory difference on muscle oxygenation and fatigue during intermittent static dorsiflexion. *European Journal of Applied Physiology*, *91*(5–6), 682–688. https://doi.org/10.1007/s00421-003-1024-y

Tamez-Duque, J., Cobian-Ugalde, R., Kilicarslan, A., Venkatakrishnan, A., Soto, R., & Contreras-Vidal, J. L. (2015). Real-time strap pressure sensor system for powered exoskeletons. *Sensors (Basel, Switzerland)*, *15*(2), 4550–4563. https://doi.org/10.3390/s150204550

Tan, C. W., Coutts, F., & Bulley, C. (2013). Measurement of lower limb volume: Agreement between the vertically oriented perometer and a tape measure method. *Physiotherapy*, *99*(3), 247–251. https://doi.org/10.1016/j.physio.2012.12.004

Tanda, G. (2016). Skin temperature measurements by infrared thermography during running exercise. *Experimental Thermal and Fluid Science*, *71*, 103–113. https://doi.org/10.1016/j.expthermflusci.2015.10.006

Tatterson, A. J., Hahn, A. G., Martin, D. T., & Febbraio, M. A. (2000). Effects of heat stress on physiological responses and exercise performance in elite cyclists. *Journal of Science and Medicine in Sport*, *3*(2), 186–193. https://doi.org/10.1016/s1440-2440(00)80080-8

Thomas, D. Q., Fernhall, B., Blanpied, P., & Stillwell, K. (1995). Changes in Running Economy and Mechanics During a Submaximal 5-km Run. *The Journal of Strength & Conditioning Research*, *9*(3). https://journals.lww.com/nsca-jscr/Fulltext/1995/08000/Changes_in_Running_Economy_and_Mechanics_During_a.9.aspx

Todd, M. (2015). Compression hosiery choices for managing chronic oedema. *British Journal of Community Nursing*, *20*(7), 318–320. https://doi.org/10.12968/bjcn.2015.20.7.318

Toolis, T., & McGawley, K. (2020). The Effect of Compression Garments on Performance in Elite Winter Biathletes. *International Journal of Sports Physiology and Performance*, *16*(1), 145–148. https://doi.org/10.1123/ijspp.2019-0790

Trenell, M. I., Rooney, K. B., Sue, C. M., & Thompson, C. H. (2006). Compression garments and recovery from eccentric exercise: A31P-MRS study. *Journal of Sports Science and Medicine*, *5*(1), 106–114.

Troynikov, O., Wardiningsih, W., Koptug, A., Watson, C., & Oggiano, L. (2013). Influence of material properties and garment composition on pressure generated by sport compression garments. *Procedia Engineering*, *60*, 157–162. https://doi.org/10.1016/j.proeng.2013.07.054

Turner, A. N., & Stewart, P. F. (2013). Repeat Sprint Ability. *Strength & Conditioning Journal*, *35*(1). https://journals.lww.com/nsca-scj/Fulltext/2013/02000/Repeat_Sprint_Ability.5.aspx

Upton, C., Brown, F., & and Hill, J. (2017). Efficacy of compression garments on recovery from a simulated rugby protocol. *Journal of Strength and Conditioning Research*, *31*(11), 2977–2982.

Upton, C. M., Brown, F. C. W., & Hill, J. A. (2017). Efficacy of compression garments on recovery from a simulated rugby protocol. *Journal of Strength and Conditioning Research*, *31*(11), 2977–2982. https://doi.org/10.1519/JSC.0000000000002145

Van den Kerckhove, E., Fieuws, S., Massagé, P., Hierner, R., Boeckx, W., Deleuze, J. P., Laperre, J., & Anthonissen, M. (2007). Reproducibility of repeated measurements with the Kikuhime pressure sensor under pressure garments in burn scar treatment. *Burns*, *33*(5), 572–578. https://doi.org/10.1016/j.burns.2006.08.032

Varela-Sanz, A., España, J., Carr, N., Boullosa, D. A., & Esteve-Lanao, J. (2011). Effects of gradual-elastic compression stockings on running economy, kinematics, and performance in runners. *Journal of Strength and Conditioning Research*, *25*(10), 2902–2910. https://doi.org/10.1519/JSC.0b013e31820f5049

Venckunas, T., Trinkunas, E., Kamandulis, S., Poderys, J., Grunovas, A., & Brazaitis, M. (2014). Effect of lower body compression garments on hemodynamics in response to running session. *Scientific World Journal*, *2014*. https://doi.org/10.1155/2014/353040

VERAART, J. C. J. M., PRONK, G., & NEUMANN, M. H. A. (1997). Pressure Differences of Elastic Compression Stockings at the Ankle Region. *Dermatologic Surgery*, *23*(10). https://journals.lww.com/dermatologicsurgery/Fulltext/1997/10000/Pressure_Differences_of_Elastic_Compression.17.aspx

Villaseñor-Mora, C., Sanchez-Marin, F. J., & Calixto-Carrera, S. (2009). An indirect skin emissivity measurement in the infrared thermal range through reflection of a CO2 laser beam. *Revista Mexicana de Fisica*, *55*(5), 387–392.

Vinckx, L., Boeckx, W., & Berghmans, J. (1990). Analysis of the pressure perturbation due to the introduction of a measuring probe under an elastic garment. *Medical and Biological Engineering and Computing*, *28*(2), 133–138. https://doi.org/10.1007/BF02441768

Wakeling, J. M., Tscharner, V. V. O. N., Nigg, B. M., & Stergiou, P. R. O. (2001). Muscle activity in the leg is tuned in response to ground reaction forces. *Journal of Applied Physiology*, *91*, 1307–1317.

Wang, Y., Cui, Y., Zhang, P., Feng, X., Shen, J., & Xiong, Q. (2011). A smart mannequin system for the pressure performance evaluation of compression garments. *Textile Research Journal*, *81*(11), 1113–1123. https://doi.org/10.1177/0040517511398942

Watanuki, S., & Murata, H. (1994). Effects of wearing compression stockings on cardiovascular responses. *The Annals of Physiological Anthropology = Seiri Jinruigaku Kenkyukai Kaishi*, *13*(3), 121—127. https://doi.org/10.2114/ahs1983.13.121

Watmough, D. J., & Oliver, R. (1968). Emissivity of Human Skin in vivo between 2.0µ and 5.4µ measured at Normal Incidence. *Nature*, *218*, 885–886. https://doi.org/10.1038/218885a0

Whitehead, N. P., Allen, T. J., Morgan, D. L., & Proske, U. (1998). Damage to human muscle from eccentric exercise after training with concentric exercise. *The Journal of Physiology*, *512 (Pt 2*(Pt 2), 615–620. https://doi.org/10.1111/j.1469-7793.1998.615be.x

Whitehead, N. P., Weerakkody, N. S., Gregory, J. E., Morgan, D. L., & Proske, U. (2001). Changes in passive tension of muscle in humans and animals after eccentric exercise. *Journal of Physiology*, *533*(2), 593–604. https://doi.org/10.1111/j.1469-7793.2001.0593a.x

Wilkinson, J. D., Leggett, S. A., Marjanovic, E. J., Moore, T. L., Allen, J., Anderson, M. E., Britton, J., Buch, M. H., Del Galdo, F., Denton, C. P., Dinsdale, G., Griffiths, B., Hall, F., Howell, K., MacDonald, A., McHugh, N. J., Manning, J. B., Pauling, J. D., Roberts, C., … Murray, A. K. (2018). A Multicenter Study of the Validity and Reliability of Responses to Hand Cold Challenge as Measured by Laser Speckle Contrast Imaging and Thermography: Outcome Measures for Systemic Sclerosis–Related Raynaud's Phenomenon. *Arthritis and Rheumatology*, *70*(6), 903–911. https://doi.org/10.1002/art.40457

Williams, K. R., & Cavanagh, P. R. (1987). Relationship between distance running mechanics, running economy, and performance. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, *63*(3), 1236–1245. https://doi.org/10.1152/jappl.1987.63.3.1236

Williams, K. R., Cavanagh, P. R., & Ziff, J. L. (1987). Biomechanical studies of elite female distance runners. *International Journal of Sports Medicine*, *8 Suppl 2*, 107–118. https://doi.org/10.1055/s-2008-1025715

Winke, M., & Williamson, S. (2017). Comparison of a Pneumatic Compression Device to a Compression Garment During Recovery from DOMS. *Medicine & Science in Sports & Exercise*, *11*(3), 375–383. http://www.ncbi.nlm.nih.gov/pubmed/29795729%0Ahttp://www.pubmedcentral.nih.gov/articler ender.fcgi?artid=PMC5955306

Xiong, Y., & Tao, X. (2018). Compression garments for medical therapy and sports. *Polymers*, *10*(6), 663. https://doi.org/10.3390/polym10060663

Yamamoto, S., Miyachi, H., Fujii, H., Ochiai, S., Watanabe, S., & Shimozato, K. (2016). Intuitive Facial Imaging Method for Evaluation of Postoperative Swelling: A Combination of 3-Dimensional Computed Tomography and Laser Surface Scanning in Orthognathic Surgery. *Journal of Oral and Maxillofacial Surgery : Official Journal of the American Association of Oral and Maxillofacial Surgeons*, *74*(12), 2506.e1-2506.e10. https://doi.org/10.1016/j.joms.2016.08.039

Yang, C., Xu, Y., Yang, Y., Xiao, S., & Fu, W. (2020). Effectiveness of Using Compression Garments in Winter Racing Sports: A Narrative Review. *Frontiers in Physiology*, *11*(August), 1–10. https://doi.org/10.3389/fphys.2020.00970

Zaproudina, N., Varmavuo, V., Airaksinen, O., & Närhi, M. (2008). Reproducibility of infrared thermography measurements in healthy individuals. *Physiological Measurement, 29*(4), 515–524. https://doi.org/10.1088/0967-3334/29/4/007

Zhou, C., Yahathugoda, C., De Silva, L., Rathnapala, U., Owen, G., Weerasooriya, M., Rao, R. U., Weil, G. J., & Budge, P. J. (2019). Portable infrared imaging for longitudinal limb volume monitoring in patients with lymphatic filariasis. *PLOS Neglected Tropical Diseases*, *13*(10), e0007762. https://doi.org/10.1371/journal.pntd.0007762

Zhuang, Q., Harlock, S. C., & Brook, D. B. (2002). Transfer Wicking Mechanisms of Knitted Fabrics Used as Undergarments for Outdoor Activities. *Textile Research Journal*, *72*(8), 727–734. https://doi.org/10.1177/004051750207200813

Chapter 12: Appendices

- **Appendix 1 – Participant Information Sheet for Data Collection 1**
- **Appendix 2 – Participant Statement of Consent for Data Collection 1**
- **Appendix 3 – Participant Health Screen for Data Collection 1**
- **Appendix 4 - Participant Information Sheet for Data Collection 2**
- **Appendix 5 - Participant Health Screen for Data Collection 2**
- **Appendix 6 - COVID-19 Symptom Questionnaire for Data Collection 2**
- **Appendix 7 – Compression Garment Pressure Profiles Figure**
- **Appendix 8 – Comfort Questionnaire Visual Analogue Scale for Chapter 8**

Appendix 1

Participant Information Sheet for Data Collection 1

The Effect of Compression Tights on the Movements, Forces and Thermal Responses of Treadmill Running

Invitation and Brief Summary

Compression sport clothing is used by athletes to help them recover from exercise. Many athletes are now choosing to wear this type of tight fighting clothing whilst they train and compete. There is little scientific evidence to identify if this is beneficial. We are recruiting runners to be involved in testing different types of compression running tights. This study will involve 3-dimensional scans and thermal images of your legs and pelvis and 30 minutes of treadmill running at your own comfortable pace, to be repeated on 5 different occasions. This study is expected to require a net time commitment by you of 6 hours (approximately evenly split between the 5 sessions). Please note, that some images are collected with only minimal clothing, such as underwear or small sports shorts, which ever you prefer. Two investigators will be present at all times. As part of this study, you will have three bespoke pairs of athletic tights manufactured for your body shape. At the end of this study you will be able to keep at least one pair of these tights.

Your Participation

You will have been provided this information sheet a minimum of 24 hours prior to your first visit. This allows you time and the opportunity to request further information and to make an informed decision regarding whether you wish to participate. If once you have read this document, you wish to obtain further guidance, please use the contact details at the end of this document.

Study Requirements:

You will visit the lab on 5 occasions, with each visit lasting approximately 120 minutes. You will be scanned to obtain a 3-dimensional image of your legs and pelvis and a thermal image of your legs prior to and following a treadmill run. These images are collected with you wearing minimal clothing. You will be required to complete a 5 minute treadmill running warm-up, 30 minutes of continuous running on a treadmill and then a further 5 minutes treadmill running as a cool down. You will be running at a pace you consider to be comfortable for all parts of this study. All running will be completed on a treadmill similar to the one in the figure below (Figure 1). The run will be performed with minimal upper body clothing (no t-shirt for males or sports bra for females). Participants can wear a tight fitted sports t-shirt if they want to.

Figure 1. Instrumented treadmill used for testing

Clothing:

You should wear appropriate clothing for running on a treadmill, to include well-fitting running shoes (laces tied), shorts and t-shirt. Please bring small shorts or wear appropriate underwear to allow 3D scans of your limbs to be taken with you wearing minimal clothing. We recommend tight fitting shorts and a vest top. If you do not have a vest top, then please bring a tight fitting t-shirt. Examples of best clothing include lycra shorts, racing vest tops, female performance crop tops.

Location:

The biomechanics laboratory (CEL001/CELS002) in the CELS building, Clifton Campus, Nottingham Trent University, NG11 8NS and the Lee Westwood Sports Centre, Clifton Campus, Nottingham Trent University, NG11 8NS.

Restrictions during Testing:

Consumption of excessive alcohol 24 hours before the trials.

Restrain from vigorous physical activity 24 hours before the trials.

Restrain from consuming caffeine on trial days.

Retain from applying body creams and/or lotions (excluding the face) on trial days.

Testing Protocol

You will visit the laboratory wearing comfortable clothing and your regular exercise trainers or shoes. You will make 5 visits, of which the first requires fewer measurements. A diagram is provided below to show the measurements and activities you will undertake and the order of these.

When you arrive at the laboratory, 3-dimensional scans with a strobe device will be made to measure the shape of your legs and pelvis and then thermal images will be made to measure the temperature of your legs from the front and back. During these scans you must be wearing minimal clothing such as your underwear or short sports shorts (you decide which of these you feel most comfortable to be scanned in). None of these scans include facial features. After the scans you will run a self-selected 5 minute warm-up on a treadmill in your own sports clothing. Following the warm-up you will be re-scanned with the thermal imaging camera and reflective markers will be stuck to various land marks in order to measure your running technique. For your first visit to the laboratory you will then move straight on to the 30 minute treadmill run in your own running shorts, but for the 2nd, 3rd and 4th visits to the laboratory we will provide you with a pair of bespoke compression athletic tights to wear and will ask you to place a pressure sensor inside the back of the leg when you put these on. We will measure pressure inside the tights and then remove the pressure measuring device. You will run on a treadmill at a pace you determine as being comfortable and could be described as “Light” for 30 minutes. After running on the treadmill we will take another set of thermal images and scans of the legs and pelvis, again whilst you are wearing minimal clothing. Following these scans, you will be given 5 minutes to complete a self-selected cool-down, which might include further running and stretches.

Your motion whilst running is measured by sticking reflective markers to your skin, strapping them around the lower leg or wearing a headband. The markers are detected using a motion analysis camera system. See Figure 2 for the common sites where these markers are placed and Figure 3 which represents those areas where markers will never be placed.

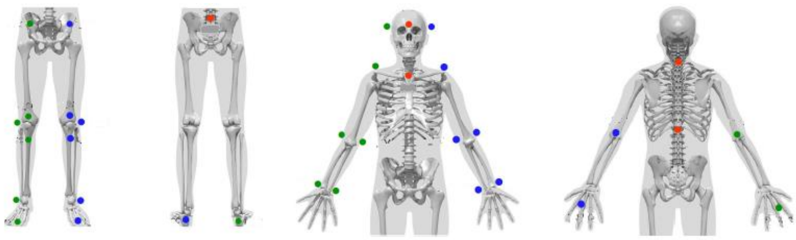


Figure 2: Example of reflective marker locations on the feet, legs, pelvis, torso, shoulders and head band

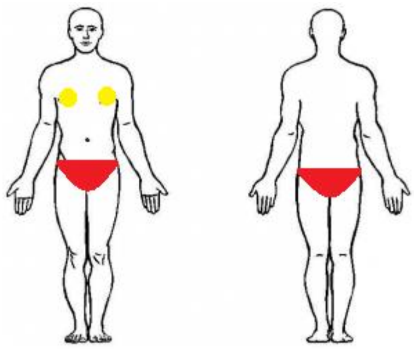
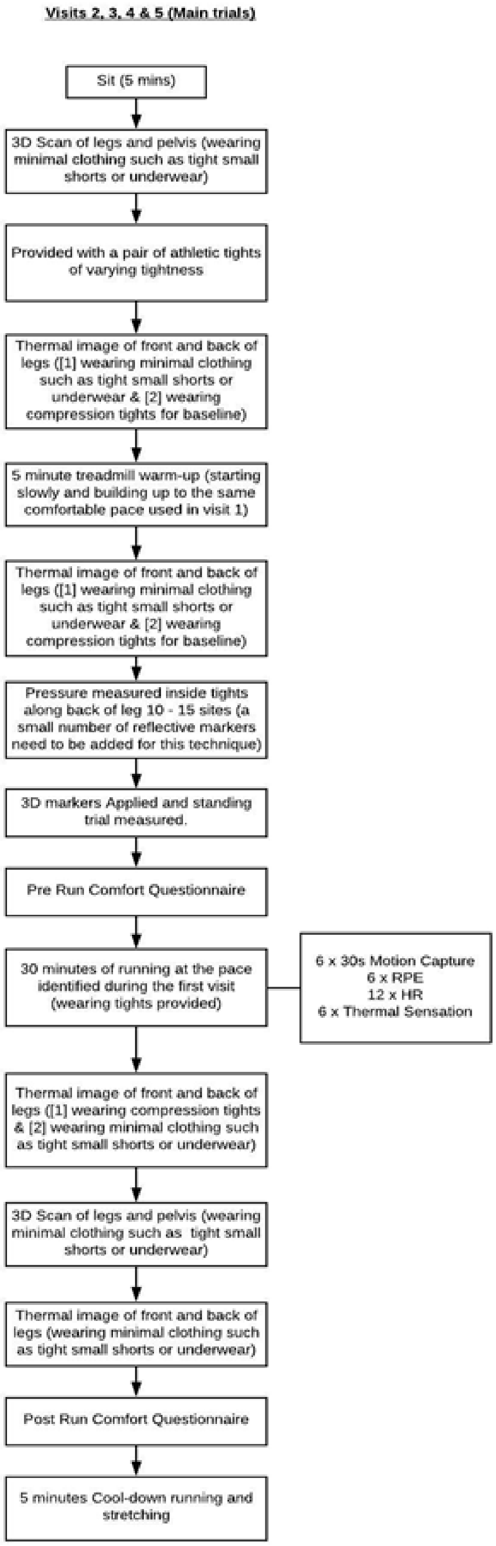


Figure 3. Prohibited marker placement areas for both men and women (red) and women only (yellow).

Overview of the procedures:



What are the possible benefits of taking part?

As part of this study, you will have three bespoke pairs of athletic tights manufactured for your body shape. At the end of this study you will be able to keep at least one pair of these tights. Furthermore you will be able to get feedback on your running technique.

Potential Risks to You:

- Fatigue/tiredness from running trials.
- Small risk of tripping/falling on the treadmill and in the laboratory.
- Risk of allergic reaction to tape used to attach markers to the body.
- Although it is extremely unlikely, high intensity exercise has been known to reveal unsuspected heart or circulation problems and very rarely these have had serious or fatal consequences.
-

Confidentiality:

Data collected may be presented in various forms (journal articles, papers etc.), personal information will be treated in confidence. No names will be associated with the data in the presentations.

If at any point you decide to withdraw from the study your data will be destroyed.

Contact Details:

Jack Ashby

Email: jack.ashby2013@my.ntu.ac.uk

Tel: 07429080873

Address: Clifton Campus, Clifton Lane, Nottingham, NG11 8NS

Dr. Martin Lewis

Email: martin.lewis@ntu.ac.uk

Tel: 01158483522

Address: NHB168, Clifton Campus, Clifton Lane, Nottingham, NG11 8NS.

Appendix 2

Participant Statement of Consent to Participate in the Investigation Entitled:

The Effect of Compression Tights on the Movements, Forces and Thermal Responses of Treadmill Running

1) I, *[name of participant]* agree to partake as a participant in the above study.

2) I understand from the participant information sheet, which I have read in full, and from my discussion(s) with *[name of investigator]* that this will involve me completing a total of 4 visits to the laboratory with up to 40 minutes of treadmill running at each visit (motorized instrumented treadmill), in addition to being scanned and thermal images collected with me in minimal clothing. Furthermore, I understand that a pressure sensor will be used inside the tights provided to me in order to measure the clothing's fit.

3) It has also been explained to me by *[name of investigator]* that the risks and side effects that may result from my participation are as follows: tiredness and/or fatigue and the small risk of tripping/falling and musculoskeletal injuries during the trials and in the laboratory. Potential allergy to plaster. I also understand that although it is extremely unlikely, high intensity exercise has been known to reveal unsuspected heart or circulation problems and very rarely these can have serious or fatal consequences.

4) I confirm that I have had the opportunity to ask questions about the study and, where I have asked questions, these have been answered to my satisfaction.

5) I undertake to abide by University regulations and the advice of researchers regarding safety.

6) I am aware that I can withdraw my consent to participate in the procedure at any time and for any reason, without having to explain my withdrawal and that my personal data will be destroyed and that my medical care or legal rights will not be affected.

7) I understand that any personal information regarding me, gained through my participation in this study, will be treated as confidential and only handled by individuals relevant to the performance of the study and the storing of information thereafter. Where information concerning myself appears within published material, my identity will be kept anonymous.

8) I confirm that I have had the University's policy relating to the storage and subsequent destruction of sensitive information explained to me. I understand that sensitive information I have provided through my participation in this study, in the form of contact details, body shape 3D images and thermal images will be handled in accordance with this policy.

9) I confirm that I have completed the health questionnaire and know of no reason, medical or otherwise that would prevent me from partaking in this research.

10) I understand that the information collected about me will be used to support other research in the future, and may be shared anonymously with other researchers.

Participant signature: _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ **Date: _ _ _ _ _ _ _ _ _ _ _**

Independent witness signature: _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ **Date: _ _ _ _ _ _ _ _ _ _ _**

Primary Researcher signature: _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ **Date: _ _ _ _ _ _ _ _ _ _ _**

Appendix 3

Health Screen for Data Collection 1

Name or Number ....

Please complete this brief questionnaire to confirm fitness to participate:

1. **At present,** do you have any health problem for which you are:

(a)	on medication, prescribed or otherwise	Yes ☐ No ☐
(b)	attending your general practitioner	Yes ☐ No ☐
(c)	on a hospital waiting list	Yes ☐ No ☐

2. **In the past two years,** have you had any illness which require you to:

(a)	consult your GP	Yes ☐ No ☐
(b)	attend a hospital outpatient department	Yes ☐ No ☐
(c)	be admitted to hospital	Yes ☐ No ☐

3. **Have you ever** had any of the following?

(a)	Convulsions/epilepsy	Yes ☐ No ☐
(b)	Asthma	Yes ☐ No ☐
(c)	Eczema	Yes ☐ No ☐
(d)	Diabetes	Yes ☐ No ☐
(e)	A blood disorder	Yes ☐ No ☐
(f)	Head injury	Yes ☐ No ☐
(g)	Digestive problems	Yes ☐ No ☐
(h)	Heart problems	Yes ☐ No ☐
(i)	Problems with bones or joints	Yes ☐ No ☐
(j)	Disturbance of balance / coordination	Yes ☐ No ☐
(k)	Numbness in hands or feet	Yes ☐ No ☐

(l) Disturbance of vision Yes ☐ No ☐

(m) Ear / hearing problems Yes ☐ No ☐

(n) Thyroid problems Yes ☐ No ☐

(o) Kidney or liver problems Yes ☐ No ☐

(p) Allergy to nuts, alcohol etc. Yes ☐ No ☐

(q) Any problems affecting your nose e.g. recurrent nose bleeds Yes ☐ No ☐

(r) Any nasal fracture or deviated nasal septum Yes ☐ No ☐

4. **Has any,** otherwise healthy, member of your family under the age of 50 died suddenly during or soon after exercise? Yes ☐ No ☐

5. Are there any reasons why blood sampling may be difficult? Yes ☐ No ☐

6. Have you had a blood sample taken previously? Yes ☐ No ☐

7. Have you had a cold, flu or any flu like symptoms in the last Month? Yes ☐ No ☐

<u>Women only</u>

8. Are you pregnant, trying to become pregnant or breastfeeding? Yes ☐ No ☐

If YES to any question, please describe briefly if you wish (e.g. to confirm problem was/is short-lived, insignificant or well controlled.)

....

Appendix 4

Participant Information Sheet for Data Collection 2

The Assessment of garment pressure and limb size when wearing made to measure compression garments.

Brief Introduction:

In recent years there has been interest in the use of compression garments as a recovery aid following exercise. It has been suggested that wearing compression garments enhances the flow of blood to tired muscle and helps the body recover quicker than it otherwise would. However, the research studies that have examined if and how compression garments may help individuals recover from exercise have not found consistent results. A possible explanation for the mixed research results is the lack of information on the amount of pressure actually applied by a garment to the body (this is known as a pressure profile). Most research does not directly measure the pressure profile. It is important that the amount of compression applied by a garment can be measured and done so reliably. This will ensure the fit and amount of compression exerted by a garment is appropriate. Therefore, a reliable and valid method for assessing garment pressure and providing a better pressure profile is warranted. Therefore, the primary aim of the current study is to develop a novel method for assessing graduated pressure in a lower body compression garment (tights). Secondary aims are to investigate the compression profile produced by 'made to measure garments' and to compare this method with the standard method as proposed in previous research (Brophy-Williams et al, 2015). In addition, the study will aim to use a 3D scanner to investigate its reliability and validity and whether it can show day to day changes in muscle size which could reflect muscle inflammation.

Study Requirements:
Participants will be recreationally active. Participants will be healthy and between the age of 18- 45 years.

Location:
CELS (003) Biomechanics Laboratory, Nottingham Trent University, Clifton Campus, College Drive, Nottingham, NG11 8NS.

Restrictions During Testing:

- No alcohol or additional supplementation to be taken 24 hours prior to testing.
- No vigorous exercise in the 48hrs hours prior to the experimental trials.
-

Testing Protocol:

Procedures and measurements will identical for all 3/4 experimental trials. Prior to any trials the participant will have 24 hours to complete a health questionnaire and informed consent form indicating that they are willing to be a participant in the study. The signing of this consent form does not prevent the participant from leaving the study at any point without giving a reason. During each experimental trail each participant's stature, body mass, and skinfolds will be assessed and the compression profile of a made-to-measure garment will be assessed using two different methods: the standard Brophy-Williams approach (Brophy-Williams et al., 2015) and a new method the study research team are utilising. Pressure during both methods will be examined using a Kikuhime pressure monitoring device (MediGroup, Melbourne, Australia). The device consists of an oval-shaped sensor, emitting pressure readings to a transducer connected via rubber tubing. On this device pressure is constantly displayed on the transducer, reported in 1 mmHg increments.

Prior to any pressure measurements each participant will be marked, with reflective markers, at specific anatomical locations such as: 1) the lateral malleolus (ankle), 2) the lateral femoral condyle (knee), 3) the greater trochanter and 4) the iliac crest (see Figure 1). An additional marker will be placed on the right foot to distinguish each limb on the data. Once a participant is marked, a static capture will be performed using Qualisys track manager software (Qualisys AB, Göteborg, Sweden) and six motion capture cameras (Miqus M1). Following the static capture participants will undergo the first protocol for measuring pressure. The initial protocol will use the method used in previous research (Brophy-Williams et al., 2015). This method involves pressure measurements at six separate landmarks across the leg, three at the side and three at front. These landmarks will be identified and marked with a permanent marker pen prior to each participant wearing the compression garments. Once all landmarks are correctly marked, the participants will dress into their compression garment ensuring that the ankle and iliac crest markers are still positioned correctly. Pressure will then be recorded at each landmark whilst standing. To measure at each landmark, participants will pull down their compression garments for the sensor of the pressure monitoring device to be placed on the location, and then pulled back up and smoothened to gain a valid pressure reading. This will be repeated until all six landmarks are recorded on each leg. The entire protocol will be captured on Qualisys track manager, an extra marker described as a 'wand' will be placed upon every landmark after a pressure measurement, this will identify the precise location of each measurement across the leg in reference to the markers used during the static capture.

The second protocol to be used in this experiment is newly developed for this research study. Rather than measuring pressure at six separate locations, numerous measurements will be made along the leg from four aspects: anterior, posterior, medial and lateral. Using multiple positions will help understand if compression throughout the entirety of the leg is of a graduated nature. Participants will dress into their compression garment and the pressure sensor will be placed at the most distal point of the leg. The pressure will be recorded as the sensor is pulled up the leg. As described previously, each measurement will be captured by Qualisys track manager and a 'wand' will be used to identify the location of the measurement. After each measurement, the sensor will be slowly pulled up the leg in approximately 10 cm segments.

Following the compression garment pressure measurements, the 3D scanner (Artec Leo, Central Scanning Ltd, Bromsgrove UK) will be used. For this protocol participants will stand as still as possible with their legs shoulder width apart. A trained operator will then scan the lower and upper body of a participant. The 3D scanner will provide a 3D model of a participant's body. A 3D scan will be performed with and without wearing the compression garment. The scans will be assessed for changes in muscle/leg size over the 3/4 trials, which will allow the study to investigate the reliability of the 3D scanner measurements. Following the 3D scan, a water displacement method will be used to compare limb volume measures between a method used in previous research (water displacement method) and a new method using the 3D scanner previously mentioned. This will be done to investigate the validity of the 3D scanner in terms of measuring limb volumes. For the water displacement method participants will use both upper and lower body limbs (arms and legs). Firstly, the participants will be marked around the circumference of the wrist and ankle using a permanent marker pen. A second mark will be placed around the circumference of the elbow and the knee. Then a defined area will be located but not marked at 60-70% up the thigh defined by the knee joint centre and greater trochanter, this will also be done for the arm. Participants will be instructed not to remove the marks during the duration of the study. The protocol will measure water volume for the hand and foot first and then remove this from the partial and whole limb calculations. Therefore, this would involve participants submerging their whole arm and leg into a water container and the spill over will be measured and used for the calculation. The measurements from the water displacement method will be compared to the new 3D scan method.

To conclude the experimental trials, a skin fold assessment will be performed on the participants. This will involve the measurement of the size of a fold of skin at specific sites on the calf and thigh and upper body.

Potential Benefits to You:

- Gain an understanding of the effect of compression garments and how they potentially could influence recovery. Also, gain an understanding of the methods of measuring compression garment pressure, reliability and validity.

Potential Risks to You:

- There may be some discomfort when performing the skin fold assessment. This assessment may leave bruising of the assessed location.
- There may be a potential risk that the double sided tape, used to apply the reflective makers, could cause irritation to the skin.
- Given the current situation in the UK (and around the World) interactions between people from different households carries a risk of COVID19 infection. Other than when certain measurements are being made, the researcher will ensure they maintain a two-metre distance from participants. All facilities in which research is being conducted have been COVID19 risk assessed. To mitigate any risks when the need for particular measurements requires that a 2-m distance cannot be maintained, all participants will be provided with PPE (personal protective equipment – specifically a surgical mask and face shield). In addition, the researcher will also wear PPE.

Contacts:

Mr Jack Ashby:	jack.ashby2013@my.ntu.ac.uk	
Dr John Morris:	john.morris@ntu.ac.uk	0115 8488058
Dr Caroline Sunderland:	caroline.sunderland@ntu.ac.uk	0115 8486379

Appendix 5

Health Screen for Data Collection 2

Name or Number ....………………

Please complete this brief questionnaire to confirm fitness to participate:

1. **At present,** do you have any health problem for which you are:

(a) on medication, prescribed or otherwise — Yes ☐ No ☐

(b) attending your general practitioner — Yes ☐ No ☐

(c) on a hospital waiting list — Yes ☐ No ☐

2. **In the past two years,** have you had any illness which require you to:

(a) consult your GP — Yes ☐ No ☐

(b) attend a hospital outpatient department — Yes ☐ No ☐

(c) be admitted to hospital — Yes ☐ No ☐

3. **Have you ever** had any of the following?

(a) Convulsions/epilepsy — Yes ☐ No ☐

(b) Asthma — Yes ☐ No ☐

(c) Eczema — Yes ☐ No ☐

(d) Diabetes — Yes ☐ No ☐

(e) A blood disorder — Yes ☐ No ☐

(f) Head injury — Yes ☐ No ☐

(g) Digestive problems — Yes ☐ No ☐

(h) Heart problems — Yes ☐ No ☐

(i) Problems with bones or joints — Yes ☐ No ☐

(j) Disturbance of balance / coordination — Yes ☐ No ☐

(k) Numbness in hands or feet — Yes ☐ No ☐

(l) Disturbance of vision — Yes ☐ No ☐

(m) Ear / hearing problems — Yes ☐ No ☐

(n) Thyroid problems Yes ☐ No ☐

(o) Kidney or liver problems Yes ☐ No ☐

(p) Allergy to nuts, alcohol etc. Yes ☐ No ☐

(q) Any problems affecting your nose e.g. recurrent nose bleeds Yes ☐ No ☐

(r) Any nasal fracture or deviated nasal septum Yes ☐ No ☐

4. **Has any,** otherwise healthy, member of your family under the age of 50 died suddenly during or soon after exercise? Yes ☐ No ☐

5. Are there any reasons why blood sampling may be difficult? Yes ☐ No ☐

6. Have you had a blood sample taken previously? Yes ☐ No ☐

7. Have you had a cold, flu or any flu like symptoms in the last Month? Yes ☐ No ☐

COVID19

8. Do you think you have had COVID-19? Yes ☐ No ☐

9 If YES, was this confirmed via a swab test? Yes ☐ No ☐

10. If YES, was this confirmed via an anti-body test? Yes ☐ No ☐

11. State the dates over which you had COVID-19 symptoms:

FROM ______________________ TO ______________________

NB Please note that in the 7-day period prior to any visit to the University to undertake a trial in a research study or to visit a University research facility YOU WILL NEED TO COMPLETE a COVID-19 symptom questionnaire. Please DO NOT come to the University if you have not completed this questionnaire and the member of research staff supervising the research study has not confirmed you should attend.

If you have answered YES to any question above, please describe briefly (e.g. to confirm problem was/is short-lived, insignificant or well controlled.)

....

....

Appendix 6

COVID-19 Symptom Questionnaire for Data Collection 2

1. Study Title: ____

2. Participant Name: ____

3 Date: ____________________________________

4. Do you have:

A high temperature / fever Yes ☐ No ☐

A sore throat Yes ☐ No ☐

A new continuous cough* Yes ☐ No ☐

Loss of, or change in, taste or smell Yes ☐ No ☐

* A new, continuous cough means coughing for longer than an hour, or three or more coughing episodes in 24 hours.

5. Have you, or anyone you share a house with, been in close contact with anyone with a suspected or confirmed case of COVID-19 in the last two weeks? Yes ☐ No ☐

6. Have you travelled to a 'high-risk' region for COVID-19 in the last two weeks?

Yes ☐ No ☐

7. Please confirm that ALL of the questions 4-6 have been answered "NO" and that there are no reasons why you should not participate in the research study:

Yes – I can confirm that all of my responses to questions 4-6 above were "NO" ☐

No – I answered "Yes" to some or all of the questions 4-6 above. ☐

Appendix 7

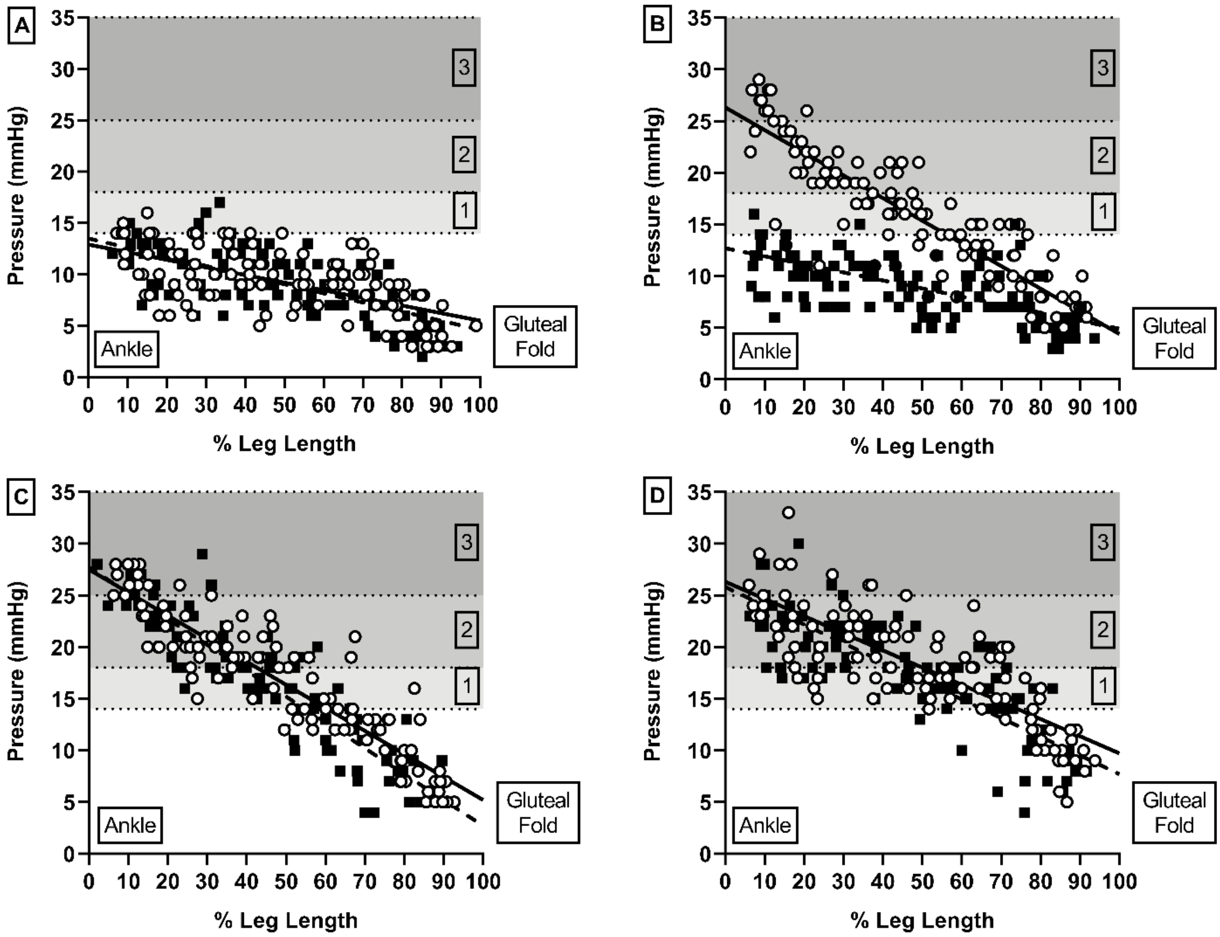


Figure 12.1. Pooled data presenting pressure profiles for the left and right legs in the (A) control, (B) asymmetrical and (C) high gradient and (D) medium gradient compression garment conditions. Class one (14 – 17 mmHg) clinical compression threshold indicated by light grey shading, Class two (18 – 24 mmHg) clinical compression threshold indicated by medium grey shading and Class three (25 – 35 mmHg) clinical compression threshold indicated by dark grey shading (BS-6612; 1985). The dashed trendline corresponds to the left leg pressure gradient and the filled trendline corresponds to the right leg pressure gradient.

Appendix 8

Participant Name or N-Number: **Date:**
Trial: FAM / C / S / B / U
Pre Colour: **Post Colour:**

1. Fabric Comfort – Is the material comfortable? Does it causes any itching or discomfort?

*Most **Comfortable** Imaginable* *Most **Uncomfortable** Imaginable*

2a. General Comfort (Left Leg) - Ability to move, material density/thickness, skin comfort, heat comfort, material fiber type, pressure.

*Most **Comfortable** Imaginable* *Most **Uncomfortable** Imaginable*

2b. General Comfort (Right Leg) - Ability to move, material density/thickness, skin comfort, heat comfort, material fiber type, pressure.

*Most **Comfortable** Imaginable* *Most **Uncomfortable** Imaginable*

3a. Compression (Left Leg) – How tight does the garment feel on this leg? How much pressure do you feel? Is the pressure comfortable?

*Most **Comfortable** Imaginable* *Most **Uncomfortable** Imaginable*

3b. Compression (Right Leg) – How tight does the garment feel on this leg? How much pressure do you feel? Is the pressure comfortable?

*Most **Comfortable** Imaginable* *Most **Uncomfortable** Imaginable*

4. Temperature – Is your lower body temperature comfortable when wearing the garment?

*Most **Comfortable** Imaginable* *Most **Uncomfortable** Imaginable*

5. Breathability – Does the garment wick away moisture? Do you feel wet/humid when wearing the garment?

*Most **Comfortable** Imaginable* *Most **Uncomfortable** Imaginable*

Figure 12.2. Displays an example of the comfort questionnaire used in Chapter 8 which consists of 7 visual analogue scales for comfort variables.