Effects of Compression Garments during Exercise and Recovery Activities on Muscle Oxygenation Responses

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Copyright statement

Abstract

The evolution of elite sport has increased the number of fixtures and competitions athletes complete, thus requiring the development of strategies to improve recovery and performance. One such strategy is the application of compression garments. Research examining the effects of compression garments on blood flow and muscle oxygenation are equivocal, suggesting that further research and new methods are needed to enhance understanding. A limitation in the current literature has been the examination of standardised ('off the shelf') garments and their effects in sporting and recovery settings. A standardised garment does not take into consideration individuals' limb geometry, which has an influence on the amount of compression pressure applied, potentially limiting physiological responses. Therefore, the purpose of this thesis was to explore muscle oxygenation responses when wearing different types of bespoke compression garments.

The use of Near-infrared Spectroscopy (NIRS) to measure muscle oxygenation has been shown to be reliable. However, there has been minimal research to date that has assessed reliability measures of NIRS when wearing compression. ***Chapter 4*** outlines the use of a Near-infrared Spectroscopy to be a reliable method to assess Tissue Saturation (TSI), oxyhaemoglobin (O_2Hb) and deoxyhaemoglobin (HHb) concentration changes in the gastrocnemius and the vastus lateralis. Participants undertook 20 minutes of laying down, seating, walking, jogging and seating across four trials (2 control, with no garment applied and 2 with bespoke compression tights). Compression ranged from 5.6 - 13 mmHg in the compression tights. There were no differences observed between O_2Hb and HHb responses in control and compression tights trials ($P>0.05$). Tissue saturation demonstrated moderate to good reliability (1- 4.5% CV) in both control and compression tights trials in the gastrocnemius and vastus lateralis. Coefficient of variation for oxyhaemoglobin concentration changes from the baseline ranged from 0.6 - 8.8% in the gastrocnemius and the vastus lateralis in both control and compression tights trials. ICC values for oxyhaemoglobin responses ranged from

0.35-0.89 in the gastrocnemius and vastus lateralis in control and compression tights trials respectively. Deoxyhaemoglobin reliability varied from moderate to good reliability (*ICC*: 0.41 to 0.93: CV: 0.61 to 9.9%) across both control and compression tights trials in the gastrocnemius and vastus lateralis muscle. Systematic bias was -25.0 to 11.7 ΔμM across both control and compression tights trials in both gastrocnemius and vastus lateralis muscles. ***Chapter 4*** concludes that NIRS assessment provides reliable values when assessing oxygenation changes with the application of compression garments and without.

The purpose of ***Chapter 5*** was to provide insight into the effects of compression socks and bespoke compression tights on muscle oxygenation responses. The experimental protocol consisted of 20 minutes of the following activities: *supine, seating, walking, jogging and seating.* Compression profile ranged from 15.5- 22.3 mmHg in the compression socks trials. ***Chapter 5*** data demonstrated that bespoke compression tights (3.2 ± 10.5 ΔμM) increased O_2Hb concentration changes in the vastus lateralis in the laying supine position (P=0.04). HHb increased when compression tights were applied in the walking stage (2.8 ± 13.5 ΔμM) at the gastrocnemius muscle (P=0.03) and in the seating (0.75 ± 5.3 ΔμM) position in the vastus lateralis (P=0.03). Tissue saturation reduced in both gastrocnemius (72.2 ± 6.7%) and vastus lateralis (72.7 ± 4.3%) muscles when compression tights were applied during the walking stage (P<0.05). Compression tights (ranging 3.8 to 6.5 ΔμM) were favoured to improve oxyhaemoglobin responses more in comparison to use of compression socks (-0.7 to 3.8 ΔμM) across the protocol.

The objective of ***Chapter 6*** was to design new bespoke compression and assess perceived comfort levels prior to engaging in stationary positions such as laying down, 75° head up tilt and standing. The awareness of participant comfort levels when wearing compression is of key importance especially if athletes need to wear them for prolonged periods of time. Graduated, uniform and reverse graduated compression tights were produced and perceived comfort assessed. A visual analogue scale was used to assess comfort, ankle fitting, knee fitting and compression. The reverse (4.1±2.8 cm) graduated was the least favoured design in comfort, this could be put down to lack of familiarity as no one has worn a garment of this design prior. Graduated (11.6±1.7 cm) and uniform (9.4±3.2 cm) provided acceptable comfort ratings across different phases of the protocol.

The aim of ***Chapter 7*** was to build on ***Chapter 5*** and provide more insight into the effects of bespoke compression tights and their influence on oxygenation during stationary activities. In this study, a range of new bespoke compression tights were manufactured with a purpose to provide a different type of compression profile. Graduated, reverse graduated, uniform and control compression garments were used across 5 visits, (further details on objective for each profile can be found in the methods section). Ten, healthy active males (age 28.4±3.6 years and body mass 81.3±11.2 kg; mean ± SD) completed 5 trials across a 30-day period. Participants undertook 3 stationary (decubitus, 75 ° Head up Tilt and standing) activities for approximately 20-45 minutes. Reverse (71.5 ± 7.6 %) graduated compression garment provided the highest amount of tissue saturation in the standing position in the gastrocnemius, in comparison to the use of no garment (63.3 ± 8.6%) and the other garment trials ($P<0.05$). The higher levels of compression on the upper extremity of the leg, could have had an influence in improving the amount of oxygen in the gastrocnemius, further research in an exercise specific setting is warranted to understand this mechanism. HHb responses were highest in the graduated profile (10.2±7.0 ΔμM) in the gastrocnemius, this was observed in the tilt position and was higher in comparison to the rest of the trials ($P<0.05$). The graduated (4.4 ± 3.4 ΔμM) compression profile also provided an increase in HHb in the vastus lateralis in the tilt position in contrast to the use of the control (-4.8 ± 4.7 ΔμM) garment ($P<0.05$).

Overall, the thesis provides an indicator that made to measure compression garments can influence muscle oxygenation responses. It is also apparent that a graduated profile can influence oxygenation responses in both gastrocnemius and vastus lateralis. Further research should begin to expand on this work and begin to investigate the influence of made to measure compression on exercise and recovery specific protocols.

Acknowledgements

What a journey, I have thought about writing this section about a million times, so here we are, lets do this.

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confidence when I had none, gave me hope when I had none, made me believe in myself, when I never did. Without a doubt this one is for you both.

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“Out the door, just in time…”

Abbreviations

%	Percentage
ANOVA	Analysis of Variance
Bpm	Beats per minute
THb	Total Haemoglobin
O_2Hb	Oxyhaemoglobin
TSI (%)	Tissue Saturation Index
Hhb	Deoxyhaemoglobin
CG	Compression Garment
NIRS	Near infrared Spectroscopy
PU	Perfusion Unit
Km	Kilometer
r	Pearson Correlation
CV	Coefficient of variation
ATT	Adipose Tissue Thickness
ATP	Adenosine Triphosphate
mmHg	Milometers of mercury
mm	Milimeters
cm	Centremeters
DPF	Differential Path Factor
RPE	Rating of perceived exertion
VO_{2max}	Maximal oxygen uptake
HR	Heart rate
SD	Standard Deviation
t	Time
LOA	Limits of Agreement
Q	Cardiac Output
SV	Stroke Volume
C	Control
CT	Compression Tights
CS	Compression Socks
UCT	Uniform Compression Tights
GCT	Graduated Compression Tights

ICT	Inverse Compression Tights
CO UM	Cardiac Output Ultrasound Monitor
CM	Compression Measurements
BP	Blood Pressure
PO	Pulse Oximetry
mVO_2	Muscle Oxygenation Consumption
KPM	Kikuhime Pressure Monitor
RGCT	Reverse Graduated Compression Tights
CNAP	Continuous-Near Infrared Arterial Pressure
µmol	Micromoles
ΔµM	Change from the baseline in micromoles

Publications

Conference Abstracts

- Biddulph, B, Morris, J, Lewis, M and Sunderland C (2019) Reliability of near infrared spectroscopy with and without compression tights during recovery activities. *Journal of Sports Sciences.* The British Association of Sport and Exercise Sciences Conference, Leicester City King Power Stadium. https://doi.org/10.1080/02640414.2019.1671688

- Biddulph, B., Morris, J., Lewis, M. and Sunderland, C. (2021) The effects of compression tights and socks on muscle oxygenation. *Journal of Sports Sciences,* **39 suppl 2**, 36. DOI: 10.1080/02640414.2021.1978748 .

Publications

- Biddulph, B, Morris, J.G, Lewis, M, Hunter, K. and Sunderland, C (2023) Reliability of Near-Infrared Spectroscopy with and without Compression Tights during Exercise and Recovery Activities. *Sports*, 11, 23. https://doi.org/10.3390/ sports11020023

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Chapter 1: General Introduction.

1.1 Introduction

The use of compression garments has predominately originated from the medical profession where they are used to help/prevent vascular issues in the body (**Figure 1.1**). Compression therapy benefits the healing process in patients that have leg ulcers in comparison to patients who did not have any compression (O'Meara et al., 2010; Nelson and Bell-Syer 2014; Partsch 2013).Compression socks were first invented in 1950 by a German engineer called Conrad Jobset and were the first type of garment to be manufactured. Compression garments moved into the sporting domain in around the 1980s where athletes began to use them to aid the recovery process. Today, compression garments have become widely established and utilised across all levels of sport. Increased participation in sport has led to athletes looking for modalities to enhance performance and recovery. Franke et al. (2021) in a cross sectional study identified that approximately 47.5 % (*n*=246) of athletes use compression garments because they perceive they will help them reduce injury. It is clear that compression garments are favorable with athletes due to the popular perceived benefits on performance, recovery, and injury prevention.

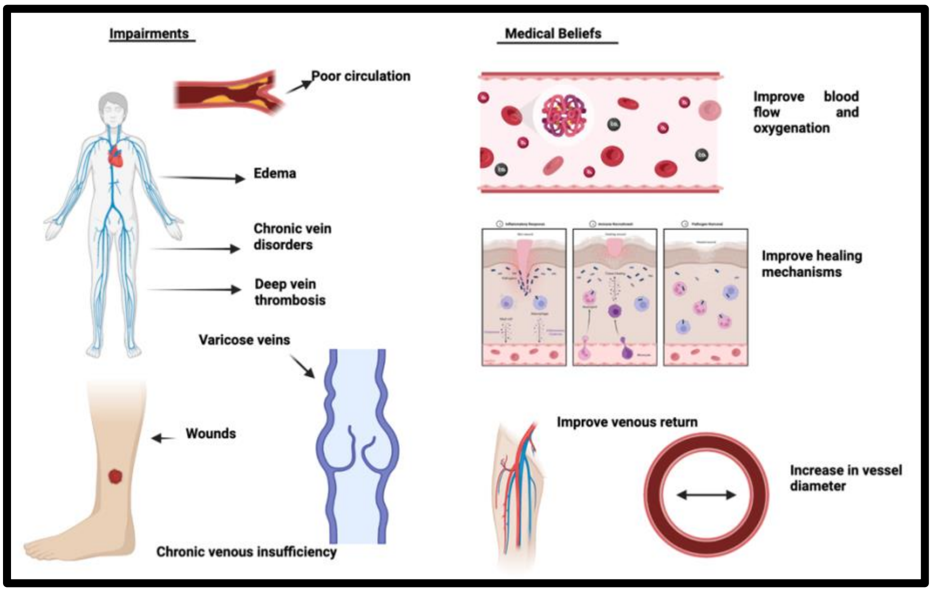


Figure 1.1. Visual diagram of how compression is used to treat potential vascular impairments within the medical field.

Research has demonstrated that the effectiveness of compression garments to aid sports performance is equivocal (Higgins et al., 2009). Higgins et al. (2009) observed no effects of different types of garments on performance metrics (sprinting and jumping), however there were slight improvements shown in sprinting performance. Improvements in jumping and cycling performance have been observed with the application of compression garments (Kraemer et al., 1998; Driller and Halson, 2013). However the full effectiveness of the garments in recovery have yet to be fully assessed, (Pruscino et al., 2013). Due to the popularity of compression, there has been extensive development of different types of garments, meaning further research is needed to assess the different types of compression garments and their possible effects in recovery and performance (Bottaro et al., 2011). Manufacturers in the sporting industry claim for compression garments to enhance recovery and improve performance, however scientifically these statements have yet to be fully accepted. There are a variety of garments on the market. Compression socks and compression tights are the most popular.

A key limitation of the research is that it is difficult to assess the effectiveness of the compression garments when they aren't assessed for the amount of pressure exerted onto the muscle site. Different interface pressures have been attributed with different responses in blood flow and oxygenation, thus impacting the overall effect during and after performance, (Daschombe et al., 2011). Some research has demonstrated no effects on cycling performance but again, varied interface pressures were demonstrated with the garments, thus emphasizing a greater need to assess interface pressure during compression research (Scanlan et al., 2008; Burden and Glaister 2011).

Research has outlined some musculoskeletal benefits when wearing compression. Wang et al. (2013) found that compression wear reduced muscle activation in the rectus femoris and the gastrocnemius during running performance. The implications suggest that muscle activation during performance focuses on quality instead of quantity with respect to muscle force production. Quantifying muscle activation is of key relevance to the influence of performance and reducing any onset of fatigue. Muscle oscillation has been shown to reduce with the application of compression tights (Valle et al., 2013; Wang et al., 2013). The reduction in muscle oscillation suggests that a reduction in vibration at skeletal muscle tissue level could have implications for performance and muscle oxygenation. Broatch et al. (2018) assessed cycling performance through the use of Near Infrared Spectroscopy to indicate improvements in blood flow within the vastus lateralis with the use of standardised compression garments. Due to wide range of garments available, lack of rigor in study design, there is a need for further research examining the effects of compression garments on muscle oxygenation and blood flow.

1.2. Popularity of wearing Compression

The use of compression within sport has become ever popular within the past 10 years. Both team and individual sports have seen athletes use varied types of compression in attempt to aid performance and recovery. A recent study by Franke et al. (2021) outlined the popularity of compression garments by administering a questionnaire to 512 athletes. Interestingly the use of compression for athletes was to aid with injury prevention and perceptual benefits within performance and recovery. Compression has been predominately used for endurance based athletes such as runners. However athletes from the NBA have begun to wear compression sleeves due to the perceived effects in improving technical tasks such as shooting, although there is minimal research to support this hypothesis. **Figure 1.2** observes the different types of compression garments that are available and the influences on physiological responses.

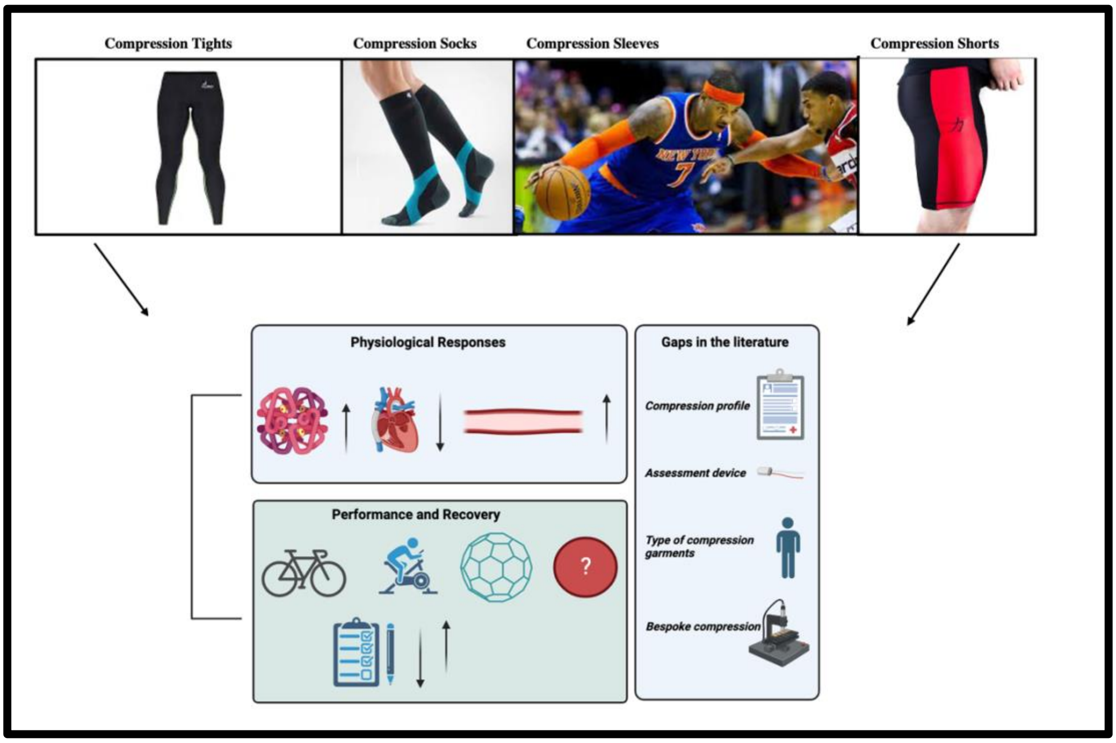


Figure 1.2 Summary of different types of compression and the potential gaps in the literature

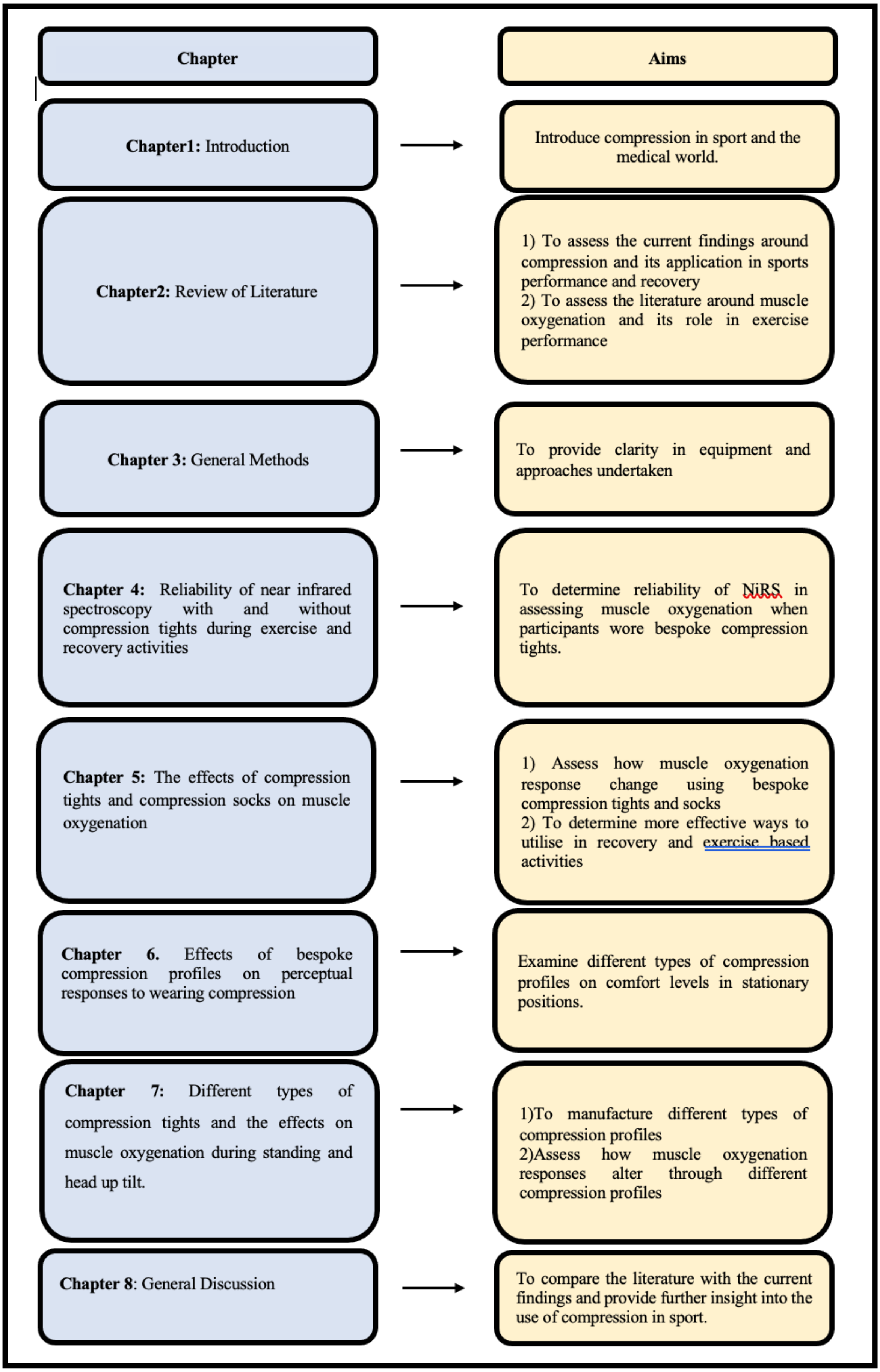


Figure 1.3 Overview of thesis chapter and aims.

Chapter 2: Review of Literature.

Chapter 2: Review of Literature

2.1. Introduction

This chapter outlines the key benefits of compression garments and how they can play a role in sports performance and recovery. The chapter will also discuss variables that influence the effectiveness of compression garments and in particularly how the research outlines the effectiveness. The chapter will introduce muscle oxygenation and how Near-infrared spectroscopy can be used to assess concentration changes of haemoglobin in skeletal muscle tissue. The chapter will also use review of literature tables to draw trends in the research surrounding the use of compression and alterations in muscle oxygenation.

2.2. Compression Garments

There are a wide range of different types of compression garments that are available on the market. Different types of compression garments will have different contrasting responses that can influence the athletes desire to wear them. For example NBA athletes currently favour wearing compression sleeves as it is perceived that they can help them execute shots (Kraemer et al., 1996).

The introduction of compression garments stems from the medical world and its application with vascular impaired patients (Duffield and Portus, 2007). Ancient Egyptians were known to use bandaging and compress on injured wounds to help within the healing process (Bhattacharya, 2012). The application to the sports industry has arisen in the past decade with more athletes looking for different modalities to assist with recovery and performance. There has been widespread contradictory information that has highlighted varied responses in performance and recovery when wearing compression garments (Jimenez et al., 2016). Different types of compression, include compression tights, compression socks, compression sleeves and compression shorts. The theory for using compression suggests that there is an increased presence in venous blood velocity, which could improve hemodynamics for performance and recovery (MacRae et al., 2011).

Compression tights which exerted a pressure of 23-24 mmHg at the calf reduced venous pooling in both supine and standing positions (Bringard et al., 2006). Contradicting to that, other evidence suggests that blood flow is increased in the venous system and increases in arterial inflow have been demonstrated (Ibegbuna et al., 2003; Agu et al., 2004). However the subjects that participated in the study already had disorders relating cardiovascular efficiency. A decrease in venous diameter and volume as well as increasing venous flow velocity have been observed as an effect of the compression (Ibegbuna et al., 1997; Parsch and Parsch, 2005). The purpose to this research will be to assess any particular changes in oxygenation as some studies have shown positive effects in upright positions (Mayberry et al., 1991; Lord and Hamilton, 2004).

2.3. Graduated Compression Tights

Graduated compression tights (GCT) have been used in the medical industry to aid with circulation post surgery (Brophy-Williams et al., 2015; Weller et al., 2010). The alignment of compression is organised where higher levels originate from the ankle and then decreasing pressure subsequently follows up towards the greater trochanter. A graduated compression profile is the most standard method of compression and is commonly used in the research (Rugg and Sternlicht, 2013; Hetchen, 2019; Perez-Soriano et al., 2019). Research has suggested that this method of compression is the best approach to gain the most physiological benefits, this is due to the compression increasing blood flow up the limb enabling a quicker return of blood to the heart (Brophy-Williams et al., 2015:

Lawrence and Kakkar, 1980). In improving blood to the heart, more oxygenated blood can be redistributed back to the working muscles.

2.4. Compression Profile

Compression profile is the specific design of a particular garment. Compression measurements are measured in “ a millimetres of mercury” (mmHg). The compression profile has particular interest in today’s sport science research as the pattern or design of compression can provide a potential physiological benefit to the wearer. At present there is minimal research that has assessed different types of compression profile. However, with advancements in technology and the ability to manufacture bespoke compression garments, different compression profiles can now be researched.

2.5. Uniform Compression

Uniform compression tights is where the level of compression is similar across the limb length (**Figure 2.1**). There is minimal research to date that has assessed the application of uniform compression.

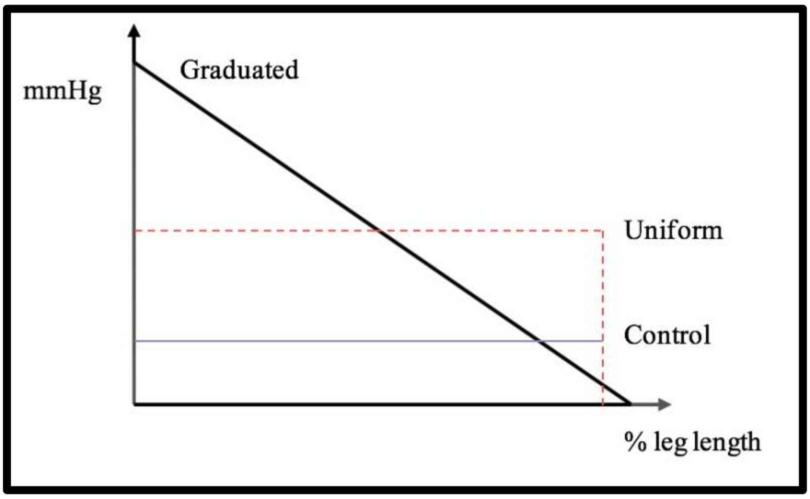


Figure 2.1 Uniform compression garment design in comparison to other garment designs.

Uniform compression would have the average compression of a graduated garment across its whole length. This consistent level of compression potentially may allow a more productive influence of oxygenation in the muscle. In order to understand the impacts of compression, the make, tensile structure, level of compression and fit must be taken into encounter to fully see the potential benefits (Brophy-Williams et al., 2015).

2.6. Compression Tights and Sporting Performance

Compression tights originate from the hip and cover the lower extremity down to the ankle. In general, research has shown that compression tights do not have a negative influence on performance, and may have positive effects in some circumstances (Driller and Halson, 2013). However there has been equivocal evidence regarding the impact of compression tights on sporting performance (Weakley et al., 2021). This can be explained by the need to further understand the physiological responses when wearing compression tights. Some research has observed no performance improvements when wearing compression tights in running and cycling (Daschombe et al., 2011; MacRae et al., 2012; Sperlich et al., 2011; Venckunas et al., 2014; **Table 2.1**). Driller and Halson (2013) did associate compression tights with an improvement in cycling performance where they observed a small increase in power output. However some literature has found that compression tights can improve sporting performance (Higgins et al., 2007; Driller and Halson, 2013). Higgins et al. (2007) detected greater distances travelled in a simulated netball game when compression tights were worn. Minimal effects on physiological responses such as heart rate and oxygenation have been reported, particularly in relation to their influence on sporting performance (Higgins et al., 2007; Duffield and Potus, 2007). Increasing levels of oxygenation have occurred through using compression tights but have had no desired effects on running and cycling performance (Scanlan et al., 2008; Menetrier et al., 2011; Dascombe et al., 2011). It is worth noting that the studies included have not consider using made to measure compression garments subsequently this can influence the overall physiological influence of the garment (Ashby et al., 2021).

2.7. Compression Socks

The rationale for compression socks is to aid blood flow in the gastrocnemius and improve venous return. Compression socks cover the lower extremity below the knee. Compression socks have had favourable responses in comparison to compression tights with greater improvements in running performance (Kemmler et al., 2009; Brophy-Williams et al., 2019). Brophy-Williams et al. (2019) outlined that subsequent running performance could be affected using compression socks. They were able to show that repeated time trial performances did improve but initial time trial performances did not. The study did not identify physiological mechanisms for the performance benefits, and thus this requires further investigation.

Del Coso et al. (2013) observed that the use of compression socks did not aid ironman performance time. The study did not outline any physiological assessment measures during the race to indicate potential influences on race performance. Pre and post measures were taken after the race and identified that compression socks did not influence muscle soreness. It is clear that the application of compression socks produce varied physiological responses but these responses have not been corresponded with a benefit in running performance (Menterier et al., 2011; Vercruyssen et al., 2014; Kerherve et al., 2019; Rennerfelt et al., 2019). The link between compression socks and oxygenation has provided mixed information with increases and decreases being illustrated when running at different intensities (Menterier et al., 2011; Vercruyssen et al., 2014; Kerherve et al., 2019; Rennerfelt et al., 2019). Compression socks have also been associated with reducing muscle activation in the lower limb when running suggesting an improved in efficiency leading to a reduction in fatigue (Lucas-Cuevas et al., 2017).

2.8. Compression Garments and Recovery

Compression socks have been proven to show improvements in recovery for up to 24 hours post exercise (Gill et al., 2006; Ali et al., 2007). Compression socks have been observed to show improvements in the recovery process within 30 minutes of maximal exercise, subsequently enhancing blood lactate clearance (Berry and Mc Murray, 1987). Kraemer et al., (2010) illustrated that muscle swelling and soreness appeared to be lower in the group that wore a full compression outfit in comparison to the control group who did not wear the garment, these effects were demonstrated from an intense resistance-based work out. Even though pressure from the garment was not measured, it would be interesting to observe if this variable impacted the recovery measures even more. The application of compression tights have also been illustrated as an effective post-match recovery strategy in elite rugby players (Gill et al., 2006). Gill et al. (2006) looked at other recovery strategies including contrast water therapy and compression tights with low impact exercise and reported improved recovery post performance with a lower creatine kinase concentration. Bovenschen et al. (2014) observed a reduction in blood volume after exercise with the application of compression stockings. The study failed to acknowledge or analyse in detail muscle oxygenation or provide accurate blood flow measurements. However, this can suggest that if blood flow were to decrease then muscle oxygenation opportunities will become limited in the early stages of recovery. Thus there is a need to research the physiological responses when wearing compression garments

2.9. Running Economy

Running economy (RE) is defined as the metabolic cost of movement at a specific submaximal running speed (Shaw et al., 2014; McManus et al., 2020). Running economy is an effective determinant in performance for athletes. Improvements in running economy have been shown to lead to improvements in distance running performance (Fallowfield and Wilkinson, 1999). Variables such as "metabolic, cardiorespiratory, biomechanical and neuromuscular" need to be considered as determinants of running economy for athletes (Barnes and Kilding, 2015). Running mechanics with the use of compression has provided equivocal findings with research finding no changes with lower limb compression (Varela-Sanz et al., 2011; Stickford et al., 2014). Recent literature has discovered minimal influences of compression on biomechanical parameters (knee and hip ROM °) whilst running (Palya and Kiss, 2020). However the compression values at the calf (10.5 mmHg) and thigh (6 mmHg) were fairly low to potentially warrant any changes in running gait (Palya and Kiss, 2020). Contrastingly, with higher values of compression (23 ± 2 mmHg) at the calf changes in biomechanics (*lower ground contact time, higher leg stiffness*) during running have been observed (Kerherve et al., 2017).

Running economy has been shown to improve at 65% $\dot{V}O_2max$ using commercial (Skins) compression tights (McManus et al., 2022). McManus et al. (2020) obtained compression pressures of 8.9 mmHg at the calf and 6.8 mmHg at the thigh. The study observed participants obtained lower (1.05 kcal·kg^{-1} ·km^{-1}) RE values at 65% VO_{2max} within the compression trial in comparison to the no garment trial (1.08 kcal·kg-1 ·km-1). Contrastingly, Stickford et al. (2015) did not find any differences in running economy in trained distance runners using compression, subsequently VO_{2max} did not differ when participants undertook running speeds between 220 – 320 m·min^{-1}. However, they did not assess compression.

Table. 2.1 Review of literature. Compression garments responses to exercise/ activity.

Author	**Participants**	**Type of compression**	**Exercise/ Activity**	**Level of Compression (mmHg)**	**Compression Profile**	**Outcome**
Brown et al. (2022)	11 Elite Judo Athletes	Stockings (Isobar, bespoke)	Bench press, counter jump performance, grip strength, isometric knee extension (12h, 24h and 36h assessed post training).	***M***= 17 ± 5 (thigh); 17 ± 5 (calf) ***F***= 19 ± 4 (thigh); 25 ± 5 (calf)	Not stated	↔ No effects on any activities at 12h, 24h and 36h post training
Edgar et al. (2022)	55 New Zealand military officers.	Compression Tights (2XU)	27 participants wore CG for 4-6 hours and .28 participants wore military attire every evening for a 6 week period. 2.4km, max press up and curl ups were assessed pre and post 6 weeks military training	**Ankle**: ***Pre*** 25.4 ± 2.1; ***Post*** 19.7 ± 1.8. **Calf**: ***Pre***; 21.6 ± 2.8; ***Post***; 18.3 ± 3.1 **Thigh**: ***Pre***; 15 ± 4.3; ***Post***; 11.8 ± 3.1	Graduated	↔ No statistical effects on any of the measures

Smale et al. (2018)	15 trained cyclists	Low-and medium grade compression tights (2XU)	Cycling at 30%, 50%, 70% and 85% of maximal power output and 4-km time trial. Stroop task was undertaken at each increment	***Medium Grade***: ***Ankle***: 21.8 ± 6.6 mmHg ;***Knee***: 20.3 ± 6.6 mmHg. ***Thigh***; 15.4 ± 4.5 mmHg. ***Low Grade***: ***Ankle***; 8.6 ± 2.7 mmHg; ***Knee***: 14.9 ± 4.9 mmHg; ***Calf***: 9.1 ± 3.1 mmHg,	Graduated Uniform	Improved cognitive accuracy with the Stroop task with compression. Compression tights did not influence performance.
Duffield et al. (2016)	11 trained athletes	Compression Tights (Bioslyx)	10 minute protocol of sprinting and plyometric based exercises. Creatine kinase, aspartate transaminase, heart rate and muscle soreness were assessed pre and post exercise.	Not assessed	Not stated	↔ No differences observed Creatine kinase, aspartate transaminase, heart rate and muscle soreness post 24 hours.

Driller and Halson (2013)	10 cyclists	Compression Tights (2XU)	Two 30-minute cycling bouts, followed by a 60 minute passive recovery where either CG or Compression shorts were worn.	***Calf***: 20.5 ± 3.1 mmHg ***Thigh***: 11.8 ± 2.6 mmHg	Graduated	↓	Blood lactate concentration. No difference in power output.
Pruscino et al. (2013)	8 field hockey players	Compression Tights (2XU)	Hockey match simulation separated by 4 weeks to which compression or a control trial was implemented. Blood lactate was monitored. 5 counter-movement jump and squat were performed pre-exercise, 24 and 48 hr post.	***Ankle***: 19.1 ± 3.6 mmHg ***Calf***: 7.2 ± 2.8 mmHg ***Thigh***: 4.8 ± 1.6 mmHg	Graduated		No differences observed in blood or performance markers.
MacRae et al. (2012)	12 recreational cyclists	Full Body	60-min fixed loading cycling at 65% $VO_{2\,max}$. 6-km time trial.	***Rest***: ***Forearm***: 13 ± 2 mmHg; ***Thigh***: 11 ± 2 mmHg; ***Calf***: 13 ± 2 mmHg	Not stated		↑ Increase in cardiac output during exercise. No other differences observed.

Dascombe et al. (2011)	7 elite kayakers	Upper-body (Skins)	Incremental and 4-minute max performance test that simulated kayaking. Heart rate, VO_2 , power, distance, stroke rate and oxygenation	Not assessed	Not stated	↔ No differences observed across all measures.
Goh et al. (2011)	10 recreational runners	Compression Tights (Skins)	Four 20 minute treadmill tests at first ventilatory threshold followed by a run to exhaustion within cold and hot conditions using a control and CT garment.	***Calf:*** 13.6 ± 3.4 mmHg ***Thigh***: 8.6 ± 1.9 mmHg.	Graduated	No differences observed within heart rate, RPE, time to exhaustion between conditions.
Scanlan et al. (2008)	12 trained cyclists	Compression Tights	60 minute time trial performance	***Ankle***: 19.5 ± 3.4 mmHg ***Calf***: 17.3 ± 3.0 mmHg ***Mid thigh***: 14.9 ± 2.3 mmHg ***Upper thigh***: 9.1 ± 2.2 mmHg.	Graduated	Assessed blood lactate concentration, heart rate, oxygenation. No statistical differences observed.

Higgins et al. (2009)	9 Netballers	Compression Tights (Skins)	15 minute circuit simulating activities within a game, repeated four times.	Not assessed	Not stated	↑ Greater distances occurred with the use of CT.

2.10. Interface pressures

The garment/interface pressure needs to be considered to determine the benefit for performance and recovery (Daschombe et al., 2011; Driller and Hanson., 2013; Beliard et al., 2015). Location and exertion of pressure from the compression garment have been recently illustrated as fundamental for the validity of gathering data surrounding performance and recovery (Brophy-Williams et al., 2015). Interface pressures, measured in mmHg, are associated with the amount of compression that is fixated on the garment. Most studies do not illustrate the actual force exerted from the garment (MacRae et al., (2011). It is therefore essential to measure the force exerted from the garment, particularly when assessing its physiological effects on recovery (Sakadian, 2015). Values of > 30mmHg of pressure exerted by the garment have been highlighted as a key baseline pressure to observe reduction of blood flow after high intensity exercise (Sperlich et al., 2013). Compression shorts of 37mmHg, of pressure have been shown to reduce blood flow post exercise after high intensity cycling (Sperlich et al., 2013). However, values of 15 mmHg have been reported to increase blood flow (Liu et al., 2008). Lawrence and Kakkar (1980) have highlighted that a faster blood flow will occur with gradient of 18 mmHg at the ankle, 14 mmHg at the calf, 8 mmHg at the knee, 10 mmHg at the lower thigh and 8 mmHg at the upper thigh. Providing minimal elasticity and a tighter fit to the participant will potentially have a greater ergogenic effect. In conclusion, compression garments need to be suited to the body composition of the subject to allow the full effectiveness of the garment as most garments will lose the initial tension of the fabric (Troynikov et al., 2010).

2.11. Perceptual responses

Factors such as level of compression, material and sizing of the garment are known to be key determinants of comfort when wearing compression garments (Lucas-Cuevas et al., 2014; MacRae et al., 2011). There are mixed findings to identify the perceived benefits of wearing compression during exercise, suggesting that more research is needed to assess factors that influence these perceived benefits. In general the greater level of compression has been associated with higher levels of discomfort, this could be down to higher levels of constriction reducing circulation. As the predominate use for compression is post exercise, the actual activity and intensity of the initial exercise will have an influence on the perception of the affect of the compression (Ali et al., 2007; Duffield et al., 2007). Research has outlined that performance could be influenced if the garments are uncomfortable, this is due to the compression altering natural mechanical movement (Kinchington et al., 2012; Lucas-Cuevas et al., 2014).

2.12. Haemoglobin

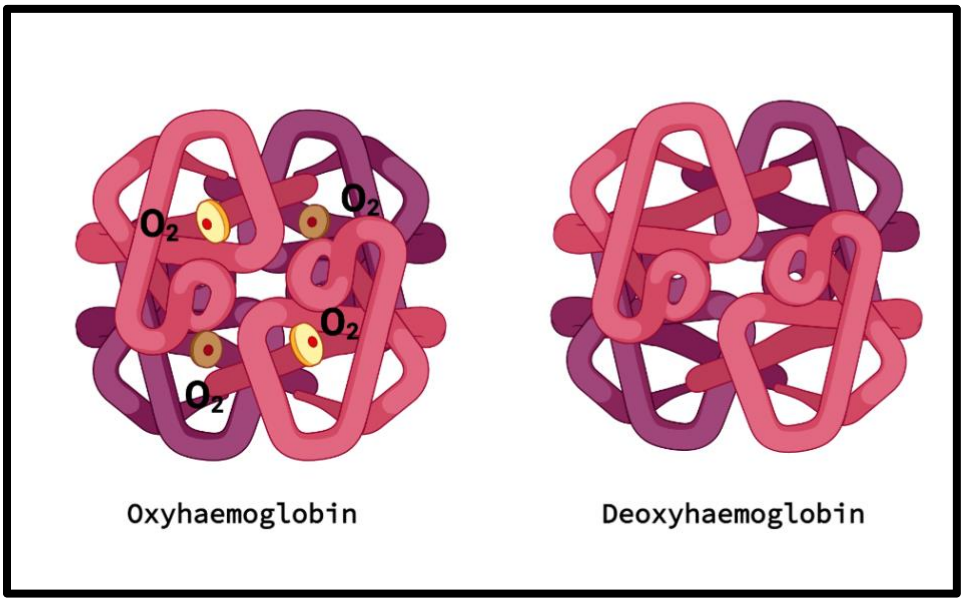


Figure 2.2. Oxyhaemoglobin and deoxyhaemoglobin molecular image.

Haemoglobin (μmol) is a protein that carries oxygen in skeletal muscle tissue (Babior and Stossel, 1994). Oxyhemoglobin (O_2Hb) and deoxyhaemoglobin (HHb) (**Figure 2.2)** are two forms of hemoglobin. Oxyhemoglobin (μmol) is joined with 4 molecules of oxygen and deoxyhemoglobin (μmol) is without oxygen. Heavily populated oxygen in the lungs is absorbed by haemoglobin to be then converted into oxyhaemoglobin to then be released into the muscle where oxygen is low (Moore et al., 2016). Exercise intensity raises oxygen consumption thus increasing the demand for oxyhaemoglobin in the muscle (Moore et al., 2016). Oxyhaemoglobin and deoxyhaemoglobin can also be identified as muscle oxygenation and deoxygenation. Total haemoglobin (tHb) is a combination of O_2Hb + HHb in the muscle. The most common form of muscle oxygen assessment is Tissue Saturation Index (TSI) or as it is also referred to as Tissue Oxygenation Index (TOI). Muscle oxygenation is often described as the overall branch of oxygenation responses and does not necessarily specify or acknowledge all key components such as tissue saturation, oxyhaemoglobin, deoxyhaemoglobin and total haemoglobin. Exercise provides varied oxy/deoxyhaemoglobin responses, depending upon the modality and intensity and the bodies ability to use oxyhaemoglobin. During exercise to exhaustion protocol, a decrease in oxyhaemoglobin responses when exercising on the bike was observed, subsequently responses increased by 13.0 ± 2.0 μmol post exercise in the vastus lateralis (Ganesan et al., 2016).

2.13. Tissue Saturation Index

Tissue saturation (TSI) is the absolute value of haemoglobin that is saturated in the muscle, this is normally represented as a percentage (%). TSI (%) is calculated at the ratio of absorbance 850/(850/760) nm x 100 at two or more depths in the tissue using NIRS (Sanni and McCully, 2019; Jones et al., 2016; **Equation 1**).In non- exercise specific conditions, 75 per cent of oxygen in the muscle is saturated leaving approximately 25 per cent utilized by the tissue (Babior and Stassel, 1994). TSI (%) values provide a good understanding of how effective the muscle is at absorbing oxygen. Theoretically an increase in oxyhaemoglobin and a decrease in TSI % can suggest that the muscle is utilizing oxygen more effectively to deal with the increase in oxygen consumption (Babior and Stassel, 1994). Science suggests that greater levels of oxygen saturation in the muscle can aid sporting performance. Increasing oxygen saturation in the muscle can fuel the muscle to sustain or enhance performance and improve recovery kinetics post exercise. Compression increases the oxyhaemoglobin response due to increase in pressure exerted, this forces an uptake of oxyhaemoglobin in the blood (Bringard et al., 2006; Babior and Stassel, 1994). The mechanisms for this increase of TSI (%) are normally associated with the following; increased skin temperature, increased skin blood flow, improved blood flow in the capillary bed, and greater circulatory effects (Bringard et al., 2006; Scanlan et al., 2008; Kraemer et al., 2010; Sear et al., 2010; Menetrier et al., 2011; Kerherve et al., 2017; Rennerfelt et al., 2019).

Equation 1

$$\mathrm{TSI} = \frac{\mathrm{kO_2Hb}}{\mathrm{kO_2Hb} + \mathrm{kHHb}}$$

K is represented as the scattering contribution, O_2 is the oxyhemoglobin and *HH*b is identified as deoxy hemoglobin.

2.14. Muscle Oxygenation and Deoxygenation responses to Compression Garments

Oxygen Kinetics

The importance of oxygen kinetics/ assessment of oxygen uptake ($\dot{V}O_2max$) is of value for athletes as it enables a better understanding of how oxygen is used in the muscle. Researchers have disclaimed the importance of oxygen kinetics as a key indicator of "adaptations through endurance training and also a measure of an individual's aerobic fitness", in turn the end product of this can see athletes prolong higher levels of intensity due to the bodies capacity to use oxygen more effectively (Whipp et al., 1981; Prinz et al., 2021). **Figure 2.3** is a schematic diagram of how oxygen uptake can alter through training status. The time and speed of response in utilising oxygen at local mitochondria level is of key importance and can determine key sporting actions as well as be factor in helping the recovery process (Kraemer at al., 2018). The application of compression potentially could be an aid in improving oxygen kinetics, however further research is needed to quantify $\dot{V}O_2max$ responses using bespoke compression.

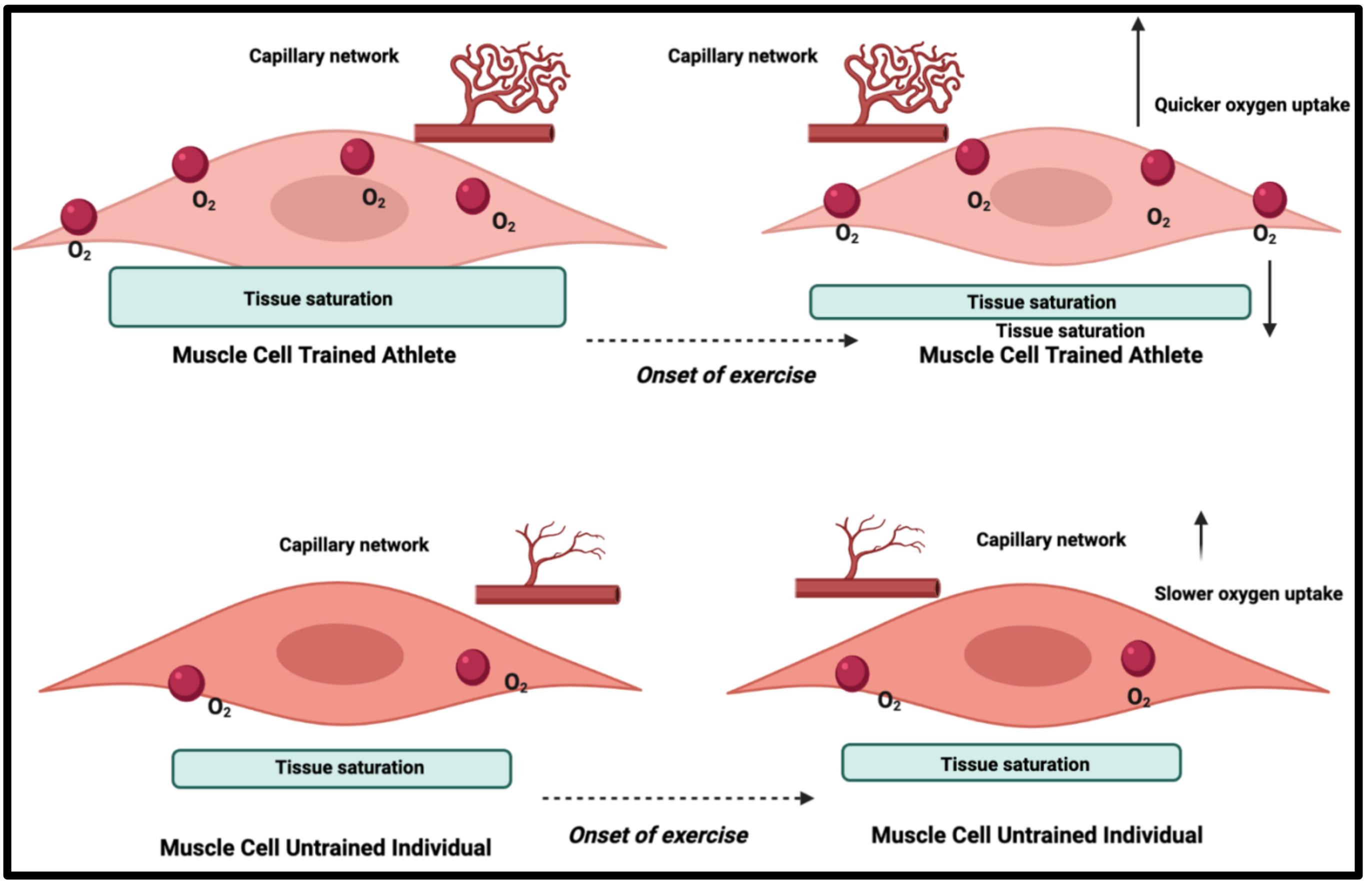


Figure 2.3. Schematic diagram of the influence of training status on oxygen uptake.

Tissue Saturation

Haemodynamics are a key area of interest for research especially when applying compression to an area. Muscle oxygenation has been commonly referred to in the research as tissue saturation, but can also be used to describe all branches of oxygenation such as oxyhaemoglobin and deoxyhaemoglobin responses. Muscle oxygenation and deoxygenation are key responses that can occur through the influence of compression. Increasing tissue saturation through compression is of key interest for athletes and coaches as it may allow athletes to sustain performance through greater availability of oxygen in the muscle. Greater availability of oxygen in the muscle will subsequently help with ATP synthesis which will allow energy production to become more consistent enabling the athlete to sustain performance levels.

The research to date is very limited to assessing the influence of compression on physiological responses. Studies have compared the application of compression garments to wearing non compression garments, and observed no impacts on heart rate and $\dot{V}O_2max$ in resting conditions (Bringard et al., 2006). However it is difficult to conclude the effectiveness of the garment when the initial purpose of the garment is not assessed in an appropriate sporting setting. When muscle oxygenation levels have been assessed effectively, the garments impacts has shown improvements at a local muscular level (Sear et al., 2010). Participants that wore a whole body compression garment (55.8 ± 7.2%) had elevated levels of tissue saturation in the vastus lateralis in comparison to without wearing the garment (53.5 ± 8.3%). Interestingly, post sprint performance, tissue saturation remained higher with the whole-body compression garment (50.4 ± 9.8%) in comparison to the no garment trial (47.9 ± 8.4%) (Sear et al., 2010).

TSI (%) values have been shown to increase thus leading to a decrease in venous pooling when compression garments have been applied (Bringard et al., 2006; **Table 2.2**). The physiological explanation behind this suggests that the garments elasticity decreases venous pooling (Hbtot concentration) at the muscle site leading to an increase in muscle oxygenation. This would be of key value for performance to observe any changes in oxygenation levels when assessing other muscle groups whilst exerting more effort for the individual. Bringard et al. (2006) suggests that the stockings have an ergogenic aid to increasing TSI values (**Table 2.2**). This theory would therefore lead to greater research needed in observing changes in oxygenation levels in bespoke compression tights. Observing oxygenation changes in the vastus lateralis would be of key interest to see if greater levels of TSI would be observed in comparison to the values that are indicated by compression socks. If compression is exerted to a working muscle then physiologically oxygenation levels would increase leading to increase values in TSI and oxyhaemoglobin (Bringard et al., 2006; Sear et al., 2010; **Figure 2.4**). In stationary conditions, O'Riordan et al., (2021) observed tissue saturation responses increased through the use of standardised manufactured compression in the gastrocnemius and thigh muscles, subsequently there conclusion suggested that higher levels of compression would increase tissue saturation responses in the muscle. Even though Kraemer et al. (2010) didn't observe oxygenation levels their protocol enabled them to distinguish clear findings to suggest that compression garments may aid recovery from a heavy resistance workout. Physiologically and mechanically their results did not illustrate changes in blood flow and oxygenation it would have been interesting to view how the values in TSI and Hbtot concentration may have differed from the workout in comparison to, the application or without wearing garments.

Contrastingly, there is some evidence that suggests tissue saturation can decrease through the application in compression at approximately 20 mmHg of pressure exerted onto the anterior compartment and the vastus lateralis muscle (Rennerfelt et al., 2019; Born et al., 2014). Rennerfelt et al. (2019) observed that tissue saturation running in the anterior compartment reduced through standardize manufactured compression stockings. The increase in oxygen uptake at local muscle level could be put down to the training status of the individuals, subsequently the Rennerfelt et al. (2019) study used healthy recreational athletes with a running background, this in tern could suggest that saturation of oxygen decreased in order for the muscle to use oxygen to help sustain the demands of the activity. Peseux et al. (2017) also identified that tissue saturation will decrease when running intensity increased. The change in pressure through compression increases muscular contraction in higher levels of intensity to which creates a tourniquet effects that can reduce tissue saturation in the muscle (Peseaux et al., 2017; Wertheim et al., 1999). Wertheim et al. (1999) showed that when walking occurred there was an increase in compression pressure at the gastrocnemius, this potentially could impact the reduction of blood flow in the muscle effecting haemodynamics (Sperlich et al., 2013).

The responses in different levels and pressures of compression inversely coincides with different responses in tissue saturation. Compression readings suggest that 15-20 mmHg should be used to have an effective response in blood flow and muscle oxygenation (Liu et al., 2008; Menetrier et al., 2015). However, the relationship between compression levels and impacts on haemodynamics is not fully understood (Dermont et al., 2015). Dermont et al. (2015) showed a strong correlation between increasing compression (16.5 – 39.5 mmHg) and increasing TSI responses, observing a + 22.6% of saturation change in from participants not wearing compression. Peseux et al. (2017) also detected increases of + 25.2 ± 2.7% tissue saturation with higher levels of compression when participants wore compression at rest in comparison to no garment. Contrastingly, Born et al. (2014) detected that compression (*TSI range*: 78.7 to 85.6%) did not influence tissue saturation responses when ice speed skaters wore a graduated profile thigh: 20.2 ± 2.2 mmHg; calf; 24.4 ± 3.1 mmHg) in comparison the control trial (*TSI range*: 97.1 to 86.5%). Menetrier et al. (2011) also observed increases in tissue saturation of 3.3 ± 0.4% when a pressure of 20mmHg was applied in comparison to when no garment was applied. Interestingly when compression was further increased to 50mmHg, Menetrier et al. (2011) detected an increase of 8.8±1.9% in tissue saturation. Through a venous hypertension protocol, Neuschwander et al. (2012) demonstrated that external compression (40 mmHg) provided an increase of 23±7% within the anterior tibialis muscle. In contrast, Rennerfelt et al. (2019) observed a decrease in tissue saturation (6±0.7%) from the baseline, this further decreased 11±1.8% when participants ran for approximately 45 minutes. Whilst the majority of literature suggests an increase in tissue saturation, the responses still may differ based on the activity and should still be further investigated, especially when assessing different types of compression.

Table 2.2 Review of Literature. Muscle oxygenation responses through the application of compression garment

Author	Participants	Device	Exercise/ Activity	Muscle assessed	Compression Assessed	Level of Compression (mmHg)	Type of compression	Duration of activity (minutes)	TSI Response	Muscle Oxygenation/ Deoxygenation
O'Riordan et al.	N=12	-	Supine Stand	Gastrocnemius/ Vastus Lateralis	Yes	12.2 to 21.8	Tights	1 hour	↑	-
Rennerfelt et al. (2019)	N=12	NIRO-200, Hamamatsu Photonics	Supine; Standing, Running	Anterior compartment	Yes	22 ± 3.1	Stockings	76 minutes	↓ (TOI%)	-
Peseux et al. (2017)	N=14	InSpectra Model 650	Low intense Jogging and seating	Gastrocnemius	Yes	24.0 ± 0.8	Sleeves	20	↑	-
Kerherve et al. (2017)	N=14	-	24km trail running	Gastrocnemius	Yes	23 ± 2	Sleeves	24km	↑	-
Book et al. (2016)	N=20	PortaLite, Artinis	MVC/ Plantar Flexion	Gastrocnemius	Yes	13.31 ± 2.43	Socks	13	-	↓ HHb

↑ Increase; ↓ Decrease; ↔ No change; - not assessed

Table 2.3 Review of Literature. Muscle oxygenation responses through the application of compression garments.

Author	**Participants**	**Device**	**Exercise/ Activity**	**Muscle assessed**	**Compression Assessed**	**Level of Compression (mmHg)**	**Type of compression**	**Duration of activity (minutes)**	**Response**	**Muscle Oxygenation/ Deoxygenation**
Dermont et al. (2015)	N=8	InSpectra Model 650	Seating	Gastrocnemius	Yes	16.5- 39.5	Sleeves	19	↑	-
Born et al. (2014)	N=10	Portamon, Artinis Medical	3000M TT (Ice Skating)	Vastus Lateralis	Yes	20.3 ± 2.3	Tights	TT	↓ P=.99	-
Neuschwander et al. (2012)	N=8	RunMan; NIM)	Hypertension	Anterior Tibialis	Yes	40-65	External	Varied	↑	-
Menetrier et al. (2011)	N=14	InSpectra Model 650	Running	Gastrocnemius	Yes	15-27 + additional compression up to 50.	Sleeves	Maximum speed	↑	-
Bringard et al. (2006)	N=12	NIRO-300, Hamamatsu Photonics	Supine and Seating	Gastrocnemius	Yes	23.6±4.8	Tights	5 minutes each	↑(TOI%)	↑ O_2Hb, HHb

↑ Increase; ↓ Decrease; ↔ No change; - not assessed

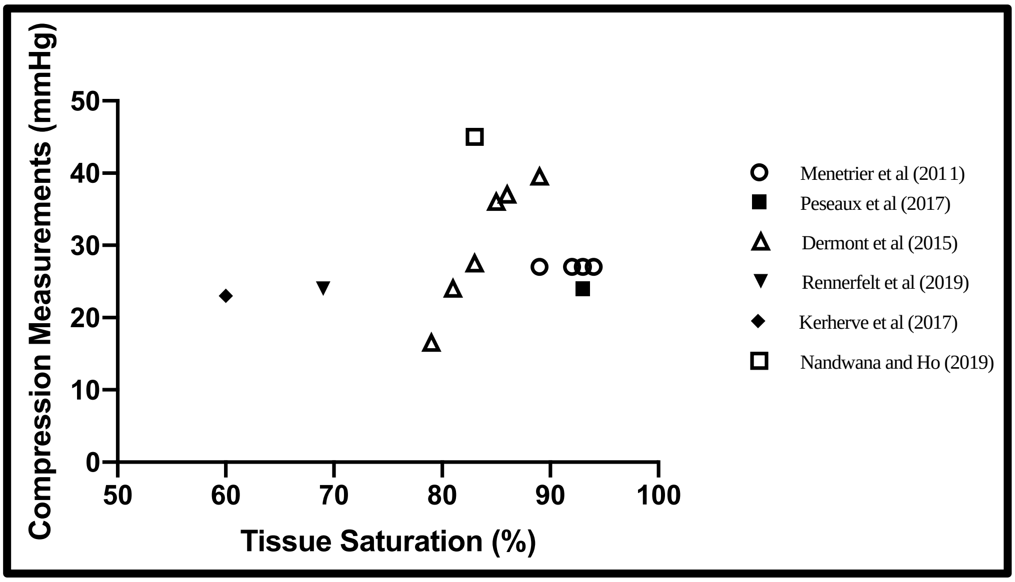


Figure 2.4. Peak compression measurements (mmHg) in the gastrocnemius in comparison to tissue saturation (%) responses in the literature.

Oxyhaemoglobin(O_2Hb) and Deoxyhaemoglogbin (HHb)

Oxyhaemoglobin and deoxyhaemoglobin concentration changes are dependent on the intensity of activity involved subsequently altering the oxygen utilisation. Agu et al. (2004) assessed limb oxyhaemoglobin and deoxyhaemoglobin responses in standing, sitting, tip toe exercise and resting supine position when using different grades of compression with the level of compression ranging from a 14-35 mmHg. When performing tip toe exercises, Agu et al. (2004) reported that with compression stockings, increases in oxyhaemoglobin responses (7.4 ± 2.9 µmol) and smaller concentration changes in deoxyhaemoglobin (3.4 ± 2.7 µmol) responses were detected in comparison to lower oxygenation values without the use of compression (*O_2Hb*; 6.7 ± 2.6 µmol; *HHb*; 7.6 ± 2.1 µmol). Agu et al. (2004) observed similar responses in the gastrocnemius when participants were walking for 5 minutes. Higher levels of compression from compression stockings observed higher oxyhaemoglobin responses (5.8±2.4 µmol) in comparison to smaller concentration changes when participants didn't apply compression (2.8±2.3 µmol). Deoxyhaemoglobin changes were also reduced through the use of higher levels of compression (6.8±3.1 µmol) in contrast to when participants did not wear compression (11.4±3.1 µmol). When standing for 5 minutes, higher levels of compression resulted higher in oxyhaemoglobin (12.0±2.2 µmol) in comparison to when no compression stocking was worn (10.2±3.2 µmol). Agu et al. (2004) study outlined that when there was muscle engagement, compression would improve the bodies approach to using oxygen. To date there has been limited research that has assessed concentration changes in oxy/deoxyhaemoglobin with the application of compression. Through high intense exercise, research has outlined that O_2Hb increase and HHb decrease is likely to result in a reduction in tissue saturation at the muscle, the theory to this suggests that the muscle is utilising oxygen more effectively in order to "reoxygenate the muscle" to help sustain performance demands (Rodriguez et al., 2019). The current literature is equivocal and it is clear that there is a great need for further research to develop bespoke compression garments and determine the physiological effects of specific compression pressures on TSI, oxyhaemoglobin and deoxyhaemoglobin.

2.15. Near Infrared Spectroscopy

Near infrared spectroscopy (NIRS) is a non-invasive device that measures “muscle oxygenation”. The portable device assesses total haemoglobin content, tissue saturation, oxyhaemoglobin, de-oxyhaemoglobin and haemoglobin difference. Through light absorption the Near infrared spectroscopy penetrates fat and muscle tissue and looks at changes in concentration in haemoglobin (**Figure 2.5**). The modified Beer- Lambert law is incorporated to show the relationship in materials absorbed and concentrated. Due to the differences in biological structure, oxyhaemoglobin (O2Hb) and deoxyhaemoglobin (HHb) can be monitored (**Equation 3**). The law suggests optical distance will provide more conclusive data based on the different tissues and their density that the light will need to travel through, this is known as the differential pathlength factor (DPF). Research suggests for muscle tissue that a DPF value between 4.0-4.95 should be used (Lucero et al., 2017; Van Beekvelt, 2002). For smaller muscle groups would suggest a smaller DPF value would be used, this is due to smaller adipose tissue surrounding the muscle making it easier for light to absorb concentration changes in haemoglobin (Celie et al., 2011). The device consists of three optodes that emit wave lengths of 760 and 850 nm. There are a range of NIRS devices such as Porta Lite and PortaMon that have been known recently to produce reliable data (McManus et al., 2018). The research currently suggests that 10Hz is an acceptable sample size to collect data (Lucero et al., 2017; Van Beekvelt, 2002). Methodological issues such as environment and daylight can have an influence on collecting reliable data, with this in mind it is noted that devices should be covered to restrict light (Van Beekvelt, 2002). Further factors such as adipose tissue or body composition of the subject will significantly impact the validity of the near infrared spectroscopy (Ding et al., 2001; Martin et al., 2009). Greater levels of body tissue will mean that the infrared light will have further to travel to detect oxygenation changes subsequently influencing the quality of the signal (van Beekvelt, 2002; Alfonsi et al., 2001; Wang et al., 2001).

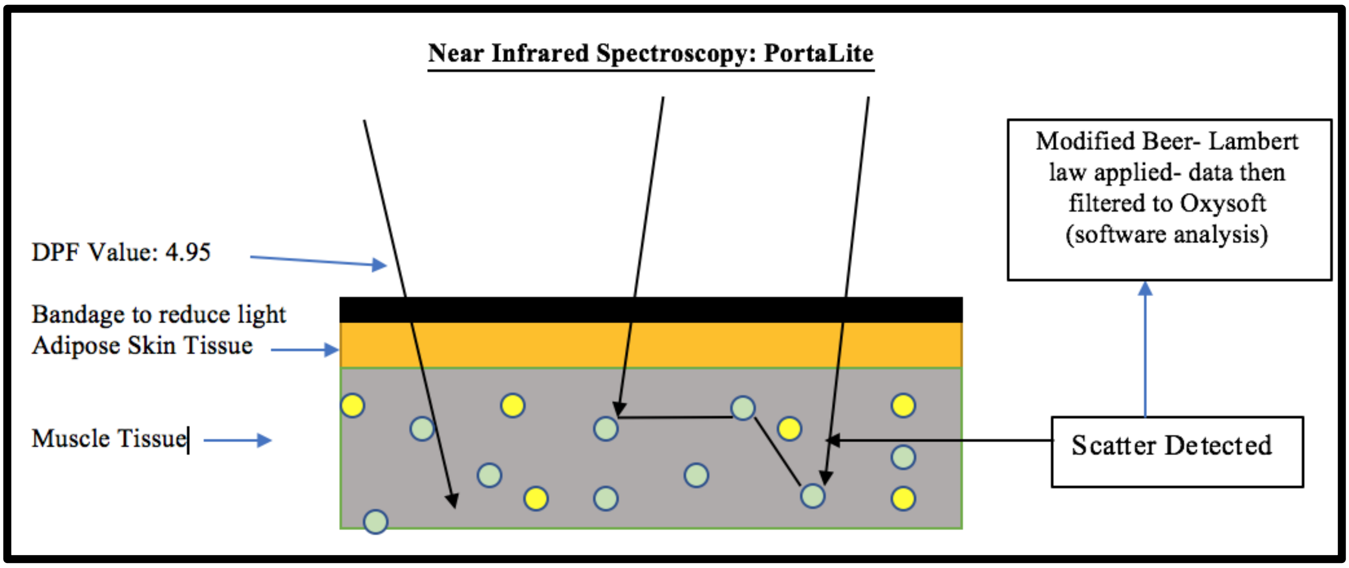


Figure 2.5. Schematic diagram of the application of the Near-infrared Spectroscopy in skeletal muscle tissue.

There has been minimal research in application of the NIRS in sports science to examine the links between oxygenation responses with the application of compression garments. The purpose of using the device will allow the thesis to measure muscle oxygenation during exercise and recovery based activities whilst applying bespoke compression garments. NIRS measurements have been illustrated as an effective instrument for measuring oxidative metabolism (Ding et al., 2001; Bambahnini 2004). However, to date no studies have examined the reliability of NIRS whilst wearing bespoke compression.

Near-Infrared Spectroscopy Calculations

Beer-Lambert Law

Beer-Lambert law is an established equation used to determine the concentration level and alterations in O_2Hb and HHb in the tissue (**Equation 2**).

Equation 2

$$A = \in C L$$

$\in$ is the extinction coefficient, *C* is the micro-molar concentration, *A* is the attenuation, and *L* is the dimension in which solution can be measured (Rolfe, 2000).

Modified Beer-Lambert Law

The new modified law accounts for the change in light attenuation allowing it to be proportional for the changes in concentration in oxy and deoxyhaemoglobin (**Equation 3**). *K* represents tissue loss, $\frac{Io}{1}$ represents light in and out, χ is the path length factor.

Equation 3

$$A = \log \frac{\mathrm{Io}}{1} = \varepsilon C \, L\chi + K$$

2.16. Near Infrared Spectroscopy Reliability

Near Infrared Spectroscopy has been shown to be reliable for the assessment for muscle oxygenation (Celie et al., 2011; Biddulph et al., 2023). However, NIRS reliability is varied and depended on the activity of the participant (**Table 2.4)**

Celie et al., (2011) observed no significant differences in deoxyhaemoglobin measurements when assessing muscle oxygenation in the forearm. Celie et al. (2011) experimental protocol was able to capture no differences in a 48-hour period and provided *ICC* of r=0.77 in SmO_2 responses when participants performed at maximum intensity. Scott et al., (2014) observed wider reliability measures in NIRS variables [O_2Hb, HHb, TSI] with CV ranging from 6.1 to 43.5% and ICC values from 0.44 to 0.87 during high resistance exercise. Lucero et al. (2017) observed strong reliability values when assessing oxygenation responses during knee extension exercise. Intraclass correlation values (0.70 to 0.98) observed strong reliability across 4 days of testing in tHb and TSI. Coefficient of variation values observed strong reliability ranging from 1.5 to 4.1 % in tHb and TSI were observed when participants performed incremental dynamic exercise (Lucero et al., 2017). It seems that when muscle contraction responses are inconsistent then the reliability of NIRS also vary its responses. In resting conditions prior to 30 and 100% MVC, NIRS demonstrates good reliability (CV; *30% MVC*: 2.4 ± 0.8: 100% MVC: 3.2 ± 2.3%) with TSI % values showing minimal changes between 3 sessions (Muthalib et al., 2010). Interestingly, when muscle engagement increased, the reliability between sessions was poorer (CV; *30% MVC*: 37.7 ± 14.1%: *100% MVC*: 11.3 ± 4.2%) subsequently suggesting that higher frequencies of muscle engagement can influence reliability values. Van Beekvelt (2002) has also found similar readings in CV (%) scores varying from 16.3-23.2% over three days of testing.

Reliability of NIRS during exercise is clearly poorer during co-coordinative multi-joint exercise whereas reliability appears better during isometric single limb (Scott et al., 2014). During exercise has shown that coefficient of variation scores for muscle oxygenation responses can vary from 6.1-43.5% with Intraclass correlation and Pearson correlation scores ranging from 0.44- 0.97 (Austin et al., 2005; Perreira et al., 2005; Scott et al., 2014; Choo et al., 2017).

Further applying pressure to the muscle and optode can alter the overall reliability of the Near Infrared Spectroscopy (Hamoaka et al., 2011). Therefore evaluating the level of compression is a determinant that should be used in protocols, especially when assessing the effectiveness of the garments, is paramount. As the NIRS functional use is based on light travelling through skin and passing through muscle tissue, adipose tissue thickness can influence the reliability of repeated measures. Homma et al. (1996) showed that the source detector distance would be a factor in skin penetration for muscle oxygenation data. If the distance is greater than 20mm then muscle oxygenation data would be considered unreliable due to greater distance in travel needed to reach muscle tissue and assess haemoglobin changes. Thus, it is important to assess reliability of NIRS whilst wearing compression which may alter adipose tissue thickness.

Table 2.4 Review of Literature: Reliability of Near-infrared Spectroscopy

Author	**Participants**	**Device**	**DPF (Wavelengths)**	**Exercise/ Activity**	**Muscle Assessed**	**ATT**	**ICC**	**CV (%)**
Biddulph et al. (2023)	N=13	PortaLite,, Artinis Medical System, BV, Elst, Netherlands	4.95 (***760-850nm***)	Laying supine, seating, walking and jogging	Gastrocnemius and Vastus Lateralis	9.0 to 11.3 cm	0.35- 0.98 across all activities.	1 - 8.8% across all activities.
Balas et al. (2017)	N=32	Oxymon; Artinis Medical System, BV, Elst, Netherlands	4.0 (***765 – 855 nm***)	Handgrip exercise (8-second contraction–2-second relief) at 60% of maximal voluntary contraction.	Forearm	Not displayed	TSI ***rest:*** 0.42 tHb ***rest***: 0.65 TSI- ***first 3 contractions***:0.48 tHb- ***first 3 reliefs:*** 0.54	TSI ***rest*** : 8.3 tHb ***rest:***12.9 TSI- ***first 3 contractions***: 21.5 tHb- ***first 3 reliefs***: 23.6
Lucero et al. (2017)	N=12	PortaLite,, Artinis Medical System, BV,	4.0 (***765 – 855 nm***)	Post 10 min rest, participants performed 3 min of isotonic knee extension (one extension every 4 seconds)	Vastus Lateralis	***Males***: 0.4 ± 0.2 cm	0.70 – 0.87	1.5 – 2.6

		Elst, Netherlands		at 5, 10, 15, 20, 25 and 30% of maximal voluntary contraction (MVC)		***Females***: 0.5 ± 0.1		
Celie et al. (2011)	N=20	Oxiplex TS, ISS, Champaign, IL, USA)	Not displayed (***750-830 nm)***	2 minutes of handgrip contraction with 1 minute recovery. Began exercise at 20% MVC was increased by 10% until exhaustion.	Forearm	6.0 ± 2.2	***[Hb + Mb]*** ***20% MVC***: 0.32 ***30% MVC***: 0.02 ***40% MVC***: 0.33 ***50% MVC:*** 0.44 ***60% MVC***: 0.55 ***69.5 -73% MVC***: 0.87 ***TSI:*** ***20% MVC:*** 0.60 ***30% MVC:*** 0.39 ***40% MVC:*** 0.57 ***50% MVC:*** 0.34 ***60% MVC***: 0.22	Not assessed.

							69.5 -73% MVC	
Crenshaw et al. (2011)	N=24	INSPECTRA Tissue Spectrometer-model 325, Hutchingson Technology Inc., MN, USA	Not displayed (***680- 800 nm***)	10%,30%,50% and 70% isometric MVC	Forearm	5.9 ± 1.6	***Tissue Saturation:*** 10%-70% MVC: 0.58-0.95.	Not assessed

Table 2.5 Review of Literature: Reliability of Near-infrared Spectroscopy

Author	**Participants**	**Device**	**DPF**	**Exercise/ Activity**	**Muscle Assessed**	**ATT**	**ICC**	**CV (%)**
Scott et al. (2014)	N=20	Portamon, Artinis Medical System, BV, The Netherlands)	Not displayed (***650- 860 nm)***	Back squat exercise, 12 sets at 70-90% of 1 rep max.	Vastus Lateralis	Not assessed	***HbO_2:, HHb and TSI*** 0.44-0.87	***HbO_2:, HHb and TSI*** 6.1- 43.5
Muthalib et al. (2010)	N=8	NIRO-200 oximeter Hamamatsu Photonics K.K., Hamamatsu, Japan.	Not displayed	10 second isometric contraction at 30% MVC and 100% MVC.	Bicep	2.7 ± 0.6 mm	Not assessed.	***Tissue Saturation baseline 30% MVC***: 3.0 ± 1.5. ***Tissue Saturation baseline 100% MVC:*** 4.4 ± 2.1
Austin et al. (2005)	N=46	Hutchinson Technology Inc, Hutchinson, MN.	Not displayed (***720-760 nm***)	Running at lactate threshold and VO_{2max}	Gastrocnemius	Not assessed	**Tissue Saturation*:*** ***Lactate Threshold***: 0.87 ***VO_{2max}***: 0.88	Not assessed

2.17. Haemodynamics

A recent meta-analysis (Lee et al., 2022), assessed 786 articles on compression garments and their influence on cardiac output, heart rate, stroke volume, blood pressure and systemic vascular resistance. Twelve articles were extracted for further analysis and concluded that large effects were observed in stroke volume and heart rate.

Cardiac Output

Cardiac output can be defined as the "amount of blood released from the left ventricle per minute" (Swanevelder, 2003). Non-invasive devices to assess cardiac output are more practical to assess changes in cardiac output (Swanevelder, 2003; Vignati and Cattadori, 2017). Cardiac output is measured using the simple of equation (Q= SV X HR). Stroke volume is defined as "the volume of blood distributed from the left ventricle of the heart during each contraction (Russ and Raja, 2020), this can calculated as the difference between the "end phases" of the diastolic and systolic volume within the left ventricle (Russ and Raja, 2020). The link between cardiac output and muscle oxygenation can provide researchers with a greater understanding of how compression can be utilised. Due to the complexity in assessing cardiac function, it is common for the research to use experimental protocols where participants are at rest (Lee et al., 2021; van Campen et al., 2021; Strenger et al., 2010).

In participants with Chronic Fatigue Syndrome, compression stockings (***compression***: 4.4±0.9 l/min; ***no compression***: 4.0±0.8 l/min) have observed increases in cardiac output when participants with Chronic Fatigue Syndrome undertook a 70 degree head up tilt activity for 15 minutes (van Campen et al., 2021). Interestingly when participants undertook the supine position, there were no significant differences ib cardiac output between measures (***compression***: 5.0±1.1 l/min; ***no compression***: 5.0±1.1 l/min), the level of compression observed was between 20-25 mmHg, subsequently no other physiological effects (heart rate and blood pressure were observed (van Campen et al., 2021). Lee et al. (2019) detected that different levels of compression on the lower extremity will influence cardiac output in healthy individuals. Low (***compression***: 2.2±1.4 mmHg: ***CO***: 2.9±0.8 l/min) and higher (***compression***: 28.8 ± 8.3 mmHg: ***CO***: 3.2±0.9 l/min) compression levels resulted in different cardiac output values. When wearing graduated compression (4.6±0.4 l/min), cardiac output increased in participants who undertook 10 minutes of a 80° head up tilt in comparison to when no compression (3.1±0.3 l/min) was worn (Strenger et al., 2010).

The theory of compression increasing blood flow suggests an increase in cardiac output (Lee at al., 2021). Lee et al. (2021) observed that compression tights can aid haemodynamics during recovery from high intensity cycling. Participants wore a high pressurised graduated compression profile (***calf***: 47.4±8.8mmHg; ***knee***: 27.5±5.0 mmHg; ***thigh***: 24.1±2.4 mmHg) for 60 minutes post performing a preload fatigue cycle activity. Higher responses when wearing compression tights ($P<0.05$) were reported for stroke volume (**CT**: 51.7 ± 19.0 cm^3: **Control garment**: 45.2 ± 17.2 cm^3) and cardiac output (**CT**: 3.7±1.4 L·min−1; **Control garment**: 3.2±1.0 L·min−1) after 45 minutes (Lee et al., 2021). However some research contradicts this and suggests that no effects occur on cardiac output when wearing different levels of compression (Sperlich et al., 2011; Lawrence and Kakkar, 1980). The circulatory infrastructure of the muscle will also bare a key influence in overall haemodynamic affect. Through a graduated compression design with the highest level of compression reported at the gastrocnemius, Lee et al. (2020) discovered enlargement of arterial structures in the gastrocnemius. This finding could be illustrated because of the gastrocnemius "*containing more blood than other regions*" (Lee et al., 2020; Avril et al., 2010). The importance on circulatory responses such as improving venous return is emphasised with higher levels compression on the calf (Ducrozet, 2004). There is limited data on different types of compression and their influence on cardiac output and there is still more evidence that is needed to ascertain the links between leg blood volume, oxygenation and cardiac responses.

Table 2.6. Compression garments effects on cardiovascular responses

Author	Participants	Ultrasound Device	Exercise/ Activity	Level of Compression (mmHg)	Type of compression	Area of the cardiac muscle assesses	Effect of Compression on Cardiac Output (L min^{-1})	Stroke Volume (ml)
Van Campen et al. (2021)	N=18	Doppler ultrasound	Supine	20-25 mmHg	Socks	Aortic Valve	↓	-
Lee et al. (2021)	N=13	Non-invasive Doppler ultrasound cardiac output monitor (USCOM Ltd)	Seated upright	***Overall***: 31.4	Tights	Aortic Valve	↑	↑
Dorey et al. (2018)	N=10		Supine	30-40 mmHg	Socks	-	↔	↔
Lee et al. (2018)	*N*=33	Non-invasive Doppler ultrasound cardiac output monitor (USCOM Ltd)	70 degree Head up tilt test and supine position	***Gastrocnemius***- 15.2 mmHg ***Thigh***- 8.5 mmHg	Tights	Aortic Valve	↓ In the HUT position v Supine	↓ In the HUT position v Supine
Barde and Deepak (2012)	*N*=38	ICG	70 degree Head up tilt test and supine position	N/A	N/A	N/A	↓ In the HUT position v Supine	↓ In the HUT position v Supine

Table 2.7. Compression garments effects on cardiovascular responses

Author	**Participants**	**Device**	**Exercise/ Activity**	**Level of Compression (mmHg)**	**Type of compression**	**Area of the cardiac muscle assesses**	**Effect of Compression on Cardiac Output (L min^{-1})**	**Stroke Volume (ml)**
Prothero et al. (2011)	*N*=15	8MHz Ultrasound probe	60 degree Head up tilt test and supine position	37.1 mmHg	Stockings	Brachial Artery ↓	In the HUT position v Supine	↓ In the HUT position v Supine
Lucas et al. (2011)	*N*=12	2-MHz, Doppler Ultrasound System	Supine, 30 minute, standing 3 min, supine 6 minute	-	Tights	-(Right middle cerebral artery)	Determined from the product of HR and SV	↔
Sperlich et al. (2011)	*N*=15	Rebreathing unit	Ramp test, running	13.6-38.8 mmHg	Socks	-	↔	↔

2.18. Blood Flow

The ability to return blood back towards the heart and regenerate deoxygenated blood to oxygenated blood is of key interest for athletes. Compressing the gastrocnemius can act as a squeezing effect to help improve the return of deoxygenated blood to the heart. Poiseuilles (1846) law on fluid mechanic's is directly specific to the link between compression and venous return. Poiseuilles law is based on the pressure difference between the beginning and end of a cylinder based structure. The flow of a substance is determined by the size of the radius and the pressure between two points, in this case it can be applied to a blood vessel. The changing point to which blood flow state changes can be determined by factors that may impact the radius size of the vessel. Compression has been known to increase the temperature at peripheral level and provide a dilating response increasing size diameter of the vessel. This response will enable the blood flow rate to increase due to the change in pressure at the two points of the vessel.

The influence of compression on venous return has provided mixed responses with some research suggesting no influences (Smale et al., 2018). Blood flow responses have varied with some research observing reductions with the use of compression (Sperlich et al., 2013). Other research has outlined that blood flow does increase within superficial and deep veins and arteries using compression (Broadtch et al., 2021; Riordan et al., 2021; Eze et al., 2006).

A recent article by Riordan et al. (2021) observed increases in "venous markers" through increases in blood within the *popliteal vein* and *femoral vein* using compression shorts, tights, and socks during the supine position. In comparison to the control trial where no compression was worn, compression tights increased *popliteal vein mean* (57.3 ± 90.1%), *popliteal vein peak* (58.9 ± 84.4%) and the *femoral vein peak* (46.4% ± 68.1%). With higher levels of compression (120 mmHg) exerted external compression has elevated blood flow within the popliteal artery (128 ± 20.4 mL/min) when participants were in the seated position (Eze et al., 2006). Higher levels of compression socks have reported that venal blood flow is higher when participants undertook a 30-minute treadmill run (Oficial-Casado et al., 2020). Compression did not influence cerebral blood flow when wearing compression tights, participants undertook an incremental cycling task to which no significant differences were observed through the use of different levels of compression (Smale et al., 2018). Interestingly, compression tights that exerted 35mmHg pressure across the thigh (*superficial*: 5.1±2.4 mL/100g/min; *deep;* 5.7±2.8 mL/100g/min) have been shown to restrict thigh blood flow in recovery from high intense exercise in comparison to when no compression was used (*superficial*: 9.8±4.2 mL/100g/min; *deep*: 12.4±5.2 mL/100g/min) (Sperlich et al., 2013). When wearing tights that exerted different levels of compression, deep veins (***low***: 11.8±7.7 mm$^{2;}$ ***medium***: 15.8±8.2 mm$^{2;}$: ***high***: 21.2±13.0 mm$^{2:}$) and arteries (***low***: 12.7±8.4 mm$^{2;}$: ***medium***: 16.6±8.4 mm$^{2;}$: ***high***: 23.4±14.8 mm^{2}) cross sectional area in the calf increased when participants wore higher levels of compression tights during resting conditions (Lee et al., 2020).

2.19. Review of literature summary

Research has highlighted that compression has a place in the world of sport and exercise. There has been well documented research that assesses compression garment and its role within performance and recovery. The majority of research have observed no improvements within sporting performance through the use of compression garments (Daschombe et al., 2011; Higgins et al., 2007; MacRae et al., 2012; Sperlich et al., 2010).

The gap in the literature suggests that more understanding is needed to determine how compression influences initial physiological functions when worn, this would provide sports scientists with a greater understanding into optimising the use of the garments for future use. There has been limited research surrounding different compression profiles and the influence on physiological mechanisms on the body. Understanding different compression profiles may provide different levels of responses on the body which subsequently could influence performance and recovery. Therefore, purpose of the thesis is therefore to provide more clarity in physiological responses towards the use of bespoke compression and different types of compression profiles.

2.20. Aims of the thesis

The research aims of the thesis are to investigate the influence of compression on muscle oxygenation and haemodynamic responses using bespoke compression tights (**Figure 2.6**). The research to date has provided equivocal responses findings of how compression can influence performance and recovery. Reliability of the NIRS in assessing muscle oxygenation through the application of compression will be the first study which will look to determine future use of NIRS.

The thesis will also explore how oxygenation responses differ when wearing compression socks and compression tights whilst undertaking the same types of recovery activities. The thesis will aim also provide further understanding in how oxygenation responds to different types of compression whilst undertaking recovery specific activities. The PhD will also look to investigate different types of compression tights and begin to assess how oxygenation may differ based on different levels of compression pressure.

Chapter 3: General Methods.

Chapter 3. General Methods

The present chapter outlines the procedures that were utilised for the studies within this thesis. Information will be provided on recruitment, experimental protocols, muscle oxygenation assessment, use of NIRS, compression assessment and compression manufacturing. All experimental trials were complete within the laboratories at Nottingham Trent University, Clifton Campus.

3.1. Participant Recruitment

Participants were recruited via advert and word of mouth. Students were primarily recruited from Undergraduate and Postgraduate courses. Participants age range was 18-45 years of age. All participants recruited were recreationally active in a range of sports. Participants were issued with a participation information sheet that documented details of each study. Participant information sheets outlined aims of the study, methodological approaches, informed consent, health screen questionnaire and a covid related questionnaire. Verbal description was also relayed to the participants prior to the formal data collection phase.

All participants that were included within the trials were male. Females were not recruited due to difficulty in controlling the menstrual cycle for potential trials.The menstrual cycle has shown to change haemodynamics (Choi et al., 2013; Colverson et al., 2007). Ideally, females could have been used within different phases of the menstrual cycle with the application of different compression garments on, however due to time limitations that Covid brought it was not a suitable option.

3.2. Ethical Approval

Prior to data collection all studies received ethical approval from Nottingham Trent University Ethical Committee. All participants completed a participant health information document that contained information on their general health and readiness to take part within each study. Participants also were asked to complete a food log 24 hours prior to each visit. Digestion can influence blood volume subsequently impacting haemodynamic responses, with this in mind, participants were encouraged to repeat and log consumption of food repeatedly prior to each trial within all chapters. Participants completed a familiarisation trial where they were informed on the trials and what was required of them. Participants were made aware that they can withdraw from the studies at any time. Participants were also made aware that there data will be kept anonymous and in align with the Data Protection Act 2018.

3.3. Inclusion and Exclusion Criteria

All participants within **Chapters 4**, **5**, **6** and **7** had to be over the age of 18 with no cardiovascular medical conditions. Participants had to be active and engage within physical activity at least 4 times per week.

3.4. Height and Body Mass

Prior to testing, anthropometric measurements were taken to determine participants height (***cm***) and mass (***kg***). Participants were asked to take their shoes off prior to having their back to the stadiometer (Leicester Height Measure Seca, Hamburg, Germany). The primary investigator instructed the participants to breathe in prior to recording the height. Participant body mass was recorded to the nearest 0.1kg using Seca 770 digital scales (Seca, Hamburg, Germany). Testing was repeated at similar times to aid with circadian habits (Dijk and Duffy, 2020).

3.5.Near infrared Spectroscopy (NIRS)

Two NIRS (Portalite, Artinis Medical Systems BV, Elst, The Netherlands) devices were used to assess changes in muscle oxygenation. NIRS initially assesses Haemoglobin difference (Hb), Oxyhaemoglobin (O_2Hb), total haemoglobin (tHb) and deoxyhaemogbin (HHb) within its raw format [\muM] and TSI%. The NIRS devices was attached to both the ***Vastus Lateralis*** and ***Gastrocnemius*** muscle. Participants had both devices attached to them while carrying out all activities within the protocol.

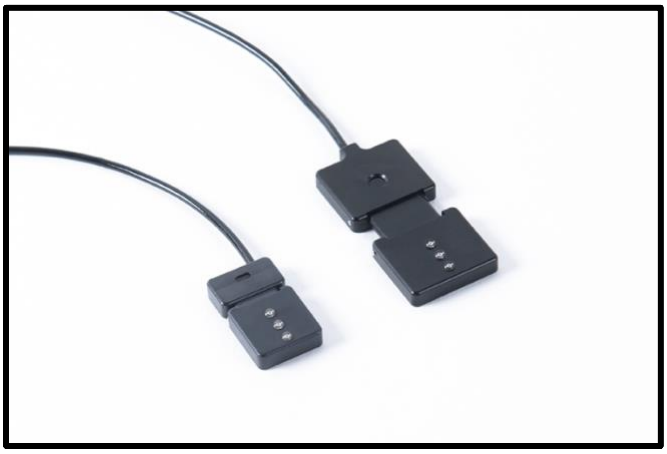


Figure 3.1 Porta Lite (Artinis Medical System) devices

3.5.1 Differential Path Factor

Differential Path Factor (DPF) determines the strength of the signal as it penetrates the tissue. The DPF value for all studies was selected at 4.95, this is based on the anatomical make up of the Gastrocnemius and Vastus Lateralis (Duncan et al., 1995; Keramidas et al., 2011; Subudhi et al., 2007; Rodriguez et al., 2019; Smith and Billaut 2010; Billaut et al., 2013). Different anatomical structures will provided different levels of difficulties for NIRS due to variables such as bone, adipose tissue and muscle structure. Originally DPF values within the use of NIRS application have ranged from 3 to 6 (Depay et al., 1988: van der Zee et al., 1990). Duncan et al. (1995) provided more specific DPF values when applying to males, females, and infants, for certain anatomical structures.

Table. 3.1. Range of ***DPF*** values in Duncan et al. (1995) study within different structures

Structure	Infants	Male	Female
Forearm		3.53 – 3.96	4.34 – 4.91
Calf		4.77 – 5.15	5.90 – 6.41
Head	4.67 – 5.38	6.07 – 6.74	5.64 – 6.27

3.5.2 Sample Rate and Wavelength

The sample rate was the amount of direction and change per second, to which it is measured in Hertz (Hz). The sample rate for the use of the NIRS was 10 Hz, which was replicated in all ***Chapters (4,5 and 6).*** This sample rate has been widely used within muscle and cerebral oxygenation research (See **Table 3.2**). There are 3 optode transmitters on each device, within each trial waves were set at 760nm and 850nm for **Chapter 4**,**5** and **7**, this was based on the work conducted by Duncan et al (1995)

3.5.3 Muscle Location

Prior to NIRS attachment, the belly of the gastrocnemius and the vastus lateralis were shaved to reduce friction and potential noise that could impact the signal (Lekete et al., 2011). The Vastus Lateralis location was approximately 15cm directly above the patella (Smith and Billaut, 2013;

Rodriguez et al., 2019). Once the location was found, the practitioner drew a cross for reference to which the NIRS device would then attach to the skin surface. When attaching the device to the gastrocnemius., the practitioner measured the biggest circumference around the medial head (Southern et al., 2013), to which a cross was again administered on the surface of the skin and used as reference to attach the device. To reduce ambient light, a bandage was lightly administered across the devices within the no garment and compression garment trials.

3.5.4 Baseline

NIRS data should be assessed to represent change from a baseline (Perrey and Ferrari, 2018). To assess concentration changes a baseline (μM) was set prior to each trial. Participants were asked to remain seated for 5 minutes at the beginning of each trial. The baseline was set when oxygenation levels were stable for a minimum of 30 seconds. After the baseline was set, the device was then set live and the participant applied the compression garment then begun the trial. Participants were instructed to remain as still as possible through the baseline stage mainly in order to " minimise motion artifacts" (Perentis et al., 2021). Remaining at rest prior to data collection is a commonly used as a method in order to gain a baseline reading so that initial muscle oxygenation responses can be observed (McMcLay et al., 2016; Wong et al., 2020; Perentis et al., 2021; Smith and Billaut, 2010).Different muscles and regions can impact blood flow and oxygenation, for the whole thesis the same individual positioned the probes for consistency purposes.

Table 3.2. Near-infrared Spectroscopy instrumentation set up in the literature.

Author	Population	Device	Wavelengths (nm)	DPF	Muscle	Sample Rate (Hz)
Duncan et al. (1995)	Adults	Not displayed	807	***Male***: 4.95 ***Female***: 6.0	Gastrocnemius	20
Subduhi et al. (2007)	Adults	Oxymon, Artinis, Artinis Medical Systems, Elst, Netherlands	780 to 850	4.95	Vastus Lateralis	10
Rodriguez et al. (2019)	Adults	Oxymon, Artinis, Artinis Medical Systems, Elst, Netherlands	Not displayed	4.95	Vastus Lateralis	10
Smith and Billaut (2010)	Adults	Oxymon, Artinis, Artinis Medical Systems, Elst, Netherlands	763 and 855	4.95	Vastus Lateralis	10
Billaut et al. (2013)	Adults	Oxymon, Artinis, Artinis Medical Systems, Elst, Netherlands	763 and 855	4.95	Vastus Lateralis	10
Pilotto et al.(2022)	Adults	PortaLite (Artinis Medical Systems, Elst, Netherlands)	760 to 850	Not reported	Vastus Lateralis	10
Cherouveim et al. (2022)	Adults	PortaLite (Artinis Medical Systems, Elst, Netherlands)	760 to 850	Not reported	Vastus Lateralis	10
Zhang et al. (2021)	Adults	PortaLite (Artinis Medical Systems, Elst, Netherlands)	Not displayed	5.5	Anterior tibialis	10
Andersen et al., (2021)	Adults	PortaMon, Artinis Medical Systems, Elst, Netherlands	760 to 850	4.0	Vastus Lateralis	10
Pramkratok and Yimlamai (2021)	Adults	PortaMon, Artinis Medical Systems, Elst, Netherlands	Not reported	4.0	Vastus Lateralis	10

3.5.5 Adipose Tissue Thickness

Subcutaneous tissue within and between individuals will differ dependent upon muscle structure, training status and body composition. Increases in adipose tissue thickness above 10mm have proven to be unreliable within NIRS assessment within the forearm (van Beekvelt, 2002). Skinfold thickness was measured using calipers (Harpenden Ltd, UK) at the sites of the NIRS devices.

Table 3.3 Skinfold and girth measurements in the thesis.

		Chapter 4 and 5	**Chapter 6**
Gastrocnemius	Skinfold (mm)	9.7 ± 4.0	5.2 ± 3.6
	Girth (cm)	39.7 ± 5.2	37.2 ± 3.2
Vastus	Skinfold (mm)	11.7 ± 4.3	5.8 ± 1.5
Lateralis	Girth (cm)	56.2 ± 5.5	52.7 ± 7.8

3.6. Data Processing

Data processing for each trial began with the use of the proprietary software, Oxysoft which is the manufacturers initial programme that runs with the PortaLite devices. Each trial was saved within its original file format (Oxy-3) through the manufacturers software, Oxysoft (Oxysoft software, Portalite, Artinis, Medical Systems BV, Elst, The Netherlands). It was then exported to MATLAB (MATLAB and Statistics Toolbox R2017a, The MathWorks, Inc, Natick, Massachusetts, United States), using a specific code (oxysoft2matlab) through the manufacturers guidance (Artinis Medical Systems).

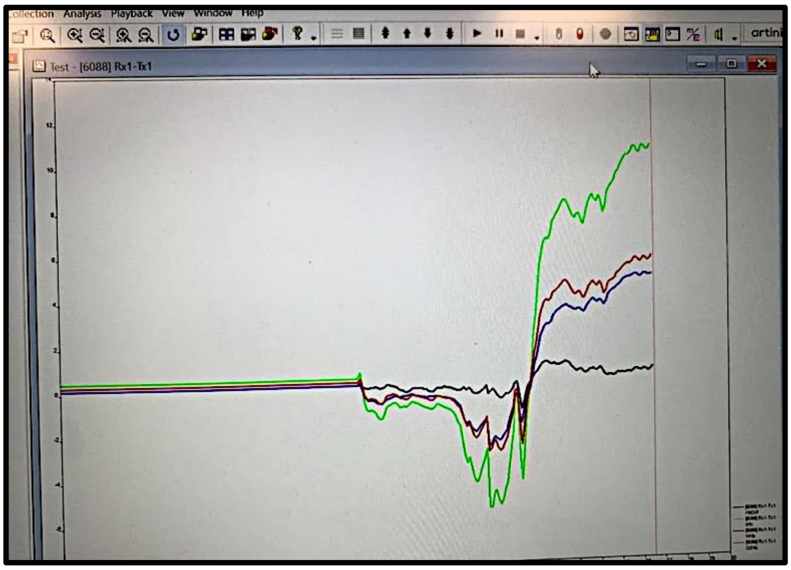


Figure 3.2 An example of live NIRS data during an isometric contraction (Hb difference, O_2Hb, tHb, HHb).

3.6.1 Filtering

MATLAB (MATLAB and Statistics Toolbox R2017a, The MathWorks, Inc, Natick, Massachusetts, United States) was used to create a Low- Pass Butterworth filter with a cut off frequency 0.2 Hz.

Table. 3.4 Comparison between filtered and non-filtered data in oxyhaemoglobin and deoxyhaemoglobin responses within a trial for one participant.

Responses observed	**Variable**	**Filtered** [\muM]	**Non Filtered** [\muM]	**P Value**
N=87930	Oxyhaemoglobin	40.6 ±7.9	40.6 ± 8.0	p=0.01
N=87930	Deoxyhaemoglobin	12.6±3.8	12.6 ± 3.7	p=0.01

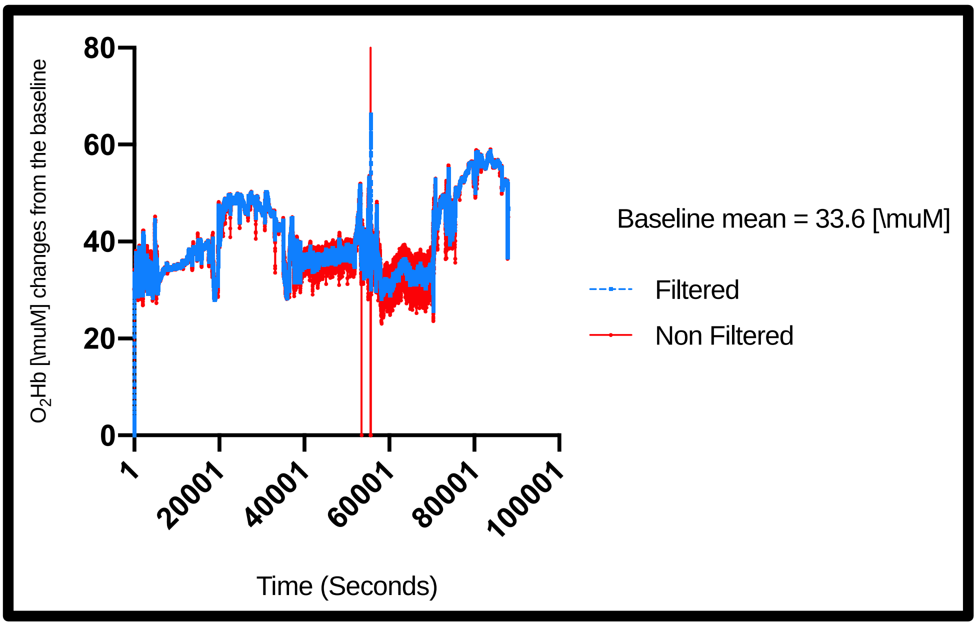


Figure 3.3 Comparison in non-filtered and filtered data in oxyhaemoglobin [O_2Hb] responses

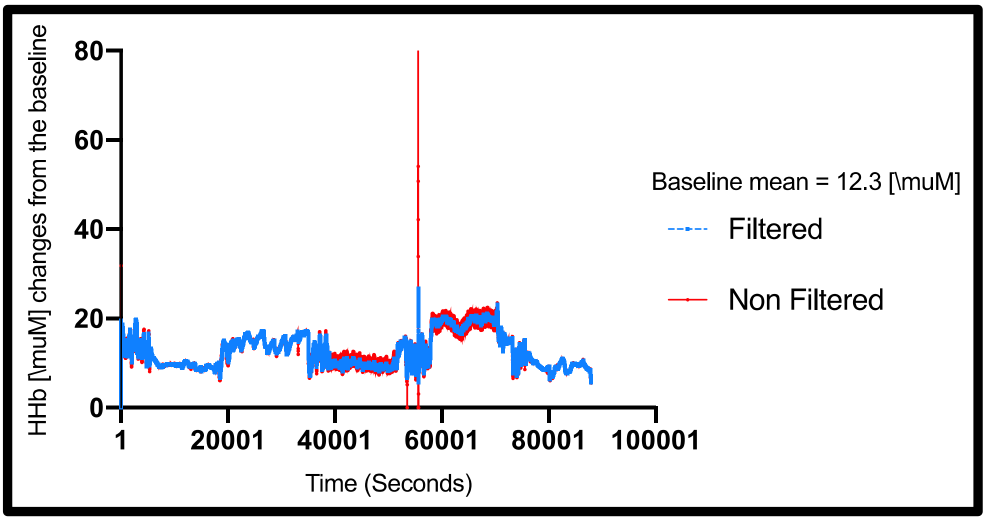
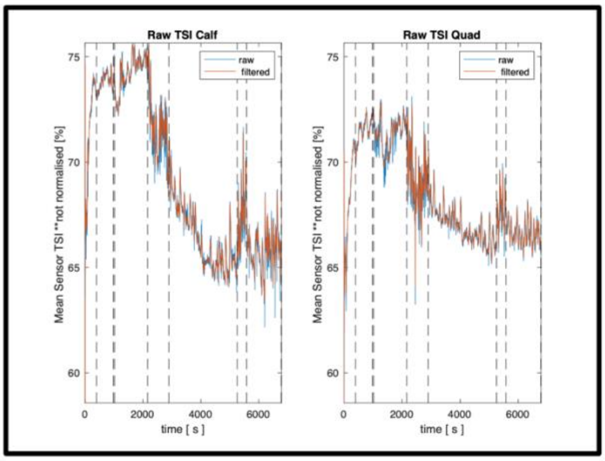


Figure 3.4 Comparison in non-filtered and filtered data in deoxyhaemoglobin [HHb] responses

The importance of filtering NIRS raw data is highlighted in **Chapter 5**. Filtering of data enables removal of internal physiological noises (Fekete et al., 2011). **Figure 3.3** and **3.4** identifies differences within filtered and non-filtered data.

Once the file was reconverted into a MATLAB file a specific code was run to enable the baseline to be reset. The baseline was set within the most stable part of the 5-minute baseline, to which changes were then re-calculated from that specific baseline. Once data was filtered, oxyhaemoglobin and deoxyhaemoglobin (ΔμM) concentration changes from the baseline and tissue saturation (%) were recorded. **Figure 3.5 – 3.10** represents a whole trial through a converted MATLAB file.



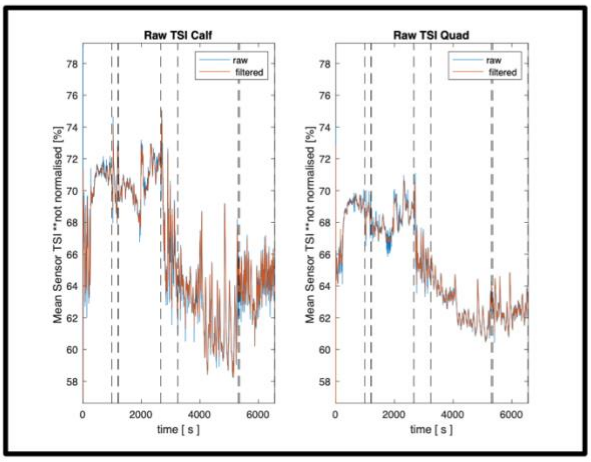
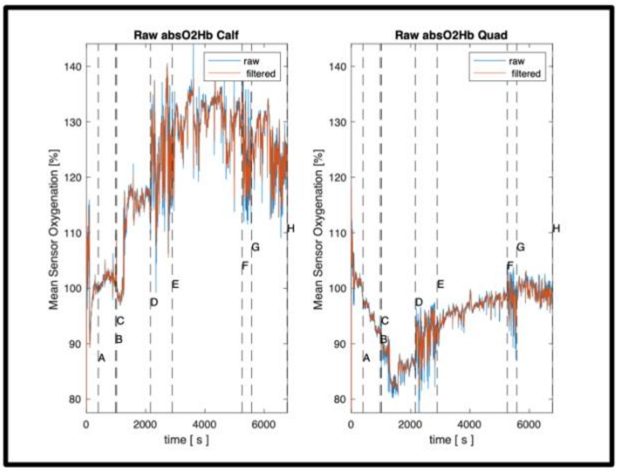


Figure 3.5. Participant 1 Graduated Compression raw TSI %. data **Figure 3.6** Participant 1 Uniform Compression raw TSI % data

Figure (A) ***Key***: A - B = Prep Phase; C - D= Decubitus; E - F= Tilt Position; G - H= Standing Figure **(B)** ***Key***: A-B= Prep Phase; C - D= Decubitus; E - F= Tilt Position; F-G Standing.



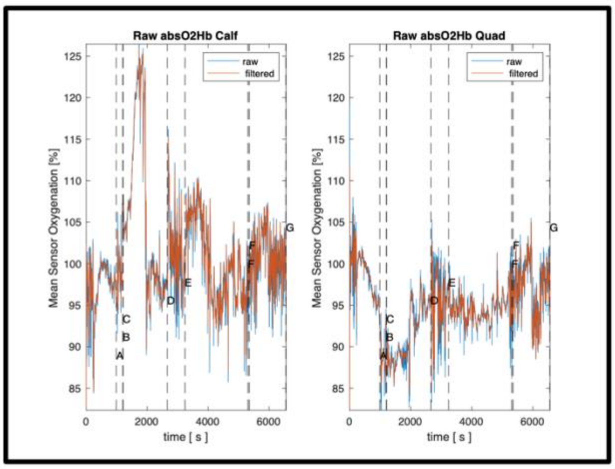
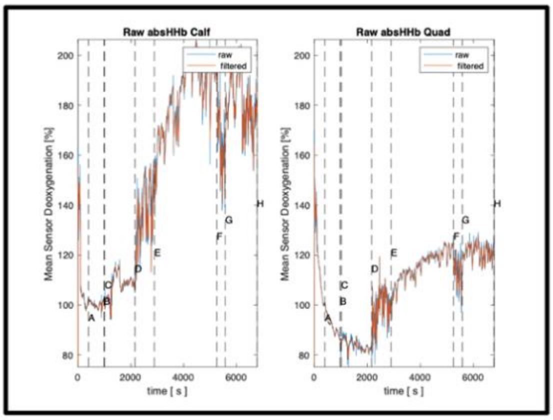


Figure 3.7 (A). Raw Absolute Oxyhaemoglobin Graduated Compression Garment. **Figure 3.8 (B).** Raw Absolute Oxyhaemoglobin Uniform Compression Garment

Figure (A)*Key*: A - B = Prep Phase; C - D= Decubitus; E - F= Tilt Position; G - H= Standing **Figure (B)** ***Key***: A-B= Prep Phase; C - D= Decubitus; E - F= Tilt Position; F-G Standing.



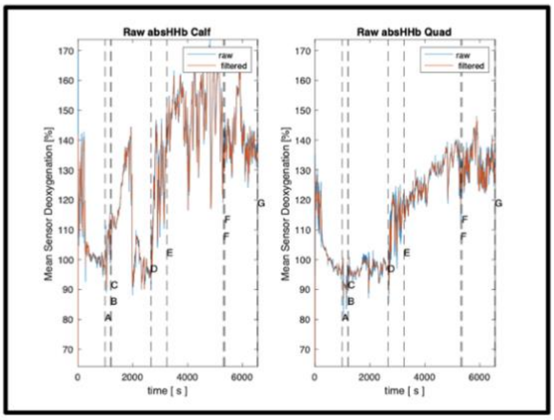


Figure 3.9. Raw Absolute De-oxyhaemoglobin Graduated Compression Garment **Figure 3.10**. Raw De-oxyhaemoglobin Uniform Compression Garment

Figure (A) Key. A- B= Prep Phase; C-D= Decubitus; E- F= Tilt Position; G-H= Standing

MatLab would then export an "Absolute Interval File". The "Absolute interval file" contained data within arbitrary units at 60 second intervals. The raw file was used to see the baseline to which it was then deduced away from the absolute interval data to in order to observe concentration changes.

The files were initially exported from CSV/text files to Excel. Baseline deductions were applied to the following categories:

- oxygenation calf/quad transmitter 1,2,3,
- deoxygenation calf/quad transmitter 1,2,3
- mean oxygenation/ deoxygenation calf/quad

Once data was calculated, mean and standard deviation were calculated for all phases of the protocol. Tissue saturation was already calculated in percentage format. Data processing procedures remained for ***Chapter 4, 5*** and ***6***. Arbitrary units are commonly expressed within the research when using NIRS (Perentis et al., 2021; Ouselati et al., 2018; Stocker et al., 2016). ***Chapter 4*** provided good reliability when assessing changes so this format was continued in ***Chapter 5*** and ***6***.

3.7. Compression Tights

Compression tights were manufactured by Kurio (Kurio Recovery, Kurio 3D Compression, Edwinstowe, Nottingham, England). Each participant was measured for made to fit compression tights that were specific to their own individual body shape. For ***Chapter 4, 5 6*** and ***7***, bespoke compression tights were manufactured (See **Figure 3.6).**

3.7.1 Bespoke Compression Manufacturing

In ***Chapter 4*** and ***5***, participants were measured for bespoke compression tights in measuring the circumferences of lower and upper extremities of the each limb. Limb length was also measured from the greater trochanter to lateral malleoli. ***Chapter 4*** and ***5***, compression tights were processed for a recovery specific compression profile that would have a graduated fit

3.7.2 Scanned Compression Tights

For ***Chapters 6*** and ***7***, bespoke compression tights were manufactured through the use of scanning the individuals body. To which each participant would stand in the anatomical position and a scan would be generated. The scans were processed and sent to the manufacturer subsequently creating a template for a specific bespoke garment. Participants would come to the laboratory to be scanned by an experience practitioner using a Artec Leo 3D scanner (Artec Group, Luxembourg, Luxembourg). ***Chapter 6*** and ***7*** the goal was to create specific compression profiles that were higher than the compression from the study in ***Chapter 4*** and ***5.*** Participants were not made aware of the compression profile of each profile within ***Chapter 6*** and ***7*** (**Table 3.2**). Compression tights were randomised for all 4 garment trials. Compression tights were kept in storage between trials for the garment to maintain its elastic properties. Compression properties were made of Elastane (22%) and Nylon (78%).

3.8. Compression Socks

Compression socks (VR Pro Plus+ Recovery, Vital Active, London, England) were made to measure through individualized measurements of shoe size, heel to knee (cm) max calf and ankle girth (cm). Compression socks were used for **Chapter 5** and **6**.

Table. 3.5. Compression profile objectives for **Chapter 6** and **7**.

Compression Tight Name	Objective
Graduated Compression Garment (GCG)	Higher levels of compression (approx. 25 mmHg) affiliated on the lower limb and graduated up the limb with lower levels of compression (15 mmHg)
Uniform Compression Garment (UCG)	Compression profile that is looking to maintain consistent pressure throughout the limb `(15-20 mmHg)
Control Garment (CG)	Lower levels of compression but within a graduated profile approx. 15-8 mmHg
Reverse Graduated Compression Garment (RGCG)	Lower levels of compression (approx. 15 mmHg) affiliated on the lower limb and graduated up the limb with higher levels of compression (approx. 25 mmHg)

3.9. Assessment of Compression

In order to assess the influence of compression, compression was assessed prior to each trial, with each participant standing upright within the anatomical position. Participants were encouraged to pull the garment up to the hips to avoid inconsistent compression pressure readings.

3.9.1 Kikuhime Pressure Monitor

A Kikuhime Pressure Monitor (KPM) (MediGroup, Melbourne, Australia) was used throughout each trial. The KPM is a non-invasive device that is fitted underneath a material to measure interface pressure. The importance in assessing compression enables the primary investigator to understand the level of compression applied to observe a potential affect (Brophy-Williams et al., 2013). The KPM has been found to be a reliable method in assessing compression pressures (Brophy-Williams et al., 2013). Coefficient of variation values between 4.17-7.4% have been demonstrated when using the KPM (Brophy-Williams et al., 2013; Parsch and Mosti, 2010)

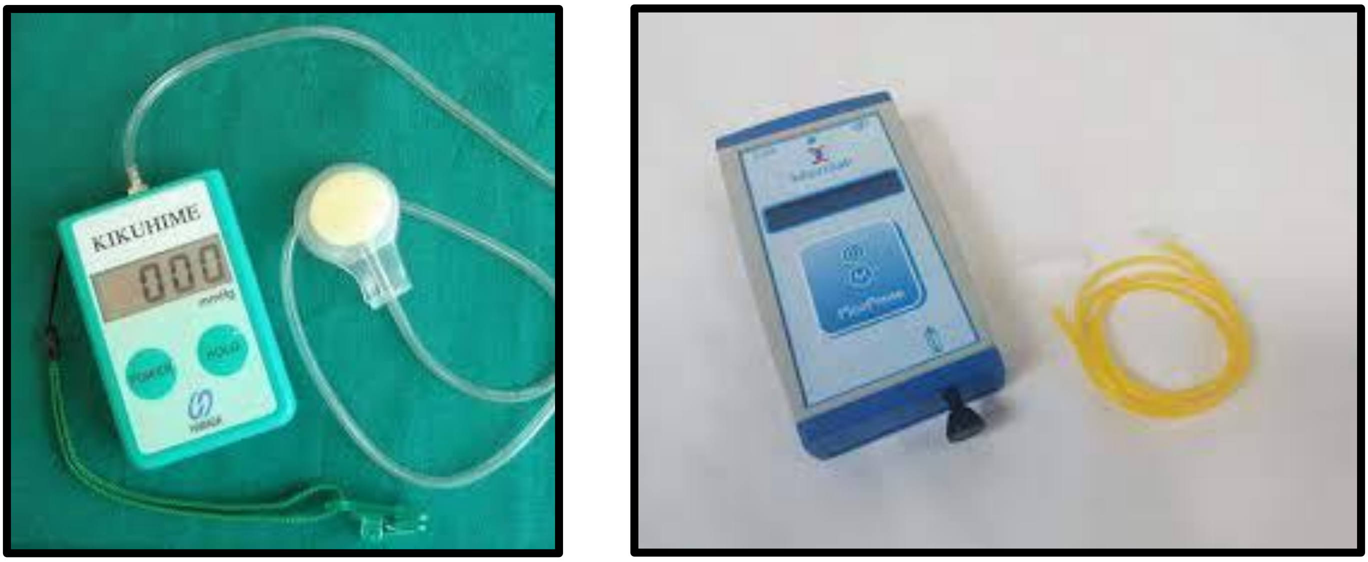


Figure 3.11 Kikuhime Pressure Monitor device and the Pico Press device

3.9.2 Pico Pressure Monitor

In ***Chapter 6*** and ***7*** the collation of compression pressure was through the use of the Pico Press (Microlab Electronica, Padua, Italy). The main reason for this was due to a fault with the Kikuhime Pressure monitor and due to Covid and manufacturer waiting time it was decided to continue with using the Pico Press. The pressure sensor is slightly bigger in surface area, this suggests more of the body can be assessed. Research has found the Pico Press to be reliable within clinical settings (Nandasiri et al., 2020).

3.10. Compression Profile

Compression profile assessments have not been thoroughly researched within a sporting domain. ***Chapters 4*** and ***5*** used Brophy-Williams et al. (2014) model in assessing compression. In ***Chapters 6*** and ***7***, Ashby et al. (2021) model in assessing compression was used.

3.10.1 Brophy-Williams et al. (2014) compression profile model

Figure 3.12. Compression assessment model for Chapter 4 and 5

For **Chapter 5** and **6 (Figure 3.12)**, the pressure monitor device was placed on 6 specific landmarks of the compression garment in using the method from Brophy-Williams et al. (2014) and Troynikov et al. (2010). (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). All participants remain stood in an upright position whilst compression was assessed.

The upright standing position enables key musculoskeletal structures to remain fixed enabling a more consistent measurement. This model in assessing compression is used across the medical profession, which was initially established by the European Committee for Standardisation (2009). The rationale in assessing compression using this method enables compression to be assessed against key anatomical landmarks without interface pressures from the garment interacting against the bone. Assessing compression against the muscle will provide a greater understanding of compression and hemodynamic responses (Ashby et al. 2021).

3.10.2 Ashby et al., (2021) compression profile model

For Chapter **6** a new method in assessing compression was applied. Compression was assessed from a posterior position of the limb. Compression was assessed at 5cm increments on the posterior surface of the right limb (Ashby et al., 2021). Recent evidence has emphasized the need to assess compression at posterior landmarks (Ashby et al., 2021; McManus et al., 2020). The radius accumulated between the anterior tibialis and gastrocnemius has suggested that compression pressure can be influenced, recommending posterior aspect of the gastrocnemius should be assessed (McManus et al., 2020). Laplace law (Young and Laplace, 1806) suggests that "*the pressure exerted by compression is directly proportional to the tension but inversely proportional to the circumference of the limb*" (MA Healthcare 2015). The new method is favored due to potential consistent compression pressures due to the "*tissue structure along the limb*" allowing for optimal pressures to be taken (Ashby et al., 2021).

Figure 3.13. Compression profile method for Chapter 6.

3.11. Visual Analogue Scale

Perception of comfort in using compression garments have been assessed through a visual analogue scales (Munderman et al., 2002; Lucas-Cuevas et al.,2017). Mundermann et al. (2002) reported reliable values in developing a visual analogue scale to assess footwear comfort. Lucas-Cuevas et al. (2017) adapted the visual analogue scale in assessing comfort in wearing compression pre and post running. The perception of comfort scale is structured on a 0-15 points system with the scale measuring at 150mm. The participant allocates a line on the scale representing how they perceive their comfort to be whilst wearing compression. The points and scaling ranges from 0 points (not comfortable at all, to 15 points (most comfortable condition imaginable). The visual analogue scale was used for the study in **Chapter 6**.

3.12. Head up tilt test (HUT)

In ***Chapter 7*** head up tilt test was used. The purpose of the head up tilt test is to alter cardiac and haemodynamic responses.   The head up tilt position will enable a redistribution of blood towards the limbs (Adami et al., 2015). A decrease in cardiac output and stroke volume have been reported with an increase in angle of the tilt position (Adami et al., 2015; Lund et al., 2017). The redistribution of blood volume through the tilt position is due to the gravitational change causing "systemic vascular resistance" re-diverting the blood back towards the legs (Cotuk et al., 2018). Research has outlined that even though there is a decrease in cardiac output and femoral artery blood flow, muscle oxygenation levels still remain elevated (Adami et al., 2015; Truiken et al., 2012). Supine to HUT position has suggested increases in tHb within the gastrocnemius. This can be put down to the generic structure of the gastrocnemius and its capability to pool blood providing a greater opportunity to saturate oxygen.

3.13. Heart Rate

Heart rate was monitored intermittently at 5 minute intervals throughout the trials and was used for studies in ***Chapter 4*** and ***5***. A standard heart rate monitor (Polar Electro Oy, Kempele, Finland) was used. Instructions were made to each participant that it must be tightly fitted in line with the xiphisternum. Heart rate was then averaged across the trial from the 5 minute interval data.

3.14 Rate of perceived exertion (RPE)

Perceptual measurements were recorded using the Borg (1982) scale ranging from 6-20. The scale was administered during the walking and jogging activities of the protocol and was monitored at 5 minute intervals. RPE was used for studies in ***Chapter 4*** and ***5*****.** Participants would verbally communicate the number of RPE that they were experiencing at 5 minute intervals.

3.15 Statistical Analyses

3.15.1 Chapter 4

Statistical analysis was performed using SPSS version 24.0 (SPSS Inc., Chicago, IL, USA). The reliability of the NIRS for the assessment of muscle oxygenation was examined using systematic bias and 95% limits of agreement (Bland & Altman, 1986), coefficient of variation (CV %) based on differences and intra-class correlation (ICC) for the control and compression condition. Hopkins (2015) spreadsheet was used to calculate CV and ICC.

A paired t-test was used initially for physiological measures to observe any significant differences between trials ($P<0.05$). Reliability measures for the ICC were categorised as >0.75, good; 0.40-0.74, moderate; and < 0.40, poor (Landis & Koch, 1977). Data is presented as mean ± SD. GraphPad Prism version 8 (GraphPad Software, La Jolla, California, USA) was used to create Bland and Altman graphs.

3.15.2 Chapter 5, 6, and 7

GraphPad Prism version 8 (GraphPad Software, La Jolla, California, USA) was used within all following chapters to assess differences between parameters, in order to do this a one-way analysis of variance (ANOVA) was chosen. One-way ANOVA used the overall mean for each trial. The ANOVA determined any differences between trials ($P<0.05$). Post-hoc Bonferroni were conducted on data to assess what key differences there were between trials ($P<0.05$). Data was inputted into tables throughout to represent trials overall mean and standard deviation as well as any differences observed between trials ($P<0.05$). Graphs were created in GraphPad. Cohen's *d* effect size was used, the scale was standardly set at small effect 0.2 < 0.5, medium effect 0.5 < 0.8, large effect > 0.8 (Cohen, 1988).

3.15.3 Power Analysis

Given the small participant sample size underpinning the analyses described in Chapter 7 (n=7), the author was asked to perform some post-experiment sample size calculations. The post-experiment power calculations (conducted using G*Power, Version 3.1.9.6, Faul et al., 2007 and 2009) suggested a sample size of 14-18 participants would have been needed to detect as statistically significant differences between conditions, given the actual effect size magnitudes obtained in the variables described below.

Variable: Tissue saturation tilt vastus lateralis (Assumed power of 0.8, Greenhouse-Geisser corrected values, Partial Eta Squared = 0.146, effect size f = 0.41, total sample size = 18).
Variable: Tissue saturation tilt gastrocnemius (Assumed power of 0.8, Greenhouse-Geisser corrected values, Partial Eta squared = 0.153, effect size f = 0.42; total sample size = 17).
Variable: Tissue saturation decubitus gastrocnemius (Assumed power of 0.8, Greenhouse-Geisser corrected values, Partial Eta squared = 0.182, effect size f = 0.47; total sample size = 14).

Chapter 4: Reliability of near infrared spectroscopy with and without compression tights during exercise and recovery activities.

Chapter 4: Reliability of near infrared spectroscopy with and without compression tights during exercise and recovery activities.

4.1. Introduction

Increased participation in sport has led to individuals examining, and investing in, interventions to enhance performance and recovery. Compression garments are one such intervention that have become widely utilised at all levels of sport (Brown et al., 2017), however research is warranted to assess their potential efficacy for use during performance and recovery (Bottaro et al., 2011). Compression garments include tights, socks, stockings, calf guards, vests and sleeves. In clinical use, compression tights have been shown to aid blood flow and oxygenation at a local muscular level (Nedelec et al., 2013; Kraemer et al., 2010). However, research relating to the benefits of compression in healthy sports people remains equivocal (Brown et al., 2017; Beliard et al., 2015), and thus rigorous methods to assess the potential benefits of compression garments is needed, particularly if mechanisms of performance and recovery benefit are to be determined.

The application of compression garments reduced venous pooling, blood flow and lactate during recovery and muscle soreness following muscle damaging exercise (Bringard et al., 2006; Berry et al., 1987; Jakeman et al., 2010; Sperlich et al., 2013), enhanced lactate removal during recovery and strength and power recovery following exercise-induced muscle damage (Jakeman et al., 2010; Rimaud et al., 2010). However, contradictory research has reported no physiological differences compared with a control when wearing compression garments during exercise and recovery (Ali et al., 2010; Trenell et al., 2006; Vecruyssen et al., 2014; Engel et al., 2016). Thus, further research is warranted to examine the physiological responses elicited, particularly blood flow and muscle oxygenation, when wearing compression garments for potential performance and recovery benefits.

Near infra-red spectroscopy (NIRS) measures relative changes in oxy- and deoxyhaemoglobin and can be used during both passive and exercise activities allowing muscle oxygen consumption and blood flow to be determined (Jones et al., 2016). NIRS can therefore be applied to studies examining the physiological responses to compression clothing to determine blood flow and oxygenation. However, to be used during exercise compression studies, the reliability of NIRS must be determined as reliability appears to be specific to the exercise type and intensity.

Studies examining the reliability of NIRS for determining muscle oxygenation have produced equivocal findings, with poorer muscle oxygenation reliability during higher intensity activities. Balas et al. (2018) assessed reliability by examining muscle oxygenation in the forearm during rest and hand-grip contractions. Tissue saturation index (TSI) and total haemoglobin (tHb) coefficient of variation values were higher for intense activity, ranging from 17.2 to 41.8% in comparison to 8.3-12.9 % during rest (Balas et al., 2016). Similarly, studies that have examined reliability of NIRS measures across a range of voluntary contractions (10% to 100% MVC) have shown reliability to vary with ICC values ranging from 0.02 to 0.96 and CV from 1.5 to 36% (Muthalib et al., 2010; Celie et al., 2012; Crenshaw et al., 2012; Lucero et al., 2018. Similarly, during co-coordinative exercise activities, such as cycling and running, reliability has been shown to be variable with CV for muscle oxygenation, tHb and TSI ranging from 6.1 to 43.5% (Austin et al., 2005; Choo et al., 2017; Scott et al., 2014). This may be related to the rapid changes in haemodynamics and blood flow that occur during exercise using co-ordinated limb movements (Scott et al., 2014). In addition, applying pressure to the muscle and NIRS optode, which would occur when wearing compression garments, can alter the overall reliability of NIRS and must be evaluated (Hamaoka et al., 2014). Variations in pressure applied to the NIRS device can alter the pathlength between the muscle and the optode subsequently impacting the signal quality (Hamaoka et al., 2014). Therefore, evidence suggests reliability is highly variable and to date no studies have assessed reliability when wearing a compression garment which may have an additional influence on reliability.

Therefore, the aim of the present study was to assess the between-day reliability of NIRS for the determination of muscle oxygenation, deoxygenation and tissue saturation index at the gastrocnemius and vastus lateralis with and without compression tights. Reliability was determined during a range of activities that may be completed during recovery from, and travel after, exercise specifically supine and seated rest, walking and slow jogging. Reliability was also determined for a range of cardiovascular measurements, specifically heart rate, blood pressure and pulse oxygen saturation.

4.2. Methodology

4.2.1. Participants

Thirteen healthy, active males (age 21.5 ± 2.7 years, body mass 82.1 ± 11.2 kg and BMI 24.6 ± 3.2 $kg.m^{-2}$) completed 4 experimental trials across a 28- day period. Institutional ethical approval was obtained from Nottingham Trent University (approval number 425). Participants were briefed and completed written consent and health declaration forms. Participants were asked to refrain from strenuous exercise, caffeine and alcohol 24 hours before each trial. Individuals were required to monitor diet for 24 hours via recorded diary prior to their first main trial and replicate this diet prior to the remaining trials.

4.2.2. Experimental Protocol

In order to minimise the training and detraining effect, four experimental trials were completed within a 28-day period. Two control and two compression trials were randomly assigned for each participant via Latin square. During the control trial, sporting attire was worn (loose shorts and t-shirt) whereas during the compression trial, custom made compression leggings (Kurio Compression Ltd, UK) and a loose-fitting t- shirt were worn. The experimental protocol was designed to replicate activities that might be used during recovery from strenuous exercise. Each protocol comprised of 20 minutes of laying supine, sitting, walking, jogging and sitting (Figure 1). For the jogging aspect, each participant selected a speed they would complete a recovery jog at (7.0 ± 0.9 km.h-1), and this was replicated for the remaining trials. Immediately following the 20 minute jog participants sat for 20 minutes to determine any changes following the jogging (Figure 1). Prior to any main trials, a familiarisation session was completed where participants were measured for custom made garments and participants were accustomed with all the equipment used and measurements being made (NIRS, pressure measures, skin fold measurements). Under each condition, the participant was asked to remain quiet throughout and minimise movement when appropriate.

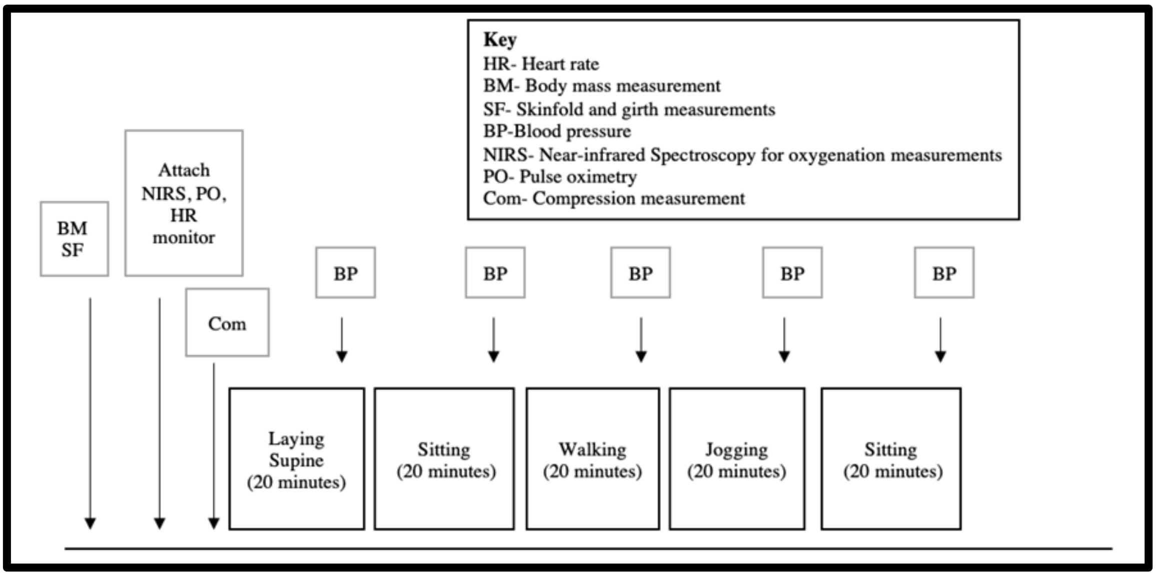


Figure 4.1. Schematic view of experimental protocol used during each trial.

4.2.3. Compression Tights

Compression tights were manufactured by Kurio (Kurio Recovery, Kurio 3D Compression Ltd, Edwinstowe, Nottingham, England). Each participant was individually measured including limb lengths, circumferences, waist and hip measurements and compression tights were custom-made for each participant lower-limb geometry, creating similar lower-limb compression profiles between left and right limbs and between participants.

4.2.4. Compression Measurements

Pressures exerted by the compression tights were recorded at the beginning of each activity (Kikuhime Pressure Monitor Medi-Group, Melbourne, Australia). Pressure readings were taken at six specific locations on the opposite limb to which the Near-infrared Spectroscopy was placed. The six locations were at the ankle bone (a), 5 cm proximal to landmark 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) (Brophy- Williams et al., 2015).

4.2.5. Physiological and Perceptual Measurements

Heart rate (Polar S810i heart rate monitor. Polar Electro Oy, Kempele, Finland) and pulse oximetry (ANP 100 Finger Pulse Oximeter, Anapulse, Surrey, UK) were recorded every 5 minutes during each activity. Blood pressure (Omron M2 Basic Blood Pressure monitor, Omron Corporation, Kyoto, Japan) was recorded at the end of each 20 minute activity. Rating of perceived exertion (RPE) was recorded every 5 minutes during the walking and jogging activities (Borg et al., 1982).

4.2.6. Near-infrared Spectroscopy measurements

Muscle oxygenation was measured using 2 portable NIRS devices with optode distances of 30, 35 and 40 mm (Portalite, Artinis Medical Systems BV, Elst, The Netherlands). Following cleaning and shaving, one NIRS device was attached to the muscle belly of the vastus lateralis, 15cm proximal to the patella head and 4cm lateral, and a second NIRS device to the gastrocnemius at maximal calf girth. NIRS was attached with double-sided discs and tape and covered with black bandage (Coban, 3M, UK) to eliminate background light. The position was marked with a permanent pen for subsequent visits. Skinfold thickness was measured using calipers (Harpenden Ltd, UK) at the sites of the NIRS attachment during the familiarisation visit. A modified version of the Beer-Lambert Law, using 2 continuous wavelengths of 760nm and 850nm and a differential path-length factor (DPF) value of 4.95 (Duncan et al., 1995), was used to determine changes in oxyhaemoglobin (HbO_2, μM), deoxyhaemoglobin (HHb, μM) and total haemoglobin (tHb) [tHb = HbO2+HHb]. Tissue saturation index (TSI) was also determined which represents the absolute measure of oxygenated haemoglobin **(TSI = [O2Hb]/([O2Hb]+[HHb])*100%).**

NIRS data was acquired at 10Hz and was continuously monitored through a bluetooth connection and instantly uploaded to the device's software (Oxysoft software, Artinis Medical Systems BV, Elst, The Netherlands). At the start of the trials, the participant was asked to sit for 5 minutes, with the baseline taken.

4.2.7. Data Processing for NIRS

MatLab (MATLAB and Statistics Toolbox R2017a, The MathWorks, Inc, Natick, Massachusetts, United States) was used to apply a 4th order Low- Pass Butterworth filter to the raw NIRS data with a low pass cut off frequency of 0.2 Hz, to remove high frequency noise (Rodriguez et al., 2018). The cut-off frequency was determined by evaluating a power spectral analysis of data in the frequency domain. TSI was measured in addition to changes from baseline were calculated for oxyhaemoglobin (HbO2), deoxyhaemoglobin (HHb) and total haemoglobin (tHb). For each 20-minute period, data were averaged per minute thus producing 20 data points per activity.

4.2.8 Statistical Analyses

Data are presented as mean ± SD. The reliability of the NIRS for the assessment of muscle oxygenation was examined using systematic bias and 95% limits of agreement (Bland and Altman, 1986), coefficient of variation (CV %) based on differences and intra-class correlation (ICC) for the control and compression condition. CV and ICC were calculated using an available spreadsheet (Hopkins 2015). A paired t-test was used initially for physiological measures to assess any significant differences ($P<0.05$). Reliability measures for the ICC were categorised as >0.75, good; 0.40 to 0.74, moderate; and < 0.40, poor (Landis and Koch, 2015). Statistical analysis was performed using SPSS version 24.0 (SPSS Inc., Chicago, IL, USA).

4.3. Results

Temperature and humidity were not different between trials (mean of all trials: 19.2 ± 2.8 °C, P=0.8; RH: 41.9 ± 11.9 %, P=>0.05).

4.3.1. Compression Pressure

Compression pressure across all landmarks was similar between the two compression garment trials (P>0.05). Coefficient of variation ranged from 1.0 to 3.6 % for all landmarks. Compression readings for individual fitted garments ranged from 7 mmHg to 19 mmHg. Highest compression readings were at the gastrocnemius (19mmHg, location c) and the lowest at the thigh (location f).

4.3.2. Anthropometric Measurements

There was no difference in body mass for the control (81.2±11.06 kg, P=0.72) and compression tights trials (82.3±11.49 kg, P=0.13). Skin fold thickness and girths were similar between trials (all P>0.05, Table 1).

Table 4.1. Skinfold and girth measurements for the control and compression trials (mean ± SD).

	Gastrocnemius		Vastus Lateralis	
	Skinfold (mm)	Girth (cm)	Skinfold (mm)	Girth (cm)
Control Trial 1	9.0±2.4,	39.5±4.3	11.3±5.1	57.0±6.1
Control Trial 2	11.3±5.1	40.1±6.1	11.6±3.1	56.5±5.2
Compression Tights Trial 1	9.2±4.0	40.5± 5.9	12.6±5.2	54.7± 5.7
Compression Tights Trial 2	9.5±4.5	38.9±4.7	11.3±3.8	56.7±5.3

4.3.3 Heart Rate, RPE and Blood Pressure

Heart rate was similar between the control and compression trials respectively ($P>0.05$). Systematic bias was -0.5 to 0.2 beats.min^{-1} (LOA: -19.3 to 33.3 beats.min^{-1}) during the control trial and -0.5 to 0.0 beats.min^{-1} (LOA: -11.1 to 19.2 beats.min^{-1}) in the compression trials. ICC values for heart rate ranged from 0.56 (moderate) to 0.76 (good) for the control condition and 0.57 (moderate) to 0.77 (good) for the compression reliability. Coefficient of variation (%) was <7.6% for both control (C) and tights (CT) (Supine: C= 6.4%, CT= 5.5%; Sitting: C= 4.0%, CT= 6.5%; Walking: C= 5.8%, CT= 7.2%; Jogging: C= 6.9%, CT= 7.5%; Sitting: C= 7.2%, CT= 5.3%). Rating of perceived exertion during walking was 6.1±0.3 and 6.3±0.8 ($P=0.58$, CV= 0.2%) in the control condition and 6.1±0.3 and 6.0±0.0 ($P=0.34$, CV= 0.1%) for the compression tights. Jogging RPE was 7.8±1.4 and 8.0±1.5 ($P=0.76$, CV=0.8%) during control and 8.9±2.5 and 8.1±1.5 ($P=0.25$, CV=1.3%) whilst wearing compression tights. Blood pressure was similar during each activity in the control and compression trials ($P>0.05$).

4.3.4. Pulse Oximetry

Oxygenation at the finger was similar throughout the control and compression trials ($P>0.05$) and demonstrated very good reliability. Systematic bias was -0.2 to 0.2% (LOA: -5.4 to 5.5%) during the control trials and 0.01 to 0.5% (LOA: -4.2 to 4.2%) for compression tights. Coefficient of variation (%) was 0.8 to 2.8% during the control condition and 0.1% to 2.0% for the compression tights trials.

4.3.5. Tissue Saturation Index

TSI reliability was moderate to good for the control trial (ICC: 0.56 to 0.96) and for the compression trial (ICC: 0.61 to 0.98) at the gastrocnemius (Table 4.2; Figure 4.2 and 4.3). At the vastus lateralis, reliability was poor to good in the control (ICC: 0.38 to 0.80) and moderate to good in the compression trials (ICC: 0.46 to 0.78; Table 4.3).

Table 4.2. Tissue saturation index (%) during the control (C) and compression tights (CT) trials at the gastrocnemius (mean ±SD).

	Control 1 (%)	Control 2 (%)	Systematic Bias (C) (%)	Bland and Altman 95% LoA	ICC	CV (%)	Compression Tights 1 (%)	Compression Tights 2 (%)	Systematic Bias (CT) (%)	Bland and Altman 95% LoA	ICC	CV (%)
Supine	76.2.±3.5	76.6±7.0	0.3	-9.9, 10.6	0.56	3.8	73.9±6.7	73.1±4.3	-0.7	-9.0, 7.4	0.73	3.0
Sitting	73.4±6.2	75.2±6.9	1.7	-3.2 6.7	0.92	1.9	73.2±8.7	71.4±6.7	-1.7	-13.4, 9.8	0.98	4.5
Walking	72.0±7.2	71.6±8.0	-0.4	-8.1, 7.2	0.87	4.0	70.9±8.0	69.7±5.6	-1.1	-13.2,10.9	0.61	4.5
Jogging	67.7±7.6	67.9±7.6	0.2	-5.8, 6.2	0.96	2.2	63.9±6.3	67.5±7.0	3.5	-5.6, 12.8	0.80	4.5
Sitting	80.8±4.6	81.3±4.9	0.5	-3.5, 4.4	0.91	1.4	80.5±5.9	78.5±6.0	-1.9	-11.5, 7.5	0.67	3.5

ICC = Intra-class correlation, CV= coefficient of variation, C= control trial, CT = compression tights trial.

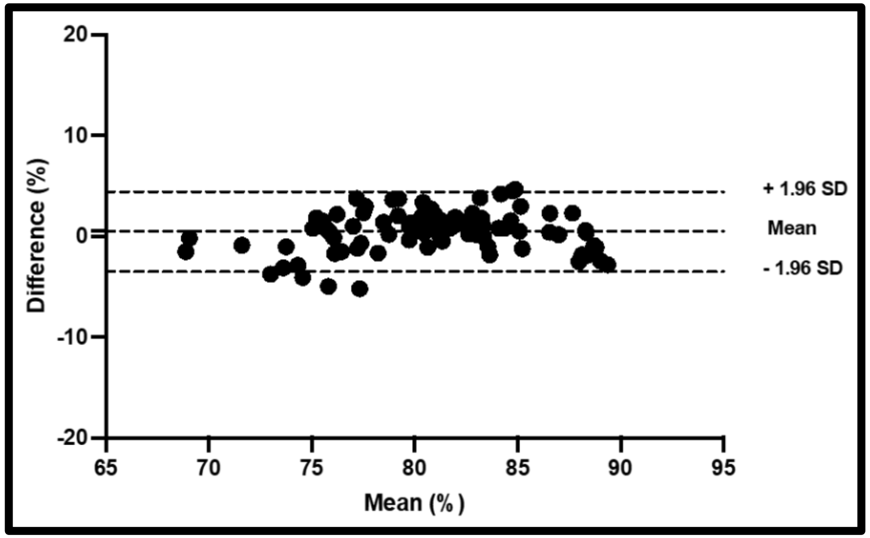


Figure 4.2: Bland and Altman plot of the sitting period post jogging in the control trial at the gastrocnemius (TSI).

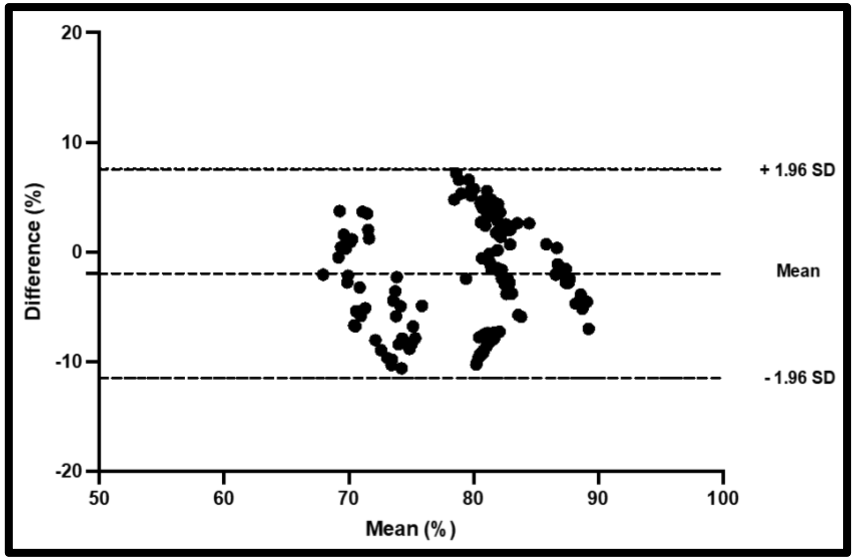


Figure 4.3: Bland and Altman plot of the sitting period post jogging in the compression tights trial at the gastrocnemius (TSI).

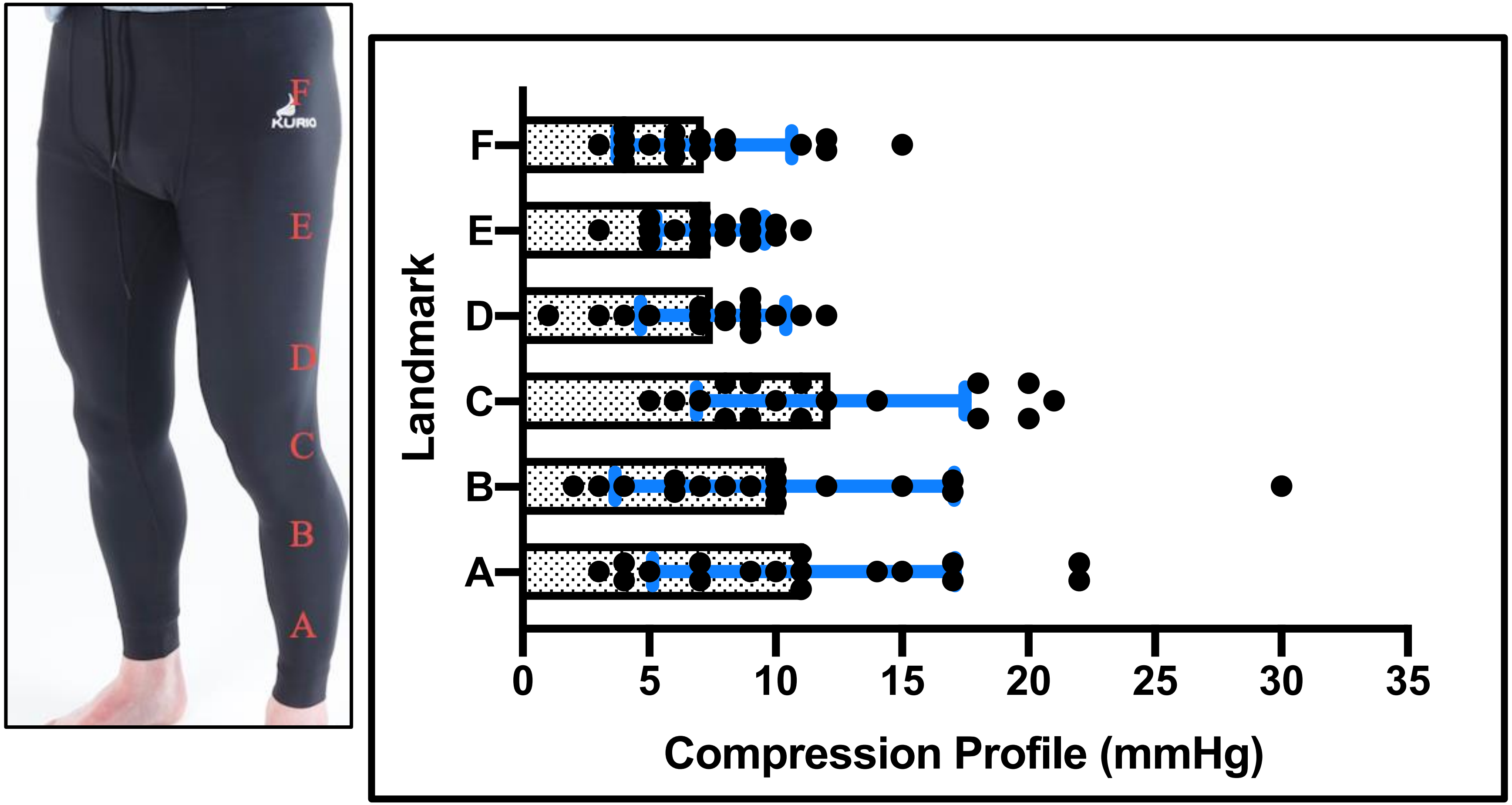


Figure 4.4 Compression profile (mmHg) for the participants within the specific landmarks in compression tights.

Table 4.3. Tissue saturation index (%) during the control (C) and compression tights (CT) trials at the vastus lateralis (mean ±SD).

	Control 1 (%)	Control 2 (%)	Systematic Bias (C) (%)	Bland and Altman 95% LoA	ICC	CV (%)	Compression Tights 1 (%)	Compression Tights 2 (%)	Systematic Bias (CT) (%)	Bland and Altman 95% LoA	ICC	CV
Supine	73.3±1.6	74.4±3.0	1.0	-4.3, 6.5	0.38	2.0	76.2±3.5	76.2±3.5	0.0	-7.0, 7.0	0.47	2.6
Sitting	70.7±4.1	71.5±4.1	0.8	-4.3, 6.0	0.80	1.9	73.3±5.0	73.9±4.5	0.6	-8.7, 9.9	0.51	3.4
Walking	72.9±4.1	73.7±4.9	0.8	-5.3, 6.9	0.77	2.2	74.4±5.2	74.7±5.5	0.2	-7.2, 7.7	0.75	2.7
Jogging	71.6±5.1	69.1±5.2	-2.4	-8.8, 3.9	0.80	2.4	65.4±5.9	65.0±6.8	-0.8	-9.2, 7.6	0.78	3.1
Sitting	72.4±5.3	70.9±5.8	-0.4	-7.2, 6.5	0.79	2.6	75.3±3.8	75.6±5.3	0.3	-9.2, 9.9	0.46	3.5

ICC = Intra-class correlation, CV= coefficient of variation, C= control trial, CT = compression tights trial.

Table 4.4. Oxyhaemoglobin responses from the baseline during the control (C) and compression tights (CT) trials at the gastrocnemius (mean±SD).

ICC = Intra-class correlation, CV= coefficient of variation, C= control trial, CT = compression tights trial.

	Control 1 (ΔµM)	**Control 2 (ΔµM)**	**Systematic Bias (C) (ΔµM)**	**Bland and Altman 95% LoA (ΔµM)**	**ICC**	**CV (%)**	**Compression Tights 1 (ΔµM)**	**Compression Tights 2 (ΔµM)**	**Systematic Bias (CT) (ΔµM)**	**Bland and Altman 95% LoA (ΔµM)**	**ICC**	**CV (%)**
Supine	-2.1 ± 6.5	0.5±5.5	2.6	-6.2, 9.6	0.68	3.5	0.9±9.4	-0.7±5.7	-1.6	-12.8, 10.0	0.62	1.0
Sitting	13.1±8.4	13.2±6.6	0.1	-7.8, 7.9	0.79	3.6	1.7±12.1	4.7±.8.0	2.4	-8.7, 12.6	0.83	1.2
Walking	1.3±5.8	0.5±5.0	-0.9	-5.6, 5.1	0.67	3.3	0.5±9.7	-0.6±19.1	-0.1	-17.9, 17.8	0.73	8.2
Jogging	-0.9±8.4	-0.6±9.7	0.2	-12.7, 13.0	0.68	6.2	-5.6±9.9	-3.6±19.3	2.0	-19.2, 22.4	0.70	8.8
Sitting	21.9±9.6	26.5±5.1	4.5	-8.1, 12.2	0.59	2.7	18.3±16.9	7.4±18.9	-11.0	-26.4, 11.9	0.84	7.5

Table 4.5. Oxyhaemoglobin responses from the baseline during the control (C) and compression tights (CT) trials at the vastus lateralis (mean±SD).

	Control 1 (ΔμM)	Control 2 (ΔμM)	Systematic Bias (C) (ΔμM)	Bland and Altman 95% LoA (ΔμM)	ICC	CV (%)	Compression Tights 1 (ΔμM)	Compression Tights 2 (ΔμM)	Systematic Bias (CT) (ΔμM)	Bland and Altman 95% LoA (ΔμM)	ICC	CV (%)
Supine	-2.4± 4.3	-3.5± 4.5	-1.1	-8.1, 6.5	0.5	0.6	-3.0±8.2	-1.0±3.3	2.1	-8.2, 10.6	0.50	4.5
Sitting	-0.8±-3.5	-1.0±7.6	-0.1	-8.6, 8.3	0.5	3.1	3.3±10.3	5.2±12.7	2.0	-7.8, 10.4	0.89	4.5
Walking	5.2±5.9	-5.7 ±3.5	-10.8	-15.5, 7.4	0.64	3.0	1.2±3.8	-0.1±5.9	-1.4	-8.1, -6.9	0.35	4.1
Jogging	1.9± 6.4	-2.6 ±5.1	-4.61	-11.6, 7.0	0.52	3.8	1.3±4.8	-1.3±7.9	-2.6	-11.7, -8.3	0.55	4.4
Sitting	5.7±5.5	-0.1± 8.4	-5.50	-17.8, 6.8	0.61	4.0	1.8±7.0	3.4±5.5	1.7	-7.8, 9.8	0.61	4.0

ICC = Intra-class correlation, CV= coefficient of variation, C= control trial, CT = compression tights trial.

Table 4.6. Deoxyhaemoglobin responses from the baseline during the control (C) and compression tights (CT) trials in the gastrocnemius (mean±SD).

	Control 1 (ΔµM)	Control 2 (ΔµM)	Systematic Bias (C) (ΔµM)	Bland and Altman 95% LoA (ΔµM)	ICC	CV (%)	Compression Tights 1 (ΔµM)	Compression Tights 2 (ΔµM)	Systematic Bias (CT) (ΔµM)	Bland and Altman 95% LoA (ΔµM)	ICC	CV (%)
Supine	-9.3±4.4	-8.1±2.7	1.1	-5.7, 7.1	0.43	2.1	-11.5±8.6	-11.0±9.4	0.3	-12.5, 14.3	0.82	4.0
Sitting	2.3±4.6	1.8±4.8	-0.5	-7.5, 6.8	0.57	2.9	-2.2±9.7	-2.1±9.4	0.1	-12.2, 12.5	0.71	5.3
Walking	-5.1±2.6	-5.6±3.5	-0.3	-4.6, 4.1	0.57	1.1	3.6±9.0	-2.0±7.8	-1.9	-15.0, 8.7	0.65	5.1
Jogging	0.1±7.4	1.7±6.1	1.6	-9.7, 11.7	0.52	1.6	10.3±12.2	5.5±12.0	-4.8	-16.0, 10.6	0.76	6.2
Sitting	-2.7±4.0	-2.9±3.4	-0.3	-5.0, 4.8	0.61	5.4	0.0±16.7	-2.0±9.9	-2.1	-25.0, -21.9	0.53	9.9

ICC = Intra-class correlation, CV= coefficient of variation, C= control trial, CT = compression tights trial.

Table 4.7. Deoxyhaemoglobin responses from the baseline during the control (C) and compression tights (CT) trials in the vastus lateralis (mean±SD).

	Control 1 (ΔμM)	Control 2 (ΔμM)	Systematic Bias (C) (ΔμM)	Bland and Altman 95% LoA (ΔμM)	ICC	CV (%)	Compression Tights 1 (ΔμM)	Compression Tights 2 (ΔμM)	Systematic Bias (CT) (ΔμM)	Bland and Altman 95% LoA (ΔμM)	ICC	CV (%)
Supine	-3.3±2.0	-4.4±2.9	-1.1	-5.2, 3.5	0.50	1.8	-1.3±7.3	-0.8±7.2	0.6	-4.4, 5.0	0.93	0.6
Sitting	-1.3±1.7	-1.3±4.6	0.0	-5.2, 5.3	0.42	2.7	-1.8±3.7	-0.7±2.9	0.9	-3.0, 4.7	0.79	1.5
Walking	-2.1±2.0	-2.6±5.9	-0.5	-7.4, 6.9	0.40	3.5	-3.3±3.5	-1.8±2.9	1.5	-4.2, 5.1	0.82	1.6
Jogging	2.2±5.5	-1.9±7.0	-4.1	-10.6, 4.3	0.81	2.8	-1.6±5.4	0.0±4.5	1.4	-2.7, 5.0	0.89	1.6
Sitting	-3.5±2.8	-3.7±4.6	-0.1	-6.0, 5.8	0.56	2.5	-3.1±5.4	-2.8±3.8	0.2	-7.5, 7.9	0.53	3.1

ICC = Intra-class correlation, CV= coefficient of variation, C= control trial, CT = compression tights trial.

4.3.6. Muscle oxygenation

Muscle oxygenation reliability for the control trial at the gastrocnemius was moderate to good with ICC ranging from 0.59 to 0.79 and CV of 2.7 to 6.2% (Table 4.4). During the compression trial, the reliability of muscle oxygenation had a CV ranging from 1.0 to 8.8% and ICC from 0.62 to 0.84 (Table 4.4). At the vastus lateralis, reliability was moderate to good in the control condition (Table 4.5; ICC: 0.50 to 0.64; CV: 0.6 to 4.0%), and was poor to good with compression (Table 4.5; ICC: 0.35 to 0.89; CV = 4.0 to 4.5%).

4.3.7. Muscle deoxygenation

Table 4.6 demonstrates moderate reliability for muscle deoxygenation at the gastrocnemius for the control trial and moderate to good for the compression conditions. At the vastus lateralis, moderate to good reliability is demonstrated for both the control and compression conditions (**Table 4.7**).

4.4. Discussion

The purpose of the present study was to assess the between-day reliability of NIRS determined muscle oxygenation, deoxygenation and tissue saturation index with and without compression tights. The relative measurement error, for tissue saturation, determined via an intra-class correlation demonstrated poor to good reliability (ICC: 0.38 to 0.96) across all activities during the control trial. In addition, the coefficient of variation values for tissue saturation were ≤4.0%. Similarly, when wearing compression tights, tissue saturation demonstrated moderate to good reliability (ICC: 0.46 to 0.98) with a coefficient of variation ranging from 2.6 to 4.5%. Muscle oxygenation and deoxygenation demonstrated moderate to good reliability (ICC: 0.40 to 0.81), with coefficient of variation values ranging from 0.6 to 6.2% across all activities in the control trial. Compression tights trials generated moderate to good reliability (ICC: 0.50 to 0.93), with coefficient of variation values ranging from 0.6 to 9.9%. There were no differences in heart rate, blood pressure, pulse oximetry and RPE during the control or compression tights trials ($P>0.05$).

Previous research investigating the reliability of NIRS during and after exercise have shown that reliability varies with exercise mode and intensity, muscle group, NIRS device and training status of participants (Balas et al., 2018, Crenshaw et al., 2012; Lucero et al., 2018; Bucheit et al., 2011). Therefore, it is imperative that reliability is determined for the specific NIRS derived variables during protocols that will be used to assess the effect of any intervention. In the control condition, for tissue saturation index at the gastrocnemius, the systematic bias (LOA) ranged from 0.1 to 1.7% (LOA: 4.4 to 10.3%) with coefficient of variation of 1.7 to 4.0%. At the vastus lateralis, in the control condition, systematic bias (LOA) for tissue saturation was 0.4 to 2.4% (LOA: 5.2-6.9%) and coefficient of variation values were 1.9 to 2.6%. This compares favourably with previous research that has reported reliability of NIRS for the measurement of tissue saturation index. Coefficient of variation during handgrip exercise was 8.3 to 24.3% (Balas et al., 2018), during biceps isometric contractions was 6.9 to 37.7% (Muthalib et al., 2010), during knee extension was 1.6 to 2.4% (Lucero et al., 2018) and during back squats was ~6.1 to 10% (Scott et al., 2014). There has been limited research examining the reliability of NIRS to measure tissue saturation index during multi-joint movement such as running and cycling. During cycling, reliability of TSI has been shown to range between 7.8 to 12.4% (Choo et al., 2017). Thus, the reliability of NIRS for the measurement of TSI during supine and seated rest, walking and jogging appears very good. Similarly, for muscle oxygenation and deoxygenation measurements during the control trial, NIRS demonstrated moderate to good reliability. For muscle oxygenation, coefficient of variation was 0.6 to 6.2% and for deoxygenation was 1.1 to 5.4%, demonstrating greater reliability than previous research (Scott et al., 2014). In summary, NIRS demonstrates good reliability for the assessment of tissue saturation and muscle oxygenation and deoxygenation whilst wearing normal sporting attire. The superior reliability reported in the present study compared to previous research is likely due to the recent advancements in NIRS technology and data processing, including filtering, specific for its use in sports science research. Despite, the fact that adding pressure to a NIRS sensor has been suggested to affect the reliability of NIRS measurements, (Hamoka et al., 2011) by altering the depth of the measurement, to our knowledge no research has sought to establish reliability when wearing compression clothing. This is surprising since several studies have used NIRS to assess the effects of compression on muscle oxygenation and haemodynamics (Bringard et al.,2006; Pesux et al., 2017; Menetrier et al., 2011). The present study showed that despite pressure being added to the NIRS device via compression clothing, it is reliable for the assessment of tissue saturation and muscle oxygenation and deoxygenation. At the gastrocnemius, coefficient of variation for tissue saturation index was 3.0 to 4.5%, muscle oxygenation was 1.0 to 8.8% and deoxygenation was 4.0 to 9.9%. Similar values were recorded at the vastus lateralis, with coefficient of variation of 2.6 to 3.5% for tissue saturation index, 4.0 to 4.5% for oxygenation and 0.6 to 3.1% for deoxygenation. One study has assessed the effect of pressure on NIRS reliability at the vastus lateralis at rest

(McManus et al., 2018). Using a thigh blood pressure cuff, pressure was applied to the NIRS sensor in 5 mmHg increments from 5 mmHg to 30 mmHg. A decrease in tissue saturation index was reported with increasing pressure with very different slopes reported for the 2 devices tested (MOXY and PortaMon). The PortaMon demonstrated a shallow slope with <3% difference in tissue saturation across the different pressures, whereas it differed by >10% with the MOXY suggesting that the MOXY should only be used if the pressure applied can be controlled. In the present study, while systematic bias, limits of agreement and coefficient of variation values demonstrated good reliability, it should be recognised that the variation was greater when wearing tights than without. This emphasises the importance of assessing reliability of NIRS before employing the technique in research studies or determining reliability as an integral part of the study. NIRS has been employed in numerous exercise and sport related research studies in recent years. It is therefore useful to determine if the reliability or measurement error reported for NIRS in the present study is lower than changes measured during sport science research. For example muscle tissue saturation has been observed to decrease by 1.3% for every 1 m.min^{-1} increase in climbing speed (Gajdosik et al., 2021) and decrease from 79.7% to 62.0% following intermittent cycling to exhaustion (Soo et al., 2021). In addition, during passive and active recovery between high intensity intermittent cycling efforts, changes in tissue saturation index ranged from 3 to 25% and muscle oxygenation ranged from 10 to 75% (Fennell and Hopker, 2021). At rest, young adults had lower tissue saturation index than middle aged men (73.2 vs 68.6 %) and it decreased by 17.4 and 22.2 % during resistance exercise (Gepner et al., 2019). Systematic bias of <3.5% and CV <4.5% for TSI at the gastrocnemius and vastus lateralis suggest that NIRS is reliable enough to detect a range of changes seen in sports science research both at rest and during exercise.

4.5. Conclusion and Practical Implications

In summary, it is imperative to determine the reliability or measurement error of NIRS before utilising it during sports science research. Despite the widespread use of NIRS within sports science there are few published reliability studies and none that have assessed reliability whilst wearing compression garments. The present study demonstrated good reliability for all activities with small systematic bias, limits of agreement and coefficient of variation values. When wearing bespoke compression tights, reliability was slightly poorer, therefore emphasising the importance of determining the measurement error of NIRS specifically for each study. To conclude, NIRS is sufficiently reliable to detect changes in TSI, muscle oxygenation and deoxygenation during a range of passive and exercise activities when wearing normal sporting attire or compression-wear. The practical implications observe that the NIRS is a reliable instrument to help assess oxygenation changes, this information provides future opportunities for other studies to use NIRS especially with more robust exercise protocols.

Chapter 5: The effects of compression tights and compression socks on muscle oxygenation.

Chapter 5: The effects of compression tights and compression socks on muscle oxygenation.

5.1. Introduction

Chapter 4 demonstrated acceptable reliability in using the NIRS whilst wearing bespoke compression garments. The present chapter looks to provide further information on how bespoke compression can influence muscle oxygenation changes through using the NIRS.

Compression garments are commonly being used in sporting settings and are highlighted as being favourable towards improving sporting performance (Brown et al., 2017; MacRae et al., 2012). Compression garments act as an external layer of material and sit on the peripheral surface of the skin. Compression socks focus on compression within the lower limb extremity (knee below) in contrast, tights focus on compression within the whole lower limb (hip and below) (Brophy-Williams et al., 2019). Physiological responses in wearing compression garments have observed positive influences such as delayed onset muscle soreness, reduce muscle damage and improved haemodynamics for performance and recovery (Hamlin et al., 2012; Sperlich 2013; Hill et al.,2014). Improvements in jumping and cycling performance have also been identified as an effect through the application of compression garments (Kraemer et al., 1998; Driller and Halson, 2013).

Muscle oxygenation and deoxygenation can be defined as "*concentration changes*" in oxyhaemoglobin and deoxyhaemoglobin within skeletal muscle tissue (Racinais et al., 2007). Oxygenation plays a pivotal role for athletes and subsequently aids the energy process which can overall impact key sporting actions. The influence of compression tights on muscle oxygenation have provided equivocal responses. Increases in muscle oxygenation at the gastrocnemius and the vastus lateralis have been observed within compression tights during submaximal exercise, supine and seating activities (Bringard et al., 2006; Sperlich 2013). Compression socks have also shown increases in muscle oxygenation (Menetrier et al., 2011; Coza et al., 2012; Kerherve et al., 2017). Other studies have contradicted these claims and have outlined minimal effects in oxygenation, oxygen economy and myoglobin concentration whilst using compression socks in exercise specific protocols (Ali et al., 2010; Del Cose et al., 2013; Book et al., 2016 Rennefelt, et al., 2019).

Rennerfelt et al. (2019) findings showed a decrease in tissue saturation in running within the anterior compartment of the muscle through the use of compression socks. The mechanics of running may impact the changes in oxygenation based on different muscle fibre recruitment that is activated through the running gait. Interestingly, Kereherve et al. (2017) identified changes in biomechanical running pattern whilst observing increases of TSI at the gastrocnemius through the use of compression sleeves. The difference in exercise intensity can also suggest that there be an optimum point where compression is of value for athletes. Bringard et al. (2006) indicated an increase response in muscle oxygenation at the gastrocnemius and provided suggestions that values increased in TSI % when participants wore compression tights during sitting and supine positions. It is clear that further investigation is needed to understand fundamental physiological mechanisms and their responses through the application of different types of compression garments and how oxygen can be utilised.

Interface pressure of the garments is of key interest when assessing the overall effects. Different interface pressures have been attributed with different levels of blood flow and oxygenation associated at the muscle site, thus impacting the overall effect during and after performance, (Daschombe et al., 2011). It is therefore essential to measure the force exerted from the garment, particularly when assessing its physiological effects,(Sakadian, 2015). Bespoke individualised compression garments are not commonly used and some findings on compression stem from the use of standardise fitting (MacRae et al., 2012; Ali et al., 2010; Bieuzen et al., 2014; Book et al., 2016;

Chan et al., 2016; Dascombe et al., 2011; Kerherve et al., 2017). In some cases, compression of the garment was not assessed (Rennerfelt et al., 2019; Sperlich et al., 2010; Vercruyssen et al 2014). Garments are therefore recommended to be bespoke and suited to the body composition of the subject to allow the full effectiveness of the garment as most garments will lose the initial tension on the fabric subsequently affecting the potential influence of the garment (Troynikov et al., 2010).

Studies conclude variables such as compression pressure, different anatomical landmark pressure, level of intensity and adipose tissue thickness are factors that will impact successful NIRS data (Van Beekvelt, 2002; McCully and Hamaoka, 2011; Brophy- Williams et al., 2013; Hill et al., 2017). To our knowledge there is minimal research to date that has assessed the relationship in oxygenation and deoxygenation across two muscles with compression tights and socks whilst undertaken activities that resemble recovery. Therefore the aim of the present study was to provide a greater understanding into assessing the effects on muscle oxygenation, muscle deoxygenation through the application of compression socks and tights.

5.2. Methodology

5.2.1. Participants

16 healthy, active males, (23.5±2.9 years , body mass 85.1±10.4 kg) completed 3 experimental trials across a 28- day period. Ethics was approved by the Ethics Committee at Nottingham Trent University. Temperature and humidity were recorded prior to each trial (19.2 ± 2.76 °C, 41.9 ± 11.9 %). Subjects undertook a range of sports varying from individual and team sports, to which most trained 3 times a week. Participants were briefed and completed written consent and health declaration forms. Participants were also asked to refrain from strenuous exercise 24 hours before

each trial. Participants were instructed to write a food diary 24 hours prior to testing to which they would replicate.

5.2.2. Experimental Protocol

In order to minimise the training and detraining effect, three experimental trials (one compression tights, one compression socks and one control) were completed within a 28 day period. The experimental protocol was designed to replicate activities that might be used during recovery. Each protocol compromised of 20 minutes of supine, sitting, walking, jogging and sitting. For the jogging aspect, each participant selected a speed (7.0 ± 0.89 km$^{.-1}$), they would complete a recovery jog at, and this was replicated for the remaining trials. Prior to any main trials a familiarisation session was completed where participants were measured for custom made garments and participants were accustomed with all the equipment used and measurements being made (NIRS, pressure measures, skin fold measurements). Under each condition the participant was asked to remain quiet and robotic throughout to allow consistent NIRS measurements.

5.2.3. Near-infrared Spectroscopy measurements

Muscle oxygenation responses were observed using a Near Infrared Spectroscopy (Portalite, Artinis Medical Systems BV, Elst, The Netherlands). NIRS was used to observe measurements in oxyhaemoglobin [HbO_2], de-oxyhaemoglobin [HHb], Tissue Saturation Index TSI = [O2Hb]/([O2Hb]+[HHb])*100%. Recent research has observed “sufficient reliability” in using NIRS with compression garments applied (Biddulph et al., 2023).The device has three optodes and data is continuously ran live through a bluetooth connection and instantly uploaded to the devices software (Oxysoft software, Portalite, Artinis, Medical Systems BV, Elst, The Netherlands). Each device was attached to the muscle belly of the vastus lateralis and the maximal calf girth and monitored muscle oxygenation at 10Hz (Lucero et al 2017). The vastus lateralis muscle belly was located at 15cm proximal to the patella head and 4cm lateral. The probe was then carefully placed with double sided tape onto the muscle belly. The Near Infrared Spectroscopy was attached prior to testing and prior to the participant starting the trial. The participant was asked to sit for 5 minutes so that baseline values could be observed. A bandage was administered around the device to reduce day light this was applied on the quadricep muscle, in the compression sock and control trial (Barstow, 2019).

Data analysis was expressed in arbitrary units, micromoles ($\Delta\mu M$) in concentration changes in oxyhaemoglobin [HbO_2] and de-oxyhaemoglobin [HHb]. Concentration (μmol) changes were calculated from each trials baseline. Tissue saturation index (TSI) is represented in percentage format. The differential path factor (DPF) value was selected at 4.95 and waves were set at 760 and 850 nm, this is based on the anatomical make up of the Gastrocnemius and Vastus Lateralis (Balaban et al 1996; Duncan et al., 1995; Keramidas et al., 2011; Subudhi et al., 2007; Rodriguez et al., 2019; Smith and Billaut 2010; Billaut et al., 2013).

5.2.4. Modified Beer-Lambert Law (Equation 1)

Organic tissues contain scattered material and can become difficult to detect haemoglobin sources (Barstow, 2019). Modified Beer-Lambert law is implemented for the change in light attenuation allowing it to be proportional for the changes in concentration in oxyhaemoglobin and de-oxyhaemoglobin. K represents tissue loss, $\frac{Io}{1}$ represents light in and out, χ is the path length factor. $\in$ is the extinction coefficient, C is the micro-molar concentration, A is the attenuation, and L is the dimension in which solution can be measured (Rolfe, 2000).

Equation 1

$$A = \log\frac{Io}{I} = \varepsilon C\, L\chi + K$$

The differential path factor (DPF) value was selected at 4.95 and waves were set at 760 and 850 nm, this is based on the anatomical make up of the Gastrocnemius and Vastus Lateralis (Balaban et al 1996; Duncan et al., 1995; Keramidas et al., 2011; Subudhi et al., 2007; Rodriguez et al., 2019; Smith and Billaut 2010; Billaut et al., 2013).

5.2.5. Compression Garments

Bespoke compression tights were made based on each individuals body composition. Compression tights were manufactured by Kurio (Kurio Recovery, Kurio 3D Compression, Edwinstowe, Nottingham, England). Compression socks (VR Pro Plus+ Recovery, Vital Active, London, England) were made to measure through individualized measurements of shoe size, heel to knee (cm) maximum calf and ankle girth (cm). Compression measurement readings were observed at the beginning of each trial and after each phase of each trial. Each participant was asked to stand in upright for compression readings to be observed. Compression garments were not washed prior to testing in order to minimise the loss of elastic properties and also for maintenance of accurate fitting.

5.2.6. Adipose Tissue Thickness (ATT) measurements

ATT measurements have been known to affect the signal strength of the NIRS (Barstow, 2019). Skinfold (Harpenden Skinfold Calipers, British Indicators Ltd, Burgess Hill, UK) and girth measurements (mm) were taken around the gastrocnemius and quadriceps to get accurate compression fittings for each participants. Measurements were taken three times at the beginning of each trial to which the mean was then taken. Quadricep girth was taken through establishing the distance between the top of the femur and the patella, half of this distance was then used. Girth (cm) and skin fold (mm) measurements were taken at the maximum aspect of the gastrocnemius medialis, after measurements a marker was placed for the NIRS to be then attached.

Table 5.1. Skinfold and girth measurements at the gastrocnemius and vastus lateralis between trials (mean ± standard deviation).

	Gastrocnemius		**Vastus Lateralis**	
	Skinfold (mm)	Girth (cm)	Skinfold (mm)	Girth (cm)
Control	4.5±1.2,	19.7±2.1	5.6±5.1	28.5± 3.0
Compression Tights	4.6±2.0	20.2± 2.9	6.3±5.2	27.3± 2.8
Compression Socks	4.7 ± 2.6	18.8 ± 1.1	5.5 ± 2.3	53.9 ± 9.9

5.2.7. Compression Measurements

A Kikuhime Pressure Monitor (Kikuhime pressure monitoring device (Medi-Group, Melbourne, Australia) was used to measure compression. Compression readings were obtained before the trial and after the trial . Compression tights measurements were assessed at six specific locations on the opposite limb to which the Near infrared Spectroscopy is placed (Brophy- Williams et al., 2015). The subsequent six locations: 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). Compression socks measurements were taken from 3 specific locations on the lower limb (a-c).

5.2.8. Data Processing

MATLAB (MATLAB and Statistics Toolbox R2017a, The MathWorks, Inc, Natick, Massachusetts, United States) was used to create a Low- Pass Butterworth filter with a cut off frequency 0.2 Hz. Near Infrared Spectroscopy (Oxysoft software, Portalite, Artinis, Medical Systems BV, Elst, The Netherlands), files were reconverted to MATLAB format to which the filter would then be applied to each trial. The cut-off frequency was determined by evaluating a power spectral analysis of data in the frequency domain. A baseline was reset when the signal was the most consistent prior to each trial, this was set at 5 minutes before the start of the first phase. MATLAB then exported each trial to Microsoft Excel (Microsoft Office, v 16.25, Microsoft, Redmond, Washington, USA).Data were analysed every Deci second to which a mean value was calculated for every 60 seconds of each phase of the protocol and then an overall mean was used within all trials.

5.2.9. Physiological and Perceptual Measurements

Rate of perceived exertion (RPE) was recorded every 5 minutes in the walking and jogging phases using the Borg scale (1982). Participants were encouraged to identify a speed that was comfortable and would be replicated in recovery from exercise. This speed was then replicated for all three trials. Blood pressure (Omron M2 Basic Blood Pressure monitor, Omron Corporation, Kyoto, Japan) was recorded at the end of each 20 minute phase. Heart rate (Polar S810i heart rate monitor. Polar Electro Oy, Kempele, Finland) and Pulse oximetry (ANP 100 Finger Pulse Oximeter, Anapulse, Surrey, UK) were recorded every 5 minutes during each phase of the protocol.

5.2.10. Statistical Analyses

All numerical values are identified as mean ± SD. Statistical analysis was performed through the application of SPSS version 24.0 (SPSS Inc., Chicago, IL, USA). A one- way analysis of variance (ANOVA) was used to assess differences (P<0.05) in NIRS parameters (Muscle oxygenation/deoxygenation/ TSI%), within all phases (supine, sitting, walking, jogging, and sitting) of the protocol and for both muscle sites. Any significant differences (P<0.05) observed would then be further analysed with a Bonferroni *post-hoc* test to conclude more specific effects in the trial. GraphPad Prism version 8 (GraphPad Software, La Jolla, California, USA) were used to create graphs. Effect size (Cohen's *d*) was used on all significant differences using trial pairings and assessed using the following thresholds: <0.2 = trivial effect - <0.5 = small effect; 0.5- 0.8 = moderate effect and >0.8 = large effect (Cohen, 1992).

5.3 Results

Sixteen participants completed the three trials across a 28-day period. Units of measurement for muscle oxygenation and deoxygenation were represented in 100% change in the base line.

5.3.1. Tissue Saturation

The gastrocnemius (**Table 3**) detected no differences between trials within the laying supine, sitting, jogging, and sitting post jogging phase of the protocol (all P>0.05). The walking phase of the protocol observed a reduction (trial effect P=0.04) in tissue saturation at the gastrocnemius with the use of compression (socks: 70.9±5.3%, d=0.61, moderate effect; tights: 72.2±6.7%, d=0.35, small effect) in comparison to the control trial (74.6±6.8%).

During the walking (trial effect P=0.03) (**Table 4**), tissue saturation in the vastus lateralis reduced using compression socks (74.7±6 %; d =0.08, trivial effect) and tights (72.7±4.3 %; d=0.44, small effect) in comparison to the control (75.2±6.8%) trial. No trial effect was observed during the laying supine and both sitting trials in tissue saturation at the vastus lateralis (all P>0.05).

5.3.2. Oxyhaemoglobin responses from the baseline (ΔμM)

There were no differences in oxyhaemoglobin responses at the gastrocnemius across the control, compression socks and tights trials (all P>0.05). Mean values (**Table 5.5**) using compression socks (1.2±7.7 ΔμM) and tights (1.1±8.7 ΔμM) were higher in oxyhaemoglobin responses from the baseline in the control (-2.9±13.3 ΔμM) trial at the gastrocnemius (P=0.36). In the vastus lateralis there was a difference (trial effect P=0.04) in the laying supine phase between the control trial (-1.1±5.1 ΔμM) and in comparison, to the use of compression socks (-3.4±6.3 ΔμM; d =0.40, small effect) and compression tights (3.2±10.5 ΔμM; d = 0.45, small effect). No trial effect was detected between sitting, walking, jogging and the seating phase after the jog in the vastus lateralis across all trials (All P>0.05). A moderate effect was observed between (d=0.55) between compression tights (4.4±8.8 ΔμM) and the control (–0.4±8.5 ΔμM) trial (P=0.44).

5.3.3. Deoxyhaemoglobin responses from the baseline (ΔμM)

There were no differences in the gastrocnemius detected between trials during the laying supine, sitting, walking, jogging, and seating phase post jog (All P>0.05). In the vastus lateralis, compression tights (0.75±5.3 ΔμM) increased deoxyhaemoglobin responses in the sitting (trial effect P=0.03), in comparison to the control (sitting: -1.2±2.5 ΔμM: d=0.47, moderate effect) and compression socks (sitting: -3.2 ± 4.4, d = 0.81, large effect) trials.

5.3.4. Compression

Higher compression readings were observed using compression socks (**Table 2**). The highest-pressure landmark was affiliated at the gastrocnemius within the use of compression socks (20.7 ± 6.3 mmHg)

Table 5.2 Compression profile (mmHg) in compression tights and socks (mean ± standard deviation).

Landmark	Compression Tights (mmHg)	Compression Socks (mmHg)
A	11.1± 5.9	21.5±8.8
B	10.3 ± 6.7	18.4±6.1
C	12.1 ± 5.3	20.7±6.3
D	7.5±2.8	
E	7.4±2.1	
F	7.1±2.1	

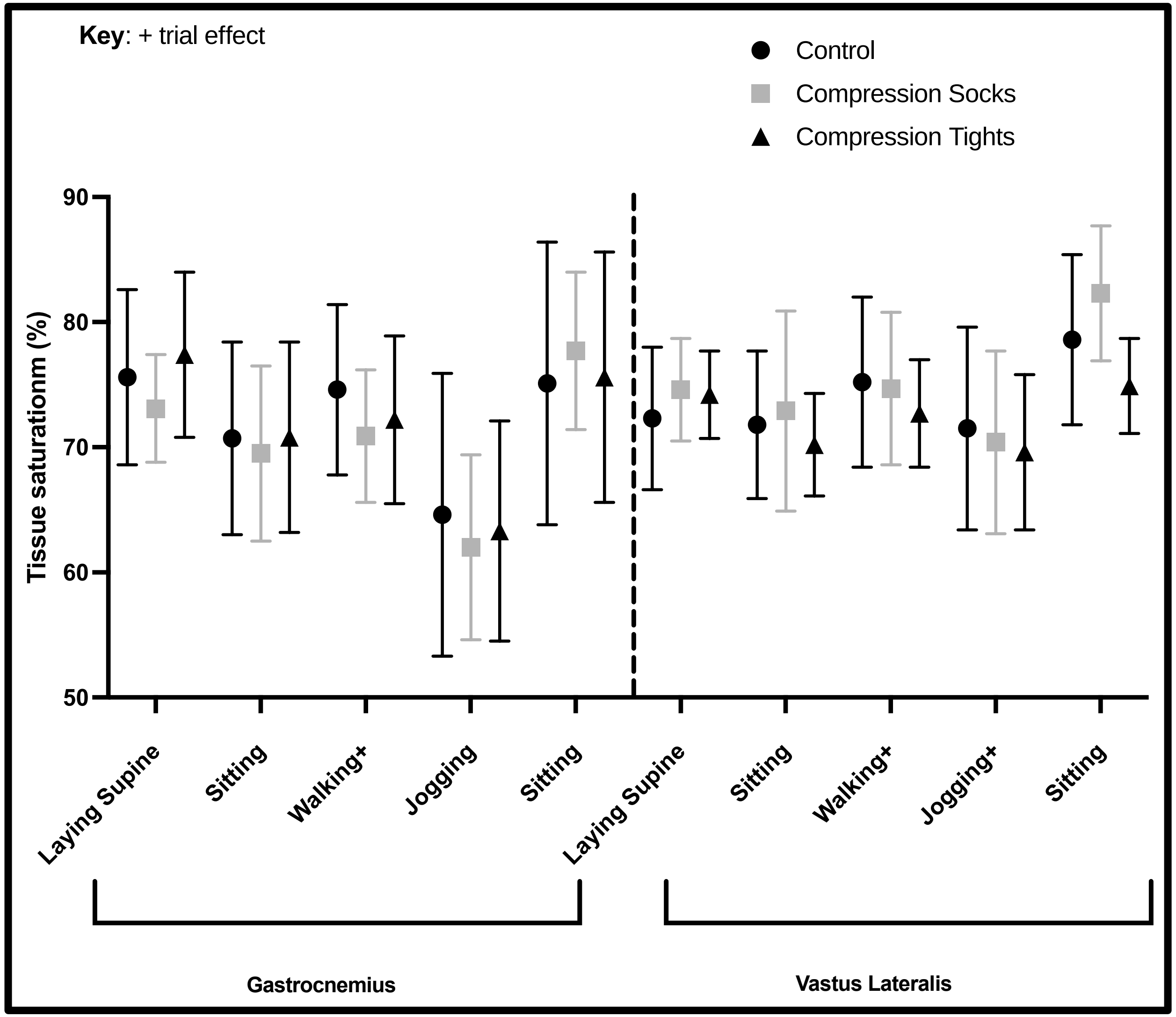


Figure 5.1: Tissue saturation (%) responses in the gastrocnemius and vastus lateralis

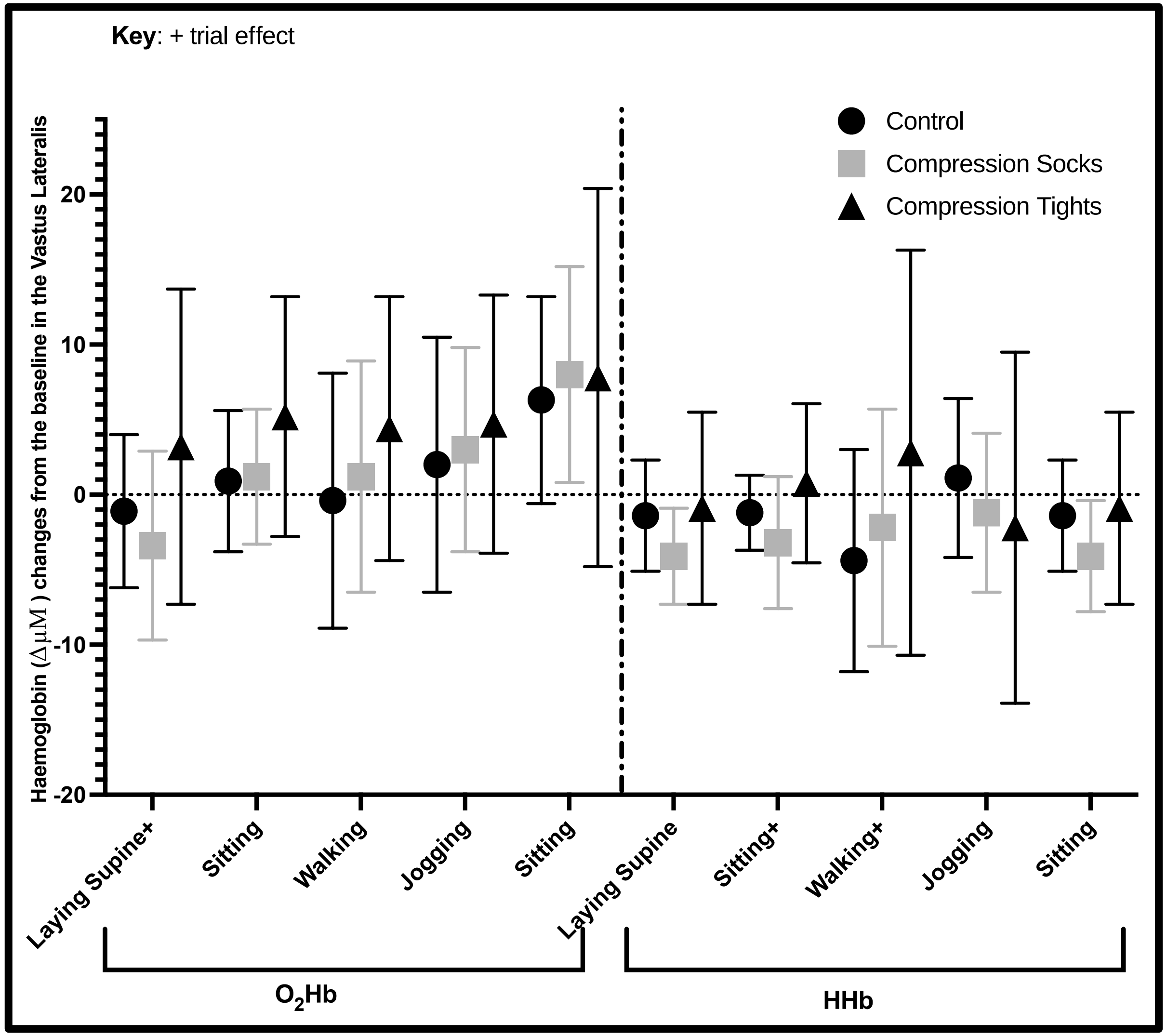


Figure 5.2. Oxyhaemoglobin and Deoxyhaemoglobin (ΔμM) responses in the vastus lateralis

Table 5.3. Tissue Saturation (%) within the gastrocnemius (^trivial effect from control, *small effect from control, **moderate effect from control, ~ small effect from socks, +moderate effect from socks, #large effect from socks)

	Control	Compression Socks	Compression Tights	One-Way ANOVA	
Laying Supine	75.6 ± 7.0	73.1 ± 3.2	77.4 ± 6.6	0.21	
Sitting	70.7 ± 7.7	69.5 ± 7.0	70.8 ± 7.6	0.79	
Walking	74.6 ± 6.8	70.9 ± 5.3*	72.2 ± 6.7	**0.04**	***C, CS***, d = 0.61: ***C, CT*** , d = 0.36: ***CS, CT***, d = 0.22
Jogging	64.6 ± 11.3	62.0 ± 7.4	63.3 ± 8.8	0.49	
Sitting	75.1 ± 11.3	77.7 ± 6.3	75.6 ± 10.0	0.65	

Table 5.4. Tissue Saturation (%) within the Vastus Lateralis) (^trivial effect from control, *small effect from control, **moderate effect from control, ~ small effect from socks, +moderate effect from socks, #large effect from socks)

	Control	**Compression Socks**	**Compression Tights**	**One-Way ANOVA**	**Cohens D**
Laying Supine	72.3 ± 5.7	74.6 ± 4.1	74.2 ± 3.5	0.55	
Sitting	71.8 ± 5.9	72.9 ± 8.0	70.2 ± 4.1	0.13	
Walking	75.2 ± 6.8	74.7 ± 6.1^	72.7 ± 4.3*~	**0.03**	***C, CS***, d = 0.08: ***C, CT*** , d = 0.44: ***CS, CT***, d = 0.38
Jogging	71.5 ± 8.1	70.2 ± 7.6	69.6 ± 6.2	0.29	
Sitting	78.6 ± 6.8	82.3 ± 5.4	74.9 ± 3.8	0.46	

Table 5.5. Oxyhaemoglobin concentration changes from the baseline (ΔμM) in the gastrocnemius

	Control	**Compression Socks**	**Compression Tights**	**One-Way ANOVA**
Laying Supine	-2.9 ± 13.3	1.2 ± 7.7	1.1 ± 8.7	0.30
Sitting	10.7 ± 8.7	13.3 ± 10.7	12.7 ± 9.7	0.74
Walking	5.2 ± 4.6	4.6 ± 12.2	5.1 ± 8.4	0.98
Jogging	1.1 ± 10.2	-1.2 ± 20.9	3.8 ± 8.5	0.70
Sitting	25.0 ±12.3	24.9 ± 12.0	16.9 ± 10.2	0.15

Table 5.6. Oxyhaemoglobin concentration changes from the baseline (ΔμM) in the vastus lateralis (*small effect from control, **moderate effect from control, +moderate effect from socks, #large effect from socks)

	Control	Compression Socks	Compression Tights	One-Way ANOVA	Cohens D
Laying Supine	-1.1 ± 5.1	-3.4 ± 6.3*	3.2 ± 10.5**+	**0.04**	***C, CS***, d= 0.40: ***C, CT***, d = 0.52: ***CS, CT***, d = 0.76
Sitting	0.9 ± 4.7	1.2 ± 4.5	5.2 ± 8.0	0.23	
Walking	-0.4 ± 8.5	1.2 ± 7.7	4.4 ± 8.8	0.44	
Jogging	2.0 ± 8.5	3.0 ± 6.8	4.7 ± 8.6	0.74	
Sitting	6.3 ± 6.9	8.0 ± 7.2	7.8 ± 12.6	0.89	

Table 5.7. Deoxyhaemoglobin concentration changes from the baseline (ΔμM) in the gastrocnemius(*small effect from control, **moderate effect from control, +moderate effect from socks, #large effect from socks)

	Control	**Compression Socks**	**Compression Tights**	**One-Way ANOVA**	**Cohens D**
Laying Supine	-10.4 ± 6.7	-6.7 ± 8.5	-5.7 ± 10.0	0.23	
Sitting	-0.7 ± 4.6	-0.1 ± 10.9	6.7 ± 14.1	0.07	
Walking	-4.4 ± 7.4	-2.2 ± 7.9*	2.8 ± 13.5**	**0.03**	***CC, CS,*** d = 0.29: ***CT, C,*** d =0.66: ***CS***, ***CT***, d = 0.45
Jogging	5.3 ± 7.2	6.9 ± 9.2	2.3 ± 12.6	0.43	
Sitting	-3.8 ± 5.6	-1.8 ± 10.2	2.0 ± 14.1	0.40	

Table 5.8. Deoxyhaemoglobin concentration changes from the baseline (ΔμM) within the vastus lateralis (*small effect from control, **moderate effect from control, +moderate effect from socks, #large effect from socks).

	Control	**Compression Socks**	**Compression Tights**	**One-Way ANOVA**	**Cohens D**
Laying Supine	-1.4 ± 3.7	-4.1 ± 3.2	-0.90 ± 6.4	0.22	
Sitting	-1.2 ± 2.5	-3.2 ± 4.4**	0.75 ± 5.3*#	**0.03**	***CT, C***, d = 0.47: ***C***, ***CS***, d =0.56: ***CT***, ***CS***, d= 0.81
Walking	-1.4 ± 3.2	-5.6 ± 3.8	-1.0 ± 6.5	0.08	
Jogging	1.1 ± 5.3	-1.2 ± 5.3	-2.2 ± 11.7	0.61	
Sitting	-1.4 ± 3.7	-4.1 ± 3.7	-0.90 ± 6.4	0.25	

5.3.5. Rate of perceived exertion

Rate of perceived exertion was lower within the use of compression tights (6.0 ± 0.2) in comparison to the control (6.4 ± 0.51) and compression socks (6.1 ± 0.3) trial (trial effect P=0.03). No significant differences were observed within the jogging phase of the protocol between trials (P=0.25).

5.3.6. Blood Pressure, Heart Rate and Pulse Oximetry

A difference (trial effect *P*=0.02) was observed in the walking phase, where compression socks (132.0 ± 10.7 mmHg) and tights (132.7 ± 13.1 mmHg) demonstrated higher systolic pressure in comparison to the control trial (122.7 ± 17.6 mmHg). There were no other differences observed between trials within systolic and diastolic blood pressure (All *P*>0.05). Heart rate (**Table 5.10**) and pulse oximetry (**Table 5.11**) were similar between trials across the protocol (All *P*>0.05).

Table 5.8. Systolic blood pressure values (mmHg) across all trials

	Control	Compression Socks	Compression Tights	One-Way ANOVA
Supine	123 ± 11.8	124 ± 15.9	126 ± 13.2	0.69
Siting	120 ± 10.2	131.5 ± 16.1	117.9 ± 15.9	**0.09**
Walking	122.7 ± 17.6	132.0 ± 10.7	132.7 ± 13.1	**0.02**
Jogging	126 ± 12.6	134 ± 13.5	139 ± 8.7	0.20
Sitting	120.5 ± 11.5	133.5 ± 19.7	122.5 ± 16	0.35

Table 5.9. Diastolic blood pressure values (mmHg) across all trials

	Control	Compression Socks	Compression Tights	One-Way ANOVA
Supine	68.4 ± 8.2	73.5 ± 14.7	74.7 ± 11.7	0.36
Siting	76.0 ± 12.0	82.4 ± 20.9	75.5 ± 7.6	0.59
Walking	77.0 ± 9.6	81.1 ± 11.6	75.9 ± 10.1	0.39
Jogging	83.5 ± 11.0	90.1 ± 18.0	86.5 ± 17.5	0.70
Sitting	76.8 ± 16	79.4 ± 12.9	74.5 ± 8.9	0.68

Table 5.10. Heart rate (beats·min^{-1}) values across all trials

	Control	Compression Socks	Compression Tights	One-Way ANOVA (Trial)	Time	Interaction (Trial by time)
Supine	64 ± 4	63 ± 2	63 ± 4	0.950	0.43	**0.04**
Siting	67 ± 4	67 ± 3	65 ± 4	0.60	0.46	0.16
Walking	82 ± 3	86 ± 5	80 ± 4	0.14	0.96	0.58
Jogging	129 ± 4	124 ± 6	131 ± 6	0.51	**0.01**	0.62
Sitting	77 ± 5	80 ± 4	72 ± 4	**0.03**	**0.01**	**0.03**

Table 5.11. Pulse Oximetry (%) in values across all trials.

	Control	Compression Socks	Compression Tights	One-Way ANOVA (Trial)	Time	Interaction (Trial by time)
Supine	97.7 ± 0.3	97.7 ± 0.29	97.4 ± 0.3	0.64	0.32	0.31
Siting	97.4 ± 0.5	97.7 ± 0.24	97.4 ± 0.34	0.85	0.26	0.59
Walking	96.8 ± 0.4	95.8 ± 1.6	97.0 ± 0.66	0.72	0.33	0.44
Jogging	96.8 ± 0.4	97.0 ± 0.25	97.5 ± 0.3	0.37	0.48	0.35
Sitting	95.5 ± 2.0	97.4 ± 0.2	98.0 ± 0.1	0.32	0.54	0.47

5.4 Discussion

The objective of the current study was to assess the effects of compression tights and socks on muscle oxygenation responses during exercise and recovery-based activities. Key findings from the study demonstrated a reduction in tissue saturation using compression tights in both gastrocnemius and vastus lateralis during the walking phase of the protocol. Further findings detected that compression tights increased oxyhaemoglobin in the vastus lateralis during the laying supine and further increases in deoxyhaemoglobin were observed in the vastus lateralis during the sitting and walking phases of the protocol. The compression profile (**Table 5.2**) of the present study provided pressures of less than 15mmHg across all landmarks with the application of compression tights. Compression pressures of >30mmHg have commonly been associated with greater changes within physiological mechanisms (Lee et al., 2020; Sperlich et al., 2011). Even though the compression profile of the present study did not quantify higher pressures, there was still some evidence to suggest bespoke compression tights do influence oxyhaemoglobin and deoxyhaemoglobin responses in exercise and recovery-based activities.

Tissue saturation is of key interest towards sports science practitioners as it provides information surrounding the level of oxygen that is being utilised within the muscle, a decrease in saturation has suggested that more oxygen is being consumed (Babior and Stussel, 1994). Research has indicated that applying compression will provide an increase in tissue saturation, this is due to a greater level of pressure being exerted onto local vessels creating a dilated response enabling more oxygen to be used (Bringard et al., 2006; Menetrier et al., 2014; Dermont et al., 2015; Sear et al., 2010). Dermont et al. (2015) observed an increase of 22.6% tissue saturation when compression increased from 16.5 mmHg to 36.5 mmHg within resting conditions. Through using a whole body compression garment, tissue saturation at the vastus lateralis has shown to increase across 45 minutes of high intense intermittent exercise (Sear et al., 2010). Sear et al. (2010) detected that through the control trial (53.5 ± 8.3%), tissue saturation was reduced in using the whole body garment (55.8 ± 7.2%), interestingly, no differences were observed in tissue haemoglobin between the control (1.11 ± 0.99 AU) and the whole body compression garment (1.10 ± 0.09 AU). In contrast, the present study observed a reduction in tissue saturation and increases in HHb in using compression tights during walking, in both the gastrocnemius and the vastus lateralis. Research has indicated that oxygenation responses can differ within different muscle groups (Rennerfelt et al., 2019). It has also been suggested that a reduction in tissue saturation is a known cardiovascular response in order to support metabolic oxygen demands within exercise activity (Rodriguez et al., 2019). The reduction in tissue saturation and increase in HHb in the present study can be associated to the transition in exercise activity from the seating to the walking phase, suggesting that more oxygen is being utilized in order to match the demands of the activity. An increase in ATP production can change quickly especially when metabolic rate rises from resting conditions to exercise (Hargreaves and Spriet, 2020). Even though there was no trial effect observed, oxyhaemoglobin responses in the vastus lateralis increased using compression tights (4.4 ± 8.8 ΔμM) in comparison to the control trial (-0.4 ± 8.5 ΔμM), subsequently this could suggest that oxygen is being consumed at a quicker rate thus reducing tissue saturation in the muscle. Research has shown that muscle oxygen uptake and energy turnover is higher when there is more contractile engagement within the muscle (Ferguson et al., 2001). Dynamic exercises such as walking and jogging have also provided similar findings in showing a decrease in tissue saturation within the muscle especially when exercise intensity increases suggesting that oxygen is consumed at a quicker rate (Rennerfelt et al., 2019 ; Born et al., 2014). Systolic blood pressure values were also higher in the walking phase and heart rate was reduced in the sitting trial post jog, to suggest some cardiac influences through the use of bespoke compression tights ($P<0.05$). A reduction in heart rate and an increase in mean arterial pressure have been observed using graduated compression garments, the influence of compression provides an improvement in venous return allowing an increase in cardiac output to occur (Lee at al., 2020). In the vastus lateralis, oxyhaemoglobin concentration changes were greater through wearing compression tights (3.2 ± 10.5 ΔμM) in the laying supine phase in comparison to the compression socks trial (-3.4 ± 6.3 ΔμM). Similar findings have shown greater responses in oxyhaemoglobin in the vastus lateralis whilst using compression tights in comparison to compression socks during supine conditions (Riordan et al., 2021). Even though Riordan et al., (2021) displayed higher compression readings in the upper extremity of the limb in the compression tights (12.2 to 13.6 mmHg) in comparison to the present study (7.1 to 7.5 mmHg), there was still enough pressure on the muscle to enforce a physiological response. The physiological mechanisms in covering the whole leg with compression enables more pressure on superficial veins to have an influence in improving venous return (Riordan et al., 2021; Benko et al., 1999). Bringard et al. (2006) has also shown that oxyhaemoglobin responses in the gastrocnemius can increase through laying supine using compression tights, even though the present study observed minimal changes in oxyhaemoglobin, this can be put down to smaller levels of compression exerted at the gastrocnemius.

The present study demonstrated using compression tights increased deoxyhaemoglobin responses in the vastus laterals during sitting. In contrast, an increase in compression has shown a reduction in deoxyhaemoglobin responses in 5 minutes with participants who had venous insufficiencies (Agu et al., 2004). Agu et al. (2004) observed applying a higher grade of compression in compression stockings would reduce deoxyhaemoglobin responses in sitting from 8.49±3.24 μmol/L to 6.89±3.16 μmol/L in the gastrocnemius, in comparison the present study observed an increase of 2.8±13.5 ΔμM in using compression tights, with the control trial (-4.4±7.4 ΔμM) observing a reduction in responses ($P<0.05$). Interestingly the compression at the gastrocnemius in Agu et al. (2004) study ranged from 11.2 to 14.02 mmHg, in contrast the present study observed higher levels of compression at the gastrocnemius (20.7±6.3 mmHg) through compression socks and detected no change in deoxyhaemoglobin responses (All $P>0.05$). Supporting evidence has demonstrated that sitting conditions of 3 hours did not change deoxyhaemoglobin responses using compression stockings (47.2±11.2 µM), oxygenation was assessed in the gastrocnemius and observed minimal changes from the baseline (45.6±12.1 µM) (Kinoshita et al., 2019).

5.5 Conclusion and Practical Implications

Compression garments have a clear influence in improving the use of oxygen within the gastrocnemius and vastus lateralis. It is clear that compression garments can influence the recovery process. Future studies would benefit from applying robust exercise/recovery protocols in order to assess oxygenation responses through the use of bespoke compression garments. The material of the garment and the strength of the material is another consideration in maintaining compression profile and the possible implications in altering haemodynamics. Further exploration on different levels/types of compression garment on oxygenation responses can also determine a better understanding for their application within the sporting domain. The practical implications to the study observe that low bespoke compression profiles can still influence oxygenation responses. A lower compression profile may be more practical for athletes who will wear them for prolong periods, subsequently a lower compression profile will help with perceived comfort levels.

Chapter 6. Effects of bespoke compression profiles on perceptual responses to wearing compression.

6.1. Introduction

The aim of the current chapter was to explore perceptual responses to bespoke compression profiles. The comfort of the individual is a key factor when assessing compression, especially if athletes have to wear the compression tights for prolonged periods post performance. Graduated designs are the most common form of compression profile that has been assessed in the research (Faulkener et al., 2013; Rugg and Sternlicht, 2013; Ali et al., 2011). Graduated designs originally stemmed from the medical setting where the design was suited to improve blood flow post recovery from surgery. The underlying principles of a graduated design began to be applied into sporting settings, where sports scientists were looking at ways to optimise recovery or even performance.

Research has seen that humidity and temperature are a factor in comfort, subsequently higher temperatures can result in less comfort for an individual (Cheng et al., 2022), this can be put down to potential skin irritation that is caused by heat and increased friction between skin and garment material. Lower levels (12-15 mmHg) of graduated compression have been associated with greater levels of comfort, in comparison to medium (18 – 21 mmHg) and higher (23- 32 mmHg) grades of compression during running performance (Ali et al., 2011). Alternatively, similar levels of compression in tights (13.5±2.5 mmHg) and sleeves (20.7±1.5 mmHg) have shown no differences in perceived comfort at the gastrocnemius when participants performed a 400-meter-high intensity sprint (Faulkener et al., 2013). Familiarisation in wearing compression garments is something that can be considered, Reich-Schupke et al. (2013) observed that participants would get used to wearing compression after 6 weeks post-surgery, subsequently suggesting that the level of compression did not influence overall comfort. The aim of the present study is to assess the comfort of bespoke compression tights. Specifically, graduated compression, uniform compression, reverse graduated compression and a control garment.

6.2. Methodology

6.2.1. Participants

Ten, healthy active males (age 28.4±3.6 years and body mass 81.3±11.2 kg; mean ± SD) completed 4 randomised trials. Ethical permission was granted by Nottingham Trent University.

6.2.2. Experimental Protocol

Participants would complete three stationary positions in the protocol. Participants laid in the decubitus position, at an angle of 75 degrees head up tilt and then stood for approximately 20 minutes each.

6.2.3. Compression Profile

Compression was assessed at the posterior aspect of the leg in 10 landmarks (Ashby et al. 2021). At approximate 5cm increments on the lower and upper extremity were assessed across the posterior aspect of the lower limb were calculated with the last landmark associated at the gluteal fold. Compression was assessed using a Pico Press (Microlab Electronica, Padua, Italy) and was applied at the beginning of each trial. Compression profiles were affiliated against UK classification of pressures. Compression pressures were aimed at exerting different pressures at different locations at the limb, pressure profiles can be associated in **Table 6.1**. Compression profiles were affiliated against UK classification of pressures. Classification 1 (14-17 mmHg); Classification 2 (18-24 mmHg); and Classification 3 (25-35 mmHg). Each garment type was assessed for the correct compression profile prior to testing procedures. All participants were scanned using a Artec Eva 3D scanner (Artec Group, Luxembourg, Luxembourg). Lower body scans were generated with participants standing stationary in the anatomical position. Scans were processed at Kurio

Compression LTD. Bespoke garments were then made with varied compression parameters set for different garments (uniform, graduated, reverse graduated and control).

6.2.4. Perceptual Responses

An adopted 15 cm visual analogue scale was used to assess comfort in all compression types used (Lucas-Cuevas et al., 2017). Comfort points range from 0-15 cm. Participants were asked to identify general comfort, ankle fitting, knee fitting and compression with a scale ranging from "not comfortable at all' to "most comfortable condition imaginable" (Mundermann et al., 2002; Lucas-Cuevas et al., 2017). Participants were asked to complete each visual analogue scale between phases of the protocol.

6.2.5. Statistical Analyses

All numerical values are identified as mean ± SD. Statistical analysis was performed through the application of SPSS version 24.0 (SPSS Inc., Chicago, IL, USA). A one- way analysis of variance (ANOVA) was used to assess differences (P<0.05) in all phases of the protocol. Any significant differences (P<0.05) observed would then be further analysed with a Bonferroni *post-hoc* test. GraphPad Prism version 8 (GraphPad Software, La Jolla, California, USA) was used to create graphs.

Table 6.1. Compression profile observed in all garments (mmHg)

Landmark	Graduated Compression Garment (mmHg)	Control Garment (mmHg)	Reverse Graduated Garment (mmHg)	Uniform Compression Garment (mmHg)
1 (Ankle)	19.5 ± 5.3	8.7 ± 2.7	8.8 ± 3.9	10.8 ± 3.9
2	19.0 ± 5.2	8.2 ± 2.4	10.5 ± 3.0	12.1 ± 2.6
3	15.6 ± 3.9	9.7 ± 3.2	12.5 ± 2.8	12.4 ± 4.9
4	18.2 ± 2.1	10.3 ± 2.7	13.7 ± 3.3	14.3 ± 2.1
5	14.9 ± 2.8	7.6 ± 3.1	14.0 ± 3.2	12.1 ± 2.6
6	10.7 ± 4.1	6.9 ± 2.2	16.6 ± 5.3	11.3 ± 4.2
7	10.4 ± 3.5	7.4 ± 2.3	16.9 ± 4.7	12.2 ± 4.2
8	8.6 ± 3.2	6.6 ± 1.8	17.6 ± 5.9	12 ± 3.4
9	7.4 ± 2.3	5.2 ± 2.8	16.5 ± 8.1	10.4 ± 2.1
10 (Gluteal Fold)	6.0 ± 1.6	5.3 ± 2.1	12.2 ± 5.6	9.0 ± 1.6

6.3 Results

6.3.1 General Comfort

In *general comfort*, the graduated compression garment (11.6±1.7 cm) was the most comfortable during the decubitus position, however this was only different against reverse graduated compression garment (trial effect, P= 0.01, *post hoc*, P=0.01, *d*=0.71, moderate effect). The control garment (11.0±4.0 cm) was the most comfortable during the tilt position against the reverse graduated compression garment (trial effect, P=0.01, *post hoc*, P=0.01, *d*=0.55, moderate effect).

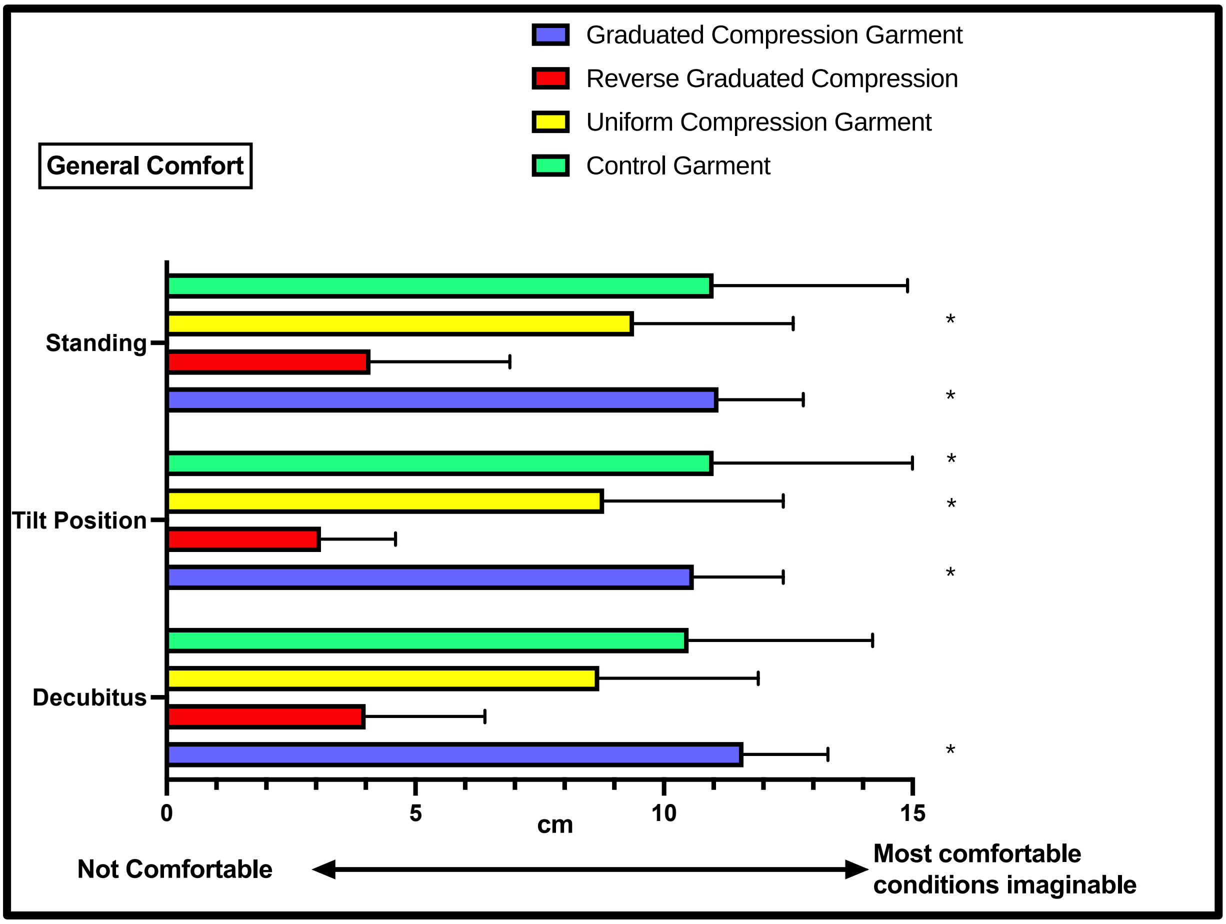


Figure 6.1 Mean ± standard deviation responses for "*general comfort*" in all garments (trial effect, P=0.01, * post hoc P<0.05 from reverse garment)

The reverse graduated compression garment (4.1±2.8 cm) was lower in comfortable rating in comparison to the uniform compression (9.4±3.2 cm; trial effect, P=0.01, *d*=0.52, moderate effect, trial effect, P=0.01) and the graduated compression garment (11.1±1.7 cm) in the standing phase (trial effect, P=0.01, trial effect, P=0.01, *d*=0.64, moderate effect). The lowest rating for general comfort was observed during the tilt phase was through the application of the reverse graduated compression garment (3.1±1.5 cm) trial.

6.3.2. Ankle Fitting

There were no differences in ankle fitting observed between the compression garments during the tilt position and the standing phase of the protocol (P>0.05). In the decubitus position, the Reverse Graduated Compression Garment (4.1±2.8 cm) was the least comfortable in comparison to the Uniform Compression Garment (10.4±2.6 cm, *d*=0.56, moderate effect), Graduated Compression Garment (9.8±2.4 cm, *d*=0.56, moderate effect) and the Control Garment (11.6±3.6 cm, *d*=0.56, moderate effect), trial effect, P=0.01, post hoc, All, P=0.01.

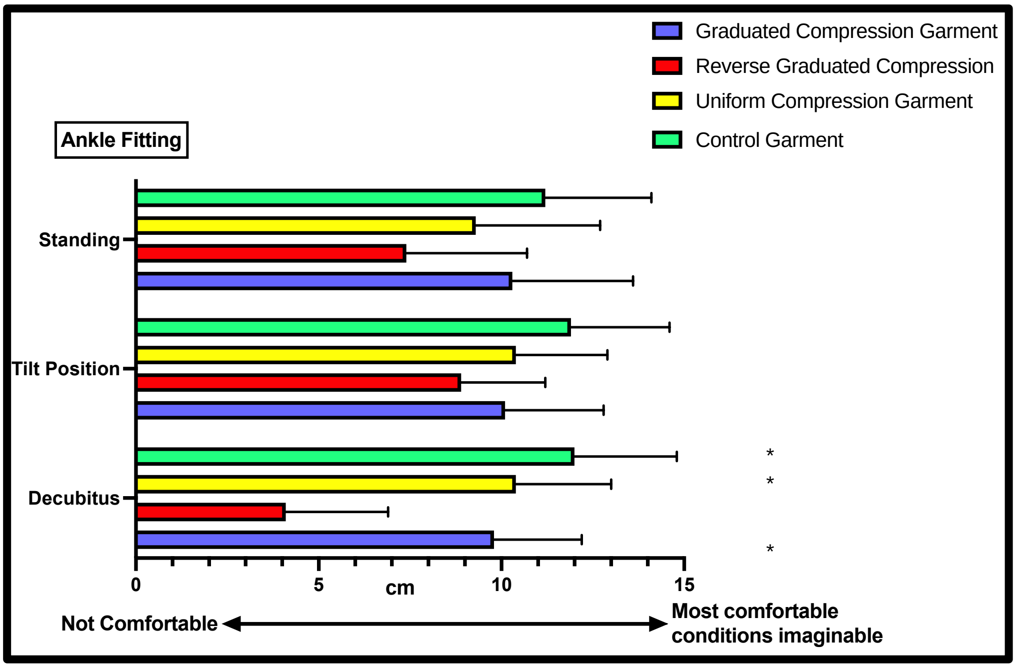


Figure 6.2 Mean ± standard deviation responses for "*ankle fitting*" in all garments (trial effect, P=0.01, * post hoc P<0.05 from reverse garment).

6.3.3. Knee Fitting

The least comfortable garment in the standing phase was the reverse graduated garment (5.3±2.7 cm), this was lower in comparison to higher comfort values that were observed within the graduated compression garment (10.8±2.4 cm, *d*=0.52, moderate effect), uniform compression garment (9.5±3.5 cm, *d*=0.49, small effect) and the control garment (11.5±2.8 cm, *d*=0.56, moderate effect), trial effect, P=0.01, All, *post hoc*, P=0.01. The reverse graduated garment (5.6±2.2 cm) was the least comfortable in the *tilt position* in comparison to the uniform compression garment (10.3±2.6 cm), trial effect, P=0.01, *post hoc*, P=0.01, *d*=0.54, moderate effect. During the decubitus phase, the reverse graduated compression garment (5.9±1.9 cm) was the least comfortable in comparison to the graduated compression (*d*=0.66, moderate effect) and control garment (*d*=0.55, moderate effect) trial effect, P=0.01, All, *post hoc*, P=0.01.

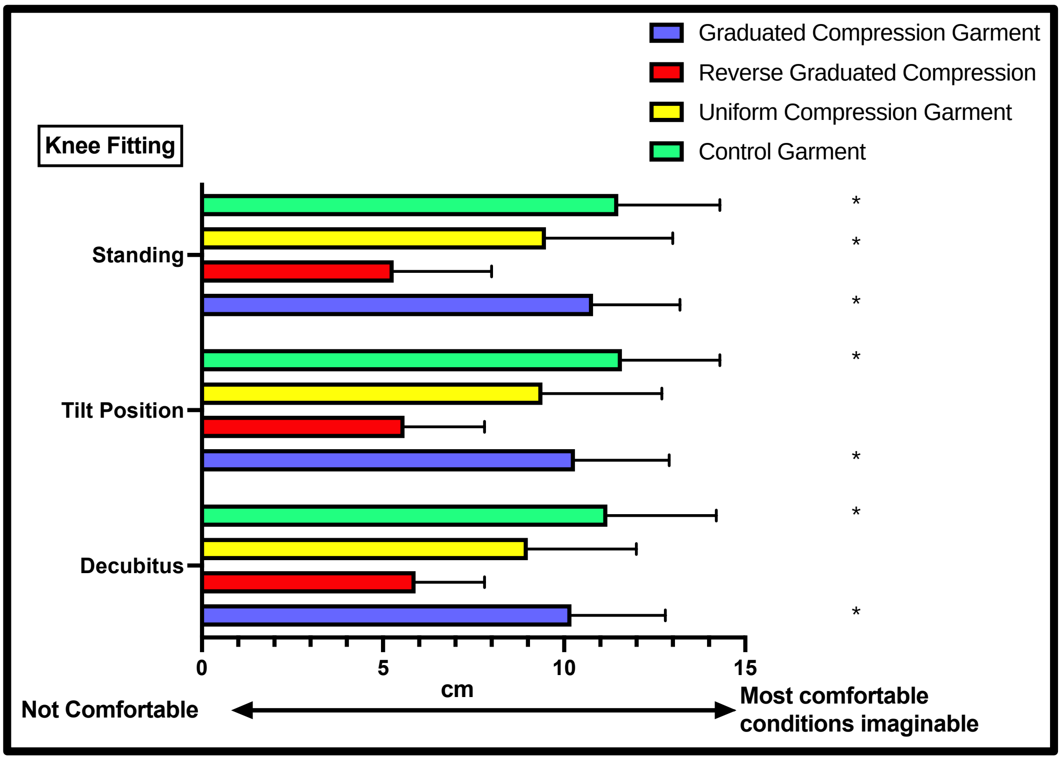


Figure 6.3 Mean ± standard deviation responses for "*knee fitting*" in all garments (trial effect, P=0.01, * post hoc P<0.05 from reverse garment).

6.3.4. Compression

General compression ratings for the reverse graduated compression garment represented the following *decubitus*, 3.9±1.9 cm; *tilt position*, 4.1±1.8 cm, *standing*, 4.2±1.8 cm. The reverse graduated garments was least comfortable in comparison to the other garment trials (trial effect, P=0.01, All *post hoc* P<0.05). The most comfortable during the *standing* phase was the control garment (*decubitus*, 11.6±3.6 cm, *d*=0.60, moderate effect; *tilt position*, 11.3±3.6 cm; d=0.59, moderate effect; *standing*, 11.4±3.7 cm, *d*=0.58, moderate effect), this was rated higher than the reverse graduated compression garment.

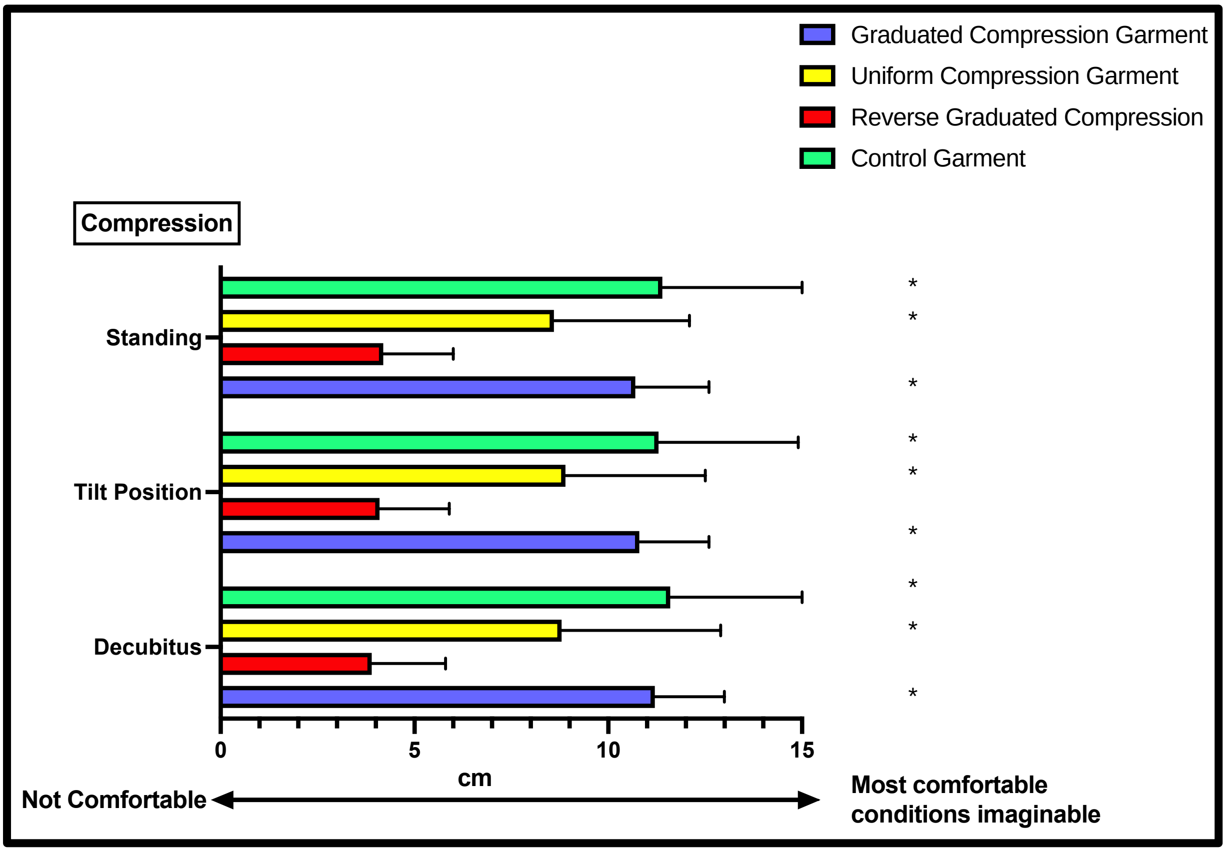


Figure 6.4 Mean ± standard deviation responses for "*compression*" in all garments (trial effect, P=0.01, * post hoc P<0.05 from reverse garment).

6.4. Discussion

The main objective of the current study was to explore perceptual responses to wearing different types of compression profiles. Comfort responses that were explored were on *comfort, ankle fitting, knee fitting and compression*.

The main finding was that the reverse graduated compression garment was the least comfortable. The design of the reverse graduated tights produced higher levels of compression at the upper extremity of the limb and this reduced gradually down the lower extremity of the limb. The reverse graduated profile is a novel design which was new for participants to wear, the lack of familiarity in wearing this garment could provide participants particular discomfort due to unfamiliar higher levels of compression in the upper extremity. As stated, prior, there has been no research that has assessed a reverse graduated profile. The majority of the research has observed that graduated compression profile to be well researched when assessing perceptual responses, however this can be put down to this compression profile being a common design that has been used in performance and recovery settings (Ali et al., 2011; Rugg and Sternlicht, 2013). Familiarity in wearing compression is a key variable as stated by Reich-Schupke et al. (2013) who observed no differences in comfort levels whilst wearing different types of compression profiles after 6 weeks post-surgery. Reich- Schupke et al. (2013) observed that patients reported a reduction in discomfort from compression stockings from week 1 to 6 with compression pressures ranging from 18- 21 mmHg.

Compression design is constantly evolving in an attempt to improve performance and recovery metrics. Uniform compression designs are not novel and have not been heavily research in a physiological, perceptual or performance setting. The design of a uniform profile observes a specific mean value across the limb. Alsopp (2012) observed that uniform profiles can change when the manufacture design adds panels. The comfort of the uniform garment in the present study observed no differences in comparison to the graduated design, suggesting a uniform design to be comfortable.

6.5. Conclusion and Practical Implications

The chapter observed the reverse graduated compression profile to be the least comfortable, with the other designs observing acceptable comfort settings. A longitudinal study design may provide more insight towards comfort levels of the reverse design and this may see participants get used to a different type of profile. The level of compression in the study was below 20mmHg across all garment trials, this would fall in line with other literature who have also stated that participants felt comfortable in wearing garments with similar levels of pressure. Therefore, different levels of graduated compression and uniform garments are all comfortable for athletes to wear. Therefore, determining which type of garment results in the greatest performance or recovery benefit for an individual can be researched, whilst ensuring comfort is maintained.

Athlete comfort is of high value, especially when athletes potentially could be wearing compression garments for prolong periods. The practical implications of the present study observed that when designing new compression garments, there should be consideration for the design of the compression profile.

Chapter 7. Different Types of compression tights and the effects on muscle oxygenation and haemodynamics during standing and head up tilt.

Chapter 7. Different types of compression tights and the effects on muscle oxygenation and haemodynamics during standing and head up tilt.

7.1. Introduction

The aim of the present study was to provide further insight into the effects of different types of compression tights on muscle oxygenation. ***Chapter 5*** observed that a bespoke graduated compression profile reduced tissue saturation and improved deoxyhaemoglobin responses in recovery specific activities such as walking, laying supine and sitting. A limitation to ***Chapter 5*** demonstrated that the pressure exerted by the graduated garment profile was not as high as first reported by some research that observed higher oxygenation responses (Dermont et al., 2015). Therefore, the aim of the current chapter was to manipulate different compression profiles, pressures and observe oxygenation responses during stationary activities.

Sports engineering is evolving, and research is allowing a better understanding of how compression garments may be beneficial in sporting settings. Different types of garments are manufactured in attempt to optimise physiological mechanisms that could influence sporting performance and recovery (Gokarneshan, 2017).

The purpose of compression tights are to improve haemodynamic responses such as increase oxygen utilization and increase oxygen availability. Research examining haemodynamic responses when wearing compression tights is limited and therefore research is needed to understand the physiological mechanisms that occur through controlled settings (Brown et al., 2017). The present study assessed different compression profiles on muscle tissue saturation, O2Hb and HHb responses in resting conditions.

The ability to understand the relationship between O_2Hb and HHb will provide sports scientists with an understanding of how compression can be fully utilised. To date there has been minimal research that assesses different compression profiles and their subsequent influence on muscle oxygenation. Greater levels of compression have been affiliated with higher levels of tissue saturation (Dermont et al., 2015). In contrast, lower levels of compression have shown smaller haemodynamics changes when using compression tights (Lee et al., 2018). Better levels of oxygen utilisation has also been affiliated through the use of compression tights, however designs of garments do not offer consistent production suggesting further clarity in physiological responses are needed to understand better use. Increases in oxyhaemoglobin in skeletal muscle have shown that oxygen utilisation is more effective when using compression tights (Bringard et al., 2006; Daschombe et al., 2011). Improvements of oxygen delivery can improve ATP production and reduce fatigue in a sports performance setting. Interestingly a recent study found that deoxyhaemoglobin and total haemoglobin concentration levels reduced through compression in resistance exercise, yet fatigue was not reduced throughout the protocol (Cotter et al., 2022). A limitation to the study observed that no compression pressures were reported due to manufacturer preferences in remaining anonymous.

Previous research has used manufactured garments and with individuals body shapes differing research is needed that provides consistent pressure across individuals. A compression profile is a specific design that is affiliated with varying pressures across the limb. The most common design of compression profile is the Graduated Compression Tights (GCT), which has compression at its highest in the lower extremity (ankle) and sees compression decrease through the upper extremity of the limb. The physiological explanation for a graduated compression fit is to improve blood flow and improve venous return through a graduated level of compression on the limb (Lawrence and Kakkar, 1980; Hill et al., 2017). Some graduated compression designs have shown minimal influences on haemodynamics responses with no effects on heart rate, oxygen uptake observed during recovery and exercise (Ali et al., 2010).

Uniform (UCT) and Reverse Graduated compression garments (RGT) are a new design of garment where minimal research has explored their overall influences on performance and recovery. Uniform compression garments allow a specific level of compression which is similar across the limb. Reverse graduation design provides a higher level of compression at the hip to and lowest level of compression at the ankle is the opposite compression profile of a graduated compression design (GCT).

Sizing, posture, and activity are key variables that can influence the compression profile (Brophy-Williams et al., 2015; Gokarnsehan, 2017). A key factor that may explain minimal influences of compression is due to standardized fitting. It is clear that bespoke compression garments should be produced for individuals to potentially obtain greater physiological effects (Brophy-Williams et al., 2015). Bespoke compression garments cater to an individual's body composition. Research has indicated that athletes are not asymmetric in limb circumferences thus emphasising a greater need for individual bespoke garments to account for differences in limbs specifications (Rauter et al., 2017). It has been suggested that there is limited information "quantifying" compression profiles and their subsequent effect on the body. This can be explained by the difficulty in producing specific customised profiles (Gokarneshan, 2017). With ever evolving technology, it is possible to create made to measure compression tights that produce specific compression profiles for different participants based on specific individuals body composition as observed in a recent study (Ashby et al., 2021).

By controlling compression profile, there can be a greater understanding towards cardiac and muscle oxygenation responses when wearing compression tights. Therefore the present study will examine different types of compression profiles such as Graduated Compression (GC), Reverse Graduated Compression (RGCT) and Uniform Compression garments (UCT). Muscle oxygenation, deoxygenation and tissue oxygenation responses to the different garments will be monitored during resting in the decubitus position, 75° degree upright tilt and standing.

7.2 Methodology

7.2.1. Participants

Ten, healthy active males (age 28.4 ± 3.6 years and body mass 81.3 ± 11.2 kg; mean ± SD) volunteered to participate and provided informed consent. Ethical permission was granted by Nottingham Trent University. Participants completed all trials at approximately the same time to minimize circadian influences. Participants were asked to refrain from alcohol and caffeine 24 hours before each trial. Participants were also asked to attempt to replicate the same diet 24 hours prior to each main trial.

7.2.2. Experimental Protocol

Main trials were completed in a randomised order. Participants were asked to complete 3 recovery-based activities with the application of either a Uniform Garment, Reverse Graduated Garment, Graduated Compression Garment or Control Garment. Participants laid in the decubitus position and were positioned at upright 75° degrees using a Tilt table for approximately 45 minutes each. Participants then completed the trial by standing for 20 minutes.

7.2.3. Compression Tights and Profile

Compression tights were manufactured by Kurio (Kurio Recovery, Kurio 3D Compression, Edwinstowe, Nottingham, England). The compression material was approximately made up of Elastane (22%) and Nylon (78%). Compression was assessed at the posterior aspect of the leg at 10 landmarks (Ashby et al. 2021). Compression pressure was measured at approximate 5cm increments on the lower and upper extremity on the posterior of the leg, with the last landmark at the gluteal fold. Compression was assessed using a Pico Press (Microlab Electronica, Padua, Italy) and was measured at the beginning of each trial. Compression profiles were affiliated against UK classification of pressures. Classification 1 (14-17 mmHg); Classification 2 (18-24 mmHg); and Classification 3 (25-35 mmHg).

Each garment type was assessed for the correct compression profile prior to testing procedures. All participants were scanned using a Artec Eva 3D scanner (Artec Group, Luxembourg, Luxembourg). Lower body scans were generated with participants standing stationary in the anatomical position. Scans were processed at Kurio Compression LTD. Bespoke garments were then made with varied compression parameters set for different garments (uniform, graduated, reverse graduated and control, **Table 7.1**).

Figure 7.1. Compression (mmHg) landmarks template using Ashby et al.(2021) model.

Table. 7.1. Compression profile objective for each compression garment.

Garment	Objective
Uniform	Mean level of compression across the upper and lower extremity of the limb.
Reverse	Higher level of compression at the gluteal fold graduating to a lower level of compression malleoli.
Graduated	Higher level of compression at the malleoli graduating to a lower level of compression at the gluteal fold.
Control	Lower levels of compression (1st class) across the limb with a graduated profile.

7.2.4. Skinfold and Girth

Skinfold (Harpenden Skinfold Calipers, British Indicators Ltd, Burgess Hill, UK) and girth measurements were taken around the gastrocnemius and quadriceps to determine skinfold and girth. Measurements were taken three times at the beginning of each trial and the mean was then taken. Quadricep girth was taken through measuring the distance between the top of the femur and the patella and deducting half of the distance. Girth and skin fold measurements were taken at the maximum aspect of the gastrocnemius medialis, after measurements a marker was placed for the NIRS to be then attached (**Table 7.2**).

Table. **7.2** Skinfold and girth measurements at the gastrocnemius and vastus lateralis (mean ± standard deviation).

Gastrocnemius		Vastus Lateralis	
Skinfold (mm)	Girth (cm)	Skinfold (mm)	Girth (cm)
5.2 ± 3.6	37.2 ± 3.2	5.8 ± 1.5	52.7 ± 7.8

7.2.5. Near-infrared Spectroscopy measurements

Two Near-infrared Spectroscopy (NIRS) devices (Portalite, Artinis Medical Systems BV, Elst, Netherlands) were attached to the muscle belly of the vastus lateralis and the maximal calf girth and monitored muscle oxygenation at 10Hz (Lucero et al. 2017). The differential path factor (DPF) determines the strength of the signal and was set at 4.95 for skeletal muscle tissue (Duncan et al., 1995; Smith and Billaut, 2013). Wavelength was set at 760nm and 850nm for all trials. Measurements of oxyhaemoglobin [O_2Hb], de-oxyhaemoglobin [HHb], Tissue Saturation Index (TSI) were recorded using the NIRS. Oxyhaemoglobin and deoxyhaemoglobin concentration changes from the baseline were expressed in arbitrary units [ΔμM] and TSI was expressed as a percentage (%).

The vastus lateralis muscle belly was located at 15cm proximal to the patella head and 4cm lateral. The probe was then carefully placed with double sided tape onto the muscle belly to minimise movement. The gastrocnemius location was located at the medialis aspect of the muscle. Additional tape was administered around the both devices within the no garment trial in order to reduce ambient day light which can influence oxygenation readings (Barstow, 2019). To determine baseline changes, each participant was asked to remain seated 5 minutes prior to each trial with no garment administered. Participants were instructed to remain as still as possible through the baseline stage mainly in order to “minimise motion artifacts” (Perentis et al., 2021). Data was ran continuous and observed through arbitrary software (Oxysoft software, Portalite, Artinis, Medical Systems BV, Elst, The Netherlands). The first 20 minutes of decubitus and tilt position was recorded and analysed, the remaining 25 minutes was used to assess cardiac function via ultrasound. The first 20 minutes was used as it allowed participants to remain still and enable stable readings (**Figure 7.2**).

7.2.6. Data Processing for NIRS

Data was exported from Oxysoft and exported into MatLab format. MatLab (MATLAB and Statistics Toolbox R2017a, The MathWorks, Inc, Natick, Massachusetts, United States) was used to apply a Low- Pass Butterworth filter to the raw NIRS data with a cut off frequency of 0.2 Hz. The filter was used to smooth the data and remove external noise (Rodriguez, Townsend, Aughey, & Billaut, 2018). Concentration changes were calculated at 60 second intervals of each activity of the trial.

7.2.7. Haemodynamics

Resting echocardiography was performed in the left lateral decubitus and tilt position by an experienced sonographer using an ultrasound machine, with the use of a 1.5-4.5MHz transducer (Siemens, Acuson P500 Ultrasound System, FROSK Edition, Muenchen, Germany). Data analysis from three stored cycles, was performed by a single observer using available software (EchoPac, version 113, GE Medical, Horton, Norway). The following LV functional measures were determined: end diastolic (EDV), modified Simpsons biplane left ventricular ejection fraction (EF), from which stroke volume, and cardiac output were calculated.

7.2.8. Statistical Analyses

All numerical values are identified as mean ± SD. Statistical analysis was performed through the application of SPSS version 24.0 (SPSS Inc., Chicago, IL, USA). A one- way analysis of variance (ANOVA) was used to assess differences ($P<0.05$) in haemodynamics and NIRS parameters (Muscle oxygenation/deoxygenation/ TSI%), for all phases (decubitus, tilt, standing) of the protocol and for both muscle sites. Any significant differences ($P<0.05$) observed would then be further analysed with a Bonferroni *post-hoc* test. GraphPad Prism version 8 (GraphPad Software, La Jolla, California, USA) were used to create graphs. Effect size (Cohen's *d*) was used on all significant differences using trial pairings and assessed using the following thresholds: <0.2 = trivial effect - <0.5 = small effect; 0.5- 0.8 = moderate effect and >0.8 = large effect (Cohen, 1992).

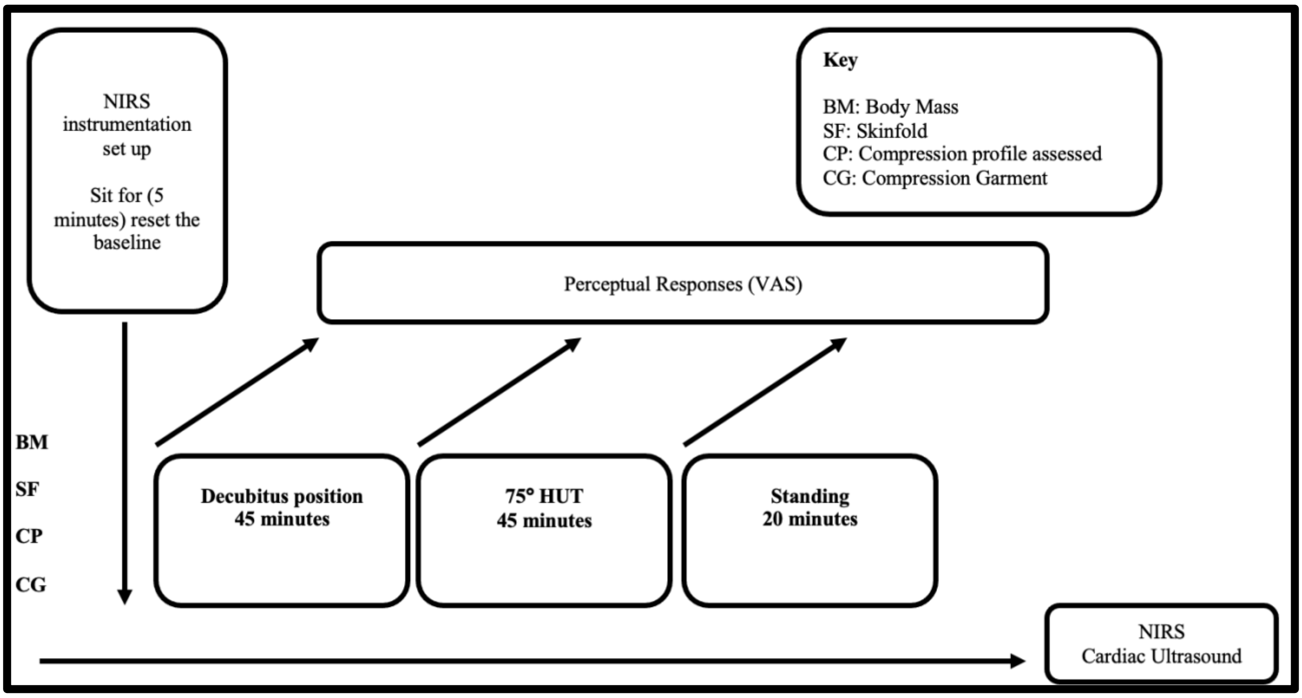


Figure 7.2. Schematic diagram of protocol

7.3 Results

7.3.1. Tissue Saturation

Gastrocnemius

Tissue saturation presented no differences in the gastrocnemius (**Table 7.3**) muscle during the decubitus (*P*=0.28) and tilt (*P*=0.35) positions. A trial effect was observed during the standing position where the Reverse (71.5±7.6%) graduated garment provided greater levels of tissue saturation in comparison to the No Garment (63.3±8.6%, *d*=0.97, large effect), Graduated (57.8±5.4%, *d*=2.08, large effect) Control (57.8 ± 6.8%, d=1.90, large effect) and Uniform (58.6 ± 5.8, *d*=1.90, large effect) garment (*P*=0.02) (**Figure 7.3**).

Vastus Lateralis

There were no differences in the vastus lateralis (**Table 7.4)** during the decubitus (*P*=0.41), tilt (*P* = 0.41) and standing position (*P*=0.46) when assessing tissue saturation.

Table. 7.3 Tissue saturation index (%) in the ***gastrocnemius*** (*large effect from no garment, ~moderate effect from no garment, #large effect from Reverse Graduated Garment)

Activity	**No Garment (%)**	**Graduated Compression Garment (%)**	**Control Garment (%)**	**Reverse Graduated Garment (%)**	**Uniform Compression Garment (%)**	**One-way ANOVA**	**Cohens d**
Decubitus	69.1 ± 4.1	67.9 ± 4.9	66.4 ± 6.3	70.3 ± 6.5	68.0 ± 4.0	P=0.285	
Tilt	62.6 ± 7.8	61.0 ± 7.7	58.6 ± 6.9	62.6 ± 8.8	58.3 ± 4.7	P=0.385	
Standing	63.3 ± 8.6	57.8 ± 5.4***#**	57.8 ± 6.8***#**	71.5 ± 7.6 *****	58.6 ± 5.8~#	**P=0.02**	**NG, GC,** *d* = 0.81: **NG, CG**, *d* = 0.81: **NG**, **RG**, *d* = 0.97: **NG, UCG**, *d* = 0.68, **GC, RG**, *d* = 2.08: **RG, UG**, *d* = 1.91; **RG**, **CG**, *d* = 1.90

Table. 7.4 Tissue Saturation index (%) in the ***vastus lateralis***.

Activity	No Garment (%)	Graduated Compression Garment (%)	Control Garment (%)	Reverse Graduated Garment (%)	Uniform Compression Garment (%)	One-way ANOVA
Decubitus	66.50 ± 5.3	68.5 ± 2.9	68.0 ± 2.9	70.6 ± 3.7	69.0 ± 3.4	P=0.41
Tilt	67.2 ± 8.1	64.0 ± 6.1	64.8 ± 3.7	65.2 ± 3.4	62.2 ± 3.7	P=0.41
Standing	64.9 ± 6.5	62.2 ± 5.3	64.6 ± 3.9	65.1 ± 3.9	61.7 ± 3.8	P=0.46

7.3.2. Oxyhaemoglobin responses

Gastrocnemius

In the decubitus (**Table 7.5**) position, the graduated compression garment (3.2±9.0 ΔμM, *d*=0.83, large effect) provided the highest concentration change from the baseline, in comparison to no garment (-3.7±7.6 ΔμM) which provided a negative concentration change from the baseline (*P*=0.56).

The tilt position observed that the Uniform (8.5±11.2 ΔμM) and Graduated (3.7±12.6 ΔμM) compression provided greater concentration changes in oxyhaemoglobin, whereas the no garment (-6.8±7.5 ΔμM), reverse (-4.2±7.4 ΔμM) and control (-2.3±6.9 ΔμM) garment provided negative responses from the baseline (*P*=0.21). During standing, the Uniform (3.8±10.7 ΔμM) garment provided the greatest O_2Hb concentration changes in comparison to a reduced concentration change from the baseline that was observed in the no garment (-3.0±7.5 ΔμM), reverse (-1.5±7.2 ΔμM), graduated (-2.7±8.4 ΔμM) and control (-3.4±7.5 ΔμM) garment (*P*=0.56).

Vastus Lateralis

No trial effect was observed in oxyhaemoglobin responses in the vastus lateralis muscle during the decubitus (P = 0.56), tilt (P = 0.21) or standing (P = 0.56) position (**Table 7.6**).

7.3.3 Deoxyhaemoglobin responses

Gastrocnemius

Deoxyhaemoglobin responses (**Table 7.5**) in the gastrocnemius observed no trial effect in the decubitus position (*P*=0.71). During the tilt position there was a trial effect (*P*=0.04), where deoxyhaemoglobin responses (**Figure 7.3**) increased through the application of graduated compression tights (10.2±7.0 ΔμM) in comparison to no garment (-3.1±3.8 ΔμM, *d*=2.36, large effect), control garment. (5.0±3.7 ΔμM, *d*=0.93, large effect), reverse graduated garment (0.5 ± 3.7 ΔμM, *d*=1.73 and the uniform garment (3.7±4.9 ΔμM, *d*=0.93, large effect). Remaining compression trials also provided a large effect (reverse graduated *d*=0.96; control garment *d*=2.16; uniform garment *d*=1.55) in comparison to the no garment trial during the tilt position. A moderate effect was observed between the reverse graduated garment and the uniform garment (*d*=0.74) in the tilt position. No trial differences were observed in the standing phase of the protocol (*P*=0.72)

Vastus Lateralis

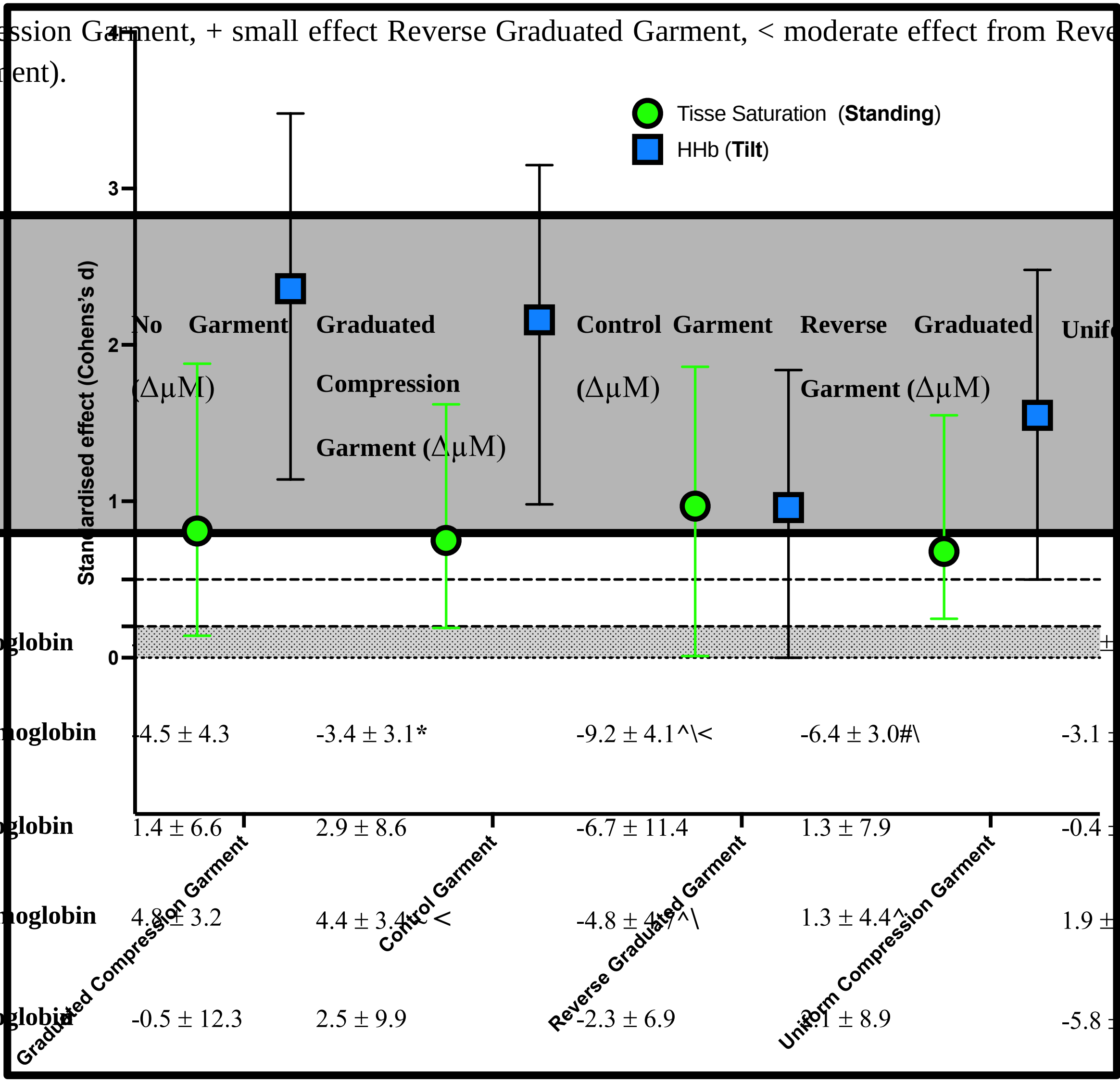
In the decubitus (**Table 7.6)** position a trial effect (*P*=0.05) was observed with the control garment (-9.2±4.1 ΔμM) showing the greatest reduction from the baseline in comparison to the no garment (-4.5±4.3 ΔμM, *d* =1.12, large effect), graduated, (-3.4±3.1 ΔμM, d = 1.60 and uniform garment (1.9±2.3 ΔμM, *d* = 0.86). A moderate effect was observed between the control garment and the reverse garment (*d*= 0.78). A trial effect (*P*=0.02) was detected in the tilt position, with the control garment (-4.8 ± 4.7 ΔμM) reducing deoxyhaemoglobin responses in the control garment in contrast to an increase in the graduated (4.4±3.4 ΔμM, *d*=2.24, large effect), no garment (4.8±3.2 ΔμM, *d*=1.12, large effect), reverse (1.3±4.4 ΔμM, *d*=1.34, large effect) and uniform garment (1.9±2.3 ΔμM, d=1.81, large effect). No trial effects were observed in the standing position (*P*=0.71).

Table. 7.5 O_2Hb and HHb ($\Delta\mu M$) concentration changes from the baseline in the ***gastrocnemius***. (*large effect from Graduated Compression Garment, ~moderate effect from Reverse Graduated Garment, #large effect from Reverse Graduated Garment, ^ small effect from Control Garment).

Table 7.6 O_2Hb and HHb concentration (ΔμM) changes in the ***vastus lateralis*** (~ trivial effect from No garment, * small effect from No Garment, # moderate effect from No Garment, ^ large effect from No Garment, > trivial effect from Graduated Compression Garment, \ large effect from

Activity N=10	*Measure*	**No Garment** (ΔμM)	**Graduated Compression Garment** (ΔμM)	**Control Garment** (ΔμM)	**Reverse Graduated Garment** (ΔμM)	**Uniform Compression Garment** (ΔμM)	**One-way ANOVA**
Decubitus	**Oxyhaemoglobin**	-3.7 ± 7.6	3.2 ± 9.0	1.0 ± 5.5	-0.86 ± 7.4	2.7 ±8.5	P=0.53
	Deoxyhaemoglobin	-9.5 ± 6.8	-6.9 ± 12.7	-2.9 ± 1.1	-7.8 ± 5.9	-6.6 ± 7.3	P=0.71
Tilt	**Oxyhaemoglobin**	-6.8 ± 7.5	3.7 ± 12.6	-2.3 ± 6.9	-4.2 ± 7.4	8.5 ± 11.2	P=0.14
	Deoxyhaemoglobin	-3.1 ± 3.8*	10.2 ± 7.0	5.0 ± 3.7*#	0.5 ± 3.7*	3.7 ± 4.9*~^	**P=0.04**
Standing	**Oxyhaemoglobin**	-3.0 ± 7.5	-2.7 ± 8.4	-3.4 ± 7.5	-1.5 ± 7.2	3.8 ± 10.7	P=0.55
	Deoxyhaemoglobin	-4.5 ± 6.4	-2.2 ± 12.9	3.5 ± 5.1	-3.3 ± 9.5	0.01 ± 7.5	P=0.72

Graduated Compression Garment, + small effect Reverse Graduated Garment, < moderate effect from Reverse Graduated Garment, | large effect from Control Garment).



Activity	*Measure* *N=10*	**No Garment (ΔμM)**	**Graduated Compression Garment (ΔμM)**	**Control Garment (ΔμM)**	**Reverse Graduated Garment (ΔμM)**	**Uniform Compression Garment (ΔμM)**	**One-way ANOVA**
Decubitus	**Oxyhaemoglobin**	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] ± 13.4	P=0.56
	Deoxyhaemoglobin	-4.5 ± 4.3	-3.4 ± 3.1*	-9.2 ± 4.1^\<	-6.4 ± 3.0#\	-3.1 ± -9.2~+|	**P=0.05**
Tilt	**Oxyhaemoglobin**	1.4 ± 6.6	2.9 ± 8.6	-6.7 ± 11.4	1.3 ± 7.9	-0.4 ± 5.9	P=0.21
	Deoxyhaemoglobin	4.8 ± 3.2	4.4 ± 3.4[illegible] <	-4.8 ± 4.[illegible]^\	1.3 ± 4.4^	1.9 ± 2.3^\+|	**P=0.02**
Standing	**Oxyhaemoglobin**	-0.5 ± 12.3	2.5 ± 9.9	-2.3 ± 6.9	[illegible].1 ± 8.9	-5.8 ± 8.0	P=0.56
	Deoxyhaemoglobin	1.2 ± 3.8	2.7 ± 2.6	-0.5 ± 4.5	-0.2 ± 4.7	3.0 ± 5.8	P=0.71

Figure 7.3. Standardised effects (Cohen's d) with 95% confidence intervals for TSI and HHb in the gastrocnemius in the standing and tilt position in comparison to no garment. Shaded area outlines a trivial effect, and dotted lines for thresholds for small, moderate, and large effects.

7.3.4. Haemodynamic responses

No differences were observed in stroke volume, cardiac output, heart rate, end diastolic and systolic volume in decubitus and standing position ($P>0.05$).

In the tilt position ($p=0.05$), ejection fraction responses were higher when wearing the graduated compression garment (62.2± 11.7%; $d= 0.20$) in contrast to no garment (60.1± 9.4%) (**Table 7.9**).

Table 7.7. Stroke volume responses (ml) decubitus and tilt position

Activity (N=7)	No Garment (ml)	Graduated Compression Garment (ml)	Control Garment (ml)	Reverse Graduated Garment (ml)	Uniform Compression Garment (ml)	One-way ANOVA
Decubitus	75.2± 15.8	81.7± 20.1	81.1±18.5	80.0± 10.9	76.4± 13.2	0.40
Tilt	62.8± 12.5	63.5± 11.9	62.0± 7.7	60.5± 8.0	68.8± 12.4	0.55

Table 7.8. Cardiac output (L·min^{-1}) responses in decubitus and tilt position

Activity (N=7)	No Garment (l/min)	Graduated Compression Garment (l/min)	Control Garment (l/min)	Reverse Graduated Garment (l/min)	Uniform Compression Garment (l/min)	One-way ANOVA
Decubitus	3.9± 0.3	3.9± 0.9	4.0±0.6	4.1± 0.6	3.6± 0.5	0.25
Tilt	4.2 ± 0.8	4.4± 0.7	4.2± 0.6	4.1±0.8	4.3± 0.6	0.91

Table 7.9. Ejection Fraction (%) responses in decubitus and tilt position (*Trivial effect from No garment; ~ trivial effect from Reverse graduated garment)

Activity (N=7)	No Garment (%)	Graduated Compression Garment (%)	Control Garment (%)	Reverse Graduated Garment (%)	Uniform Compression Garment (%)	One-way ANOVA
Decubitus	56.5±8.5	59.0± 7.0	60.1± 5.3	59.2±6.8	58.2±7.8	0.16
Tilt	60.1± 9.4	62.2± 11.7*~	60.7±8.6	57.5± 8.6*	61.7± 7.8	0.05

Table 7.10. Heart rate (beats·min^{-1}) responses in decubitus and tilt position

Activity (N=7)	No Garment (bpm)	Graduated Compression Garment (bpm)	Control Garment (bpm)	Reverse Graduated Garment (bpm)	Uniform Compression Garment (bpm)	One-way ANOVA
Decubitus	52.0± 8.0	49.0 ± 5.0	50.0± 6.0	52.0± 7	49.0± 6.0	0.74
Tilt	66.0± 7.0	70.0±10.0	69.0±10.0	70.0±10.0	66.0± 10.0	0.12

Table 7.11. End Diastolic volume (ml) responses in decubitus and tilt position

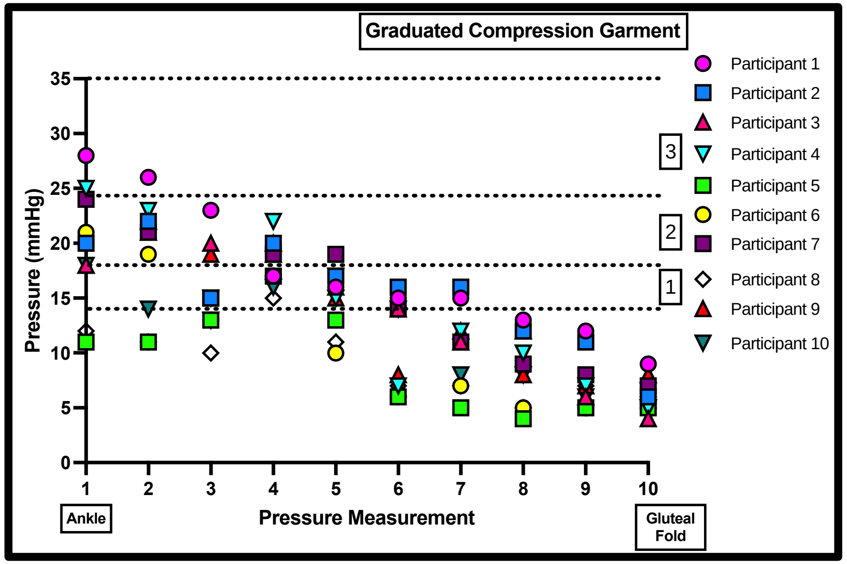
Activity (N=7)	No Garment (ml)	Graduated Compression Garment (ml)	Control Garment (ml)	Reverse Graduated Garment (ml)	Uniform Compression Garment (ml)	One-way ANOVA
Decubitus	136.5± 25.5	138.1± 27.1	136.0± 26.4	136.1± 26.8	130.8± 20.5	0.54
Tilt	104.5± 16.1	107.1± 12.0	103.4± 14.7	105.1± 12.7	105.1± 11.9	0.84

Table 7.12. End systolic volume (ml) responses in decubitus and tilt position

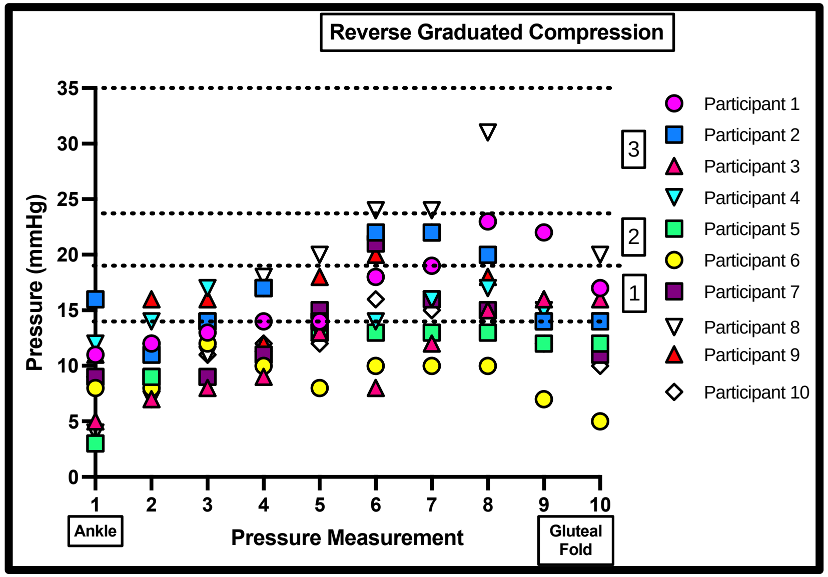
Activity (N=7)	No Garment (ml)	Graduated Compression Garment (ml)	Control Garment (ml)	Reverse Graduated Garment (ml)	Uniform Compression Garment (ml)	One-way ANOVA
Decubitus	54.1± 14.1	56.2± 12.5	54.0± 14.0	56.2± 19.7	54.2± 12.5	0.51
Tilt	43.0± 13.6	43.5± 16.7	41.2± 14.0	42.7± 13.9	40.0± 9.9	0.23

7.3.5. Compression Profile

The ***Graduated Compression Garment*** (**Figure 7.4**) provided a graduated profile with the highest amount of pressure within the lower extremity of the limb (*ranging*, 19.4 mmHg- 14.9 mmHg) and the lowest amount of pressure within the upper extremity of the limb (*ranging*, 19.7 mmHg - 6.0 mmHg)**.** The ***Reverse Graduated Compression Garment*** provided a reverse graduated profile with the highest (17.6±5.9mmHg) amount of compression within the upper extremity of the limb. Compression pressure ranged from 17.6±5.9mmHg- 8.8±3.9mmHg (**Figure 7.4**). The ***Uniform Compression Garment*** produced smaller ranges in compression pressure (14.3±2.1mmHg - 9.0±1.6 mmHg) (**Figure 7.5**). The highest level of compression was affiliated at the gastrocnemius. The ***Control Garment*** profile ranged from 10.3±2.7 mmHg- 5.2±2.8 mmHg. The highest pressure within the Control Garment (10.3±2.7 mmHg) was affiliated around the gastrocnemius (**Figure 7.5**).

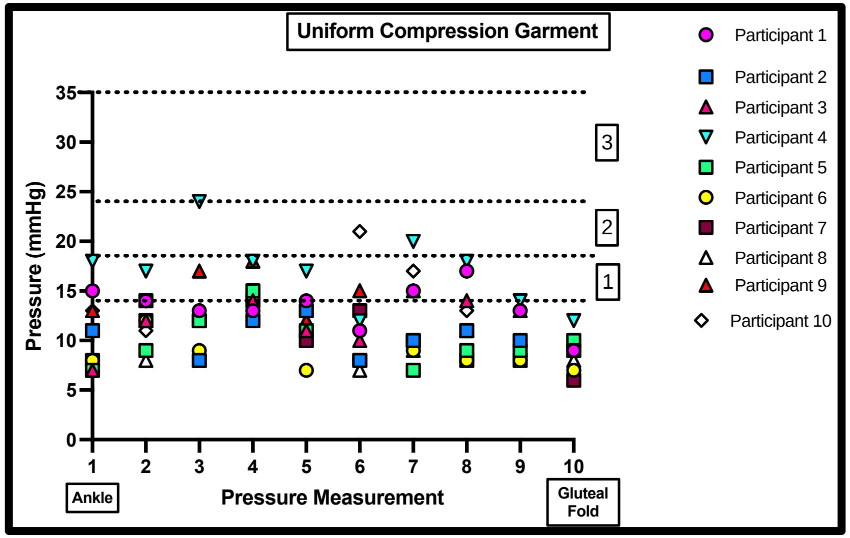


A)

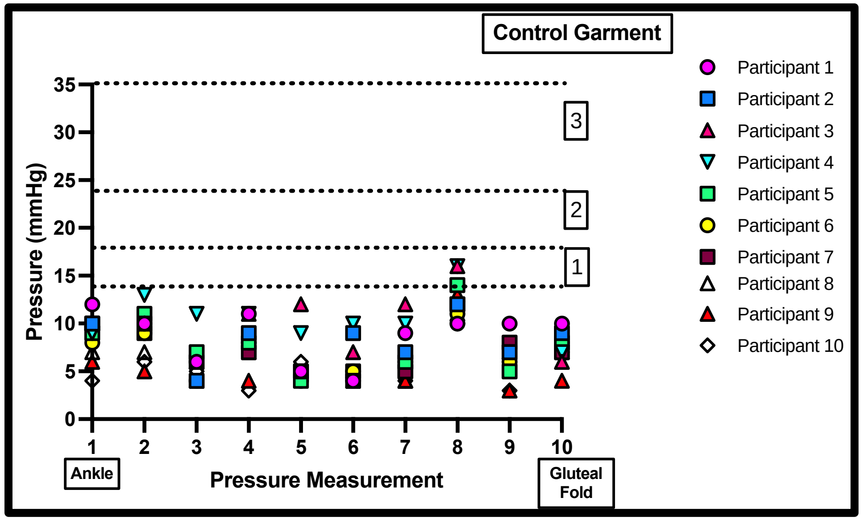


B)

Figure 7.4 Individual compression profiles (mmHg) for the ***A***) Graduated Compression Garment. ***B***) Reverse Graduated Compression



C)



D)

Figure 7.5 Individual compression profiles (mmHg) for the ***C***) Uniform Compression Garment ***D***) Control Garment

7.4 Discussion

The objective of the current study was to assess different types of compression profiles and the effects on muscle oxygenation and haemodynamics during stationary activities. The current study looked to explore bespoke made to measure compression tights that were specific for each participant's body geometry. To our knowledge this is the first study that has explored different compression profiles whilst manufacturing made to measure compression garments. The main findings of the current study observed a lower tissue saturation in the gastrocnemius during the standing position with graduated, uniform and control garments, in contrast to the reverse graduated profile . The graduated profile also provided an increase in ejection fraction (%) response and an increase in deoxyhaemoglobin responses in the gastrocnemius and the vastus lateralis during the tilt position.

Tissue saturation index (TSI) and the relationship between the haemoglobin responses in skeletal muscle warrants further investigation. Research claims tissue saturation will increase when compression is applied (Dermont et al., 2015; Peseaux et al., 2017; Coza et al., 2016; Bringard et al., 2006; Kerherve et al., 2017; Menetrier et al., 2011). Tissue saturation is the link between oxygen "availability and utilisation" and can change depending on exercise activity or intensity (Rodriguez et al., 2019). The present study did observe an increase in tissue saturation in the gastrocnemius using a reverse graduated profile (71.5 ± 7.6%) during the standing position, in contrast to all other trials. Subsequently this provided a + 2.1±8.9 ΔμM of O_2Hb in the vastus lateralis, a large effect was observed between the reverse profile and the uniform profile (d=0.93). However, the Graduated, Uniform and Control reduced tissue saturation at the gastrocnemius (P<0.05). To our knowledge, this is the first study to report a reduction in tissue saturation with the application of compression in resting conditions at the gastrocnemius muscle. Rennerfelt et al. (2019) also demonstrated a reduction in tissue saturation during supine conditions using compression stockings, the reduction in tissue saturation occurs due to an increase in intramuscular pressure enabling the use of oxygen more effectively. Notably the present study did not measure intramuscular pressure, however future research could assess intramuscular pressure to help provide further insight towards the mechanisms involved in tissue saturation responses when wearing compression. In contrast, using a graduated profile (17.2 to 12.2 mmHg), O'Riordan et al. (2021) reported an increase in tissue saturation using tights at the gastrocnemius and vastus lateralis during supine conditions, in comparison to the present study the pressure was lower which may have impacted tissue saturation responses. An increase in deoxyhaemoglobin responses through the tilt position and decrease in TSI (%) during standing in the gastrocnemius were the main findings using a graduated profile, this was also supported by an increase in ejection fraction response, suggesting an increase in the amount of blood that is pumped out in each beat (P<0.05). With a graduated profile, research has shown oxyhaemoglobin (12.0±2.2 μmol) responses in the gastrocnemius to also increase in standing positions (Agu et al., 2004). Higher levels of compression in a graduated profile were affiliated with higher levels of oxyhaemoglobin in the gastrocnemius (Agu et al., 2004).

Exercise intensity is a key variable that can influence haemoglobin concentration levels in the muscle. Without the use of compression, Smith and Billaut (2010) observed decreases of oxyhaemoglobin and increases of deoxyhaemoglobin when participants were performing high intense intermittent sprinting on a cycle ergometer. Contradictory evidence has also suggested that a graduated compression profile does not impact exercise performance (Priego et al., 2015; Ali et al., 2011). The knowledge around the literature surrounding graduated profiles and the clarity in what they do warrants further understanding especially to optimise for future use. In the present study, the level of compression at the gastrocnemius in the graduated profile (19.7 mmHg to 6.0 mmHg) was the highest in comparison to all other garment trials, this can suggest that the level of compression provides a greater opportunity in increasing deoxyhaemoglobin responses. Broadtch (2021) outlined that compression potentially impacts "lower resistant capillaries" forcing blood to be carried by "high resistant capillaries" improving oxygen utilisation. The graduated profile potentially could have aided venous blood return by increasing the pressure in the gastrocnemius, with the gastrocnemius acts as a pump in returning deoxygenated blood to the heart.

The gastrocnemius is a key structure in the venous circulation process, the level of compression can act as a dilating mechanism that is commonly involved in the process of venous return. These potential mechanisms could be another reason why O_2Hb and HHb increased responses with compression garments, especially when compression is on the gastrocnemius. Popliteal venous blood flow has been shown to increase using graduated compression tights emphasising a potential dilated response in the gastrocnemius through compression (O'Riordan et al., 2021).The present study detected an increase in deoxyhaemoglobin concentration when compression was applied to the gastrocnemius in the tilt position. Research has supported the current study and provided evidence in suggesting that applying compression improves haemoglobin responses in skeletal muscle (Riordan et al., 2021; Rennerfelt et al., 2019). Variables such as level of compression, muscle site, adipose tissue thickness and activity will have an influence on tissue saturation through NIRS assessment (Barstow, 2019). The change in activities in all the protocol poses problems for the circulatory system. Changes in venous pressure occur to help with efficient blood flow to the heart to compensate changes that occur through the resistance of gravity. The application of compression potentially acts as an aid in increasing venous pressure but also increasing the haemoglobin binding process with oxygen. This was evident in a recent study when Lee et al. (2021) observed increases in cardiac output during 5 and 45 minutes of passive recovery when participants wore compression tights.

7.5 Conclusion and Practical Implications

The purpose of the current study was determine the effect of different compression profiles on muscle oxygenation A graduated and reversed profile provided changes to muscle oxygenation in the gastrocnemius. The graduated design provided greater oxygenated responses that could be of value in a sporting setting. Any improvements in oxygenation could be put down to bespoke compression providing a sufficient amount of intramuscular pressure enabling the muscle to utilise oxygen more effectively.

A limitation to the study is the number of participants used, future investigation should use more participants to observe the effects of oxygenation through different compression profiles. Further observations in intramuscular pressures might also provide a better understanding towards the mechanisms in the muscles use of oxygen. The study provides a starting point in which compression can be fully optimised in a sports setting. Bespoke compression garments are essential in improving oxygenation responses, however further research is warranted to look at graduated and uniform profiles through an exercise setting. It is worth noting that compression may not necessarily aid performance outcomes however the information in this study provides clarity in that compression can aid physiological mechanisms for training and recovery.

The implications to this study lead to further investigation over the use of bespoke compression garments. The novel ability to manufacture new compression designs will benefit researchers and help warrant further investigations on the physiological mechanisms involved through wearing bespoke compression.

Chapter 8 General Discussion.

8.1. Summary

Through the advancements of sports technology, research in sports clothing will result in the design of different types of compression garments. With elite sport becoming even more competitive there is a greater demand for accelerated recovery methods, especially with an increase in games and competition through all sport. This potentially enables a new market for different types of compression and therefore more research is needed to bridge the gap between the practical implications of wearing compression and its influence on the physiological systems.

The research around the use of compression is very broad and more understanding of the physiological responses are needed in order to further explore the effectiveness of compression. The majority of the research to date does not quantify physiological mechanisms that occur through the use of bespoke compression, therefore the purpose of this thesis was to provide further insight towards these mechanisms.

In using standardised fitting for participants, it is difficult to assess individual effects of the garments, this is due to differences within everyone's body mass and stature (Brophy-Williams et al., 2015). The key importance in understanding the physiological mechanisms of the body is to have the ability to assess the level of compression on the participant, as different anatomical landmarks will observe different levels of compression due differences in skeletal structures. If the level of compression is not assessed, then it is difficult to draw conclusion in what is happening in the body. The ability to make bespoke compression tights is very novel and provides this thesis with a greater opportunity to understand and explore oxygenation responses through using varied compression profiles.

The main key findings of this PhD thesis can be summarised as follows:

- Data in **Chapter 4** demonstrates that Near-infrared Spectroscopy is reliable to assess muscle oxygenation responses when wearing compression garments. TSI %, oxyhaemoglobin and deoxyhaemogbloin concentration changes from the baseline all demonstrated good reliability whilst participants performed recovery-based activities.

- Bespoke compression tights were successfully manufactured and demonstrated minimal changes in compression pressure measures between trials (**Chapter 4**). The highest level of compression readings was affiliated at the gastrocnemius in the use of both bespoke compression tights and socks.

- **Chapter 5** findings indicate that bespoke compression socks and tights reduced tissue saturation in the vastus lateralis and the gastrocnemius in the walking phase of the protocol.

- Oxyhaemoglobin responses in the vastus lateralis increased in the laying supine phase of the protocol through the application of bespoke compression tights (**Chapter 5**)

- **Chapter 5** observed deoxyhaemoglobin responses increased during walking in the gastrocnemius and during the sitting phase in the vastus lateralis in using bespoke compression tights.

- Graduated compression profile reduced heart rate during supine and standing activities. The graduated profile had the lowest heart rate in comparison to all trials (**Chapter 6).**

- Participants identified that the reverse graduated compression garment to be the least comfortable garment. The graduated compression garment was favoured as the most comfy when worn (**Chapter 6)**. This information suggests that greater levels of compression at the gastrocnemius can be favoured more to be comfy in comparison to higher levels of compression within the upper extremity of the limb.

- Tissue saturation (**Chapter 7)** reduced in the standing phase using graduated compression in comparison to no garment. Reverse graduated compression provided an increase in tissue saturation in comparison to no garment.

- In the tilt position deoxyhaemoglobin responses were higher in the gastrocnemius in using the graduated profile, compression also provided higher deoxyhaemoglobin responses in comparison to when no garment was worn (**Chapter 7)**.

- Graduated compression reduced deoxyhaemoglobin responses in the vastus lateralis in contrast to no garment, in both decubitus and tilt positions (**Chapter 7)**.

Table 8.1 provides further insight into the summary of each compression garment and responses through this thesis. The table outlines perceptual, haemodynamics and oxygenation responses through a range of activities such as supine, walking, jogging, decubitus position, head up tilt position and standing.

Table 8.1 Summary of muscle oxygenation and perceptual responses for each garment (themes are predominately against the application of no garment unless stated otherwise).

Graduated Compression Garment	**Control Garment**	**Reverse Graduated Garment**	**Uniform Compression Garment**	**Compression Socks (Chapter 4 and 5)**
↓ ***reduced*** tissue saturation in the vastus lateralis and gastrocnemius during walking	↓ ***reduced*** tissue saturation in the standing position at the gastrocnemius muscle.	↑ ***highest*** tissue saturation at the gastrocnemius in the standing position.	↓ ***decreased*** cardiac output the most within the standing phase.	↓ ***reduced*** tissue saturation in the vastus lateralis and gastrocnemius during walking.
↑ ***increased*** deoxyhaemoglobin responses during walking in the gastrocnemius both muscles against all trials.	↑ **increased** HHb in the tilt position at the gastrocnemius.	↑ ***increase*** HHb in the gastrocnemius in the tilt position.	↓ ***decreased*** tissue saturation the most within the standing phase in the gastrocnemius.	↑ ***reduced*** HHb responses in the walking phase in comparison to no garment.
↑ **increased** HHb in walking and tilt activities in the gastrocnemius and increased HHb in the vastus lateralis during sitting.	↓ ***decreased*** HHb in the decubitus and tilt position at the vastus lateralis muscle.	↓ ***least*** comfortable		↑ ***increase*** HHb in the gastrocnemius in the tilt position. ↓ ***reduced*** tissue saturation in the standing position at the gastrocnemius muscle.
↑ **increased** O_2Hb in laying supine in the vastus lateralis.				
↑ **increased** ejection fraction responses in the tilt position				

8.2 Overview and Discussion of Experimental Chapter Results

8.2.1 Reliability of near infrared spectroscopy with and without compression tights during exercise and recovery activities

The aim of the first study in **Chapter 4** was to provide an understanding of how reliable the NIRS is and if it can be used whilst participants wore compression tights whilst undertaking exercise and recovery specific activities. The purpose of using the NIRS was to identify a more practical non invasive method to assess muscle oxygenation. The key limitation with the research to date in assessing compression garments and its effectiveness, is the assessment method used to identify how the body responds. The Near-infrared spectroscopy in the past has been a useful piece of technology in assessing concentration changes in haemoglobin. The application of NIRS has provided mixed reliability findings, this is due to factors such as user set up. Research has outlined that poorer reliability occurs when participants undertook higher intense exercise (Balas et al., 2018; Austin et al., 2005; Choo et al., 2017). Through higher levels of intensity, there is a greater level of engagement from the muscle, molecular changes at a cellular level are constantly changing at a quicker rate, this physiological response is performed so that oxygen can be used quickly to help the individual sustain performance, because of this, there is greater variability in NIRS performance in detecting oxygenation changes.

The NIRS device uses three optodes to capture concentration changes. Scott et al. (2014) identified that any pressure applied to the device and the optodes can change the overall reliability of the device. Within the study (**Chapter 4)** participants performed a recovery jog at 7.0±0.89 kph and walked at a speed of 4.0 kph, subsequently this reflects lower levels of intensity.

In general, compression tights trials reliability was slightly poorer in comparison to the control trials, supporting Scott et al. (2014) claim that adding pressure to the optodes would impact NIRS reliability. When physical activity was performed Intraclass Correlation values ranged from 0.35-0.96 in both muscles throughout control and compression tights trials. Coefficient of variation values ranged from 1.1- 8.8% when participants were walking and jogging, this was evident in both control and compression tights trials through all oxygenation assessments. The level of intensity during exercise can influence NIRS responses. CV values in cycling activity ranged from 7.8-12.4% in Tissue saturation, back squatting ranged from 6.1-10% and isometric bicep contractions ranged from 6.9- 37.7% respectively (Choo et al., 2017; Scott et al., 2014; Muthalib et al., 2010). The highest level of compression (19mmHg) was at the gastrocnemius, which did not influence reliability measures. There has been minimal research to date that has assessed compression and NIRS reliability, but in comparison to other studies, the reliability of the present study appears to be good. Further investigations are needed to assess NIRS reliability within more extreme exercise settings. The device provides acceptable reliability for measuring Tissue saturation, oxyhaemoglobin and deoxyhaemoglobin concentration changes from the baseline within skeletal muscle tissue when bespoke compression is applied.

8.2.2 Effects of compression tights and socks on muscle oxygenation responses

In the second study (**Chapter 5**) of the thesis, the objective was to assess oxygenation responses when wearing compression tights and compression socks. The study focused on using the Near-infrared Spectroscopy and applied the device to the gastrocnemius and vastus lateralis in order to assess muscle oxygenation responses when participants performed exercise and recovery specific activities.

The key findings of the study were that bespoke compression effected tissue saturation and deoxyhaemoglobin responses in both muscles. Compression socks recorded the highest compression profile (mmHg), ***A***) 21.5±8.8; ***B***)18.4±6.1; ***C***) 20.7±6.3. The main observation for the use of compression socks was the reduction of tissue saturation at the gastrocnemius (70.9±5.3%) and the vastus lateralis (74.7±6.1%) during the walking phase in comparison to the control trial ($P<0.05$). The theory behind a reduction in tissue saturation suggests that oxygen is being used more effectively (Rodriquez et al., 2019). Using Brophy-Williams et al. (2015) compression assessment profile (mmHg) template, the tights in the *second* study (**Chapter 5**) recorded a graduated profile (***A***: 11.1±5.9 mmHg; ***B***: 10.3±6.7 mmHg; ***C***: 12.1±5.3 mmHg; ***D***: 7.5±2.8 mmHg; ***E***: 7.4±2.1 mmHg; ***F***: 7.1±2.1 mmHg). The main phase of the protocol that observed oxygenated responses was the walk, the transition from the seating position to walk provides a shift in oxygen requirement needed to complete the activity.

Oxyhaemoglobin responses are critical for cells to function. The more oxyhaemoglobin that is transported to the mitochondria, the greater the ability for muscles to function, this is because of the important role oxygen plays within the ATP process. As exercise intensity increases the oxygen consumption demand also increases, this places a further importance on the role of oxyhaemoglobin and its responsibility in helping muscular contraction, subsequently because of this tissue saturation is reduced because the muscle is utilising oxygen more efficiently. Bespoke compression tights observed a reduction in tissue saturation during the walking phase in both gastrocnemius (72.2±6.7%) and vastus lateralis (72.7±4.%) muscle in comparison to the control trial, where no garment was worn (*P*<0.05). The key findings suggest that compression may help oxygen utilisation in the muscle especially when oxygen demand increases, subsequently this theory was supported by an increase in deoxyhaemoglobin in the walking phase at the gastrocnemius muscle (P<0.05). Compression tights (+2.8±13.5 ΔμM) and compression socks (-2.2±7.9 ΔμM) provided greater responses in deoxyhaemoglobin in contrast to the control trial (4.4±7.4 ΔμM), this was also supported with a higher response in systolic pressure using compression during the walking stage.

A well-documented physiological response associated with compression is an increase in skin temperature (MacRae et al., 2012; Doan et al., 2003; Duffield et al., 2008; Houghton et al., 2009). Even though **Chapter 5** did not measure skin temperature, the fundamental principles in increasing skin temperature and the impacts in tissue oxygenation are best observed in Michel (1974) findings in oxygen transportation, subsequently the level of compression and contact within the skin can increase peripheral temperature. The increase in temperature increases the offload of oxygen within the cells due to the increase in demand from physical activity thus increasing oxyhaemoglobin (Popel, 1989).

Chapter 5 observed increases in deoxyhaemoglobin responses during walking, this can be affiliated to the oxygen dissociation curve (Michel, 1974) principle. The oxygen dissociation curve suggests that as temperature increases the quicker oxygen is offloaded from haemoglobin within the muscle, this is down to the increase in ATP demands. This can explain two theories in **Chapter 5 (See figure 8.1)**;

1. Tissue saturation % decrease is governed by the increase in skin temperature in that compression delivers to the skin by providing another form of insulation, this increase in temperature decreases or plateaus oxygen saturation due to the increase in releasing of oxygen from haemoglobin.

2. Increase in muscle deoxygenation is associated with an increased availability of haemoglobin to bind with oxygen and release to able to produce ATP in the production of energy.

The influence of compression can potentially be applied to the Krogh (1919) cylinder model. The model looks at the relationship between oxygen transport, capillaries and tissue. The cylinder resembles a capillary and the amount oxygen that can be diffused within. The Krogh (1919) cylinder model suggests that; tissue oxygen consumption is in a constant flow; capillaries receive an equal amount of oxygen supply; distribution of flow is constant and consistent; capillaries are equal in space. The importance of this model is of key interest when assessing the impacts of haemodynamics using compression. Krogh (1919) model identifies that the rate of haemoglobin to be steady and constant, the application of compression could increase this rate forcing more oxygen to be offloaded from the bounded oxygen molecule as outlined in **Chapter 5**.

This theory would support the current data outlined in **Chapter 5**, in that muscle deoxygenation increased through the walking phase, the increase in off loading of oxygen from haemoglobin would cater for the new increase ATP demands that physical activity brings (Grainger et al., 1984).

Krogh et al. (1922) also identified that different muscle groups would pose different internal anatomical structures, this would suggest that some muscles were not consistent in anatomical structures with alignment of muscle fibres this can potentially influence overall haemodynamics and the success of oxygen diffusion. The gastrocnemius and vastus lateralis will both have different anatomical make ups and the genetics of an individual’s skeletal features will influence the overall capacities of utilizing oxygen.

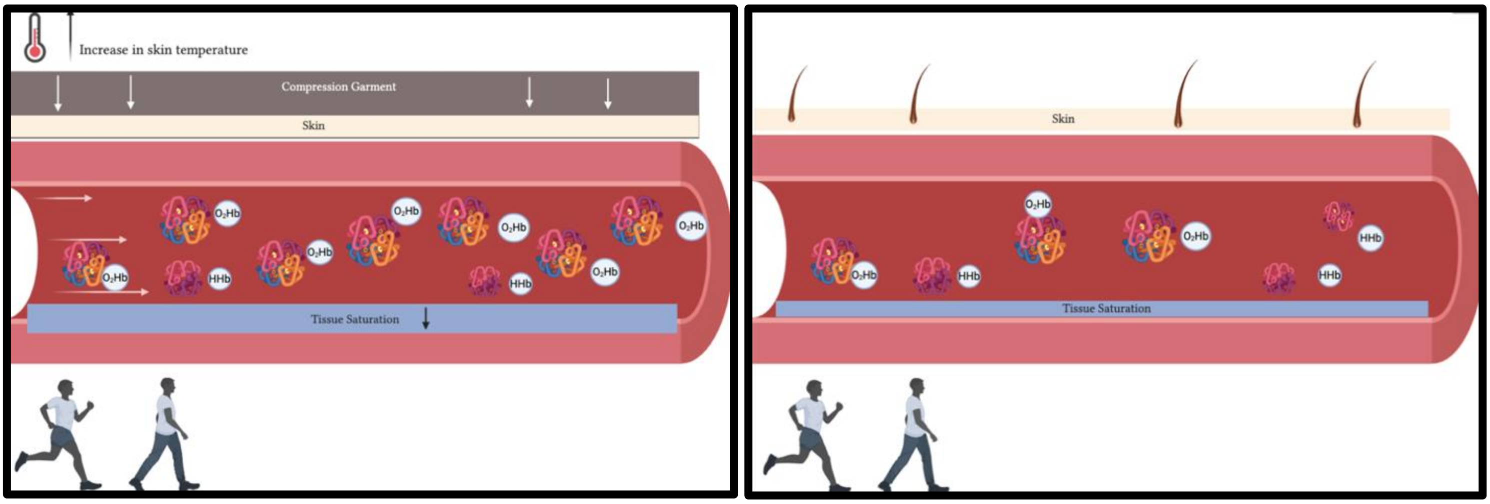


Figure 8.1. Schematic illustration of the influence of compression on the hemodynamic response of oxyhaemoglobin and deoxyhaemoglobin during walking and running exercises.

A decrease in tissue saturation in the muscle has been commonly linked with greater levels of oxygen being consumed (Babior and Stussel, 1994). The added effect of compression potentially can accelerate this mechanism of improving the oxyhaemoglobin binding process (**Figure 8.1**). It is of course too early to make assumptions on the implications for future sporting performance and recovery from the current set of data. However the findings suggest that bespoke compression tights can be used to help improve oxygen utilisation in the gastrocnemius and vastus lateralis. Future studies should look at using exercise protocols to outline further understanding in how muscle oxygenation may alter using compression tights.

A key limitation to **Chapter 5** is that participants did not exert themselves through an exercise protocol, and therefore were not subjected to physiological responses that would occur through the recovery process following intense exercise.

8.2.3 Effects of Bespoke Compression Profiles on Perceptual Responses

Athlete comfort when wearing compression is of key importance especially if athletes need to wear them for prolonged periods. To date there has been no research that has provided data on comfort levels while wearing a wide range of compression profiles in stationary positions. Graduated designs are commonly used to optimise physiological responses such as improving venous return, however, there has been minimal research on uniform and reverse graduated designs. The purpose of this pilot chapter observed that the reverse graduated design to be the least comfortable garment to wear across all examined traits (*comfort, knee fitting, ankle fitting, compression*). The chapter observed that graduated, uniform and control garments were more favorable in comfort, this could be down to participant familiarity of the compression profile that was applied through the respected trials. **Table 8.2** summarises different levels of compression and comfort levels. Location of pressure, familiarity in wearing and level of compression are key components that influence comfort. When participants have worn graduated compression ranges of 7.2 to 24mmHg, they have reported the garments to be comfortable (Ali et al., 2011; Faulkener et al., 2013; Rugg and Sternlicht 2013). When compression pressure is closer to 30 mmHg, participants have expressed levels of discomfort (Ali et al., 2011). Future bespoke compression designs should take this into consideration when manufacturing garments with higher levels of compression, anything higher than 25 mmHg could potentially be uncomfortable for participants and potentially deter athletes from future use.

Table 8.2. Comfort outcomes in compression profiles and pressures.

Author	Compression profile and pressures	Outcome
Chapter 6	Graduated Compression Tights: ***Ankle***: 19.5 mmHg ***Calf***: 18.2 mmHg	Comfortable
Lucas-Cuevas et al., (2017)	Graduated Compression Stocking: ***Ankle***: 24 mmHg ***Calf***: 21 mmHg	Comfortable
Rugg and Sternlicht (2013)	Graduated Compression Tights: ***Ankle***: 18.0 mmHg ***Calf***: 12.6 mmHg ***Thigh***: 7.2 mmHg	Comfortable
Ali et al., (2011)	Graduated Compression Stocking:	
	Low Pressure Profile: 12- 15 mmHg	Comfortable
	Medium Pressure Profile: 18 – 21 mmHg	Comfortable
	High Pressure Profile: 22- 32 mmHg	*Uncomfortable*
Faulkener et al., (2013)	Compression Tights: ***Calf***: 20.7 mmHg	Comfortable
Chapter 6	Reverse graduated profile: ***Thigh***: 17.6 mmHg **Calf**: 12.5 mmHg	*Uncomfortable*

8.2.4 Effects of different compression profiles on muscle oxygenation and haemodynamic responses

The fourth study (***Chapter 7***) of the thesis built upon earlier understanding from ***Chapter 5*** in relation to haemoglobin responses when using bespoke compression tights. The study investigated at varying the compression profile within 4 garments. The study was able to provide suitable compression profiles for the Reverse, Control, Graduated and Uniform Compression garment. This is the first study that has experimented on using new compression profiles. Participants undertook low intense activities such as laying in the decubitus position, 75 degree head up tilt position and standing, each for approximately 20-40 minutes.

Ejection fraction increased in the tilt position in graduated and uniform compression profiles ($P<0.05$). No other haemodynamic responses were observed, this could be down to the lower level of compression that was observed. The compression profiles for this study were higher in comparison to the first and second study (***Chapter 4*** and ***5).*** The graduated compression profile in ***Chapter 4*** and ***5*** ranged from *12.1* mmHg - *7.1* mmHg in comparison to the graduated compression profile in ***Chapter 6*** that ranged from, 19.7 mmHg - 6.0 mmHg. The study opted for a new compression method assessment in comparison to ***Chapter 4*** and ***5*** to which 6 landmarks were assessed. Compression was assessed at approximately 5 cm increments on the posterior aspect of the leg and identified 10 landmarks. This new method adopted by Ashby et al., (2021) identifies that the posterior structure of the leg to be denser in allowing a smaller variation in mmHg, it also provides an opportunity to assess more anatomical landmarks.

Research has outlined that skin temperature will increase through the application of compression tights (Priego et al., 2015). The increase in skin temperature presents a dilating effect to superficial vessels within the limb, this subsequently can alter venous pressure and present a better opportunity for the body to utilise oxygen. The greatest oxyhaemoglobin concentration changes were observed in the decubitus position through using a graduated compression garment (decubitus: 3.2 ± 9.0 ΔµM; tilt position: 3.7±2.6 ΔµM), this occurred at the gastrocnemius (*P*<0.05). A difference was observed in deoxyhaemoglobin responses where the graduated profile increased concentration changes the most in contrast to other garment and no garment trials (P<0.05). Similar trend in chapter 5 was observed where deoxyhaemoglobin changes increased in the sitting (*P*=0.07) and walking (*P*=0.03). This can suggest that a graduated profile could be beneficial in influencing muscle oxygenation in the gastrocnemius.

Predominantly the gastrocnemius was the main muscle that was effected through the use of newer compression profiles with increases of oxyhaemoglobin changes from the baseline (Uniform: +1.3 to 5.7 ΔµM; Reverse; + 1.0 to 2.8 ΔµM) in the protocol, this was supported in similar results in ***Chapter 5***.

The Control Garment (+0.5 to 2.2 ΔµM) which had a similar compression profile to the graduated compression tights in ***Chapter 5*** also increased oxyhaemoglobin responses in the vastus lateralis across the protocol.

The activities involved in the study are predominately chosen as they allow the physiological responses to be determined when recovery and different compression profiles. The Reverse Graduated (- 0.86 to – 4.2 ΔµM) compression garment provided no influences on oxyhaemoglobin responses in the vastus lateralis across the protocol in contrast to no garment (P>0.05).The Reverse Graduated garment could have potentially hindered the efficiency of venous blood flow thus influencing the oxygen utilisation process. A very similar trend to ***Chapter 5***, ***Chapter 7*** demonstrated that tissue saturation in the gastrocnemius muscle would decrease from the use of compression in comparison to the no garment trial, this was observed in the standing position (*P*<0.05). Saturation varied from 57.8% to 58.6% in all compression profiles apart from the Reverse

Graduated Garment which observed an increase of 71.5±7.6 % which was greater than the no garment trial (63.3±8.6%).

Participants in the present study were asked to remain stationary throughout activities, this effectively will enhance NIRS reliability. As discovered in ***Chapter 4***, reliability of NIRS will decrease when participants perform higher bouts of motion and activity. The transition in activities in the trial could potentially influence oxygenation responses especially going from a head up tilt position to standing position, subsequently this is due to the dramatic change in hydrostatic pressure through the change in gravity acting on blood flow. However, the data was recorded over a prolonged period to allow for this.

8.2.5 Summary of results

Bespoke compression garments were used throughout the whole of the thesis. In 3d scanning participants, each individual was able to wear bespoke garments that were fitted for their own individual body composition. Overall, the findings of the study highlighted that compression does influence oxygenation responses in a range of recovery specific activities.

After reviewing the pressure profile in **Chapter 4** and **5** studies, modifications were able to be made with the manufacture in increasing the compression profile. **Chapter 7** observed increases in compression and provided the ideal profiles for the varied compression tights made. The main assessment method of muscle oxygenation was using NIRS. NIRS assessment method provide good levels of reliability between trials. It is clear that there a benefits in wearing compression especially in enhancing oxygenation responses.

8.3. General Discussion

The following discussion looks to conclude some key findings from the literature and the present research provide further insight into the physiological mechanisms that occur when wearing bespoke compression tights.

8.3.1 Compression Profile

To our knowledge this is the first study that has scanned individuals leg geometry and manufactured made to measure compression. Manufacturing bespoke compression garments is difficult and this is down to the differences in individuals unique body shape.

Without an understanding towards the design of a garment it is difficult to understand the potential physiological benefit. Some research has identified increases in oxygenation through higher levels of compression but failed to clarify the compression profile which if stated could provide a stronger understanding towards the actual response mechanisms (Reich-Schupke et al., 2017).
Assessing compression is of key value especially in understanding the influence of compression garments. ***Chapter 5*** observed high levels of compression using compression socks, this resulted in varied responses for oxyhaemoglobin and deoxyhaemoglobin. Interestingly the oxygenation response could be influenced by the overall compression profile across the limb subsequently enhancing venous return. Brophy-William et al. (2015) and Ashby et al. (2021) have both provided different methods for assessing compression. Brophy-Williams et al. (2015) compression assessment profile is effective and provides an indication of the compression profile and was used within ***Chapter 4*** and ***5***. The Brophy-Williams et al. (2015) model looks at assessing compression across six anatomical landmarks within the anterior aspect of the lower and upper extremity of the limb.

However, the general structure of the anterior aspect of the limb makes it difficult to get consistent readings due to the spongy nature of the limb. Ashby et al. (2021) devised a method that used 10 landmarks on the posterior aspects of the limb. ***Chapter 6*** and ***7*** adopted Ashby et al. (2021) in assessing compression profile. More compression readings across the limb provided a better understanding of the level of compression and provided clarity in the design of the profile. The Pico Press and Kikuhime Pressure Monitor are standard devices that are used within the field of sports and exercise medicine that are primarily used in assessing compression (Ashby et al., 2021; Brophy-Williams et al., 2015; Oficial et al., 2017). **Chapter 4, 5**, and **6** only assessed compression within one limb, it is recommended that future research should assess both limbs. Participants in general are commonly likely to have differences within limb geometry (Ashby et al., 2021). This potentially could mean differences within physiological responses especially when assessing localized muscle oxygenation responses.

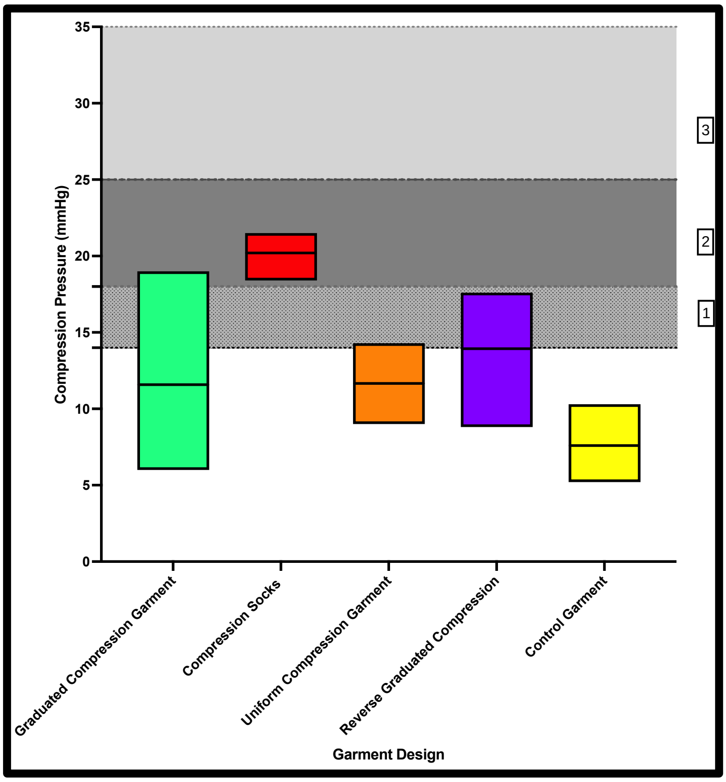


Figure 8.2. Compression pressures ranges (mmHg) across different garment designs in comparison to the different levels of medical classification throughout the thesis.

Chapter 4 and ***5*** provided a low-level graduated profile and ***Chapter 6*** provided a higher-level graduated profile. Both compression profiles resulted in increases in oxyhaemoglobin within the gastrocnemius and vastus lateralis. The compression profiles design objectives were met, however a small limitation to the compression profiles would suggest that the pressures were lower than expected (**Figure 8.1**). Compression pressures of 30 + mmHg have commonly been associated with greater physiological changes (Lee et al., 2021; Sperlich et al., 2011). **Table 8.1**, summarises different types of compression profiles and the key physiological responses that were affiliated within the thesis. The strength of the current study outlines that lower level graduation can still have the same effects as higher graduated designs, the practicality for this is that athletes do not have to wear higher levels of compression that they may find uncomfortable as wearing a lower pressured graduated can still aid oxygenation responses. The outcome to the research in this thesis has made suggestions that the compression profile of a garment is needed to be assessed in comparison to just randomised higher levels of compression.

8.3.2 Tissue Saturation responses when wearing compression

Figure 8.3 provides a visual representation of tissue saturation in skeletal muscle with the application of different bespoke compression garments throughout different activities. Tissue saturation is the amount of oxygen that is layered within the muscle and is represented in a percentage format. Some literature has found that tissue saturation will decrease using compression (Born et al., 2015; Rennerfelt et al., 2019). It is clear through ***Chapter 4***, ***5*** and ***7*** that tissue saturation will vary depending on the activity that is involved. Most of the research that assesses muscle oxygenation will often use TSI as the main predominant finding. However, tissue saturation does not necessarily highlight the full picture in terms of involvement within the ATP production process. At a molecular level tissue saturation is constantly changing and the trade off in the ATP process can change at a quick rate (Rodriguez et al., 2019). This trade off can be influenced by the demand of oxygen which can be determined by the intensity and activity to which an individual is working at.

Interestingly ATP utilisation is higher in the last stages of exercise in comparison to the start (Bangsbo et al., 2001). Bangsbo et al. (2001) also outlined that ATP production in concentric exercise to be lower in mechanical efficiency in contracting muscles. Research has also shown that muscle oxygen uptake and energy turnover is higher when there is more contractile engagement within the muscle (Ferguson et al., 2001). With this in mind, assessing oxygenation levels can be difficult due to ever changing muscle contractile patterns that occur through exercise.

8.3.3 Activities

Different activities and positions will change haemodynamics this is due to the demand and utilisation of ATP to help within skeletal muscle fibre engagement. The demand for ATP and oxygen will constantly change due to metabolic demands, and because of this the balance of O_2Hb and HHb will constantly change within the blood to assist in sustaining ATP utilisation.

Figure 8.3, outlines the different level of responses in O_2Hb, HHb and TSI through different types of compression garments during a wide range of activities in the gastrocnemius that have occurred in this thesis. The seating activity observed higher values of oxyhaemoglobin in the compression socks. This could be down to the mechanics of the seating position forcing more venous pressure within the gastrocnemius, this pressure increase is potentially due to the higher levels of constriction at the knee where the compression sock sits. Compression socks also further increased deoxyhaemoglobin responses during both walking and jogging activities. The findings potentially suggest that higher levels of intense activity may mean a greater response in oxygenation, this is due to the increase in oxygen that is needed to fuel ATP and engage in muscle contraction.

Higher levels of engagement at the muscle will warrant more interaction between oxy and deoxyhaemoglobin production, again this response is due to the new demands of the activity. Contrastingly a recent study assessed the effects of high intense interval exercise on muscle (*vastus lateralis*) and cerebral oxygenation and concluded reductions in oxyhaemoglobin were observed without the use of compression (Perentis et al., 2021). Manchado-Gobatto et al. (2020) also observed a decrease in tissue saturation while participants performed high intense exercise. Even though the present thesis did not apply an intense exercise protocol it was apparent that through walking and jogging, there potentially could be benefits to using compression tights to aid oxyhaemoglobin responses further and reduce tissue saturation.

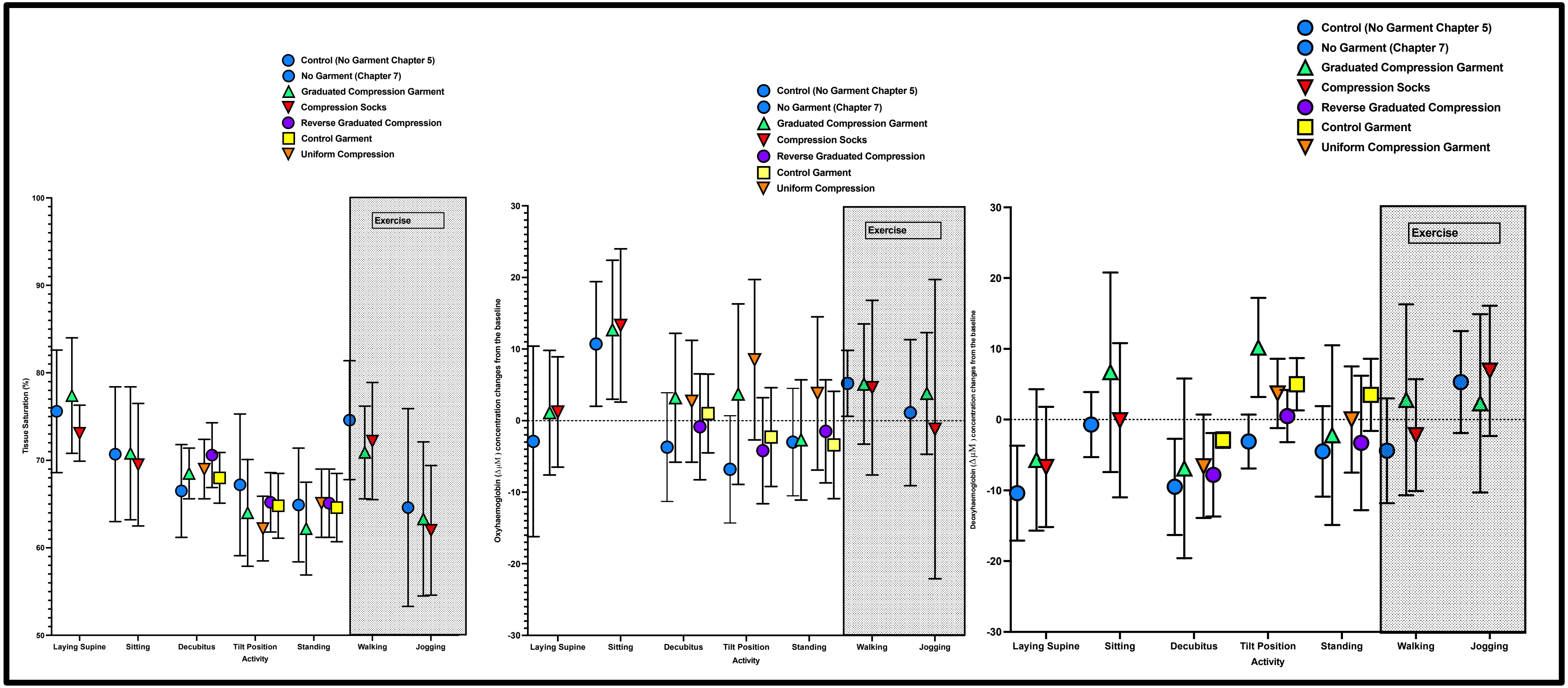


Figure 8.3. Tissue saturation, O_2Hb and HHb responses within the gastrocnemius (overall mean and SD) through different types of activities with the use of different types of compression profiles used across the thesis. *Shaded area indicates exercise.

During stationary activities the higher graduated compression profile observed higher responses in deoxyhaemoglobin (**Figure 8.3**). Post exercise, in the seating position, ***Chapter 5*** outlined that oxyhaemoglobin responses increased. Through no compression, oxyhaemoglobin responses have been shown to increase post cycling exercise (Stocker et al., 2016). With the application of no compression, Stocker et al. (2016) outlined that oxyhemoglobin values ranged from 1.09 ± 1.32 μmol. 30 secs to 6.34 ± 1.88 μmol. 90 seconds post exercise performance in the vastus lateralis. In comparison after the jogging phase (**Chapter 5**), the no garment trial (4.2±4.6 μmol) provides similar responses across 20 minutes. Interestingly, **Chapter 5** observes that oxyhaemoglobin responses are greater post exercise in comparison to the application of no garment in Stocker et al., (2016) oxygenation responses. The information is not fully comparable due to the differences in experimental protocol between both studies, however it offers another an insight into the potential benefit of bespoke compression tights.

Participants have seen declines in oxyhaemoglobin responses when exercising to exhaustion. Oueslati et al., (2018) assessed oxygenation responses with participants cycling to exhaustion during 75-85% of max work load (*MWL*). The study reported values in the vastus lateralis of O_2Hb (*85*% *MWL*-20.2 ± 3.6 μmol; *75%* -13.0 ± 4.3μmol) and an increase of HHb (85% MWL, 14.0 ± 3.9 μmol; 75% 14.0 ± 4.8 μmol). It is clear that when the rate of intensity becomes too high the body cannot match the demands thus showing a decline of oxyhaemoglobin from the baseline. Future experimental protocols should look to use bespoke graduated and uniform profiles to observe if there could be any improvements in oxygenation responses through a time to exhaustion protocol.

In the standing position Agu et al. (2004) observed higher oxyhaemoglobin responses through higher levels of compression (***Class III; ankle pressure***; 29.1±0.8 mmHg; ***calf pressure*** 14±1.0 mmHg) in comparison to lower levels of compression (***Class I***; ***ankle pressure***; 16.8±0.4 mmHg;

calf pressure 11.2 ± 0.9 mmHg). With the use of compression stockings, *class I* produced 10.2± 2.8 μmol in comparison to class III which increased to 12.0 ± 2.2 μmol, this was both higher than the no stocking trial (10.2±3.2 μmol). ***Chapter 6*** observed an increase of 3.8±10.7ΔμM with oxyhaemoglobin through the use of a uniform compression garment, subsequently this was the only compression garment that observed a positive response from the baseline. Through NIRS analysis, Agu et al. (2004) provided higher oxyhaemoglobin readings but this can be put down to higher levels of compression at the ankle and the fact that participants were wearing a compression stocking. It is also worth noting that participants within Agu et al. (2004) study had venous insufficiencies.

Interestingly Agu et al. (2004) also observed a decrease in deoxyhaemoglobin responses in comparison to the use of no garment (10.7±2.2 μmol) with higher levels of compression. *Class III* reported deoxyhaemoglobin values of 6.38±2.7 μmol) in comparison to a higher deoxygenation response of 8.9±2.7 μmol in the *Class I* stocking. Agu et al. (2004) study outlined that compression stockings enable the muscle to utilise oxygen more effectively especially when compression increases and when participants are standing. In similar to Agu et al., (2004) research, ***Chapter 6*** observed a decreases of deoxyhaemoglobin in the no garment trial (-4.5±6.4 ΔμM), control garment (standing, -2.1±5.1 ΔμM), reverse graduated compression garment (*standing;* -3.3±9.5ΔμM), graduated compression profile (*standing*; - 2.2±12.9 ΔμM). In contrast the uniform profile (0.01 ± 7.5ΔμM) provided a slight increase in deoxyhaemoglobin through compression tights. This could potentially provide further evidence that a bespoke compression profile can influence oxygenation responses greater than the use of compression socks or stockings.

With no garment, Smith and Billaut, (2010) observed oxyhaemoglobin concentration changes to decrease (***approximate range***, -7.0 μmol - -15.0 μmol) and deoxyhaemoglobin responses to increase (***approximate range***, 2 μmol- 17.0 μmol) whilst participants performed 10 intermittent sprints on a cycle ergometer. Smith and Bilaut (2010) concluded that muscle oxygenation decreases rapidly as sprinting begins but also begins to plateau the further into the exercise. Findings in ***Chapter 5*** has shown that oxyhaemoglobin responses increase further during a recovery jog especially in comparison to no compression. In the gastrocnemius, oxyhaemoglobin (CT: 3.8±8.5 ΔµM : C:1.1±10.2 ΔµM: d=0.29, small effect): responses were greater when using compression tights through the recovery jog, subsequently deoxyhaemoglobin changes (CT: 2.3±12.6 ΔµM: C: 5.3±7.2 ΔµM: d=0.29, small effect) were lower in contrast to the control trial, suggesting that compression helps oxygen utilisation. Further research would benefit from assessing muscle oxygenation responses through using compression especially when participants exercise at high intensities such as intermittent sprinting.

In high-intense exercise, whole body compression garments (WBCG) have shown to increase tissue saturation through a 45-minute session in comparison to no garment (overall mean and SD, ***control***, 53.5±8.3 %; ***WBCG***, 55.8±7.2 %) the vastus lateralis (Sear et al., 2010). Without compression, Muthalib et al. (2010) observed minimal differences in tissue saturation in 10-second isometric contractions when assessing 30% of maximal voluntary contraction (***TSI range***, 57.5±5.9% - 58.3±4.9%) and 100% maximal voluntary contractions (***TSI range***, 58.0±5.4%- 59.1- 4.4%) in the biceps brachii. The duration of the activity will place further stress on the ATP demands, thus impacting oxygen consumption. During ice skating, tissue saturation responses in the quadricep provided minimal differences between compression and no compression (Born et al., 2004). Even though there were no significant differences, compression (***TSI range***, 78.7±7.5%- 85.6±5.3%) mean and SD values were slightly smaller in comparison to the no garment trial (***TSI range***, 79.1±7.5 %- 86.5±4.8%). **Chapter 5**, also observed reductions in tissue saturation, in comparison to Sear et al., (2010), oxygenation was assessed in the 1st, 3rd and last minute of performance in a 3000-m ice race simulation suggesting that the intensity of activity would influence oxygen utilisation. The increase in ATP production needed for performance would suggest higher levels of oxygen are being utilised thus showing a reduction in saturation at the muscle, this mechanism occurs to help sustain performance at different levels of intensity.

8.3.4. Haemodynamics

Chapter 7 did observe an increase in ejection fraction responses through wearing a graduated compression profile, this was observed in the tilt position ($P<0.05$). The theory behind a graduated profile is to improve venous return to the heart, with the increase amount of oxygenated blood that is being pumped per beat could suggest that the body can use oxygen more effectively thus coinciding with an improved deoxyhaemoglobin response that was also observed in the tilt position in both the gastrocnemius and vastus lateralis ($P<0.05$). A limitation to the data is the amount of participants, however future research should be encouraged that a bespoke graduated design does favour positive cardiovascular responses for athletes.

8.4 Limitations

The current thesis must acknowledge a number of limitations throughout each chapter and study:

8.4.1 No exercise and recovery protocol

The thesis assessed a wide range of recovery like activities. However there was no exercise protocol that would enable participants to fully experience recovery. This means it is difficult to make concrete claims that compression influences muscle oxygenation post exercise. Participants did perform some exercise in ***Chapter 4*** and ***5*** as they performed a recovery jog, but participants did not engage in moderate or intense exercise. This suggests that future studies should look to apply exercise specific protocols with the application of bespoke graduated compression tights and assess oxygenation changes post exercise.

8.4.2 Participants

The cohort of participants for the thesis can be generalized as healthy active males. It is therefore difficult to make claims that these responses would occur for other populations. Further research should look at different levels of athletes. Trained athletes will potentially have a greater ability to utilize oxygen in the muscles and thus needs further investigation. Research in the past has assessed oxygenation levels with older participants who have vascular insufficient conditions (Agu et al., 2004). Participants improved limb oxygenation through higher levels of compression (Agu et al., 2004). This potentially suggests there is further room for investigation within different populations within the medical and sports and exercise settings. The number of participants was small, this was again due to the complications of Covid-19 and recruiting participants whilst maintaining health and safety standards. It is hard to generalize the findings within the whole population, however it is clear that there are some benefits in using bespoke compression tights.

8.4.3 Compression Pressure

The present thesis identified that compression profiles were suitable for specific compression garments, however the level of compression did fluctuate between participants. Ideally the Uniform and Graduated profiles would have observed higher pressures throughout the limb. As identified through the discussion, higher pressures have observed physiological responses. Even though the profiles in ***Chapter 5*** and ***6*** provided oxygenation responses, it would have been of good value to have higher values in compression to see if there are optimum amounts of pressure that exert an equal optimum response in improving oxygen within the muscle. Higher values of compression have been commonly associated with increases in tissue saturation. The strengths of the study were the advancement in making bespoke compression tights for participants. The evolution in technology enabled this study to produce a compression profile template for each participant. It is clear that there are factors such as material, posture can impact the compression profile for participants. When making bespoke compression tights future research should look at multiple participant scans as this may encounter for future morphological changes. Another consideration could be to have a shorter "window" in which scans, manufacturing of the garments and testing could be performed.

8.4.4 Blood Flow

The initial plans of the thesis was to use a laser doppler to assess blood flow within the gastrocnemius and the vastus lateralis. However due to reliability issues of the device, the method of blood flow assessment was eradicated. In assessing muscle oxygenation changes, blood flow would have been ideal especially in making key connections between the relationship of venous pooling and concentration changes of oxygen.

8.4.5 Adipose Tissue Thickness

The reliability of the NIRS is dependent on the amount of adipose tissue thickness that it must enter through. Van Beekvelt et al. (2002) has identified that tissue thickness over 10mm can potentially hinder NIRS assessment of skeletal muscle tissue. ***Chapter 4*** ,***5*** and ***7*** gastrocnemius ATT values met Van Beekvelt's et al. (2002) guidelines. The vastus lateralis (***Chapter 4*** and ***5***) was slightly over 10mm, however NIRS reliability was good throughout all oxygenation responses. The participants in the studies represented a small sample of individuals from varied sports with trained backgrounds, subsequently this helped a reduction of ATT observed at both muscle groups.

8.4.6 NIRS set up

Like any NIRS device the initial set up can set a trend for misinterpretation of data. A key set up with the NIRS is that the data is based on oxygenation responses from the baseline. If participants come into a trial from some form of physical activity then unfortunately this could impact oxygenation levels due to the already higher level of hemoglobin binding engagement. Some protocols have not outlined participants to sit and remain restless. This process is important especially when applying a garment after the baseline, the limitation to the majority of the research is the clarity in how the NIRS has been used and this should be addressed within future research especially in order to gain consistent readings. The majority of research within using NIRS does not outline how they assess predominate changes from the baseline. The only recent evidence to provide information to there NIRS analysis, was through a study assessing changes in oxygenation through cycling, eccentric and concentric exercise (Perentis et al., 2021). For our baseline, each participant would sit still for 5 minutes, this would help provide some control over each trial and determine that any oxygenation response observed were from a resting condition.

8.5. Strengths of the thesis

The research provided in the current thesis provided novel work. At present there is no research that has been able to manufacture bespoke compression tights. The manufacture of a bespoke compression tight is a strength as it enables the garment to be tailored to the body composition of the individual, this enables approaches in research to be more effective as any mechanisms or responses of the garment are specific to the individual. The ability to manufacture bespoke compression garments has also meant that different compression profiles have also been able to be designed. The use of the NIRS has also been a strength towards the thesis, this is because the device is non-invasive and this helps the practicality of this instrumentation to be used in a wider setting.

8.6. Practical Implications

The practical implications of the thesis outline that bespoke compression garments potentially are more effective than standardized compression garments, and further importance should be drawn to the compression profile especially when assessing key responses. The implications moving forward should also observe that a graduated profile to be more favourable in improving oxygenated responses, this could potentially lead to improve recovery mechanisms from exercise.

8.7. Conclusion and Future research

The purpose of the current thesis was to provide further understanding of the oxygenation responses to bespoke compression garments. The thesis determined that good reliability shows for a Near-infrared Spectroscopy assessing oxygenation using bespoke compression garments.

The studies conclude that bespoke graduated compression tights aid the bodies ability to utilise oxygen within the gastrocnemius and the vastus lateralis. The objectives of this thesis were to provide further understanding in oxygenation responses with the use of bespoke compression garments.

At present there has been minimal research that looked at the underlying physiological responses with the application of bespoke compression tights and the potential differences within different compression profiles. Future research should begin to look at the following:

- The effects of running economy and muscle oxygenation responses through the application of bespoke graduated and uniform compression tights. The thesis identified that Uniform and Graduated profiles can influence muscle oxygenation responses. Applying a running economy specific protocol will be provide further insight between the connection of these hemodynamic responses and the influence within a performance setting.

- Administering a recovery specific protocol from exercise will hopefully provide a greater understanding towards how different compression profiles will change muscle oxygenation responses. The current thesis has outlined different types of compression and their influence on oxygenation responses, subsequently this was through dynamic exercise and some form of stationary activities.

- Upper extremity compression garments have recently become popular within sports such as basketball, this due to the athletes perceptual responses on technical tasks such as shooting. With this in mind, future research should look at muscle oxygenation responses within compression sleeves and begin to generalize an idea in how they can contribute to performance. In providing a greater understanding towards oxygenation responses through different sporting actions, sports scientists can benefit from how compression sleeves can be utilised specifically for contributing to the success of performance.

Chapter 9 References.

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Chapter 10: Appendices.

Appendices

Appendix 1: Participant Information Sheet, Health Screening, Ethical Application

A1: Reliability of Near-infrared Spectroscopy with and without compression tights

A1: The Effects of Compression Tights and Socks on muscle oxygenation

A2: The Effects of Different types of Compression on muscle oxygenation and cardiac output

Appendix 2: Data collection sheets

A21: Reliability of Near-infrared Spectroscopy with and without compression tights

A21: The Effects of Compression Tights and Socks on muscle oxygenation

A22: The Effects of Different types of Compression on muscle oxygenation and cardiac output

Appendix 1 (edit as appropriate)

Participant Statement of Consent to Participate in the Investigation Entitled:

The effect of different levels and types of compression on cardiac output and muscle oxygenation

1) I, ____________________ 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 Brett Biddulph, James Donaldson, Dr Caroline Sunderland and/or Dr John Morris that this will involve me completing 4 separate trials assessing cardiac output measurements and oxygenation whilst wearing compression garments.

3) It has also been explained to me by Brett Biddulph, James Donaldson, Dr Caroline Sunderland and/or Dr John Morris that the risks and side effects which may result from my participation are as follows:
   - There may be some discomfort when performing the skin fold assessment. This assessment may leave bruising of the assessed location.
   - Slight skin irritation when applying the NIRS device.

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 health questionnaire form 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.

11) I confirm that I am aware that I need to complete a COVID19 symptom questionnaire prior to every trial in the study / visit to the University's research facilities.

12) It has been explained to me that there may be additional risks arising from the current COVID pandemic. I have read the participant information and undertake to abide by the special measures which have been explained to me for this study together with such Government Guidelines that are at the time prevailing.

Participant signature: Date:

Independent witness signature: Date:

Primary Researcher signature: Date:

*When completed: 1 for participant; 1 for researcher site file; 1 to be kept in medical notes (if appropriate).

Health screen

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 Yes ☐ No ☐ Month?

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.)

COVID-19 Symptom Questionnaire

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. ☐

Participant Information Sheet

The effect of different levels and types of compression on cardiac output and muscle oxygenation

Invitation and brief summary

- Brief Introduction: Many athletes use compression garments to aid them in performance and recovery. There are clear findings to suggest that different types of garment can improve recovery and performance. However, how these garments improve performance and recovery is still unproven. This study is particularly focused on whether oxygenation is altered by wearing compression garments. Therefore the purpose of the study is to provide further information on whether compression garments alter blood flow, muscle oxygenation and cardiac output.

- Study Requirements: Participants will be recreationally active. Participants will be healthy and between the age of 18- 45 years.

- Location: ISTEC Physiology Lab, 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 24 hours prior to the trials.

Experimental design:

You will be required to visit the lab on 6 occasions: The first will be a preliminary visit, then there will be a familiarization visit and visits 3-6 will be the main trials. During these trials, in a randomized order you will wear 3 different types of compression tight and in 1 trial you will wear a control or no compression garment.

Preliminary visit

You will have a non-invasive 3D scan taken to allow the production of your compression garments. In addition, the non-invasive equipment that we are using during the study, near infra-red spectroscopy and Ultrasound will be shown to you and further details provided. You will be able to ask any questions you may have.

Familiarisation visit

You will complete the protocol with no intervention. Cardiac output by ultrasound and muscle oxygenation by near infra-red spectroscopy will be assessed for you to understand the proceedings and you will complete all aspects of the protocol.

Main Trials (5)

You will complete 5 main trials separated by at least one day in a randomized fashion. Each trial will compromise the same repeated protocol (see below). E.g. First trial - wearing Uniformed compression tights. Second trial- wearing graduated compression tights. Third trials - no compression garment. Fourth trial- higher levels of compression

Below is the protocol which you will complete during each main trial visit.

Preliminary Testing Stage (Approx 10 minutes)

The following will take place on arrival at the lab:

- Urine Sample
- Body Weight
- Skin Fold Measurements- gastrocnemius (calf muscle) and the vastus lateralis (quadriceps muscle)
- Attach the portable Near Infrared Spectroscopy Device on the vastus lateralis (quadriceps) and gastrocnemius (calf) muscle belly. It is then the data becomes live and is exported to the computer via bluetooth.
- Put made to measure compression tights on.

Activity 1. Lying on your side

- You will lie on your side for 20-45 minutes, during which time heart rate, blood pressure and cardiac output will be measured.
- Towards the end of the 45 minutes a device for measuring the pressure of your garment will be pulled up the back of your leg.

Activity 2. Tilt position

- You will lie on a tilt table for 20-45 minutes at an angle of 75°, during which time heart rate, blood pressure and cardiac output will be measured.
- Towards the end of the 45 minutes a device for measuring the pressure of your garment will be pulled up the back of your leg.

<u>Activity 3. Standing</u>

- You will stand up for 20-45 minutes, during which time heart rate, blood pressure and cardiac output will be measured.
- Towards the end of the 45 minutes a device for measuring the pressure of your garment will be pulled up the back of your leg.

All testing will be completed 2 hours after eating. Test timings will remain consistent across the 5 trials for reliability purposes.

Potential Benefits to You:

- To understand the impacts of compression garments and how they potentially could influence recovery from sport.
- Given made to measure compression.

Potential Risks to You:

- There may be some discomfort when performing the skin fold assessment. This assessment may leave bruising of the assessed location.
- Slight skin irritation when applying the NIRS device.
- 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.

You are free to withdraw from the study at any time, without providing a reason. If at any point you decided to withdraw from the study your data will be destroyed.

Contacts:

Brett Biddulph: brettbiddulph@nottinghamcollege.ac.uk
Mr James Donaldson james.donaldson@ntu.ac.uk
Dr Caroline Sunderland: caroline.sunderland@ntu.ac.uk 0115 8486379
Dr John Morris: john.morris@ntu.ac.uk

Appendix 2

Participant Statement of Consent to Participate in the Investigation Entitled:

The effect of different levels and types of compression on cardiac output and muscle oxygenation

1) I, ____________________ 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 Brett Biddulph, James Donaldson, Dr Caroline Sunderland and/or Dr John Morris that this will involve me completing 4 separate trials assessing cardiac output measurements and oxygenation whilst wearing compression garments.

3) It has also been explained to me by Brett Biddulph, James Donaldson, Dr Caroline Sunderland and/or Dr John Morris that the risks and side effects which may result from my participation are as follows:
   - There may be some discomfort when performing the skin fold assessment. This assessment may leave bruising of the assessed location.
   - Slight skin irritation when applying the NIRS device.

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 health questionnaire form 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.

11) I confirm that I am aware that I need to complete a COVID19 symptom questionnaire prior to every trial in the study / visit to the University's research facilities.

12) It has been explained to me that there may be additional risks arising from the current COVID pandemic. I have read the participant information and undertake to abide by the special measures which have been explained to me for this study together with such Government Guidelines that are at the time prevailing.

Participant signature: Date:

Independent witness signature: Date:

Primary Researcher signature: Date:

*When completed: 1 for participant; 1 for researcher site file; 1 to be kept in medical notes (if appropriate).

Health screen

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 Yes ☐ No ☐ Month?

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.)

____

____

____

____

COVID-19 Symptom Questionnaire

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. ☐

Participant Information Sheet

Study 3. The effect of different levels and types of compression on cardiac output and muscle oxygenation

Invitation and brief summary

- Brief Introduction: Many athletes use compression garments to aid them in performance and recovery. There are clear findings to suggest that different types of garment can improve recovery and performance. However, how these garments improve performance and recovery is still unproven. This study is particularly focused on whether oxygenation is altered by wearing compression garments. Therefore the purpose of the study is to provide further information on whether compression garments alter blood flow, muscle oxygenation and cardiac output.

- Study Requirements: Participants will be recreationally active. Participants will be healthy and between the age of 18- 45 years.

- Location: ISTEC Physiology Lab, 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 24 hours prior to the trials.

Experimental design:

You will be required to visit the lab on 6 occasions: The first will be a preliminary visit, then there will be a familiarization visit and visits 2-6 will be the main trials. During these trials, in a randomized order you will wear 3 different types of compression tight and in 1 trial you will wear a control or no compression garment.

Preliminary visit

You will have a non-invasive 3D scan taken to allow the production of your compression garments. In addition, the non-invasive equipment that we are using during the study, near infra-red spectroscopy and Ultrasound will be shown to you and further details provided. You will be able to ask any questions you may have.

Familiarisation visit

You will complete the protocol with no intervention. Cardiac output by ultrasound and muscle oxygenation by near infra-red spectroscopy will be assessed for you to understand the proceedings and you will complete all aspects of the protocol.

Main Trials (4)

You will complete 4 main trials separated by at least one day in a randomized fashion. Each trial will compromise the same repeated protocol (see below). E.g. First trial - wearing Uniformed compression tights. Second trial- wearing graduated compression tights. Third trials - no compression garment. Fourth trial- higher levels of compression

Below is the protocol which you will complete during each main trial visit.

<u>Preliminary Testing Stage (Approx 10 minutes)</u>

The following will take place on arrival at the lab:

- Urine Sample
- Body Weight
- Skin Fold Measurements- gastrocnemius (calf muscle) and the vastus lateralis (quadriceps muscle)
- Attach the portable Near Infrared Spectroscopy Device on the vastus lateralis (quadriceps) and gastrocnemius (calf) muscle belly. It is then the data becomes live and is exported to the computer via bluetooth.
- Put made to measure compression tights on.

<u>Activity 1. Lying on your side</u>

- You will lie on your side for 45 minutes, during which time heart rate, blood pressure and cardiac output will be measured.
- Towards the end of the 45 minutes a device for measuring the pressure of your garment will be pulled up the back of your leg.

<u>Activity 2. Tilt position</u>

- You will lie on a tilt table for 45 minutes at an angle of 75°, during which time heart rate, blood pressure and cardiac output will be measured.
- Towards the end of the 45 minutes a device for measuring the pressure of your garment will be pulled up the back of your leg.

Activity 3. Standing

- You will stand up for 45 minutes, during which time heart rate, blood pressure and cardiac output will be measured.
- Towards the end of the 45 minutes a device for measuring the pressure of your garment will be pulled up the back of your leg.

All testing will be completed 2 hours after eating. Test timings will remain consistent across the 5 trials for reliability purposes.

Potential Benefits to You:

- To understand the impacts of compression garments and how they potentially could influence recovery from sport.
- Given made to measure compression.

Potential Risks to You:

- There may be some discomfort when performing the skin fold assessment. This assessment may leave bruising of the assessed location.
- Slight skin irritation when applying the NIRS device.
- 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.

You are free to withdraw from the study at any time, without providing a reason. If at any point you decided to withdraw from the study your data will be destroyed.

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Data Collection Sheet: The effects of compression tights and compression socks on blood flow and oxygenation

Name:______________________________ Date__________________

Trial__________________ Speed for run: __________km.h^{-1}

Pre- Fluid Weight_______________ Post-Fluid Weight_______________

Pre- Fluid Weight_______________ Post-Fluid Weight_______________

Pre-Body Mass_________________ Post Body Mass________________

Pre Test- Anatomical Landmark Measurements (Right Leg)

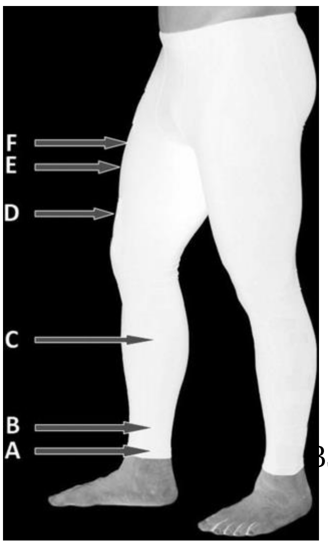
	mm

Compression Measurements

Note: When taking the reading from the Kikuhime Monitor Pressure Device, make sure the participant rolls the

Brophy- Williams et al., (2015)	mmHG
Landmark A – 5 cm above ankle bone	
Landmark B- 5 cm above A	
Landmark C - same as above max calf girth	
Landmark D - 10cm below E	
Landmark E (Need to find first) the mid-point between the inguinal crease and the superior– posterior border of the patella	
Landmark F- 5cm above E	

garment up slowly and gently to minimise stretching of the garment.



1. Attach Near Infrared Spectroscopy to the maximal calf girth and the vests lateralis (10cm proximal to the superior border of the patella and 5cm lateral the landmark- keep attached throughout the test.

Begin Near Infrared Spectroscopy- run live until phase ends (A-B)

Start: Press A on events to start phase 1.

End: Press B to complete phase 1 - Take Compression measurements

Phase 1: Supine

Blood Pressure (mmHg)

5 minutes	10 minutes	15 minutes	20 minutes

Pulse Oximetry Reading (%)

5 minutes	10 minutes	15 minutes	20 minutes

Heart Rate (beats.min^{-1})

5 minutes	10 minutes	15 minutes	20 minutes

Landmark A - 5 cm above ankle bone	
Landmark B- 5 cm above A	
Landmark C - same as above max calf girth	
Landmark D - 10cm below E	
Landmark E (Need to find first) the mid-point between the inguinal crease and the superior– posterior border of the patella	
Landmark F- 5cm above E	

Comprsion Measurements

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Phase 2: Sitting

Near Infrared Spectroscopy- (C-D)
Beginning: Press C to start phase 2
End: Press D to complete phase 2

Blood Pressure (mmHg)

5 minutes	10 minutes	15 minutes	20 minutes

Pulse Oximetry Reading (%)

5 minutes	10 minutes	15 minutes	20 minutes

Heart Rate (beats.min^{-1})

5 minutes	10 minutes	15 minutes	20 minutes

Compression Measurements

Brophy- Williams et al., (2015)	mmHG
Landmark A - 5 cm above ankle bone	
Landmark B- 5 cm above A	
Landmark C - same as above max calf girth	
Landmark D - 10cm below E	
Landmark E (Need to find first) the mid-point between the inguinal crease and the superior– posterior border of the patella	
Landmark F- 5cm above E	

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Phase 3: Walking (4 km.h^{-1})
Begin: Press E- Near Infrared Spectroscopy- run live until phase ends (E- F)
End: Press F to complete phase 3
Blood Pressure (mmHg)

5 minutes	10 minutes	15 minutes	20 minutes

Pulse Oximetry Reading (%)

5 minutes	10 minutes	15 minutes	20 minutes

Heart Rate (beats.min^{-1})

5 minutes	10 minutes	15 minutes	20 minutes

RPE

5 minutes	10 minutes	15 minutes	20 minutes

Compression Measurements

Brophy- Williams et al., (2015)	mmHG
Landmark A - 5 cm above ankle bone	
Landmark B- 5 cm above A	
Landmark C - same as above max calf girth	
Landmark D - 10cm below E	
Landmark E (Need to find first) the mid-point between the inguinal crease and the superior– posterior border of the patella	
Landmark F- 5cm above E	

Phase 4: Running - select a low speed- speed will be repeated, please record.
Running speed selected/ from trial 1:_____________________km/h

Begin: Press G- Near Infrared Spectroscopy- run live until phase ends (G-H)
End: Press H to complete phase 4
Blood Pressure (mmHg)

5 minutes	10 minutes	15 minutes	20 minutes

Pulse Oximetry Reading (%)

5 minutes	10 minutes	15 minutes	20 minutes

Heart Rate (beats.min^{-1})

5 minutes	10 minutes	15 minutes	20 minutes

RPE

5 minutes	10 minutes	15 minutes	20 minutes

Compression Measurements

Brophy- Williams et al., (2015)	mmHG
Landmark A - 5 cm above ankle bone	
Landmark B- 5 cm above A	
Landmark C - same as above max calf girth	
Landmark D - 10cm below E	
Landmark E (Need to find first) the mid-point between the inguinal crease and the superior– posterior border of the patella	

Phase 5: Sitting
Begin: Press G- Near Infrared Spectroscopy- run live until phase ends (G-H)
End: Press G to complete phase 5

Blood Pressure (mmHg)

5 minutes	10 minutes	15 minutes	20 minutes

Pulse Oximetry Reading (%)

5 minutes	10 minutes	15 minutes	20 minutes

Heart Rate (beats.min^{-1})

5 minutes	10 minutes	15 minutes	20 minutes

RPE

5 minutes	10 minutes	15 minutes	20 minutes

Compression Measurements

Brophy- Williams et al., (2015)	mmHG
Landmark A - 5 cm above ankle bone	
Landmark B- 5 cm above A	
Landmark C - same as above max calf girth	
Landmark D - 10cm below E	
Landmark E (Need to find first) the mid-point between the inguinal crease and the superior– posterior border of the patella	

	Calf Girth:	Calf Skinfold:
Participant		
	Vastus Lateralis Girth:	Vastus Lateralis Skinfold:
Date		
Trial		
Temperature (aim for 21 degrees)		
Humidity		

NIRS: Add Prep Phase Start End
Movement minimal, remember to tell participant
Add another phase blood pressure
Compression (Right Leg)
5 minutes sit still, bias
A: Prep Phase B End (15 minutes)
C Decubitus D End (45minutes)
5 minutes on the TILT
E Start Tilt F End
G Start Standing H End Standing

Compression (Right Leg)

	1	2	3	4	5	6	7	8	9	10
Pre										
Decubitus										
Tilt										
Standing										

Pulse Oximetry

	0	5	10	15	20	25	30	35	40	45
Pre										
Decubitus										
Tilt										
Standing										

Blood Pressure

	0	5	10	15	20	25	30	35	40	45
Pre										
Decubitus										
Tilt										
Standing										

General Comfort Scale (Munderman et al., 2002)

Not comfortable all **Most comfortable condition imaginable**

Not comfortable all **Most comfortable condition imaginable**

Not comfortable all **Most comfortable condition imaginable**

Ankle Fitting

Not comfortable all **Most comfortable condition imaginable**

Not comfortable all

Most comfortable condition imaginable

Most comfortable condition imaginable

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Knee Fitting

Not comfortable all

Most comfortable condition imaginable

Not comfortable all

Most comfortable condition imaginable

Not comfortable all

Most comfortable condition imaginable

Compression

Not comfortable all

Most comfortable condition imaginable

Most comfortable condition imaginable

Not comfortable all

Not comfortable all

Most comfortable condition imaginable