The Influence of Sports Compression Garments on Blood Flow and Post-Exercise Muscle Recovery

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Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

August 2021

Abstract

Sports compression garments (SCG) are commonly used in athletic applications to improve recovery from exercise. Although the underlying mechanisms are not yet fully understood, they may be closely associated with alterations in blood flow, consistent with that reported in therapeutic medicine. As such, SCG have been implicated in increasing venous and muscle blood flow, and subsequently reducing symptoms of exercise-induced muscle damage (EIMD). However, research investigating the effects of SCG on blood flow, particularly during the post-exercise period, is limited.

Chapter 2 systematically reviewed and analysed the effects of SCG on peripheral measures of blood flow (i.e., venous and muscle blood flow) at rest, during, immediately post, and in recovery from a physiological challenge. From the 19 studies included in this meta-analysis, SCG appear to enhance venous and arterial measures of peripheral blood flow during and in the recovery of a physiological challenge. Also, this chapter highlighted that further research should aim to address the limitations of current compression research by reporting the pressure of the SCG, the blinding of participants, and assessing changes in blood flow during recovery.

The first experimental study of this thesis (Chapter 3) aimed to comprehensively investigate the effects of three different SCG types (socks, shorts, and tights) on resting markers of venous return, muscle blood flow and muscle oxygenation. Although sports compression tights were the most effective garment, all SCG types positively affected lower-limb blood flow. Thus, SCG may be a practical strategy for augmenting blood flow in the lower limbs at rest.

The next study of this thesis (Chapter 4) aimed to investigate the effects of SCG on blood flow post-eccentric resistance exercise, and the influence on aspects of muscle recovery. This study also aimed to determine if the placebo effect is responsible for the improved exercise recovery associated with SCG use post-exercise. This was achieved by incorporating a placebo intervention that participants were informed was as effective as SCG for recovery and matching belief between the SCG and placebo conditions. Compression tights used post-exercise appear to increase blood flow and enhance psychological and

performance indices of exercise recovery compared to both placebo and control conditions. These findings highlight that the benefits of SCG are likely not due to a placebo effect.

The final study of this thesis (Chapter 5) investigated the effects of SCG on skeletal muscle microvascular blood flow by using contrast-enhanced ultrasound (CEU), a novel technique in compression research. In addition, macrovascular blood flow (i.e., femoral artery), muscle oxygenation, and exercise performance were measured before, during, and following repeated-sprint exercise (RSE). Compression tights attenuated muscle microvascular blood flow following exercise, but a divergent increase in femoral artery blood flow was also observed. However, despite these compression-induced alterations in macro and microvascular blood flow, there was no difference in exercise performance with SCG.

Based on this thesis's findings, SCG appear to benefit macrovascular blood flow, with a divergent effect on microvascular blood flow. Also, compression-induced increases in blood flow for up to 4 h post-resistance exercise coincided with improved muscle recovery.

Student Declaration

"I, Shane F. O'Riordan, declare that the PhD thesis entitled "The Influence of Sports Compression Garments on Blood Flow and Post-Exercise Muscle Recovery" is no more than 80,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

"I have conducted my research in alignment with the Australian Code for the Responsible Conduct of Research and Victoria University's Higher Degree by Research Policy and Procedures.

Signature:  **Date:** 20-Aug-2021

Acknowledgements

Let me start by extending a huge thank you to my principal supervisor Dr James Broatch. I cannot express enough in words my appreciation for everything you have done for me over these last few years. Apart from the second to none support and guidance in getting this PhD over the line, it is the times outside of this that I will most fondly remember. In Canberra, the welcome you provided to me from day one, fantastic mate! I immediately felt part of the AIS family, which was so important as I had just travelled across the globe to a new city not knowing anyone. Although there have been stressful times, the laughs far outweigh them with the trip to the Irish Club in Canberra (bust a move), and the infamous 'aaaaahh yeah', are the standout moments! Thanks Broatchy, I can safely say without you as my principal supervisor, I would not be where I am today.

To my co-supervisors, David, Sally and Shona, thank you for the continued support over the past four years. Although it has been a challenging past 18 months for everyone, I cannot thank you enough for your efforts in making me the researcher I am today. Also, Shona, an extra special thank you for the opportunity to assist you as a recovery physiologist at the Australian Open for the past two years. Even though the 2021s event was slightly different due to COVID, the energy, the laughs and the experience will never be forgotten.

To my amazing family, Mom, Dad, Michelle, Denis, Declan and the little rascals, Mairead and Niamh. You have always been there for me, even though I am on the other side of the world! No matter how stressful this journey got, your constant belief and confidence in me is appreciated more than you will ever know. Thank you for being my own little fan club.

And finally, to Amy. My absolute rock these last few months! Through all the late nights, working weekends and the 'joys' of being a PhD student, you were always there for me without question. The confidence and belief you instil in me each day pushes me to be my best.

List of Publications and Presentations

Publications from PhD Research:

- **O'Riordan, S. F.,** McGregor, R., Halson, S. L., Bishop, D. J., and Broatch, J. R. (2021). Sports compression garments improve resting markers of venous return and muscle blood flow in male basketball players. *Journal of Sport and Health Science.* https://doi.org/10.1016/j.jshs.2021.07.010
- Broatch, J. R.*, **O'Riordan, S. F.*,** Keske, M. A., Betik, A.C., Bishop, D. J., Halson, S. L., and Parker, L. (2021). Reduced post-exercise muscle microvascular perfusion with compression is offset by increased muscle oxygen extraction: Assessment by contrast-enhanced ultrasound. *The Federation of American Societies for Experimental Biology Journal*. 35(5), e21499. *indicates equal contribution and shared first authorship. https://doi.org/10.1096/fj.202002205RR
- **O'Riordan, S. F.,** Bishop, D. J., Halson, S. L., Clark, S., and Broatch, J. R. (2021). Do sports compression garments alter measures of peripheral blood flow? a systematic review with meta-analysis. *Sports Medicine* (in review).
- **O'Riordan, S. F.,** Bishop, D. J., Halson, S. L., Clark, S., and Broatch, J. R. (2021). Compression tights enhance post-exercise blood flow and compression induced benefits in muscle recovery are not due to the placebo effect. *Scientific Reports* (in preparation).

Publication from Adjunct Work:

- Weakley, J., Broatch, J.R., **O'Riordan, S.F.,** Morrison, M., Maniar, N., and Halson, S.L. (2021). Putting the squeeze on compression garments: current evidence and recommendations for future research – a systematic scoping review. *Sports Medicine* (in review).
- Davis, J.K., Oikawa, S.Y., Halson, S.L., Stephens, J., **O'Riordan, S.F.,** Luhrs, K., Sopena, B., and Baker, L.B. (2021). In-Season Nutrition Strategies and Recovery Modalities to Enhance Recovery for Basketball Players. *Sports Medicine* (in review).

Conference Presentations:

- **O'Riordan, S -** Sports compression garments: effects on post-exercise blood flow and recovery. *Applied Physiology Conference.* Oct 28th-30th, 2019. Melbourne, Australia.
- **O'Riordan, S** - Influence of sports compression garments on blood flow, exercise performance and post-exercise recovery. *Institute for Health and Sport, Higher Degree by Research Student Conference.* Dec 10th, 2020. Online, Australia.
- **O'Riordan, S** - Influence of sports compression garments on post-exercise blood flow and muscle recovery. *Research to Practice, Exercise and Sports Science Australia Conference.* May 6th-8th, 2021. Online, Australia.

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List of Abbreviations

1RM	One repetition maximum
ABF	Arterial blood flow
AR	Arterial reserve
CEU	Contrast-enhanced ultrasound
CI	Confidence intervals
CK	Creatine kinase
CMJ	Countermovement jump
CSA	Cross-sectional area
DOMS	Delayed-onset muscle soreness
EDV	End-diastolic velocity
EF	Ejection fraction
EIMD	Exercise-induced muscle damage
ES	Effect size
Hb	Haemoglobin
HHb	De-oxyhaemoglobin
IMTP	Isometric mid-thigh pull
LDH	Lactate dehydrogenase
mBF	Muscle blood flow
MCAv	Middle cerebral artery blood flow velocity
MPS	Muscle protein synthesis
MRI	Magnetic resonance imaging
NIRS	Near-infrared spectroscopy
O_2Hb	Oxyhaemoglobin
PBF_{mean}	Mean popliteal artery blood flow rate
PBV_{mean}	Mean popliteal artery blood velocity

PET	Positron emission tomography
PSV	Peak systolic velocity
RFD	Rate of force development
RI	Resistance index
RPE	Rating of perceived exertion
RSE	Repeated-sprint exercise
RVF	Residual volume fraction
SCG	Sports compression garments
SMD	Standardised mean difference
tHb	Total haemoglobin
TQR	Total quality of recovery
VBF	Vein blood flow
VER	Venous emptying rate
VFI	Venous filling index
V_{mean}	Time-averaged mean blood flow velocity
V_{peak}	Time-averaged peak blood flow velocity
VRV	Venous reserve volume

CHAPTER ONE

Literature Review

1.1 Introduction

Recovery from exercise is defined as a multifaceted (e.g., physiological and psychological) restorative process relative to time[1] and is an integral part of an athlete's training and competition schedule. Coaches and athletes regularly face the challenge of balancing training load and recovery to maximise the adaptive response to exercise training. Insufficient recovery can result in fatigue between training sessions, potentially contributing to increased risk of injury, overtraining, and impaired performance.[2] Conversely, achieving adequate recovery following exercise is essential to restore physiological and psychological functions, enabling athletes to train more frequently or compete at their best.[3]

A large body of research has focused on modalities designed to improve recovery after exercise, with one of the most prevalent techniques being sports compression garments (SCG).[4] The underlying mechanisms by which SCG enhance recovery are closely associated with alterations in blood flow. For example, compression has been reported to increase muscle blood flow[5,6] and venous return,[7,8] both of which have important implications for post-exercise recovery. However, most research to date has investigated the effects of SCG on blood flow during exercise,[9–11] with insights into their effects on blood flow during recovery limited. In addition, evidence to support a beneficial effect of SCG on blood flow is mixed, with SCG reported to increase,[9,11,12] have no effect,[13–15] and even reduce blood flow.[16] These contrasting findings may be explained by variations in the methodologies implemented in compression research, including techniques used for quantifying changes in blood flow, and the level of compression applied.

Another limitation with SCG research performed to date is that there is limited research available investigating the adaptive responses of regular SCG use during a period of extended training (i.e., 3+ weeks). Nevertheless, the long-term application of SCG may serve to maintain training quality and intensity by attenuating muscle damage, inflammation, and fatigue associated with exercise training.[1,4] Considering muscle blood flow is critical for processes underlying training adaptations (e.g., muscle protein synthesis; MPS),[17,18] regular compression-induced increases in muscle blood flow may provide a means to augment these responses and potentially enhance the adaptive responses to exercise training.

This literature review aims to critique the available research regarding the use of SCG, emphasising the effects of SCG on measures of blood flow, its use as a recovery modality following exercise, and its potential for improving the training response to exercise. With the rise in popularity of SCG by athletes as a recovery modality, further research into the underlying mechanisms is warranted.

1.2 Sports Compression Garments

1.2.1 Background

Compression garments are traditionally utilised in clinical settings for the treatment of numerous circulatory conditions (e.g., deep vein thrombosis and chronic venous insufficiency),[19,20] namely as a means to improve venous return and reduce lower-limb venous pooling.[21,22] A large body of research has highlighted the positive effects of compression garments for reducing rates of venous thromboembolism post-surgery,[23] swelling from acute inflammation and lymph deficiencies,[24] and improved healing rates in patients with chronic leg ulcers.[25]

Considering the importance of blood flow for sport and exercise performance,[26] compression garments have recently been utilised in the sporting environment as an ergogenic aid for performance and recovery. Sports compression garments are designed to provide graduated external compression to a limb, typically increasing in pressure from the distal to proximal portions of the limb they are covering.[27] Sport apparel companies market a variety of SCG styles (e.g., socks, shorts, tights, and arm sleeves), and the level of pressure is dependent on the mechanical properties of the garments (e.g., fabric structure, material, and size), as well as the individual's limb shape and size.

The first studies to investigate the ergogenic effects of SCG during exercise measured their effectiveness in improving blood flow[28,29] and lowering lactate concentrations.[30,31] Subsequently, a plethora of research has investigated the effects of SCG to enhance exercise performance[9,32–37] and recovery.[38–44] Compression has been reported to benefit many aspects of exercise performance, including total distance covered,[45] time to failure/exhaustion,[37,46] power output,[8,9,47,48] and jump performance.[49,50] Additionally, SCG have been reported to improve subsequent exercise performance,[43,51,52] enhance removal of muscle

metabolites,[7,8,53] and minimise symptoms of exercise-induced muscle damage (EIMD) and inflammation.[54,55] The potential mechanisms underlying these benefits include enhanced blood flow,[5,56] improved proprioception,[57,58] reduced muscle oscillation,[50,59] increased lymphatic outflow,[60,61] and reduced space available for swelling and oedema to occur.[7,53] However, the effects of SCG use on performance and post-exercise recovery are contradictory, with studies also showing no improvement in performance[62–64] or recovery measures.[65–67]

A potential explanation for these contradictory findings is the methodological heterogeneity employed in published studies, including participants' training status, body area used for compression (e.g., calf, thigh, leg, arm, or upper body), and exercise modality implemented (e.g., endurance vs resistance).[68–70] In addition, the degree of pressure applied and gradient distribution is considered critical for the effectiveness of SCG.[43,71] Thus, variations in these parameters may contribute to the inconsistencies observed in previous research. Furthermore, pressure measurements are often not reported,[48,50,72] highlighting the need for future compression research to report the degree of pressure applied.

1.2.2 Design and Application of Sports Compression Garments

1.2.2.1 *Sports Compression Garment Types and Design*

Sport apparel companies market SCG as a means to improve performance and/or enhance post-exercise recovery. SCG are designed to provide external pressure to the limb they are covering. The degree of external pressure results from the interrelation between the fit of the garment, the properties of the textile materials, the size and shape of the limb covered, and the exercise/activity performed.[73] These garments are available for upper- and lower-body segments, with lower-body compression garments most widely researched.[9,16,74–76] For the purpose of this review, Fig 1-1 provides an outline of different SCG types, as well as the relevant area of the body each type covers.

The type of SCG used during exercise and recovery is primarily dictated by the sport or activity demands, namely the muscle groups used. Exercise modes explored in compression research vary from endurance exercise[9,77–84] to resistance exercise,[7,54,55,58,85–89] and other tasks including kicking, striking, and throwing,[90–93] balancing,[94–96] jumping,[86,97,98]

and standing.[24,99] This variation has resulted in research investigating various SCG types, including arm sleeves,[5,54,67] t-shirts,[93,100,101] long-sleeved t-shirts,[102,103] socks,[66,76,78,104] shorts,[16,105,106] tights,[9,74,75,80] and a combination of long-sleeved t-shirts and tights to apply compression to the whole body.[7,45,55,107,108] However, little information exists if a particular type of SCG is more beneficial than others. Research directly comparing different SCG styles suggest garments that cover a greater volume of muscle mass (e.g., tights cover greater leg muscle mass than socks) result in better attenuation of EIMD responses following uphill running[79] and a soccer match.[83] In contrast, garment type (socks, tights, or whole-body) had no impact on sub-maximal and maximal endurance performance.[109] Considering only a handful of studies have directly compared different SCG styles,[79,83,109] more research is needed in this area to help delineate the most effective SCG type to use. In addition, other aspects of SCG use, including textiles materials, level of pressure exerted, and the duration of wear might be crucial factors in determining the effectiveness of SCG for exercise performance and recovery.

Figure 1-1: Compression garment types and area of the body covered.

1.2.2.2 *Materials*

Advances in textile materials and finishing technologies have helped improve the functionality of SCG. Compression garments are typically made from a specific blend of nylon, polyamide, polypropylene, lycra, spandex, wool, elastomer, and/or elastane.[50,110–112] Table 1-1 lists the material compositions of six different commercial brands, which are knitted together to form yarns (a continuous length of interlocked fibres; Fig 1-2).[113] The pressure exerted by SCG are dependent on the extensibility and elastic recovery of these knitted fabrics.[114] The material used in SCG are typically knitted with two types of yarns, an inlay-yarn to apply compression and ground or body yarn to provide the material's thickness and stiffness.[114,115] Increasing the thickness of the inlay-yarn's elastic core can help achieve higher levels of compression.[114,115] Also, arranging the fabric in a course (crosswise) direction, as well as increasing fabric layers, results in a higher interface pressure (pressure exerted between the garment and the skin).[116] In addition, the yarns' high elastane composition creates a negative fit, where the garment is smaller than the limb size. This enables the garment to stretch, recoil, and apply pressure to the underlying limbs.

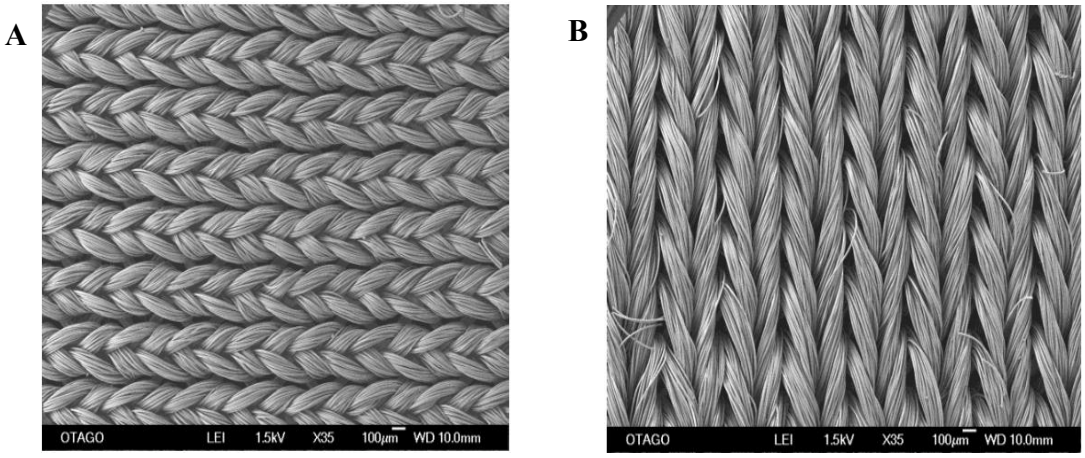

Figure 1-2: Sports compression garments magnified (x 35) using an electron microscope. A: out fabric surface, B: inner fabric surface. *Adapted from Laing et al.*[113]

Short term deformations in structure, and subsequent reductions in pressure, are expected while wearing SCG. Also, repetitive stretching or continuous strain over a long duration of wear (e.g., endurance exercise or recovery) may decay the elastic properties of the fabrics (i.e., stress relaxation),[113,117] potentially resulting in permanent pressure degradation.[118] For example, SCG pressure has been reported to decrease by up to 2.3 mmHg

following a 400-m running bout.[119] In addition, regular washing of medical compression garments has been shown to reduce the level of pressure via stretching of the elastic materials,[120] which is likely to occur with SCG also. Therefore, athletes/individuals regularly using SCG should be aware that the level of pressure applied may deteriorate over time. Also, when assessing the long-term effects of SCG use on training adaptations, investigators should ensure the level of pressure applied is maintained by frequently assessing garment pressure (e.g., once a week).

Table 1-1: Materials of compression garments from different brands.

Brand	Material
1	75% polypropylene; 20% elastomer; 5% polyamide
2	95% polypropylene; 3% elastomer; 2% polyamide
3	60% nylon; 10% elastane; 30% polyester
4	85% polyamide; 15% spandex
5	60% polyamide; 25% elastane; 15% polypropylene
6	55% polyamide; 17% wool (merino); 15% spandex; 13% polypropylene

Adapted from Pérez-Soriano et al.[111]

Considering individuals may wear SCG for extended periods of time during and after exercise, garment comfort is of great importance. Attributes of the materials that ensure comfort include adequate air permeability, moisture transmission, heat dissipation, and lack of skin irritation.[113,114] These design characteristics have collectively led to reports that SCG feel like a 'second skin'.[7,121] However, the level of pressure exerted by SCG is the most important consideration for maximising comfort of wear, with a suggested pressure comfort zone of between 14.7 to 29.4 mmHg.[114] A decreased perception of comfort arises due to the unpleasant feelings of constriction associated with high-pressure levels.[113] However, feelings of comfort or discomfort from compression are highly dependent on the part of the body compressed. For example, wearing compression exerting pressure as low as 4.2 mmHg on the abdomen can negatively influence feelings of comfort.[122] Therefore, SCG manufacturers need to design a garment that exerts a comfortable level of pressure and positively alters physiology.

1.2.2.3 *Pressure*

The level of pressure and the gradient distribution (i.e., the difference in pressure between two points) of SCG are considered crucial for their efficacy.[27,74,123,124] The garment's mechanical properties, including fabric structure, material, and size, are essential for determining pressure. Additionally, an individual's limb shape, size, and posture will influence the degree of pressure exerted on the underlying limbs. As such, the current sizing system (i.e., sized according to an individual's height and mass or maximal limb girth) is flawed,[125] as it can lead to wide inter-individual variations in pressure, and may result in individuals receiving insufficient or even excessive levels of pressure.[27] Conversely, some manufacturers provide custom-fitted garments with better precision in the pressure exerted.[27] However, due to cost, this option is not widely available.

Determining the most effective pressure level required for SCG is difficult due to the high heterogeneity in existing literature, with previous studies using pressure values ranging from ~ 5 mmHg[6,44,65,126–128] to 40 mmHg.[16,37,123,129,130] Studies have attempted to address this problem by investigating the effects of varying SCG pressure levels on exercise performance or recovery.[43,62,74,75,98,129,131–133] For example, compression tights exerting 'medium' pressure (calf: 17.9 mmHg, thigh: 16.1 mmHg) better attenuated decreases in jump height post-exercise as compared with 'high' pressure compression tights (calf: 29.2 mmHg, thigh: 26.2 mmHg).[75] Conversely, jump height recovery was unaffected by compression tights exerting pressures of 0, 10, or 25 mmHg at the thigh.[98] A potential explanation for these differences is the level of pressure exerted by the garments, as both pressure and gradient distribution are important characteristics of SCG.[71,134] Specifically, Mizuno et al.[75] reported a positive graduated external compression (i.e., decreasing in pressure from distal to proximal portions of the leg),[27] whereas Zinner et al.[98] did not report pressure values. These contradictions, and the lack of reporting pressure details in SCG research, highlight that the level of pressure required for compression-induced benefits is not yet fully understood.

The majority of SCG claim to provide a positive graduated external compression to a limb, which is proposed to be more beneficial than non-graduated or uniform pressure[135,136]. The gradual decrease of applied pressure from distal to proximal in the lower leg is recommended, as distal pooling of blood and fluid due to gravity is frequently observed in

clinical populations.[20,21] Conversely, applying the highest pressure to the muscle belly (i.e., calf musculature in the lower leg), as compared with the rest of the limb, is reported to enhance venous pump function.[137] In this instance, the authors suggest that higher blood volumes are likely to pool in the muscle belly than distal parts of the leg (i.e., ankle). Also, SCG are suggested to be beneficial for recovery regardless of a positive pressure gradient.[138] Furthermore, studies that report pressure levels frequently do so at only two sites, the calf and mid-thigh. These sites reflect a positive graduated SCG,[139–141] but fail to provide information on the graduated pressure details across the limb's length. When pressure is measured at additional landmarks, such as the six-site profile (Fig 1-3), a negative pressure gradient (i.e., higher pressure exerted at maximal calf girth) to the lower leg has been observed.[59,77,134,139] This highlights the need to include extra pressure sites, not only at the calf or thigh, in compression research. A detailed account of the pressure and gradient distribution of SCG will help identify if a garments pressure gradient, whether positive or negative, is a determinant for SCG efficacy.

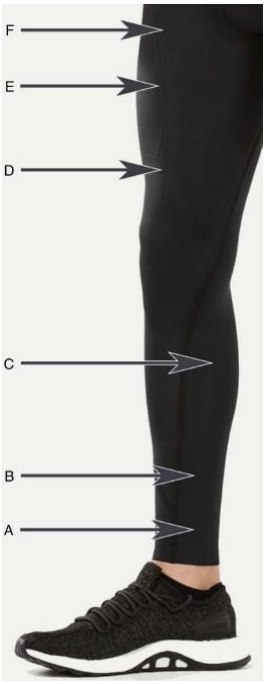

Figure 1-3: Landmarks where garment pressure measurements are taken: A (5 cm proximal to the distal border of the medial malleolus), B (5 cm proximal to A), C (medial aspect of the maximal calf girth), D (anterior aspect of the thigh 10 cm below landmark E), E (midpoint between the inguinal crease and the superior-posterior border of the patella), and F (5 cm proximal to landmark E) *Adapted from Broatch et al.*[59]

Posture may also influence the level of pressure exerted by SCG. For example, SCG are reported to elicit higher pressures when an individual is standing as compared with a supine position.[139,142] These higher pressures are attributed to the muscles' contraction upon

standing,[142] reflecting the garment's stiffness and stress relaxation characteristics.[113] Thus, posture-induced pressure changes are important considerations for individuals using SCG for exercise recovery in different situations (e.g., standing, sitting, or lying down). Furthermore, pressure values with compression tights at the calf and thigh can fluctuate by up to 6 mmHg during cycling exercise.[63] Like posture changes, the increased pressure is due to the contraction of the muscles during cycling. However, the practical significance of pressure changes during exercise is yet to be determined.

Currently, there is no classification system for the pressure of SCG or consensus on the optimal level of pressure required. In clinical settings, the level of pressure exerted by the garment is determined by the severity of the pathology,[143] with classes/grades identified with pre-determined compression ranges (Table 1-2). In addition, the levels of pressure vary from country to country.[144] Therefore, a classification system similar to Table 1-2 is warranted for the effective use and prescription of SCG to enhance exercise performance and recovery.

Table 1-2: Compression classes of medical grade garments used in several countries (values in mmHg).

Class	USA	UK	France	Germany
I	15-20 (moderate)	14-17 (light)	10-15	18-21 (light)
II	20-30 (firm)	18-24 (medium)	15-20	23-32 (medium)
II	30-40 (extra firm)	25-35 (strong)	20-36	34-46 (strong)
IV	40+		> 36	> 49 (very strong)

The values indicate the level of compression (mmHg) exerted by the hosiery at a hypothetical cylindrical ankle. *Adapted from Rabe et al.*[144]

A limitation of SCG research is that many studies investigating the efficacy of SCG for performance or recovery fail to either report[49,67,78,89,93,97,105,145–148] or measure[11,66,83,86,104,127,128,130,149–151] the exact interface pressures applied by the garments. This information is critical to understand the level of pressure required to influence performance or exercise recovery positively. Furthermore, without these pressure values, it is not easy to compare and interpret findings. For instance, the level of pressure exerted in several studies showing no benefit may have been too low or high to enhance exercise performance or recovery.[74] A review paper by MacRae et al.[69] highlights this limitation, and encourages

future research to include a comprehensive pressure profile (pressure values across the garment) and area of the body covered.

1.2.2.4 *Duration*

There is little consensus if exercise duration influences the efficacy of SCG as exercise durations studied range from a single movement[91,92,95,97,147,152] to 4+ h of running[78,153,154] and garments are worn throughout the activity. Compression has been reported to improve physiological (e.g., muscle oxygenation, muscle damage markers, heart rate, energy cost) and performance measures (e.g., distance covered, running speed, perceived exertion) during running exercises ranging in duration from < 30 min,[77,141,155,156] 30 to 45 min,[45,131,157–159] 2 h,[75,79,159] and 4 h.[78] Conversely, SCG provide no benefit when worn during running exercises of similar durations.[123,129,153,160–163] Similarly, in cycling exercises,[63,164] resistance exercises,[87,88,105,165] and team sports activities,[83,166] when the duration of activity is the same, contradictory findings exist for the benefit of SCG use. Thus, exercise duration likely has little influence on the efficacy of SCG use during exercise. The level of pressure and type of SCG used during exercise might be of more importance, as discussed previously *(1.2.2.1 Sports Compression Garment Types and Design, 1.2.2.3 Pressure)*.

Given the proposed benefits of SCG on post-exercise recovery, the duration of wear after exercise is an essential consideration. Still, this duration differs between studies, with times ranging from 12 min[12,167] to 5 days.[54] Compression research that focuses on the influence of immediately donning SCG for short periods (< 12 h) post-exercise report conflicting findings. Cerqueira et al.[67] reported that wearing SCG for 12 h post eccentric elbow flexions does not influence recovery measures (strength, swelling, perceived muscle soreness). In contrast, SCG, when worn for 12 h post plyometric exercises[52] and a competitive rugby match,[168] enhanced recovery of jump performance and muscle damage markers, respectively. The study by Cerqueira et al.[67] failed to report pressure values for the compression arm sleeve and may not have exerted sufficient pressure to improve indices of recovery in the upper arm. Shorter times researched include 12 min,[12,167] 20 min,[169] 60 min[8,16] and 80 min.[170] These shorter applications of SCG post-exercise have been reported to reduce lactate concentration,[8,170] limb swelling,[8] muscle pain,[170] attenuate decreases in mean cycling power output[8,167,169,170] and enhance femoral artery blood flow.[12] Research into the use of

SCG during the acute phase post-exercise (< 6 h) is warranted to determine if an 'optimal' duration of wear is possible. Despite a 2016 survey in elite Australian athletes[171] reporting the most common duration for using SCG post-exercise was 1 to 4 h, there is a severe lack of research on SCG use in the hours post-exercise. As such, research on this acute phase post-exercise will provide practical information for athletes with training sessions or events separated by a few hours.

The majority of studies have examined the effects of SCG worn for long durations (> 24 h), with recovery benefits evident from wearing garments for durations of 24,[7,42,127] 48[37,53,98] and 72 h[43,74,172] post-exercise. These longer durations appear to effectively enhance various markers of recovery including perceived muscle soreness,[7,43,65,127,172] muscle damage markers,[53,98,172] muscle swelling[7,55,172] and exercise performance such as strength,[55,74,127,172] jump height,[42,74] repeated sprint ability[72] and time trial performance.[37,44] Compression applied for ≥ 24 h post-exercise appears to be most beneficial for improved exercise recovery.[68,138] A potential explanation for these advantageous effects is the extended duration by which compression can aid venous return, lymphatic outflow, and muscle swelling.[68] As the greatest increases in muscle soreness and inflammation typically occur in the immediate 24 h post-exercise,[173] the application of compression during this time will likely maximise the clearance of metabolic by-products,[138] potentially enhancing the repair process[53,174] and attenuating EIMD.[68]

The impact of wearing SCG during sleep is unclear. In studies highlighting the recovery benefits of SCG use for ≥ 24 h post-exercise,[7,37,42,43,53,74,98,127,172] garments were only removed for showering and bathing. Thus, the participants in these studies would have also been required to wear the garments during sleep. However, these studies did not discuss the additional benefits that sleep has on recovery from exercise (i.e., restorative processes associated with sleep), which would have likely confounded their results. The benefits of adding SCG to night-time sleep is unclear, as only a handful of studies have addressed this specifically.[85,89,126] For example, SCG worn for 12 h, including night-time sleep, did not influence recovery measures following lower-body resistance exercise.[85] Conversely, SCG worn during night-time sleep only (8 h) promote localised muscle fatigue recovery (a greater maximal voluntary isometric contraction of knee extensor muscles).[89] Considering sleep is a

fundamental recovery tool,[175] the wearing of SCG during this night-time sleep should not negatively impact sleep (i.e., uncomfortable, overheating). Disruption of sleep might negate the potential benefits of wearing SCG during this time. However, as research is limited, the effects of SCG worn during night-time sleep remain elusive.

1.2.3 Proposed Mechanisms of Action

1.2.3.1 *Venous Return*

The primary function of the venous system is to return blood to the heart from the periphery,[176] a process termed venous return. The primary mechanism promoting venous return is the pressure gradient between the peripheral vascular system (i.e., mean systemic pressure) and the heart (i.e., right atrial pressure).[177] Also, the rate of venous flow to the heart determines the level of end-diastolic filling, which in turn is an important determinant of cardiac output.[178] As described by Berger and Takala,[179] the heart can only pump out what flows into it.

Veins of the lower extremity are classified into superficial, deep, and perforator veins[180,181] (Fig 1-4A). Superficial veins are located between the dermis and the muscle fascia.[182] They are composed of a network of veins (e.g., greater saphenous vein, lesser saphenous vein, and several accessory veins), and receive the venous drainage from subcutaneous and muscle tissue.[181,183] Perforator veins, which pass through the muscle fascia, connect and facilitate venous blood flow from the superficial venous system to the deep venous system.[184] Deep veins, classified as either intramuscular or intermuscular,[185] include the popliteal and femoral veins. An important feature of the venous system is the valves within the veins. These one-way bicuspid valves prevent reflux (backflow), ensure blood flows in the correct direction to the deep venous system and towards the heart.[181]

Factors including gravity and the rhythmic contraction of muscles can alter venous return. For example, in an upright standing position, the pressure gradient of the veins increases due to gravity.[186] As a result, blood pooling occurs in the lower limbs leading to reductions in venous return and cardiac output.[187] Conversely, the contraction of skeletal muscles prevents blood pooling and maintains venous return.[188,189] In essence, muscular contraction compresses the deep veins, and translocates blood centrally and proximally.[188,190]

Additionally, prolonged venous pooling due to an ineffective skeletal muscle pump can increase blood clotting risk and develop venous pathologies.[190,191] A standard intervention in the treatment of venous pathologies is compression garments.[192]

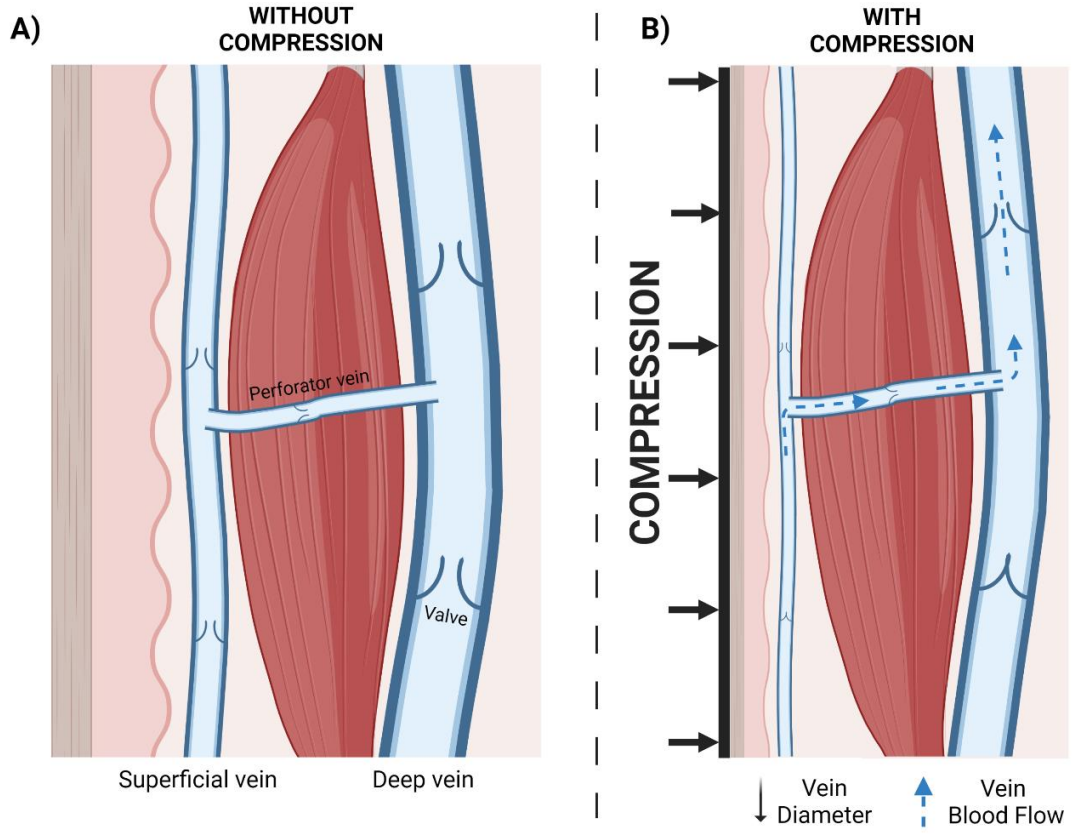

Figure 1-4: A) Venous system anatomy, and B) mechanisms of compression garments in altering venous blood flow. Created with Biorender.com.

Medical compression garments are designed to apply a high level of pressure (30 to 60 mmHg)[193] to the limb, and the level of pressure is dictated by the clinical severity of the venous pathology[184,185] (Table 1-2). They are used to treat a host of conditions, including deep vein thrombosis, chronic venous insufficiency, and varicose veins.[182,185,194] Symptoms of edema, pain, pruritus, and ulcers[184,194] occur due to incompetent valves, muscle pump dysfunction, and persistent ambulatory venous hypertension (i.e., inadequate decreases in venous pressure to facilitate venous return).[182,184] Compression garments aim to counteract these pathophysiological mechanisms via a mechanical decrease in vein diameter, which in turn will improve valve competence and reduce venous reflux.[137] As a result, blood is diverted from superficial veins, through perforator veins, and into deep veins, leading to an

increase in deep venous velocity, reduced venous pooling, and improved venous return[21,195] (Fig 1-4B). Due to consistent reports of compression garments augmentation of venous blood flow and muscle pump functionality in patient cohorts,[21,137,196–204] it is a cornerstone treatment for venous pathologies.[185,194,205,206] Despite the differences in venous physiology between individuals with venous insufficiencies and healthy individuals (e.g., valvular incompetence and vein wall weakness),[207] the benefits associated with compression garments are also evident in healthy individuals.

In healthy individuals, medical compression garments are shown to augment measures reflective of venous function,[71,204] including reduced vein cross-sectional area[56,71,208] and blood pooling,[209] as well as increased venous blood flow velocity[56,71,210,211] and flow volume.[210] For example, compression stockings have been reported to reduce popliteal cross-sectional area and concurrently increase peak venous flow velocity of the femoral vein.[56] Similarly, wearing compression socks has been reported to increase peak popliteal vein blood velocity by 46.2%.[211] However, reports also show compression garments to have no effect on venous peak flow velocity.[15,212] A potential explanation for these discrepancies is the low level of compression (calf: 14 mmHg, thigh: 10 mmHg) reported in the study by Stein et al.[15]. Two studies[71,212] have assessed varying levels of compression stockings on popliteal vein peak blood velocity in healthy participants. Mayberry et al.[212] observed no change in popliteal vein peak blood velocity assessed in two different compression stockings (Stocking 1: ankle 25 mmHg, calf 19 mmHg, thigh 11 mmHg; Stocking 2: ankle 33 mmHg, calf 21 mmHg, thigh 17 mmHg). Conversely, Liu et al.[71] reported graduated compression stockings exerting light (10-14 mmHg), mild (18-21 mmHg), moderate (25-32 mmHg) and strong (36-46 mmHg) levels of pressure across the leg (highest at the ankle) to increase popliteal vein peak blood velocity by ~10%, ~25%, ~30% and ~26%, respectively. However, these changes were only evident at 70 and 170 min after wearing the garments. In support of the findings by Liu et al.,[71] compression socks (calf 21 mmHg) increased popliteal vein peak and mean flow velocity by ~25% in healthy individuals during 120 min of seated rest.[210]

The overall positive influence of medical compression garments on indices of venous return in healthy individuals provides a mechanistic framework for SCG to enhance venous

return during, and in the recovery from, exercise (discussed in sections *1.2.4.2 Influence of Sports Compression Garments on Blood Flow During Exercise* and *1.2.5.4 Influence of Sports Compression Garments on Blood Flow During Recovery*).

1.2.3.2 *Muscle Blood Flow*

The arterial system is responsible for the delivery of blood from the heart to the periphery, including skeletal muscle.[213] The flow rate through this system is highly dynamic[214] and dictated by the interplay between arterial diameter, arterial pressure, and peripheral resistance.[213] Also, it is closely associated with the metabolic demand of the muscle.[214,215] For instance, skeletal muscle blood flow increases by almost 100-fold during exercise,[216] which is necessary to match the metabolic demand for oxygen in the contracting muscles.[215,217] Furthermore, total skeletal muscle blood flow is regulated by the constriction/dilation of the larger arterioles (arteriole 1 and 2; Fig 1-5).[218] While skeletal muscle microvascular blood flow (i.e., capillaries), responsible for substrate delivery and exchange with the myocyte, is controlled by the smaller arterioles (arteriole 3, 4 and 5; Fig 1-5).[218] Thus, increased blood flow is vital for delivering oxygen, nutrients, and hormones to the skeletal muscle.[215,218,219]

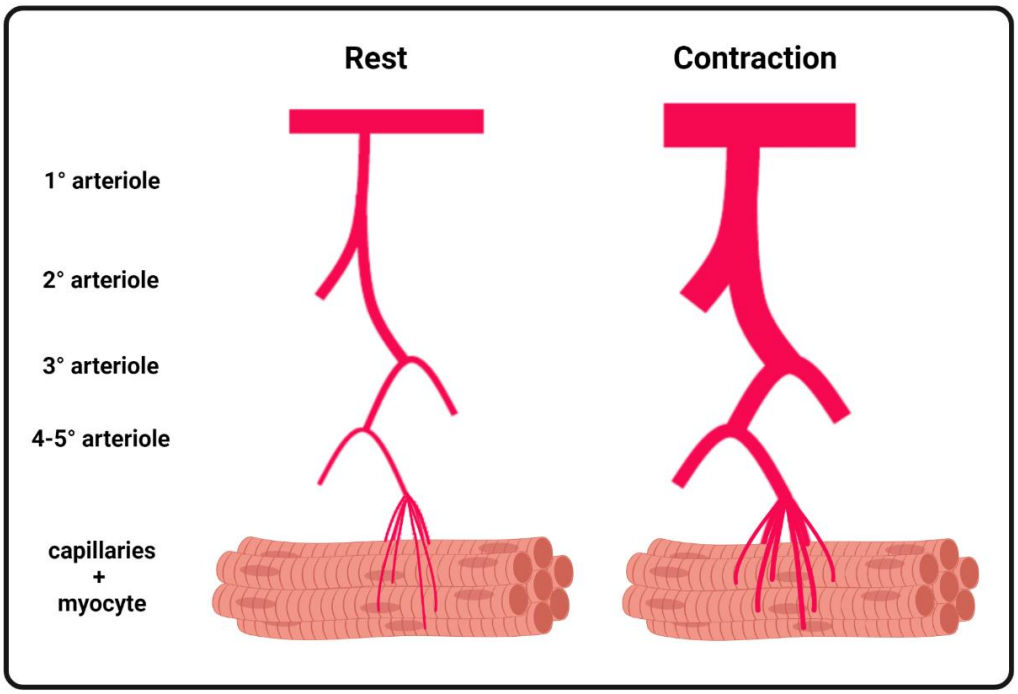

Figure 1-5: Skeletal muscle blood flow and order of arterioles to capillaries in contact with the myocyte. *Adapted from Keske et al.*[218] Created with Biorender.com.

Compression garments have been reported to enhance arterial, and muscle blood flow.[5,9,220] The underlying mechanism for compression-induced increases in arterial and/or muscle blood flow is not fully understood. In contrast to the venous system, due to the thick-walled structure of the arterioles, changes in arterial flow with compression are not a result of a mechanical reduction in vessel size. Also, the arterial system enhances blood flow by increasing vessel size (i.e., vasodilation).[221] Compression garments apply a level of external pressure to the limb that increases intramuscular pressure by approximately the same value.[222,223] Subsequently, this reduces the arteriolar transmural pressure gradient,[224] which is the pressure difference between inside and outside the vessel.[223] According to the Bayliss effect,[225] this fall in pressure gradient will result in vasodilation, termed the myogenic response[226,227] (Fig 1-6A). This myogenic response will decrease arterial flow resistance[228,229] and improve arterial and/or muscle blood flow.[5,230] Other proposed mechanisms for compression-induced muscle blood flow changes include venular-arteriolar communication[5,231] (Fig 1-6B) and skin vasomotor reflexes[5,232,233] (Fig 1-6C). Compression-induced increases in venous flow velocity will increase venous endothelial cell shear stress,[234] resulting in the release of endothelial dilators (e.g., nitric oxide).[235,236] By virtue of location, alterations in venous circulation likely have a regulatory role in modulating arterial flow dynamics.[237] Evidence for venular-arteriolar communication has been shown using intermittent pneumatic compression in rodent models,[238,239] but is yet to be established with compression garments and in humans. The skin vasomotor reflex mechanism suggests the external pressure applied to the skin's surface activates nociceptors of capsaicin-sensitive nerve fibres. As a result, neuropeptides are released and induce vasodilation in the underlying tissues.[232,233] The venular-arteriolar communication and the skin vasomotor reflexes may also act in synergy[5] with the myogenic response to augment muscle blood flow with compression; more research is required to differentiate between the causal factors.

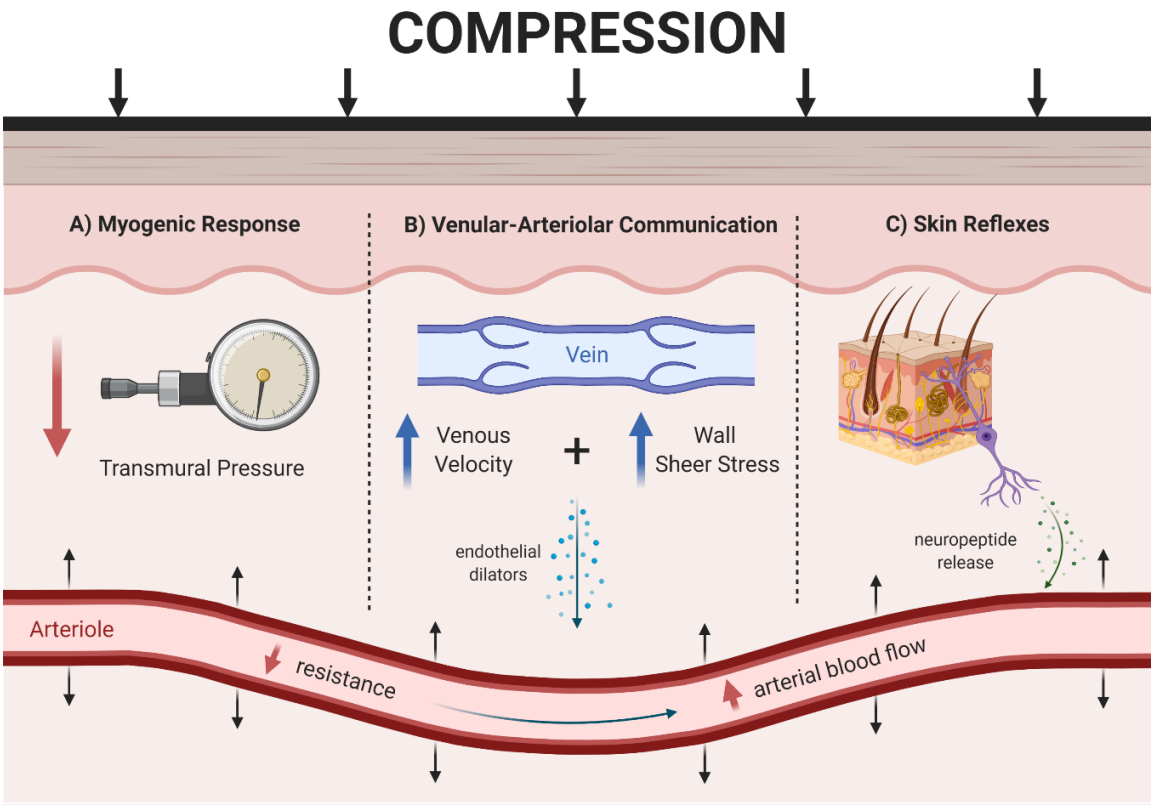

Figure 1-6: Proposed mechanisms for compression-induced changes in muscle blood flow including: A) Myogenic Response, B) Venular-Arteriolar Communication, and C) Skin Reflexes. Created with Biorender.com

In clinical settings, less is known about the influence of compression garments on muscle or arterial blood flow. A potential reason for this limitation is that compression is suggested to be harmful in patients with arterial blood flow pathologies (i.e., arterial ulcers, peripheral arterial disease).[240,241] The recommendations for individuals with reduced ankle-brachial pressure index (a screen test for peripheral artery disease)[240–242] to avoid compression or apply a "supervised modified" compression[240] are controversial as they are primarily supported by experience rather than outcome data.[240,243,244] Research investigating the effects of compression in patients with arterial blood flow pathologies highlights that compression may be a safe and valuable intervention.[240,245–248] For example, Mosti et al.[240] reported that compression bandages exerting up to 40 mmHg at the ankle did not negatively affect arterial perfusion as measured by laser doppler flux. However, pressures > 40 mmHg reduced arterial perfusion in patients with mixed arterial and venous disease. In the same study, pressures of 20 to 30 mmHg and 31 to 40 mmHg increased arterial perfusion by 33% and 28%, respectively. Also, lower compression levels applied to the ankle (≤ 18 mmHg) are

reported to enhance calf muscle blood flow[195] and improve muscle oxygenation[21] (an indirect method used to quantify changes in muscle blood flow) in clinical populations. These findings suggest compression therapy may be a helpful strategy to augment blood flow in patients with arterial pathologies, provided the pressure is below 40 mmHg.

Compression-induced changes in muscle blood flow are also reported in healthy populations. For example, Bochmann et al.[5] reported compressive sleeves (13 to 23 mmHg) increased arterial perfusion of the foreman, as measured by venous occlusion plethysmography, more than two-fold when compared with no compression. In agreement, compression bandages of the lower leg (forefoot to the knee) that exerted either 28 mmHg[230] or 40 mmHg[220] at the ankle increased below-knee blood perfusion, assessed using nuclear magnetic resonance flowmetry, by 23% and 28%, respectively. However, in contrast to the findings of Mayrovitz and Larsen,[220] thigh blood flow was reduced by ~ 50% with the application of a compression bandage to the upper thigh exerting 40 mmHg of pressure.[28] Although the pressure levels were identical between the studies, the compression bandage applied to the thigh was only 12 cm in width.[28] The narrow width of the bandage may have resulted in a tourniquet effect as the pressure was applied to only a concentrated area of the thigh. Conversely, increased blood flow was observed with compression bandages that covered the entire lower leg and applied a graduated distribution of pressure,[220] a feature considered crucial for the effectiveness of compression therapy.[71,134] These findings highlight that the beneficial effects of compression for muscle blood flow are dependent on the level of pressure applied, as well as the area compressed.

The application of compression appears to augment muscle and arterial blood flow. Thus, the use of SCG may enhance blood flow to the contracting muscles during and post-exercise (discussed in sections *1.2.4.2 Influence of Sports Compression Garments on Blood Flow During Exercise* and *1.2.5.4 Influence of Sports Compression Garments on Blood Flow During Recovery*).

1.2.3.3 *Muscle Damage and Oedema*

Muscle damage occurs following unaccustomed exercise,[249] eccentric muscle contractions,[250] and/or long-duration[251] or strenuous high-intensity exercise.[252] The etiology of EIMD begins with myofibrillar disruption[253] due to mechanical loading or eccentric

lengthening of the muscle during exercise.[250] During eccentric contractions, sarcomeres lengthen in a non-uniform manner and stretch beyond myofilament overlap.[250,254] Consequently, tension is increased on passive structures, sarcomeres experience "popping",[173,255] and deformation of non-contractile proteins occur.[256] Further, a higher level of fibre disruption results from repeated eccentric contractions,[254,257] leading to subsequent excitation-contraction coupling dysfunction.[173,250]

Following the initial phase of muscle damage, a secondary inflammatory response ensues from the disrupted intracellular calcium homeostasis, cell necrosis, and myofibrillar protein release.[258,259] The release of these proteins (e.g., creatine kinase; CK, c-reactive protein, myoglobin) into the interstitial fluid increases tissue osmotic pressure.[172,260] As a result, oedema occurs due to the fluid absorption from the circulatory system, thus increasing the interstitial fluid and intra-compartmental pressure in order to equalise osmotic pressure.[172] In addition, oedema may inhibit lymphatic and venous drainage of the area leading to further cell lysis and muscle damage.[68,172,261] Furthermore, increased swelling due to oedema may stimulate pain receptors, causing pain[262,263] and hampering muscle function.[264]

Compression may alleviate symptoms of EIMD,[265] but the exact underlying mechanism to mitigate these inflammatory responses is not yet fully understood. When used during exercise, SCG are reported to reduce muscle oscillation[58,59] and improve muscle function,[166] potentially decreasing initial muscle trauma, post-exercise muscle damage, and the subsequent inflammatory responses.[50,58,266] In addition, the external pressure created by SCG may reduce post-exercise inflammation by aiding the removal of myofibrillar proteins,[53,54,75,174] under the premise that compression increases venous return[8,21,22] and lymphatic outflow,[261,267] with the latter's role being to remove fluid and proteins from interstitial tissue.[260,268] Oedema could also be reduced with SCG by limiting the space available for swelling to occur,[53,85] and changing the tissue pressure gradient allowing for reabsorption and removal of excess lymph fluid.[193,261] Therefore, SCG are utilised during and post-exercise to minimise the EIMD symptoms of muscle soreness, muscle swelling, reduced muscle function, and elevated levels of intramuscular proteins[173,257,269–272] (discussed further in section *1.2.5.2 Exercise Induced Muscle Damage)*.

1.2.4 Sports Compression Garments During Exercise

1.2.4.1 *Exercise and Performance*

Multiple studies report enhanced exercise performance with the use of SCG. For example, wearing SCG during exercise has been reported to improve jump performance,[49,50,273] repeated sprint ability,[9,48] cycling power,[9,47,64,81,274] running performance,[45,141,156,159,275] maximum voluntary contraction strength,[276] team-sport performance,[277] balance tasks,[94,95,278,279] and technical skills (e.g., football kicking velocity, as well as golf shot, basketball free throw, and baseball pitching accuracy).[90,91,93] A potential contributor to the enhancement of exercise performance is improved proprioception[57] and reduced muscle oscillation.[50,59] Also, additional input to the mechanoreceptors through compression can lead to enhanced muscle coordination, joint stability,[57,58] reduce muscle fibre recruitment[280] and decrease muscle fatigue.[156]

Conversely, several studies highlight SCG to have no effect on performance when worn during resistance exercise,[87,105,165] kayaking,[140] speed skating on ice,[281] roller skiing,[33] double poll sprinting,[103] half ironman triathlon time,[282] a rugby match simulation,[166] or technical drills (e.g., throwing accuracy or golf swing).[121283] Furthermore, numerous investigations report no change in jump,[106,284] cycling,[63,80] or running performance[32,36,77,119,124,154] when wearing SCG. Notwithstanding the considerable heterogeneity in SCG characteristics (i.e., garment type, pressure applied), these neutral findings might be in part explained by the psychological factors (i.e., placebo effect) associated with SCG use. For instance, SCG use has been reported to improve exercise performance and/or ratings of perceived exertion (RPE), without any concurrent alterations in physiological variables (e.g., heart rate, VO_2, lactate, or skin temperature).[47,48,119,141,285] Also, participants' positive perception and belief in SCG are suggested to aid exercise performance.[161,286] Thus, compression research should aim to minimise any placebo effect by attempting to blind participants and researchers to the SCG intervention.

1.2.4.2 *Influence of Sports Compression Garments on Blood Flow During Exercise*

A proposed benefit of SCG use during exercise is to augment the skeletal muscle pump action, thus enhancing blood flow back to the heart (i.e., venous return).[212,287]

Compression-induced changes in central haemodynamics (e.g., heart rate, stroke volume, cardiac output) are frequently used as surrogate measures of venous return.[288] However, the benefit of SCG on these measures during exercise is equivocal, with both positive[9,33,75,124,289,290] and no effects reported.[35,79–81,128,291–293] For example, Broatch et al.[9] and Dascombe et al.[124] reported that wearing SCG tights lowered heart rate during repeated sprint cycling and running time to exhaustion, respectively. The compression-induced decrease in heart rate is likely due to increased end-diastolic filling and stroke volume from enhanced venous flow and venous return.[287] In contrast, studies have reported that SCG covering the entire lower limb, similar to the above studies,[9,124] have no effect on heart rate during various types of exercise, including cycling,[80] running,[10,103] alpine skiing,[133] and a simulated rugby game.[166] A limitation of central haemodynamic measures is that they do not provide information on peripheral changes in venous or muscle blood flow with compression (i.e., in the limb covered by the garment). Also, changes in blood flow during exercise are difficult to quantify. Many techniques used to assess venous and arterial/muscle blood flow (e.g., Doppler ultrasound, plethysmography, magnetic resonance imaging (MRI) etc.) require the participant to stop exercising to obtain an accurate measure/reading. As a result, these techniques are often utilised during rest intervals[5,9] or at the end of exercise.[11,14,294–297] Although these methods are limited in affording a true representation of blood flow during exercise, they help indicate blood flow changes in the previous exercise bout. A technique frequently used in SCG research to overcome this problem and indirectly measure changes in blood flow is near-infrared spectroscopy (NIRS).[48,103,124,133]

The emitted near-infrared light can penetrate several millimetres into the biological tissue and is used to quantify the oxygenation status of light-absorbing chromophores (e.g., haemoglobin (Hb).[298] Depending on whether or not oxygen is bound to the iron core within each haem,[298] the NIRS signal represents relative concentrations of oxygenated (O_2Hb) and deoxygenated (HHb) haemoglobin.[299] The sum of O_2Hb and HHb equates to the total amount of haemoglobin (tHb) and provides an index of the blood volume in the tissue.[6,300] In addition to tHb, changes in HHb concentrations reflect intramuscular oxygenation status[6] and provide an indirect measure of venous flow.[124] However, despite these metrics providing information on peripheral venous circulation, research assessing changes in Hb with SCG is unclear, as studies report either a positive effect[13,124,133,301] or no effect[45,48,103,140,281] of compression

(Table 1-3). These contrasting findings might be a consequence of heterogeneity in SCG characteristics between studies. For example, Dascombe et al.[124] reported that lower-body SCG of two different sizes (undersized and regular size garments) enhanced venous function (tHb, HHb), as measured with NIRS, during a progressive maximal test and time to exhaustion exercise protocols. In support of this, lower-body garments also positively altered venous return during heel raises[13,301] and simulated alpine skiing.[133] Conversely, no changes in NIRS derived venous measures were observed with lower-,[48,281] upper-,[103,140], and whole-body compression garments[45]; this is potentially due to differences in pressure applied and the type of garments used in these studies.

Although NIRS provides valuable information regarding the effects of compression on indices of venous return (i.e., tHb, HHb) during exercise, it is unable to directly measure venous structure, blood velocity, and/or blood flow. Other techniques such as air plethysmography[297] and MRI[295] have been used immediately post-exercise to provide an indication of the effects of sports compression socks on venous haemodynamic measures during a 10-km run and 30 min of running at 75% maximum aerobic speed, respectively. Similar to changes with NIRS, there were equivocal findings. Using air plethysmography, venous filling index and residual volume fraction, measures of valvular competence and ambulatory venous pressure, respectively, were improved with sport compression socks.[297] Whereas no changes were found in popliteal vein flow volume using MRI.[295] These contrasting findings highlight the need for other methods that provide reliable and real-time information in venous structure and flow (e.g., Doppler ultrasound),[302,303] to not only quantify changes in venous flow with compression but to also determine the mechanism of compression on the venous system (i.e., decreased vein diameter, increased venous blood velocity).

Muscle oxygenation or oxygen uptake, also assessed with NIRS, is closely related to tissue blood flow.[301] Therefore, it is frequently used as an indirect measure of muscle blood flow during exercise. However, research during exercise is equivocal with reports suggesting compression to increase,[45,64,140,301,304] have no effect,[9,36,48,103,281,305] or even reduce muscle oxygenation[133,306] during exercise (Table 1-3). Although an indicator of the balance between oxygen supply and consumption,[307] there is conjecture to the meaning of changes in muscle

oxygenation with compression. For example, lower[133] and higher[45] levels of *vastus lateralis* oxygenation have been reported with sports compression tights during exercise. The lower levels are attributed to either attenuated oxygen supply or elevated oxygen utilisation, whereas the high level reflects increased oxygen supply. Although muscle oxygenation is used as an indicator of oxidative metabolism,[133] it is limited in the information obtained regarding blood flow to the muscle. Alternatively, NIRS with venous occlusions (rapid inflation of a pressure cuff around the limb to between 60-80 mmHg)[298] provides a non-invasive and reliable measurement of localised muscle blood flow.[308] Despite its limitation in requiring participants to cease exercising due to venous occlusions, it is a method that can provide an indication of compression-induced changes in muscle blood flow during exercise.

Sports compression tights increased muscle blood flow by ~ 18% during repeated sprint cycling exercise when assessed by NIRS with venous occlusion.[9] Conversely, using the same measurement technique, no changes in muscle blood flow were evident with compression socks during trail running exercise.[36,305] The variation in exercise protocol and garment styles used might explain these contrast findings. For instance, Broatch et al.[9] propose the limited rest between supramaximal sprints in their study increased muscle blood flow demand, thus increasing the capacity for improved blood flow with SCG. Also, garments only apply pressure to the underlying blood vessels. For instance, tights cover the entire lower limb but socks cover the lower leg only. Thus, the observed increase in muscle blood flow in sports compression tights,[9] but not socks,[36,305] might be explained by tights' ability to influence the upper- and lower-leg blood vessels. However, no research has investigated the effects of sports compression garment type on lower-limb blood flow.

Table 1-3: Summary of studies assessing the effects sports compression garments on peripheral blood flow during exercise.

Study	Participants	Garment Type	Activity	Measurement Technique	Peripheral Blood Flow Variable
Bochmann et al. 2005 [5]	Healthy 5M	Arm sleeve	Rhythmic hand exercise (70 min)	Venous occlusion plethysmography	↑ Arterial blood flow
Book et al. 2016 [13]	Healthy 5F, 7M	Socks	Plantar flexion (5 min)	Near-infrared spectroscopy Doppler ultrasound	↑ Total haemoglobin ↔ Arterial blood flow velocity ↔ Artery blood flow
Born et al. 2014 [281]	Ice speed skaters 6F, 4M	Tights	Ice skating (3000-m race simulation)	Near-infrared spectroscopy	↔ Total haemoglobin ↔ Muscle oxygenation
Born et al. 2014 [48]	Track and team sports 12F	Tights	Running (30 x 30-m repeated sprints)	Near-infrared spectroscopy	↔ Total haemoglobin ↔ Muscle oxygenation
Boucourt et al. 2015 [304]	Athletes 11	Socks	Cycling (incremental test)	Near-infrared spectroscopy	↑ Muscle oxygenation
Broatch et al. 2018 [9]	Recreationally active 11F, 9M	Tights	Cycling (4 x 10 6-s sprints)	Near-infrared spectroscopy with venous and arterial occlusions	↔ Muscle oxygen uptake ↑ Muscle blood flow
Castilho-Junior et al. 2018 [297]	Amateur runners 6F, 4M	Socks	Running (10 km)	Air plethysmography	↑ Venous filling index ↔ Ejection fraction ↑ Residual volume fraction
Coza et al. 2012 [301]	Recreationally active 16M	Calf sleeve	Resistance (80 heel raises)	Near-infrared spectroscopy	↑ Total haemoglobin ↑ Muscle oxygenation

Table 1-3: continued.

Study	Participants	Garment Type	Activity	Measurement Technique	Peripheral Blood Flow Variable
Dascombe et al. 2011 [124]	Middle distance runners 11M	Tights	Running (incremental test and time to exhaustion)	Near-infrared spectroscopy	↑ Total haemoglobin ↑ Muscle oxygenation
Dascombe et al. 2013 [140]	Elite flat-water kayakers 2F, 5M	Upper body	Kayaking (incremental test)	Near-infrared spectroscopy	↔ Total haemoglobin ↔ Muscle oxygenation
Dorey et al. 2018 [130]	Healthy 4F, 6M	Socks	Cycling (60 min)	Transcranial Doppler ultrasound	↑ Middle cerebral artery velocity
Fuijii et al. 2017 [164]	Recreationally active 9M	Tights	Cycling (45 min)	Venous occlusion plethysmography	↑ Arterial blood flow
Kerherve et al. 2017 [36]	Trail runners 14M	Socks	Running (24-km Trail)	Near-infrared spectroscopy with venous and arterial occlusions	↔ Muscle oxygen uptake ↔ Muscle blood flow ↔ Muscle oxygenation
Macrae et al. 2012 [63]	Trained cyclists 12M	Full body	Cycling (60 min plus 6-km time trial)	Venous occlusion plethysmography	↔ Arterial blood flow
Mann et al. 2016 [296]	Amateur runners 12F, 18M	Socks	Running (incremental test)	Venous occlusion plethysmography	↑ Arterial blood flow ↑ Arterial reserve
Oficial-Casado et al. 2020 [295]	Runners 10M	Socks	Running (30 min)	Magnetic resonance imaging	↔ Vein blood flow
Rennerfelt et al. 2019 [306]	Runners 10F, 10M	Socks	Running (10 km)	Near-infrared spectroscopy	↓ Muscle oxygenation

Table 1-3: continued.

Study	Participants	Garment Type	Activity	Measurement Technique	Peripheral Blood Flow Variable
Riexinger et al. 2021 [294]	Recreationally active 7F, 9M	Socks	Jumping and resistance (5 x 10 drop jumps, 5 x 50 heels raises)	Intravoxel incoherent motion	↔ Microvascular blood flow ↔ Microvascular perfusion
Scanlan et al. 2008 [64]	Trained cyclists 12M	Tights	Cycling (1-h time trial and incremental test)	Near-infrared spectroscopy	↑ Muscle oxygenation
Sear et al. 2010 [45]	Amateur team sports 8M	Full Body	Running (45 min high intensity intermittent)	Near-infrared spectroscopy	↔ Total haemoglobin ↑ Muscle oxygenation
Smale et al. 2018 [80]	Trained cyclists 15M	Tights	Cycling (incremental test)	Transcranial Doppler ultrasound	↔ Middle cerebral artery velocity
Sperlich et al. 2013 [133]	Alpine skiers 12M	Tights	Skiing (3 min simulation)	Near-infrared spectroscopy	↑ Total haemoglobin ↓ Muscle oxygenation
Sperlich et al. 2014 [103]	Endurance athletes 10M	Upper body	Skiing (3 x 3-min sprints)	Near-infrared spectroscopy	↔ Total haemoglobin ↔ Muscle oxygenation
Vaile et al. 2016 [11]	Wheelchair rugby 10M	Socks	Wheelchair rugby (4 x 8-min simulation)	Venous occlusion plethysmography	↑ Muscle blood flow
Vercruyssen et al. 2014 [305]	Trained runners 11M	Socks	Running (15.6-km trail)	Near-infrared spectroscopy with venous occlusions	↔ Muscle oxygen uptake ↔ Muscle blood flow

F = females, M = males, ↑ a positive effect of compression, ↓ a negative effect of compression, ↔ no effect of compression

Despite the importance of microvascular (i.e., capillaries) blood flow for the delivery and uptake of oxygen and nutrients in the muscle,[218,219] only one study has investigated compression-induced changes in microvascular flow during exercise.[294] In this study the use of sports compression socks during plyometric and eccentric exercises did not alter microvascular perfusion, which was assessed immediately post-exercise using intravoxel incoherent motion, a non-invasive MRI technique based on particle displacement measurements.[294] However, a limitation of this study was that participants acted as their own control by wearing the SCG on one leg only. Thus, a potential systemic response with compression might be responsible for the lack of change in microvascular perfusion between legs. Nonetheless, this study's novelty highlights that further investigations using techniques that assess changes in microvascular flow with SCG are warranted. Also, studies using blood flow techniques that determine changes in arterial vessel structure and flow (e.g., Doppler ultrasound) are needed to provide information on the underlying mechanism of compression on arterial and muscle blood flow (i.e., vasodilation).

1.2.4.3 *Benefits of Improved Blood Flow During Exercise*

Augmented venous return during exercise will improve end-diastolic filling and stroke volume via the Frank-Starling mechanism,[177] resulting in a reduced heart rate to maintain a similar cardiac output.[159,274,287] Considering heart rate is a valid measure of exercise intensity[309] and energy expenditure,[310] the decreased cardiovascular strain (i.e., lower heart rate) with SCG may provide a novel method to reduce energy cost during exercise and postpone muscle fatigue.[289] Additionally, reduced heart rate and increased stroke volume are contributing factors to an improved exercise economy.[311] Therefore, a compression-induced increase in venous return hypothetically permits individuals to exercise at a given workload with less cardiovascular demand (i.e., a lower percentage of maximal heart rate),[9,159,274] thus improving exercise economy.[156]

Lactate accumulation resulting from hypoxia and the associated acidosis can be a limiting factor in maximal exercise.[312] Compression-induced improvements in venous return may assist in the clearance of lactate from skeletal muscle during exercise. Enhanced lactate removal may increase the capacity for athletes to exercise at higher intensities, thus improving performance. However, research supporting this mechanism is limited as most

compression research shows no effect of SCG on blood lactate levels when worn during exercise.[9,33,80,140,149,281] Also, when compression-induced reductions in blood lactate are evident, no change in exercise performance has been reported.[103,313] Conversely, Rimaud et al.[314] observed higher blood lactate concentrations at the end of maximal incremental cycling with compression stockings. The authors suggest their findings are a result of alterations in local blood flow due to compression. However, this study's exact mechanism underlying the effect of compression on lactate accumulation is limited, as changes in local blood flow were not measured. Alternatively, Berry et al.[30] proposed that compression-induced blood lactate reduction may result from vessel constriction and decreased lactate perfusion from the muscle bed. Thus, SCG research that quantifies changes in venous return and blood lactate levels during exercise is warranted.

Exercise is associated with a significant rise in muscle blood flow, up to 20-fold on average, which is necessary to meet the 20 to 50 fold increase in oxygen demand of skeletal muscle.[315] Further enhancing oxygen supply to skeletal muscle during exercise would be beneficial as oxygen supply is considered a limiting factor for endurance performance.[133] Wearing SCG during exercise may help improve muscle oxygen supply to meet the enhanced metabolic demands of exercise. For example, Sear et al.[45] reported increased muscle oxygenation during intermittent high-intensity running when wearing SCG, resulting in an 8.5% improvement in total distance covered.

The energy requirements of skeletal muscle increase significantly during exercise and are fuelled by the catabolism of intramuscular glycogen and triacylglycerols, as well as blood glucose and free fatty acids.[315,316] Therefore, increased blood flow to the skeletal muscle microvasculature is essential for supplying blood-borne nutrients during exercise.[317,318] Considering SCG have been reported to improve arterial perfusion,[5] they may also enhance nutrient delivery to the exercising muscles and subsequent glucose uptake and free fatty acid oxidation. In turn, SCG worn during exercise could postpone the development of fatigue and improve performance.[319] However, knowledge about the effect of SCG on microvascular blood flow and nutrient delivery to muscle during exercise is scant[294] and requires further investigation.

1.2.5 Sports Compression Garments and Recovery

1.2.5.1 *Exercise Performance*

The desired effect of any recovery intervention is to expedite the recovery process by mitigating the physiological and mechanical strain associated with exercise. Therefore, the aim of wearing SCG post-exercise is to enhance the recovery of muscle function and aid subsequent exercise performance. However, similar to exercise performance with SCG (section *1.2.4.1 Exercise and Performance*), the evidence to support enhanced recovery of exercise performance with SCG is equivocal.

In support of the use of SCG in the recovery from exercise, performance improvements have been reported in tests assessing muscle strength,[39,52,55,74,89,127,320–323] power,[7,38,44,169] running,[37,39,72,76,77,292] cycling,[44,81,170] and jump[14,39,42,52,74,321,323] performance. Furthermore, these compression-induced benefits have been reported following different exercise modalities, including plyometrics,[39,52,74,323] running,[14,37,39,42,76,77,322] cycling,[38,44,81,169,170] resistance exercise,[7,55,321] eccentric exercise,[54,89,127,172,320] soccer,[292] and simulated team-sport exercise.[72] However, findings are inconsistent with respect to the benefits of SCG on exercise recovery. For instance, SCG have been reported to have no effect on numerous exercise recovery metrics, including muscle strength,[40,41,43,67,86,166,284,324,325] running,[53,166,326,327] and jump[41,53,65,86,324,326,328,329] performance. A potential explanation for these contradictory findings is the methodological heterogeneity employed in published studies, including participant training status, body area used for compression (e.g., calf, thigh, leg, arm, or upper body), duration of wear post-exercise, and exercise modality implemented (e.g., endurance vs resistance).[51,68–70] Also, the amount of pressure applied and gradient distribution are critical for SCG.[43,71] Thus, variations in these parameters and the lack of measuring[66,83,86,104,127,128,150] or reporting pressure details,[49,78,89,93,97,105,146,147,291] contribute to the inconsistencies observed in previous research. Furthermore, it is important to reiterate that the participant's belief and positive perception of SCG could contribute to these inconsistent findings (discussed further in section *1.2.5.3 Perceptual Measures*).

1.2.5.2 *Exercise Induced Muscle Damage*

Exercise-induced damage to the muscles contractile elements increases myofibrillar protein concentrations, inflammatory markers, and muscle swelling.[269] As such, these indirect measures of muscle damage are commonly used to assess the effectiveness of SCG to reduce the symptoms of EIMD.[7,39,66,74,83,321,325,330] The exact mechanism is not fully understood, but augmented venous blood flow[8,21,22] and lymphatic outflow[261,267] with SCG may aid the removal of the myofibrillar proteins, subsequently reducing secondary inflammation and muscle swelling.

A protein extensively used to assess muscle damage recovery is CK,[41–43,54,86] as it increases to a greater magnitude than other myofibrillar proteins after muscle damage.[249] Compression-induced improvements in venous flow and lymphatic outflow are suggested to augment the removal of CK. Numerous studies support this benefit with reduced CK levels reported with SCG use.[7,39,41,53,98,121,132,168,172] Conversely, there is also evidence to support no influence of SCG use on the removal of CK.[43,74,75,79,81,86,321,324,329,330] Other myofibrillar proteins utilised in SCG research include lactate dehydrogenase (LDH),[7,53,54,83,325,330] myoglobin,[55,74,75,79,84,331] and fatty-acid binding protein.[32,84] Similarly, evidence supporting the use of SCG to alleviate the increase of these proteins is conflicting. Aside from the heterogeneity in the characteristics of SCG (e.g., type, pressure, duration), factors that influence the magnitude of myofibrillar protein release[70] may explain these contrast findings including, the training status and gender of the participants,[332–334] the type and familiarity of the exercise intervention[335] and the primary site of muscle damage.[70,172]

Compression may also attenuate the secondary inflammatory response in the muscle. Following the initial trauma, fluid and plasma protein influx to the muscle occurs, increasing tissue osmotic pressure,[172,260] and functions to aid regeneration of the injured tissue.[249] The application of SCG during this process could alter the tissue pressure gradient allowing for the removal of excess lymph fluid.[193,261] Also, this could aid in the clearance of inflammatory markers, including CRP and inflammatory cytokines (e.g., interleukin-1β, interleukin-6, tumour necrosis factor-α). However, the benefit of SCG on inflammatory markers is not supported in the literature,[14,42,43,65,74,86,127,325,330] potentially due to compressions lack of effect on lowering myofibrillar protein concentrations (i.e., CK, LDH etc.) in these studies.

Limb circumference is frequently used to indicate muscle swelling and oedema,[8,42,55,66] with an attenuation of increased limb circumference (decreased swelling) a favourable response. The pressure exerted by SCG may reduce swelling by limiting the space available for swelling to occur,[53,85] and changing the tissue pressure gradient allowing for reabsorption and removal of excess lymph fluid.[193,261] However, similar to other indicators of EIMD, the effectiveness of SCG on limb circumference is equivocal with reports of compression to reduce[7,39,54,76,83,104,172] or to have no effect[42,53,55,66,324,328] on limb swelling. For example, compression tights reduce mid-thigh girth swelling, following an eccentric muscle damage protocol (20 x 20-m sprints plus 100 drop jumps).[39] In contrast, there were no thigh or calf circumference changes with compression tights post 120 min of running.[79] Further highlighting methodological heterogeneity (e.g., exercise intervention) may explain the contrast findings in SCG research.

Magnetic resonance imaging with T2-weighting has been used to assess the benefits of SCG on exercise-induced intramuscular oedema.[66,131,294,336,337] Compression-induced benefits on intramuscular oedema were evident following 35 min of running with sports compression tights[131] and sports compression socks.[336] Reduced oedema with SCG were attributed to the removal of metabolites due to improved peripheral circulation and/or reduced muscle oscillation.[131,336] Until recently, this measurement technique had not been utilised to quantify the effect of SCG post-exercise. In contrast to the studies by Miyamoto and Kawakami,[131,336] wearing a sports compression sock for 6[294,337] or 60 h[66] post exercise (plyometrics and eccentric calf muscle exercise) had no effect on intramuscular oedema. However, as only one calf was exposed to compression in these studies, the influence of a systemic inflammatory response cannot be discounted.[66,294,337] Further research is required into the effects of SCG that covers both limbs post-exercise on exercise-induced intramuscular oedema.

1.2.5.3 *Perceptual Measures*

Delayed-onset muscle soreness (DOMS) frequently occurs following unaccustomed activity,[249] or exercise comprising eccentric muscle contractions (e.g., resistance exercise, downhill running, eccentric cycling).[338–340] The level of soreness associated with DOMS typically peaks around 24 to 72 h post-exercise,[340] and is due to muscle swelling and oedema

in response to the exercise-induced damage of the muscle fibres.[249,340] Due to its detrimental effects on exercise performance,[340] muscle soreness is frequently used to assess the efficacy of SCG use for recovery post-exercise.[8,42,52,66,67,127,172,341]

The benefit of SCG on perceptual measures of muscle soreness following exercise is well documented.[38,41,52,74,86,330,342,343] Kraemer et al.[172] reported a decrease in participant's level of DOMS when compressive arm sleeve was worn for 72 h post an EIMD protocol (arm curls; 2 sets of 50 repetitions). Similar findings of reduced muscle soreness have been reported following different exercise modes, including whole-body resistance exercise,[7,55,86] plyometric jumping exercise,[52,53,323] intermittent running,[121,287] marathon[43,343] or ultramarathon running,[330] and team sports (basketball simulation, soccer match, rugby simulation, hockey simulation).[41,65,72,82,166,326,327] In addition, SCG are reported to improve ratings of fatigue,[55,72,326,327] recovery,[65] and vitality.[7] In further support of SCG benefits on perceptual measures of recovery, numerous systematic reviews and meta-analyses report moderate[70,138] to large positive effects[286] of compression. For instance, a review by Marqués-Jiménez et al.[70] reported SCG to have a greater positive effect on DOMS as follow up times increased (i.e., greatest positive effect at 72 and 96 h post-exercise compared to < 48 h post-exercise). These psychological improvements observed with SCG use may be the result of less structural damage to muscles,[50,58,266] improved venous return leading to the removal of muscle metabolites,[12,172,313] and/or increased lymphatic outflow resulting in less swelling.[53,85,193]

Conversely, there are numerous reports of SCG use not to influence perceived muscle soreness.[42,66,74,77,79,85,165,324,328,329] The contrast findings could be due to differences in the training status of participants, the familiarity of the exercise protocol, and/or an inadequate level of eccentric loading (and hence muscle damage). With an inadequate level of muscle damage, it is difficult to determine the influence of SCG on muscle soreness. Furthermore, caution is advised when interpreting these psychological metrics due to the subjectivity of these measurements,[70] and reports that SCG benefits psychological outcomes without affecting performance and/or physiological measures.[43,65,119,141,284,287]

A concern with using perceptual measures to quantify recovery in SCG research is that participants' positive perception and belief in the garment may improve exercise

performance and recovery.[77,161,284,286] Consequently, the augmented exercise recovery with SCG could be due to a placebo effect. Previous research has tried to account for this potential placebo effect by incorporating 'sham' placebo interventions, including ultrasound[39,43,74] and carbohydrate drinks.[41,324] Alternatively, similar style garments with a low amount of pressure have been utilised in an attempt to blind participants.[75,79,150] However, due to the high amount of pressure exerted on the limb with SCG, participants can easily decipher if they are in the compression intervention group. Thus, the inability to blind participants is a challenge with compression research. Furthermore, despite the attempts of previous research to account for the placebo effect, these studies are limited in that belief in the placebo intervention compared with SCG was not assessed. As a result, the presence of a placebo effect cannot be discounted.[39,41,43,74] Therefore, future studies should try to better control for the placebo effect (i.e., measure belief in placebo and SCG interventions) as it can influence sports performance,[344,345] to fully determine the influence of SCG on parameters of exercise recovery.

1.2.5.4 *Influence of Sports Compression Garments on Blood Flow During Recovery*

Although SCG are widely used as an ergogenic aid post-exercise to enhance recovery, investigations into the underlying mechanism of changes in blood flow measures are lacking. In studies assessing changes in central haemodynamics (e.g., stroke volume, cardiac output, heart rate) post-exercise with compression, there is contrasting evidence with positive[12,38,107,108] and no effects[10,44,291,314] reported. A suggested reason for these contrasting findings is that the change in blood flow is greater in maximal than in submaximal exercise.[346] Thus, the exercise intensity might be important to observe the benefits of SCG on haemodynamic variables.[291] Additionally, SCG characteristics (i.e., pressure, type) may contribute to these equivocal findings. For example, favourable compression effects were evident in studies that used whole-body compression[107,108] or sports compression tights with pressures $\geq$ 27 mmHg.[12,38] In contrast, no changes were reported with sports compression socks[314] or sports compression tights that either failed to report pressure values[291] or had pressure values $\leq$ 18 mmHg.[10,44] However, as previously stated, central haemodynamic measures are limited in determining compression-induced changes in peripheral blood flow.

Enhanced exercise recovery reported with SCG is often attributed to the compression-induced increases in venous and muscle blood flow. However, limited research is available (Table 1-4) as most studies that investigate compression-induced changes in peripheral blood flow have focused on responses during exercise.[9–13,16,36] Similar to during exercise, NIRS-derived metrics (e.g., tHb, muscle oxygenation) are the most commonly used measures to investigate the influence of SCG on blood-flow responses post-exercise. Despite the paucity of research available after exercise, contrasting findings are evident for SCG effect on NIRS metrics of venous (tHb) and arterial (muscle oxygenation) blood flow.

For tHb values, the application of compression for 5 min post-exercise resulted in no change with sports compression socks,[13] whereas sports compression tights enhanced tHb.[133] A potential explanation for these differences could be the greater area under compression with tights compared to socks. As a result, sports compression tights may improve the action of the lower-limb skeletal muscle pump. In support of this, end-diastolic velocity[12] and venous emptying rate,[10] both indices of venous flow, are augmented post-exercise with sports compression stockings and tights, respectively. Further research measuring the effects of SCG on the venous system by techniques that quantify changes in venous structure and venous blood flow (i.e., Doppler ultrasound) is warranted. Additionally, research investigating changes in venous blood flow beyond 30 min post-exercise is lacking, even though SCG are typically worn for several hours post-exercise.[171]

Table 1-4: Summary of studies assessing the effects of sports compression garments on peripheral blood flow in recovery from exercise.

Study	Participants	Garment Type (duration)	Activity	Measurement Technique	Peripheral Blood Flow Variable
Book et al. 2016 [13]	Healthy 5F, 7M	Socks (5 min)	Plantar flexion (5 min)	Near-infrared spectroscopy Doppler ultrasound	↔ Total haemoglobin ↔ Arterial blood flow velocity ↔ Artery blood flow
Boucourt et al. 2015 [304]	Athletes 11	Socks (10 min)	Cycling (incremental test)	Near-infrared spectroscopy	↑ Muscle oxygenation
Menetrier et al. 2011 [157]	Endurance trained 14M	Calf Sleeve (30 min)	Running (30 min plus run to exhaustion)	Near-infrared spectroscopy	↑ Muscle oxygenation
Menetrier et al. 2015 [12]	Endurance trained 15M	Tights (12 min)	Cycling (9 x 5-min intervals)	Doppler ultrasound	↑ Arterial blood flow ↑ Time-averaged mean velocity ↑ End diastolic velocity ↑ Peak systolic velocity ↑ Resistance index
Rennerfelt et al. 2019 [306]	Runners 10F, 10M	Socks (5 min)	Running (10 km)	Near-infrared spectroscopy	↓ Muscle oxygenation
Riexinger et al. 2021 [294]	Recreationally active 7F, 9M	Socks (6 h)	Jumping and resistance (5 x 10 drop jumps, 5 x 50 heels raises)	Intravoxel incoherent motion	↔ Microvascular blood flow ↔ Microvascular perfusion
Sperlich et al. 2013 [16]	Recreationally active 6M	Shorts (35 min)	Cycling (incremental test)	Positron emission tomography	↔ Superficial muscle blood flow ↓ Deep muscle blood flow
Sperlich et al. 2013 [133]	Alpine skiers 12M	Tights (5 min)	Skiing (3-min simulation)	Near-infrared spectroscopy	↑ Total haemoglobin ↑ Muscle oxygenation
Venckunas et al. 2014 [10]	Recreationally Active 13F	Tights (30 min)	Running (4 km plus 400-m sprint)	Air plethysmography	↔ Arterial blood flow ↔ Venous reserve volume ↑ Venous emptying rate

F = females, M = males, ↑ a positive effect of compression, ↓ a negative effect of compression, ↔ no effect of compression.

Regarding changes in muscle oxygenation, values are reported to either increase[133,157,304] or decrease[306] post-exercise with SCG. In these studies, increased muscle oxygenation was reported with pressure values of ~ 15 mmHg at the ankle and ~ 27 mmHg at the calf (manufacturer reported values).[157,304] In comparison, pressure values were only reported at the ankle (25 mmHg; manufacturer reported values)[306] in the studies reporting a decrease in muscle oxygenation. As muscle oxygenation was measured proximal to the ankle (i.e., 12 cm below the fibula or lateral condyle of the tibia),[157,304,306] information on the pressure applied to the calf would help provide context for the decreased values of muscle oxygenation. Brophy-Williams et al.[77] reported pressure values of 37 ± 4 mmHg (measured) at the calf in the same sports compression socks, and considering pressure values of ~ 37 mmHg have been reported to reduce muscle blood flow post-exercise,[16] the reduced muscle oxygenation values reported by Rennerfelt et al.[306] may be explained by an attenuation in oxygen supply. These findings highlight the importance of assessing the amount of pressure provided by garments on the underlying musculature, as it is apparent that there may be an 'upper threshold' of pressure applied by SCG that are beneficial for blood flow responses. As such, assessing pressure values will aid our understanding of SCG effect on changes in peripheral blood flow.

Contrasting findings are also evident for more direct measures of arterial blood flow, with reports for compression to increase,[12] have no effect,[10,13] or reduce[16] measures post-exercise. As highlighted previously, the reduced muscle blood flow post-exercise with compression may be explained by the high level of pressure exerted on the limb (~ 37 mmHg).[16] Book et al.[13] reported no changes in popliteal artery blood flow or velocity at 5 min post-exercise with sports compression socks. In contrast, arterial blood flow and velocity were augmented for up to 9 min post-exercise in sports compression stockings.[12] These conflicting reports suggest that the type of SCG (i.e., percentage of lower limb exposed to compression) may also determine the compression-induced changes in arterial blood flow. Nevertheless, research also reports no change in arterial blood flow 30 min post-exercise with sports compression tights.[10] Compression-induced changes in arterial blood flow post-exercise, and beyond 30 min post-exercise, require further investigation.

1.2.5.5 *Benefits of Improved Blood Flow During Recovery*

Compression-induced augmentation of venous blood flow is hypothesised to aid in removing muscle metabolites (e.g., CK and lactate) and minimising the symptoms of EIMD and inflammation.[68] For example, SCG worn for 24 h after a full-body resistance training session lowered CK concentrations[7] in resistance-trained (heavy resistance training for a minimum of two years) females and males. Post-exercise inflammation exacerbates the release of damaged contractile proteins into the interstitial fluid,[70] resulting in oedema due to increased fluid absorption from the circulatory system and increasing intracompartmental pressure. By promoting lymphatic outflow, SCG may reduce exercise-induced oedema, thus attenuating the inflammatory response and preventing further muscle damage.[70] Considering the inflammatory response begins in the early hours (1 to 4 h)[269] after exercise, a crucial omission is that no research has investigated the effects of SCG on venous blood flow during this period.

By improving arterial perfusion and muscle blood flow,[5] SCG may also augment post-exercise nutrient delivery. Considering that blood flow is positively correlated with muscle glucose uptake,[347] SCG-induced increases in blood flow may enhance the recovery process by augmenting post-exercise muscle glycogen replenishment. To the author's knowledge, only one study has investigated the effect of SCG during recovery on glucose uptake. Sperlich et al.[16] reported no change in glucose uptake (as measured using an intravenous injection of ^{18}F-FDG tracer followed by a positron emission tomography (PET) scan), while wearing sport compression shorts during recovery from a 30-min cycling protocol. A reduction in muscle blood flow was also noted during the 35-min post-exercise recovery period. The high level of pressure exerted by the sports compression shorts (37 mmHg) may have mechanically hindered muscle blood flow (as compared with a control condition), resulting in no change in glucose uptake. Additionally, the microvasculature (i.e., capillaries) are in direct contact with the muscle and are responsible for the delivery and uptake of nutrients.[218] However, only one study has investigated SCG effects on post-exercise microvascular blood flow and perfusion.[294] No changes were evident with sports compression socks at 30 min post-exercise. Although microvascular blood flow was reassessed at 6 and 48 h post-exercise, any potential compression-induced changes were

unlikely as sports compression socks were removed following the 30 min post-exercise measurement. Again, a limitation of this study was the use of compression on one leg only.

Increased blood flow is also positively correlated with rates of MPS.[17,18] In addition, MPS is stimulated following resistance exercise,[348] and is considered an essential component of the adaptive response to resistance training (i.e., increased muscle mass).[349,350] Considering the evidence supporting SCG-induced increases in arterial perfusion and muscle blood flow,[5,9,12] SCG may provide a novel method to augment rates of MPS following resistance exercise. In support of this potential mechanism, upregulated markers of MPS[351,352] are evident with other methods shown to increase local blood flow (e.g., heat stress).[353] However, markers of MPS are yet to be investigated with SCG.

1.3 Sports Compression Garments and Training Adaptation

A limitation with SCG research performed is most investigations have focused on the effects of SCG worn during,[9,79,88,277] or after (i.e., recovery phase (< 72 h)),[66,74,98,172] a single exercise session, with little insight into the effects of repeated SCG use on training adaptations. Despite reports that SCG enhance performance acutely,[9,45,48–50,159,273,276] little information exists if these translate to long-term benefits (i.e., improved training adaptations). Only four studies (Table 1-5) have investigated the effects of regular SCG use (≥ 2 weeks) on exercise performance and adaptations to training.[34,354–356]

Lucas-Cuevas et al.[354] investigated the effects of wearing either sports compression socks during running sessions for three weeks on stride kinematics and impact acceleration, with the latter associated with overuse injuries.[357] At the end of three weeks, SCG reduced impact acceleration, assessed using lightweight tri-axial accelerometers, compared to a non-compressive placebo stocking. These findings suggest that the regular use of SCG during running may play a protective role in reducing the impact accelerations experienced via a compression-induced reduction in muscle vibrations. However, caution is advised as SCG (or placebo stockings) were worn during testing sessions at the end of the three weeks of training. Thus, it is difficult to determine if the beneficial findings were due to the regular use of SCG for three weeks (i.e., training adaptation) or the acute response of wearing SCG during testing.

Table 1-5: Summary of studies investigating the regular use of sports compression garments on adaptations to training.

Study	Participants	Garment Type (Use)	Training Program	Training Adaptation Metric	Effect of SCG
Baum et al. 2020 [34]	Resistance Trained 12M	Tights (during exercise sessions)	4 weeks lower-body resistance 3 days/week	Mass Body Fat % Leg Press 1RM Leg Press Reps to Failure Jump Height Peak and Average Power	↔ ↔ ↑ ↔ ↑ ↑
Hu et al. 2020 [356]	Novice Runners 10M	Tights (for 4 to 5 h after each exercise session)	2 weeks daily running (Started at 2 miles and increased by 0.5 miles every other day)	Heart Rate Variability	↑
Lucas-Cuevas et al. 2015 [354]	Recreational Runners 20F, 20M	Socks (during exercise sessions)	3 weeks running 3 days/week, 25 km/week	Stride Kinematics Impact acceleration	↔ ↔
Priego et al. 2015 [355]	Recreational Runners 7F, 13M	Socks (during exercise sessions)	3 weeks running 3-4 days/week, 30 km/week	Cardiorespiratory variables: V_E, HR, VO_2/kg, VCO_2/kg, V_E/VO_2, VE/VCO_2, VO_2/HR	↔ (all variables)

F = females, M = males, 1RM = one repetition maximum, V_E = minute ventilation, HR = heart rate, VO_2/kg = relative oxygen consumption, VCO_2/kg = relative carbon dioxide production, V_E/VO_2 = ventilatory equivalents for oxygen, VE/VCO_2 = ventilatory equivalents for carbon dioxide, VO_2/HR = oxygen pulse, ↑ a positive effect of compression, ↓ a negative effect of compression, ↔ no effect of compression.

In a similar study, Priego et al.[355] investigated the effects of wearing sports compression socks during three weeks of running training on different cardiorespiratory parameters (e.g., minute ventilation, heart rate, oxygen consumption, carbon dioxide production etc.) in recreational runners. Regularly wearing SCG did not influence the cardiorespiratory parameters measured in this study. Although the reason for this lack of effect with compression is not clear, the authors propose it may be due to numerous factors, including running experience of participants, compression level, and the use of a control stocking (i.e., placebo). Again, a limitation of this study is that sports compression socks (or placebo socks) were used during the testing sessions at the end of the three weeks of training with the assigned intervention.

Only one study has investigated the regular use of compression worn after exercise.[356] Sports compression tights were worn for 4 to 5 hours after each training session for two weeks in this study. The heart rate variability measure of the natural log root mean square of successive R-R intervals difference was used to detect changes in the autonomic nervous system and as an indicator of overtraining. Compression-induced augmentation of venous return may enable a greater cardiac preload, thus reducing cardiovascular stress and improving modulation of the autonomic nervous system.[291] Compared to a 'sham' intervention (same sports compression tights but two sizes larger than recommended), the use of SCG benefited the natural log root mean square of successive R-R intervals difference at the end of the two weeks. These findings are the first to highlight that SCG may limit the deleterious effects of overtraining, potentially due to improved cardiovascular responses with compression (i.e., an increased venous return may aid autonomic nervous system restoration and physical recovery). Based on these findings, regular SCG use may minimise the risk of overtraining, thus maintaining training intensity and improving training adaptations. However, further research is required to support or refute this theory.

Although there is a paucity of research that investigates the regular use of SCG, most studies have focused on endurance exercise,[354–356] and only one study conducted in resistance exercise. Baum et al.[34] reported that the use of SCG during lower-body resistance training (three days per week) for four weeks augments one repetition max (1RM) leg press and jump performance (i.e., jump height, peak power, and average power). As this is the only study conducted in resistance training, future research must corroborate these findings. Additionally, the regular use of SCG post-exercise to enhance

recovery could help to maintain training intensity and quality, thus leading to better training adaptations (Fig 1-7). However, to support this theory, further research into the regular use of SCG post-exercise, similar to Hu et al.,[356] is warranted. These investigations will help establish the impact regular SCG use may have on the adaptive response to training, and should be a focus of future SCG research.

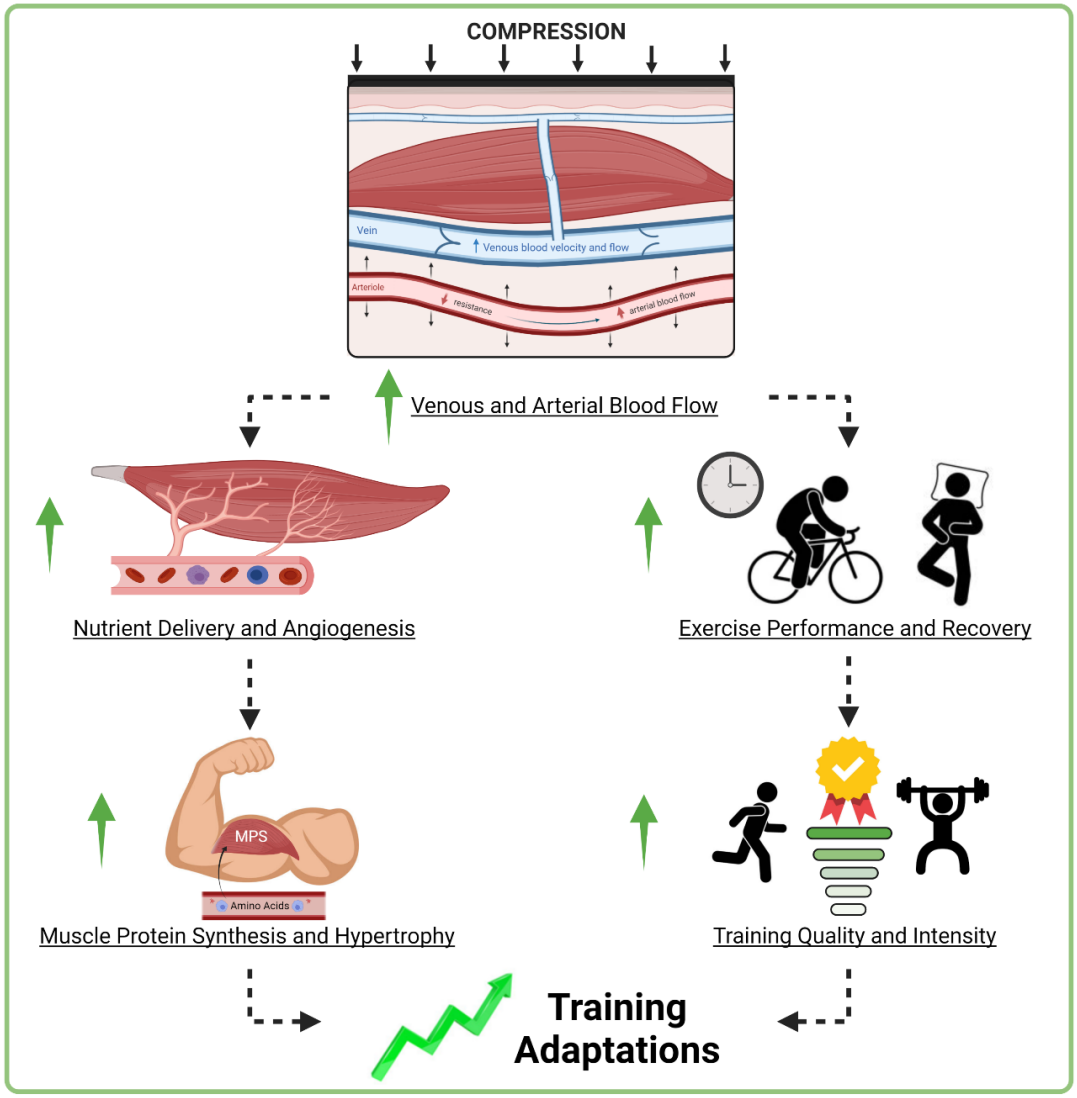

Figure 1-7: Potential mechanisms for sports compression garments to enhance training adaptations. Created with Biorender.com.

The lack of research on regular SCG use is a crucial omission considering enhanced blood flow, the proposed mechanism of SCG, may be beneficial in promoting resistance training adaptations. Resistance training stimulates MPS[348] and is regarded as a critical component of the adaptive response to resistance training (i.e., increased muscle mass, improved strength).[350,358] Regular SCG use may provide a novel method to augment rates of MPS, which is positively correlated with increases in blood flow.[359] Additionally,

regular compression-induced augmentation of blood flow could drive angiogenesis (growth of capillaries)[360] as a result of increased vascular shear stress.[361] Whether these mechanisms are altered with SCG is speculative, as no studies have investigated the influence of SCG on markers of MPS or angiogenesis, and limited research exists into the adaptive responses to resistance training (Fig 1-7).[34]

Studies utilising other methods shown to alter blood flow could provide context to the proposed compression-induced enhancement of training adaptations. For example, Campbell et al.[362] reported L-arginine supplementation, a precursor for the biosynthesis of nitric oxide (a trigger for blood vessel dilation and increased blood flow), during an 8-wk resistance training program improved 1RM bench press and Wingate peak power, as compared with a dextrose placebo. In agreement, heat stressors (e.g., hot water immersion), used to stimulate local blood supply,[353,363] can induce additional strength training benefits[364] and upregulate markers of MPS.[352] Conversely, regular cold-water immersion, a recovery technique that reduces muscle blood flow,[365] is suggested to induce detrimental effects on the adaptive response to resistance exercise training.[366,367] For instance, regular post-exercise cold water immersion (10 min) during a 12-wk resistance training period (2 days per week) attenuated satellite cell proliferation and the activity of kinases that regulate muscle hypertrophy,[368] factors associated with adaptations to resistance training.[350] In support of these findings, Fyfe et al.[369] reported that increases in type II muscle fibre cross-sectional area from resistance training (three days per week for seven weeks) were attenuated with cold water immersion (15 min) following each session. However, improvements in maximal strength (1RM leg press) were similar between groups. Considering these findings of improved[352,362,364] and reduced[368,369] training adaptations may occur due to changes in blood flow, they support the hypothesis that compression-induced increases in blood flow could have a similar effect.

These findings from the above studies[368,369] also raise the controversial question of the possible detrimental effects of recovery strategies on training adaptations. The aim of recovery strategies, like SCG, is to enable individuals to train more frequently and effectively by reducing levels of muscle damage, inflammation and soreness, resulting in greater training adaptations and improved performance in the long term. However, post-exercise inflammation and muscle damage are considered necessary to promote long-term training adaptation.[370] Thus, it is possible, similar to the observations in studies using cold water immersion,[368,369,371] that SCG may attenuate these anticipated training benefits. As

such, further research is warranted investigating the regular use of SCG during an extended resistance exercise training period (i.e., 8-12 weeks).

1.4 Summary

Although SCG are a common recovery strategy used by athletes, conclusive information on how SCG may improve recovery is lacking. Due to variations in methods applied in the current literature, it is difficult to ascertain the mechanisms by which SCG may improve recovery. In particular, the effect SCG have on blood flow post-exercise remains largely unknown. Should SCG improve blood flow during recovery, consistent with responses reported during exercise, it may provide a novel method to aid in the removal of metabolites and delivery of substrates, thereby improving muscle recovery. Also, it is currently unknown if SCG alter microvascular blood flow. Another crucial limitation of research to date is the lack of studies investigation the impact regular SCG use during recovery has on training adaptation. Given athletes' widespread use and acceptance of SCG as a recovery modality, its effects on post-exercise blood flow (venous return and muscle blood flow) must be verified. Furthermore, should SCG increase post-exercise blood flow, research investigating its effects on nutrient uptake, glycogen replenishment, and MPS are warranted.

1.5 Overall Aims

The overarching purpose of this thesis is to investigate the influence of SCG on blood flow, exercise performance, and exercise recovery. The first study aimed to investigate whether SCG alter markers of venous and muscle blood flow at rest and if differences exist between garment styles (i.e., sock, shorts, and tights). The second study investigated the effects of SCG on post-exercise blood flow and aspects of muscle recovery. The final study of this thesis aimed to investigate the impact of regular post-exercise SCG use on the adaptive responses to training (Appendix A – Information on cancelled sports compression and training study). However, due to COVID-19 restrictions in Victoria, Australia, during the majority of 2020 (over 200 days of strict lockdown measures for the last 18 months of my PhD, e.g., 5 km travel radius, work from home orders etc.), this study was not possible. To compensate for this, a systematic review with meta-analysis on the influence of SCG on peripheral blood flow (Chapter 2) and a study investigating the effect of SCG on microvascular blood flow (Chapter 5) were

included. Therefore, the aims and hypotheses of the experimental chapters of this thesis are listed below.

Chapter Two: To systematically review and analyse the effects of SCG on peripheral measures of blood flow at rest, during, immediately post, and in recovery from a physiological challenge. Additionally, this review aimed to highlight any methodological variations in compression research, including SCG details, physiological challenges and the techniques used to assess blood flow.

Chapter Three: To investigate the effects of three SCG types on markers of venous return and muscle blood flow at rest. It was hypothesised that SCG would alter measures of blood flow, and these alterations would be dependent on the type of SCG used.

Chapter Four: To investigate the influence of SCG on post-exercise recovery and blood flow, and examine if the placebo effect is responsible for any acute performance or psychological benefits. It was hypothesised that SCG would enhance post-exercise blood flow and subsequently improve indices of muscle recovery, and that these benefits would not be related to the placebo effect.

Chapter Five: To investigate the effects of SCG on muscle microvascular blood flow, femoral artery blood flow, muscle oxygenation, and exercise performance during and following RSE. It was hypothesised that muscle microvascular and femoral artery blood flow would be augmented with SCG immediately after and 1 h post-exercise.

CHAPTER TWO

Do sports compression garments alter measures of peripheral blood flow? A systematic review with meta-analysis.

The underlying mechanisms by which SCG benefit exercise performance and recovery are closely associated with alterations in peripheral blood flow (i.e., venous and muscle blood flow). However, as most systematic reviews and meta-analyses investigating the ergogenic effects of SCG have focused on exercise performance and/or recovery outcomes, a review focusing on the underlying mechanism of compression-induced changes in blood flow is warranted. Therefore, the aim of Chapter 2 was to systematically review and analyse the effects of SCG on peripheral measures of blood flow at rest, during, immediately post, and in recovery from a physiological challenge.

The manuscript for this review is in final stages of preparation:

O'Riordan, S. F., Bishop, D. J., Halson, S. L., Clark, S., and Broatch, J. R. (2021). Do Sports Compression Garments Alter Measures of Peripheral Blood Flow? A Systematic Review with Meta-Analysis. *Sports Medicine* (in review).

Sport Med, Q1; Impact Factor (2020): 11.136

Abstract

Background: One of the proposed mechanisms underlying the benefits of sports compression garments (SCG) may be due to alterations in peripheral blood flow. **Objective:** To determine if SCG alter measures of peripheral blood flow at rest, during, immediately post, and in the recovery from a physiological challenge.

Methods: A systematic literature search of databases including Scopus, SPORTDiscus and PubMed/MEDLINE. The selected studies investigated the effects of compression garments on peripheral measures of blood flow. The criteria for inclusion of studies were: (1) original papers in English and a peer-reviewed journal; (2) assessed effect of compression garments on a measure of peripheral blood flow at rest (with garments used in a physiological challenge or described as SCG only) and/or before, during, or post a physiological challenge; (3) participants were healthy and without cardiovascular or metabolic disorders; (4) a study population including athletes, physically active, and healthy participants. The PEDro scale assessed the methodological quality of the included studies. A random-effects meta-analysis model was used. Changes in blood flow were quantified by standardised mean difference (SMD) [± 95% confidence interval (CI)].

Results: Of the 872 articles identified, 19 studies were included for the meta-analysis. The results indicated SCG improve overall peripheral blood flow (SMD = 0.31, 95% CI: 0.13, 0.50, $p < 0.01$), with no overall change on venous blood flow (SMD = 0.21, 95% CI: -0.01, 0.44, $p = 0.06$), but enhanced overall arterial blood flow (SMD = 0.39, 95% CI: 0.11, 0.68, $p < 0.01$). At rest, the use of SCG was associated with no change in peripheral blood flow (SMD = -0.04, 95% CI: -0.29, 0.21, $p = 0.76$) or subgroup analysis of venous (SMD = -0.08 95% CI: -0.52, 0.35, $p = 0.71$) and arterial (SMD = -0.01, 95% CI: -0.32, 0.30, $p = 0.96$) blood flow. During exercise, peripheral blood flow was improved (SMD = 0.45, 95% CI: 0.31, 0.59, $p < 0.01$), with subgroup analysis revealing SCG to enhance both venous (SMD = 0.45, 95% CI: 0.28, 0.62, $p < 0.01$) and arterial blood flow (SMD = 0.56, 95% CI: 0.26, 0.85, $p < 0.001$). At immediately post, there was no change in peripheral blood flow (SMD = -0.00, 95% CI: -0.41, 0.40, $p = 0.99$) or subgroup analysis of venous blood flow (SMD = -0.23, 95% CI: -0.92, 0.46, $p = 0.51$) with the use of SCG. However, SCG did enhance arterial blood flow at this time point (SMD = 0.37, 95% CI: 0.12, 0.63, $p < 0.01$). In recovery, SCG improved peripheral blood flow (SMD = 1.87, 95% CI: 1.27, 2.47, $p < 0.01$) with subgroup analysis showing

enhanced venous (SMD = 0.51, 95% CI: 0.17, 0.85, $p < 0.01$) and arterial blood flow (SMD = 2.49, 95% CI: 1.65, 3.34, $p < 0.01$).

Conclusion: The use of SCG enhances peripheral blood flow, and, in particular, measures of arterial blood flow, during and in recovery from a physiological challenge.

2.1 Introduction

Sports compression garments are used in athletic settings to enhance exercise performance and recovery. These garments apply pressure to the area they are covering[27] and their use during exercise has been reported to improve numerous performance metrics, including jump height,[49,50,110,273] cycling power output,[8,9,47,64] repeated sprint ability,[9,48] and running performance.[45,46,275] When worn during the post-exercise recovery period, compression is reported to reduce ratings of muscle soreness,[52,55,121,172,284,372] decrements in subsequent exercise performance,[52,55,74,89] and muscle swelling,[7,55,172] as well as enhance the clearance of muscle damage markers.[7,83,168,172] Collectively, it is hypothesised that the ergogenic effects of SCG during and following exercise are largely associated with compression-induced increases in peripheral blood flow (i.e., venous and muscle blood flow).[68,138]

Compression-induced increases in venous blood flow[56,71,210] occur through mechanical distortion of the underlying vessels by decreasing vein diameter and improving valve competence.[137] As a result, blood is diverted from superficial veins, through perforator veins, and into deep veins leading to an increase in deep venous velocity, reduced venous pooling, and improved venous return.[21,195] In support of this mechanism, graduated compression stockings increased resting popliteal venous flow by ~30%, coinciding with a decrease in venous cross-sectional area.[71] However, compression alters muscle blood flow by a different mechanism. In essence, the application of compression increases arterial vessel size (i.e., vasodilation).[373] This reflex vasodilation, termed a myogenic response, is proposed to occur due to a reduction in arteriolar transmural pressure.[5] Subsequently, decreasing arterial flow resistance leads to increased arterial flow and blood supply to the muscle.[5]

The external pressure applied to the limb by SCG has been shown to increase venous and muscle blood flow measures in some[5,6,9,11,12,71,210], but not all studies. For instance, sports compression tights are reported to increase muscle blood flow, measured using NIRS with venous occlusions, by ~18% during repeated cycling exercise.[9] Conversely, using the same exercise protocol,[9] compression has been reported to decrease microvascular perfusion, measured using CEU, despite increased femoral artery blood flow.[373] Also, while many studies report compression to enhance venous[6,71,210] and muscle[5,9,11,12] blood flow measures, solid conclusions have yet to be established, with

some reports showing SCG do not alter venous or muscle blood flow.[13,36,305] Our recent observations[9,373] highlight that variations in blood flow measurement techniques may explain these inconsistent findings. Additionally, the contrasting reports are likely due to the high level of heterogeneity in SCG details and the intensity of physiological challenges used in compression research.

Characteristics of SCG, including the degree of pressure applied and body area covered (i.e., upper body, calf area, entire lower-limb), determine the effectiveness of the garment in altering blood flow.[71,374] In support of this, differences in venous blood flow were observed between light (14 mmHg), mild (21.2 mmHg), moderate (32.1 mmHg) and high (46.5 mmHg) degrees of pressure at the ankle in graduated compression stockings.[71] Also, compression shorts exerting high pressure (37 mmHg) have been reported to reduce muscle blood flow.[16] Additionally, as blood flow increases to meet the metabolic demand of the active muscle,[215,375] the intensity of a physiological challenge, such as exercise, may influence the efficacy of SCG to alter peripheral blood flow. For example, compression-induced increases in muscle blood flow have been reported during RSE,[9] but not during prolonged trail running.[305] However, the differences in SCG type (tights for RSE, socks for prolong trail running) may also help explain these contrast findings. Aside from providing an estimated overall effect, a systematic review with meta-analysis may identify potential relationships between previous studies regarding the influence of SCG type and/or pressure in altering peripheral blood flow.

To date, most systematic reviews and meta-analyses investigating the ergogenic effects of SCG have focused on exercise performance and/or recovery outcomes.[68–70,138,286,376] Although the benefits of SCG during and following exercise are likely related to changes in blood flow, only one systematic review has focused on haemodynamic outcomes.[288] The review concluded that wearing compression garments positively alters central haemodynamics responses (i.e., heart rate and stroke volume) at rest or after a physiological challenge. Specifically, the review highlights that compression garments increase stroke volume and decrease heart rate, with responses more pronounced after a physiological challenge. However, compression did not affect other central haemodynamic measures, including cardiac output, blood pressure, or systemic vascular resistance. Alterations in central haemodynamics with SCG may result in, and/or be a result of, increases in peripheral blood flow. For example, the augmented activity of the skeletal muscle pump with compression increases venous flow velocity

and enhances venous return.[71] In turn, end-diastolic filling and stroke volume are increased, thus reducing heart rate.[9,287] However, data regarding the influence of SCG on peripheral blood flow measures are inconclusive. Thus, a systematic review and meta-analysis of the available literature is warranted to determine the effect of SCG on measures of peripheral blood flow.

The aim of this systematic review with meta-analysis was to systematically evaluate existing literature that has investigated the effects of SCG on peripheral measures of blood flow. Additionally, this review and analysis aimed to (a) identify any differences in peripheral blood flow with SCG at rest and during, immediately post, or in recovery from, a physiological challenge; (b) highlight methodological variations in compression research, including SCG details (i.e., type and degree of pressure), physiological challenges, and the techniques used to assess blood flow.

2.2 Methods

This systematic review was conducted according to Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines.[377]

2.2.1 Literature Search

A literature search was performed using the following online databases: Scopus, SPORTDiscus and PubMed/MEDLINE. The following syntax of keywords used to find relevant papers was: ("compression garments" OR "compression clothing" OR "sports compression garments" OR "graduated compression" OR "compression tights" OR "compression socks" OR "compression stockings" OR "compression shorts" OR "compression sleeves") AND ("blood flow" OR "haemodynamic" OR "cardiovascular" OR "oxygenation" OR "venous" OR "arterial" OR "perfusion") AND ("exercise" OR "recovery" OR "rest"). Advanced search techniques from the search engines of "related words" was also included. The search of databases ended in November 2020. The reference list of obtained articles and reviews were examined to identify any further relevant studies to supplement the database searches. The study selection was independently performed by two authors (SOR and JB) to prevent selection bias.

2.2.2 Inclusion and Exclusion Criteria

Studies were included in the review on the basis of the following criteria: (1) original papers in English and in a peer-reviewed journal; (2) assessed compression garments effect on a measure of peripheral blood flow at rest (with garments used in a physiological challenge or described as SCG only) and/or prior to, during, or post a physiological challenge (i.e., exercise or an orthostatic challenge); (3) participants were healthy and did not have any cardiovascular or metabolic disorders; (4) a study population including athletes, physically active and healthy participants. For athlete classification, a participant had to either be deemed so by the authors, described as highly trained in some sport, or a member of a college team or club.[376] Studies were excluded if: (1) changes in peripheral blood flow were not assessed while wearing compression garments; (2) compression garments were used in conjunction with other treatments (e.g., nutrition, cold water immersion, stretching); (3) no control condition was included; (4) insufficient data to conduct meta-analysis after contact with authors.

2.2.3 Data Extraction

The following data were extracted from the selected studies that met the inclusion criteria: (1) participant characteristics of samples size, sex, age, and physical activity level (healthy, recreationally active, or athlete); (2) compression garment details including type, pressure, and when compression garments were worn (rest, during, and/or post-exercise); (3) outcome variable to assess compression effects on peripheral blood flow at any of the following time points: rest (before a physiological challenge), during (during a physiological challenge), immediately post (cessation of a physiological challenge or described as post), and recovery (time point after a physiological challenge or described as recovery); (4) exercise intervention. When required, the Web Plot Digitiser software (Version 4.4; TX, USA; Ankit Rohatgi, 2020) was used to extract data from figures. All data were tabulated in an Excel spreadsheet (Microsoft Corporation, Redmond, WA, USA) independently by two authors (SOR and JB). Files were cross-checked between the authors, with discrepancies resolved through discussion and agreement, or third-party adjunction (SH).

2.2.4 Risk of Biased Assessment and Methodological Quality

For the assessment of the methodology quality of studies, two authors (SOR and JB) used the 11-point PEDro scale.[378] Consultation from a third author (SH) was used to

resolve disagreements. The maximal score a study could achieve was 10 points, as the first statement was excluded as it concerns external validity. Studies were then classified as having excellent (9 to 10), good (6 to 8), moderate (4 to 5), or poor (< 4) methodological quality.[379] The PEDro scale is a valid and reliable method to assess the quality of randomised control trials,[378,380] and has been used previously in compression garment systematic reviews.[138,286,288,381]

2.2.5 Statistical Analysis

The average value of the means and average standard deviation for each outcome measure was calculated for both SCG and control groups within individual studies. The average standard deviation was calculated using guidelines highlighted in the Cochrane Handbook for Systematic Review.[382] In each study, the mean change and standard deviation[383] from rest values to during, immediately post, and recovery were determined for venous and arterial blood flow measures in the SCG and control groups. These values, in addition to rest values, were used in RevMan 5 (Review Manager, V5.4; Cochrane Collaboration) with a Random-Effects model to calculate the standardised mean difference (SMD) and 95% confidence intervals (CI) between groups (SCG versus control) during, immediately post, and in recovery. At each time point, subgroup analysis was included to quantify the SCG effect on venous or arterial measures of peripheral blood flow. SMDs were defined as small (0.20 to 0.49), medium (0.50 to 0.79), or large (≥ 0.80).[384] Heterogeneity was assessed using Cohran's Q (a chi-square test of residual heterogeneity), I^2 statistic (proportion of the residual heterogeneity on unaccounted variability) and Tau^2 (standard deviation from the study-estimate random effect). Heterogeneity among studies was evaluated by I^2 statistic as follows: low heterogeneity was assumed when $I^2 < 25\%$; moderate heterogeneity when $I^2 < 75\%$ and $> 25\%$; high heterogeneity when $I^2 \geq 75\%$.[385] A significance level of $p < 0.05$ was applied.

2.3 Results

2.3.1 Included Studies

A total of 869 articles were identified through database searches, with a further three articles identified through a manual search of reference lists. Of the 872 articles identified, 276 were duplicates, and 540 were excluded. A total of 56 articles were assessed for eligibility (Fig 2-1).

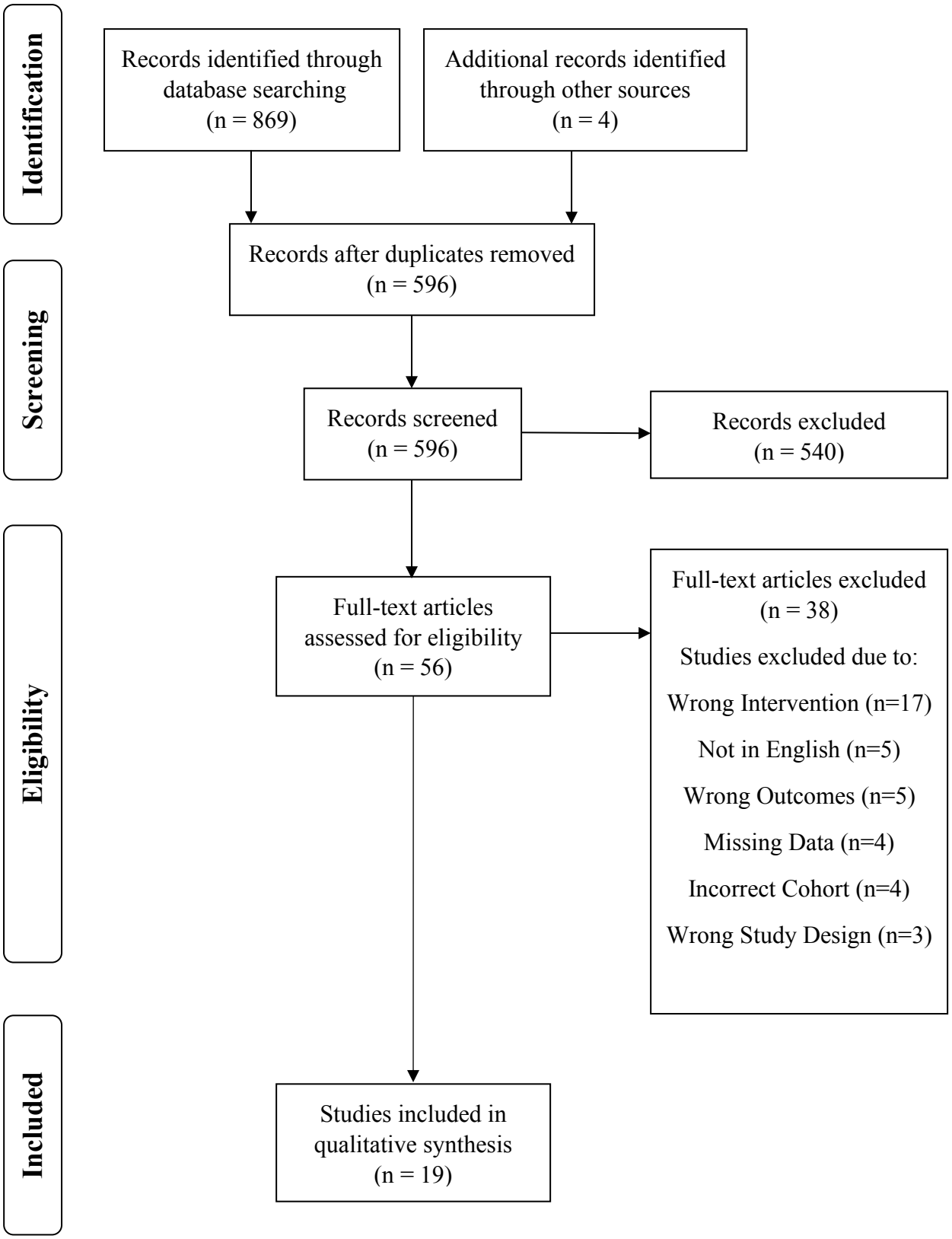

Figure 2-1: PRISMA flow diagram of literature screening process.

2.3.2 Data Extraction and Risk of Bias Assessment

Of the 56 relevant articles, 38 were excluded because of inappropriate intervention, language, outcomes, cohort, study design, or missing data (Fig 2-1). Nineteen articles that met the inclusion criteria had data extracted for inclusion in the meta-analysis (Table 2-1). Across the 19 studies, 19 different measures of peripheral blood flow were assessed. These included arterial blood flow (ABF),[10,12,296] arterial reserve (AR),[296] deep muscle blood flow (deep mBF),[16] ejection fraction (EF),[297,386] end diastolic volume (EDV),[12] middle cerebral artery blood flow velocity (MCAv),[80,130,387] muscle blood flow (mBF),[5,9,36] peak systolic velocity (PSV),[12] mean popliteal artery blood velocity (PBVmean),[13] mean popliteal artery flow rate (PBFmean),[13] popliteal vein blood flow (VBF),[295] residual volume fraction (RVF),[297] resistance index (RI),[12] superficial muscle blood flow (superficial mBF),[16] time-averaged mean velocity (TAMV),[12] total haemoglobin (tHb),[6,13,45,124,140] venous emptying rate (VER),[10] venous filling index (VFI),[297] and venous reserve volume (VRV).[10] A total of six different styles of compression garments were used to assess changes in peripheral blood flow among the 19 studies. These styles were tights (covering from above ankle to waist),[6,9,10,12,80,124,281,387] socks (covering foot to below the knee),[13,36,130,295–297,386] shorts (covering from knee to waist),[16] upper-body (covering torso plus entire arm to the wrist),[140] an arm sleeve (covering from wrist to elbow)[5] and a whole-body garment (combination of tights and upper-body garments).[45] For the 19 included studies, the mean (± SD) PEDro score was 5.8 ± 0.4 (range 5 to 6) (Table 2-2).

2.3.3 Participant Characteristics

The 19 studies included in this meta-analysis comprised a total of 241 participants (59 female and 182 male). One study included female participants only,[10] 11 studies included male participants only,[5,6,387,12,16,36,45,80,124,295,386] and seven studies included both sexes.[9,13,130,140,281,296,297] Participant cohorts were healthy,[5,13,130,387] physically active,[9,10,16] or athletes.[6,12,297,386,36,45,80,124,140,281,295,296] The mean sample size of included studies was 13 ± 6 (mean ± SD; range 5 to 30), and mean age was 25.8 ± 4.7 (range 22 to 40) years.

Table 2-1: Characteristics and summary of studies included in the meta-analysis.

Study	Cohort, sample size, sex, age (y)	Garment type	Pressure (mmHg)	Physiological challenge (timing and duration of compression)	Peripheral blood flow variable	Effect (timepoint)
Bochmann et al. 2005 [5]	Healthy 5M 25.0 ± 3.0	Arm sleeve	Forearm: 16.0 ± 5.0[a]	70-min rhythmic hand exercise (pre, during)	mBF	↑ (pre), ↑ (during)
Book et al. 2016 [13]	Healthy 5F, 7M 27.3 ± 6.4	Socks	Ankle: 30.8 ± 5.8[a] Knee: 20.2 ± 5.7[a]	5-min plantar flexion (pre, during, recovery: 5 min)	tHb PBVmean PBFmean	↔ (pre, recovery), ↑ (during) ↔ (pre, during, recovery) ↔ (pre, during, recovery)
Born et al. 2014 [281]	Ice speed skaters 6F, 4M 23.0 ± 7.0	Tights	Thigh: 20.3 ± 2.3[a] Calf: 24.4 ± 3.1[a]	3000-m race simulation (during)	tHb	↔ (during)
Bringard et al. 2006 [6]	Sportsmen 12M 26.5 ± 2.6	Tights	*Elastic tight* Calf: 5[a] *Compression tight* Calf: 24.1[a]	Supine rest (during)	tHb	↑ (during)
Broatch et al. 2018 [9]	Recreationally active 11F, 9M 26.5 ± 6.3	Tights	Thigh: 11.7 ± 2.3[a] Calf: 26.4 ± 6.4[a] Ankle: 21.5 ± 8.2[a]	Repeated sprint cycling (pre, during)	mBF	↔ (pre) ↑ (during)
Castilho-Junior et al. 2018 [297]	Amateur runners 6F, 4M 40.3 ± 5.0	Socks	Calf: 20[b] Ankle: 30[b]	10-km run (during)	VFI EF RVF	↑ (post) ↔ (post) ↑ (post)
Dascombe et al. 2011 [124]	Middle distance runners 11M 28.4 ± 10.0	Tights	*Regular garment* Thigh: 13.7 ± 2.3[a] Calf: 19.2 ± 3.2[a] *Undersize garment* Thigh: 15.9 ± 2.6[a] Calf: 21.7 ± 4.3[a]	Time to exhaustion running at 90% VO_{2max} (during)	tHb	↑ (during)
Dascombe et al. 2013 [140]	Elite kayakers 2F, 5M 25.0 ± 4.2 (F) 21.8 ± 2.8 (M)	Upper body	n.r.	Kayak ergometer: six step incremental test plus 4-min performance test (during)	tHb	↔ (during)

Table 2-1: continued.

Study	Cohort, sample size, sex, age (y)	Garment type	Pressure (mmHg)	Physiological challenge (timing and duration of compression)	Peripheral blood flow variable	Effect (timepoint)
Dorey et al. 2018 [130]	Healthy 4F, 6M 23.0 ± 2.0	Socks	30-40[b]	OC (15-min 60° HUT), 60-min cycling at 60% peak workload, and OC (pre, during)	MCAv	↔ (pre, during) ↑ (post)
Kerherve et al. 2017 [36]	Trail runners 14M 21.7 ± 3.0	Socks	Calf: 23.0 ± 2.0[a]	24-km trail run (pre, during)	mBF	↑ (pre) ↔ (during)
Mann et al. 2016 [296]	Amateur runners 12F, 18M 23.0 (F), 24.0 (M)	Socks	n.r.	Incremental running test (during)	ABF AR	↑ (post) ↑ (post)
Menetrier et al. 2015 [12]	Endurance trained 15M 22.5 ± 0.7	Tights	Thigh: 14[b] Calf: 27[b] Ankle: 15[b]	9 x 5 min cycling intervals (post-exercise: 12-min)	ABF TAMV EDV PSV RI	↑ (post) ↑ (post) ↔ (post) ↑ (post) ↑ (post)
Morrison et al. 2014 [387]	Healthy 15M 27.0 ± 4.0	Tights	10-15[a]	OC: supine to stand test (pre, during)	MCAv	↔ (pre, during)
Oficial-Casado et al. 2020 [295]	Runners 10M 35.0 ± 5.0	Socks	Medium or high compression n.r.	30-min at 75% of maximal aerobic speed (pre, during)	Popliteal VBF	↔ (pre, post)
Partsch et al. 2014 [386]	*Exp 1:* Soccer players 12M n.r. *Exp 2:* Tennis players 6M n.r.	Socks	Calf: 23[a]	Walking test (post)	EF	Exp 1: ↔ (post) Exp 2: ↔ (post)

Table 2-1: continued.

Study	Cohort, sample size, sex, age (y)	Garment type	Pressure (mmHg)	Physiological challenge (timing and duration of compression)	Peripheral blood flow variable	Effect (timepoint)
Sear et al. 2010 [45]	Team sport athletes 8M 20.6 ± 1.2	Full body	Forearm: 5.8 ± 1.0[a] Bicep: 7.3 ± 2.5[a] Chest: 5.3 ± 0.5[a] Oblique: 5.9 ± 0.8 [a] Glute: 9.2 ± 1.6 [a] Thigh: 13.1 ± 1.7[a] Calf: 15.1 ± 2.0[a] Ankle: 17.8 ± 2.2[a]	45 min prolonged high-intensity intermittent exercise (during)	tHb	↔ (during)
Smale et al. 2018 [80]	Trained cyclists 15M 28.1 ± 6.3	Tights	Thigh: 15.4 ± 4.5[a] Knee: 20.3 ± 6.6[a] Ankle: 21.8 ± 6.6[a]	4 x 8-min incremental cycling (pre, during)	MCAv	↔ (pre, during)
Sperlich et al. 2013 [16]	Physically active 6M 22.0 ± 2.0	Shorts	Thigh: 36.7 ± 4.1[a]	Incremental cycling test (pre-exercise: 20-min, recovery: 35-min)	Superficial mBF Deep mBF	↔ (pre), ↔ (recovery) ↔ (pre), ↓ (recovery)
Venckunas et al. 2014 [10]	Physically active 13F 25.1 ± 4.2	Tights	Thigh: ~17[a] Calf: ~19[a]	4-km run in 30-min plus 400-m sprint (pre, during, recovery: 30-min)	ABF VRV VER	↓ (pre), ↔ (recovery) ↔ (pre, recovery) ↔ (pre), ↑ (recovery)

↔ no significant effect from compression ($p < 0.05$), ↑ a significant positive effect from compression ($p < 0.05$), ↓ a significant negative effect from compression, *ABF* arterial blood flow, *AR* arterial reserve, *EF* ejection fraction, *EDV* end diastolic velocity, *F* female, *HUT* head up tilt test, *M* male, *MCAv* middle cerebral artery blood flow velocity, *mBF* muscle blood flow, *n.r.* not reported, *OC* orthostatic challenge, *PSV* peak systolic velocity, *PBVmean* mean popliteal artery blood velocity, *PBFmean* mean popliteal artery flow rate, *RVF* residual volume fraction, *RI* resistance index, *SCG* sports compression garment, *TAMV* time-averaged mean velocity, *tHb* total haemoglobin, *VBF* vein blood flow, *VER* venous emptying rate, *VFI* venous filling index, *VRV* venous reserve volume.

[a] Pressure measured directly, [b] Manufacturer reported pressure

Table 2-2: Quality Assessment of Included Studies Based on the PEDro Scale.

			PEDro Item Number										
Study	**Score**	**Methodological Quality**	**1***	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Bochmann et al. 2005 [5]	5	Fair	✓			✓				✓	✓	✓	✓
Book et al. 2016 [13]	6	Good	✓	✓		✓				✓	✓	✓	✓
Born et al. 2014 [281]	6	Good	✓	✓		✓				✓	✓	✓	✓
Bringard et al. 2006 [6]	6	Good	✓	✓		✓				✓	✓	✓	✓
Broatch et al. 2018 [9]	6	Good		✓		✓				✓	✓	✓	✓
Castilho-Junior et al. 2018 [297]	5	Fair	✓			✓				✓	✓	✓	✓
Dascombe et al. 2011 [124]	6	Good	✓	✓		✓				✓	✓	✓	✓
Dascombe et al. 2013 [140]	6	Good	✓	✓		✓				✓	✓	✓	✓
Dorey et al. 2018 [130]	6	Good		✓		✓				✓	✓	✓	✓
Kerhervé et al. 2017 [36]	6	Good	✓	✓		✓				✓	✓	✓	✓
Mann et al. 2016 [296]	6	Good	✓	✓		✓				✓	✓	✓	✓
Ménétrier et al. 2015 [12]	6	Good	✓	✓		✓				✓	✓	✓	✓
Morrison et al. 2014 [387]	6	Good	✓	✓		✓				✓	✓	✓	✓
Oficial-Casado et al. 2020 [295]	6	Good	✓	✓		✓				✓	✓	✓	✓
Partsch et al. 2014 [386]	5	Fair	✓			✓				✓	✓	✓	✓
Sear et al. 2010 [45]	6	Good	✓	✓		✓				✓	✓	✓	✓
Smale et al. 2018 [80]	6	Good	✓	✓		✓				✓	✓	✓	✓
Sperlich et al. 2013 [16]	6	Good		✓		✓				✓	✓	✓	✓
Venckunas et al. 2014 [10]	6	Good	✓	✓		✓				✓	✓	✓	✓

Note. 1 = Eligibility criteria specified, *not included in methodological score; 2 = Random allocation of the participants; 3 = Blind allocation; 4 = Similar baseline characteristics between groups; 5 = Blinding of participants; 6 = Blinding of the researchers who administered the intervention to participants; 7 = Blinding of the researchers who measured outcome; 8 = Adequately follow-up; 9 = Intention to treat; 10 = results of between-group statistical comparisons are reported for at least one key outcome; 11 = Measures of variability for at least one key outcome.

3.3.4 Influence of SCG on Peripheral Blood Flow

Meta-analytic outcomes for the average of all peripheral blood flow measures from the 19 included studies showed a small positive effect for SCG compared to control (SMD = 0.31, 95% CI: 0.13, 0.50, z = 3.37, $p < 0.001$) (Fig 2-2). Moderate heterogeneity amongst studies was observed (Cohran's Q = 48.30, $I^2 = 38\%$, $Tau^2 = 0.10$, $p = 0.02$). A subgroup analysis of venous and arterial flow measures revealed there was no difference in overall venous blood flow measures between SCG and control groups from 11 studies (SMD = 0.21, 95% CI: -0.01, 0.44, z = 1.89, $p = 0.06$). Across 11 studies, overall arterial blood flow showed a small positive effect for SCG compared to control (SMD = 0.39, 95% CI: 0.11, 0.68, z = 2.68, $p < 0.01$). Low heterogeneity amongst studies assessing venous blood flow were observed (Cohran's Q = 9.10, $I^2 = 0\%$, $Tau^2 = 0.00$, $p = 0.76$), whereas moderate heterogeneity was observed for studies assessing arterial measures of blood flow (Cohran's Q = 37.82, $I^2 = 58\%$, $Tau^2 = 0.20$, $p = 0.002$).

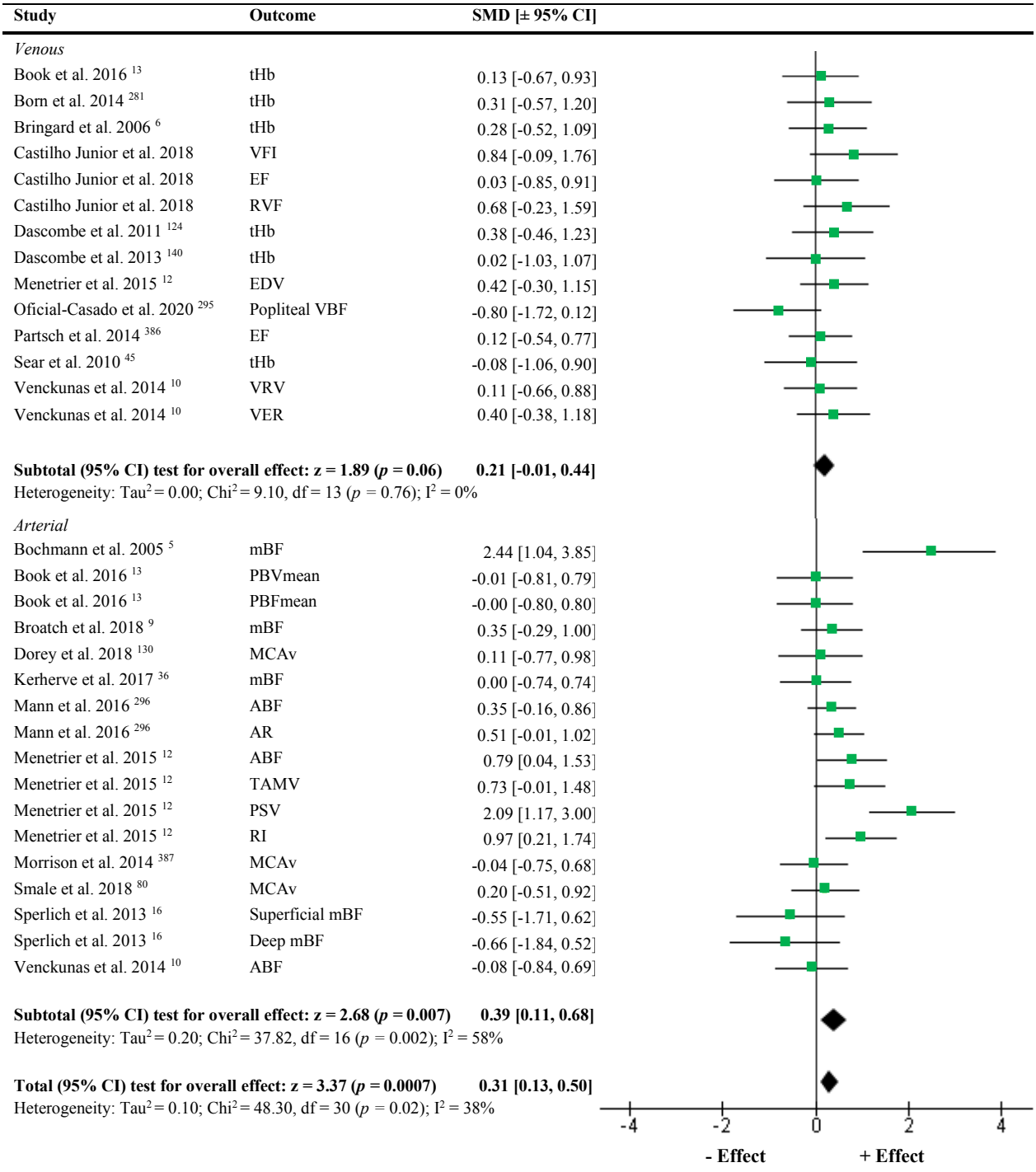

Figure 2-2: Forest plot illustrating the overall effects of sports compression garments (SCG) compared with a control on peripheral blood flow outcomes in each study. *Square boxes* represent the standardised mean effect for each study, with *lines* representing 95% CIs. A *diamond* represents the overall SMD, with its width representing 95% CIs. *ABF* arterial blood flow, *AR* arterial reserve, *CI* confidence interval, *EF* ejection fraction, *EDV* end diastolic velocity, *MCAv* middle cerebral artery blood flow velocity, *mBF* muscle blood flow, *PSV* peak systolic velocity, *PBVmean* mean popliteal artery blood velocity, *PBFmean* mean popliteal artery flow rate, *RVF* residual volume fraction, *RI* resistance index, *SMD* standardised mean difference, *TAMV* time-averaged mean velocity, *tHb* total haemoglobin, *VBF* vein blood flow, *VER* venous emptying rate, *VFI* venous filling index, *VRV* venous reserve volume.

A total of 11 studies were included for the analysis of peripheral blood flow measures at rest (Fig 2-3). There was no difference in peripheral blood flow between SCG and control groups (SMD = -0.04, 95% CI: -0.29, 0.21, z = 0.30, p = 0.76) at rest. Moderate heterogeneity amongst studies was observed (Cohran's Q = 37.31, I^2 = 46%, Tau^2 = 0.16, p = 0.01). In this analysis, a total of 11 different measures of blood flow were assessed, including four venous

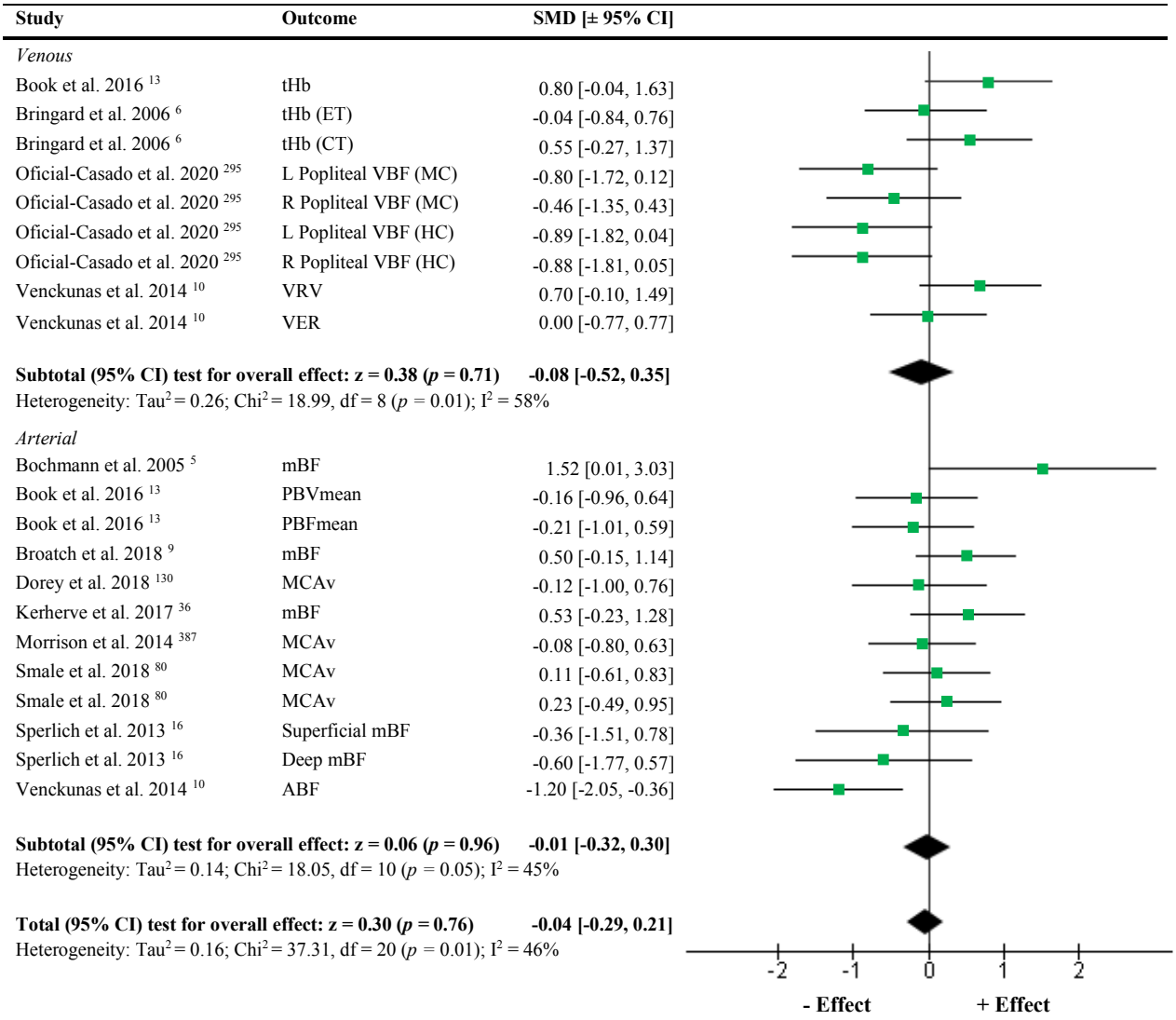

Figure 2-3: Forest plot illustrating the effects of sports compression garments (SCG) compared with a control on peripheral blood flow measures at rest prior to a physiological challenge. *Square boxes* represent the standardised mean effect for each study, with *lines* representing 95% CIs. A *diamond* represents the overall SMD, with its width representing 95% CIs. *ABF* arterial blood flow, *CT* compression tights, *CI* confidence interval, *EF* ejection fraction, *ET* elastic tights, *HC* high-pressure compression garments, *MC* medium-pressure compression garments, *MCAv* middle cerebral artery blood flow velocity, *mBF* muscle blood flow, *PBVmean* mean popliteal artery blood velocity, *PBFmean* mean popliteal artery flow rate, *SMD* standardised mean difference, *tHb* total haemoglobin, *VBF* vein blood flow, *VER* venous emptying rate, *VRV* venous reserve volume.

(tHb,[6,13] popliteal VBF,[295] VRV,[10] VER[10]) and seven arterial (mBF,[5,9,36] PBVmean,[13] PBFmean,[13] MCAv,[80,130,387] Superficial mBF,[16] Deep mBF,[16] ABF[10]). For subgroup analysis, there was no differences between SCG and control groups for venous (SMD = -0.09, 95% CI: -0.48, 0.30, z = 0.45, p = 0.65) and arterial (SMD = 0.00, 95% CI: -0.34, 0.35, z = 0.03, p = 0.98) measures of blood flow. Moderate heterogeneity was observed for studies assessing venous (Cohran's Q = 19.06, I^2 = 53%, Tau^2 = 0.21, p = 0.02) and arterial measures of blood flow (Cohran's Q = 18.05, I^2 = 45%, Tau^2 = 0.14, p = 0.05).

A total of nine studies measured peripheral blood flow during a physiological challenge (Fig 2-4). A small positive effect was evident for SCG versus control (SMD = 0.45, 95% CI: 0.31, 0.59, z = 6.31, p < 0.001). Low heterogeneity amongst studies was observed (Cohran's Q = 65.34, I^2 = 22%, Tau^2 = 0.06, p = 0.09). There were five different measures of peripheral blood flow assessed, with one venous (tHb[13,45,124,140,281]) and four arterial (mBF,[5,9,36] PBVmean,[13] PBFmean,[13] MCAv[80]) measures of blood flow. For subgroup analysis, SCG had a small positive effect on venous (SMD = 0.45, 95% CI: 0.28, 0.62, z = 5.23, p < 0.01) and a medium effect on arterial (SMD = 0.56, 95% CI: 0.26, 0.85, z = 3.73, p < 0.01) measures of blood flow. Low heterogeneity amongst studies assessing venous blood flow were observed (Cohran's Q = 10.98, I^2 = 0%, Tau^2 = 0.00, p = 1.00). Moderate heterogeneity was observed for studies assessing arterial measures of blood flow (Cohran's Q = 54.27, I^2 = 59%, Tau^2 = 0.27, p = 0.0002).

For peripheral blood flow measures immediately post a physiological challenge, six studies were analysed (Fig 2-5). There was no difference in peripheral blood flow measures for SCG versus control (SMD = -0.00, 95% CI: -0.41, 0.40, z = 0.02, p = 0.99) immediately after a physiological challenge. High heterogeneity amongst studies was observed (Cohran's Q = 77.01, I^2 = 77%, Tau^2 = 0.60, p = 0.00). A total of eight different measures of peripheral blood flow were assessed, with four venous (VFI,[297] EF,[297,386] RVF,[297] popliteal VBF[295]) and four arterial (MCAv,[130,387] mBF,[36] ABF,[296] AR[296]). Sub-group analysis revealed contrasting effects of SCG on venous and arterial measures immediately post a physiological challenge. There was no difference in venous blood flow between SCG and control groups (SMD = -0.23, 95% CI: -0.92, 0.46, z = 0.66, p = 0.51). In contrast, a small positive effect was evident for SCG versus control for arterial blood flow (SMD = 0.37, 95% CI: 0.12, 0.63, z = 2.84,

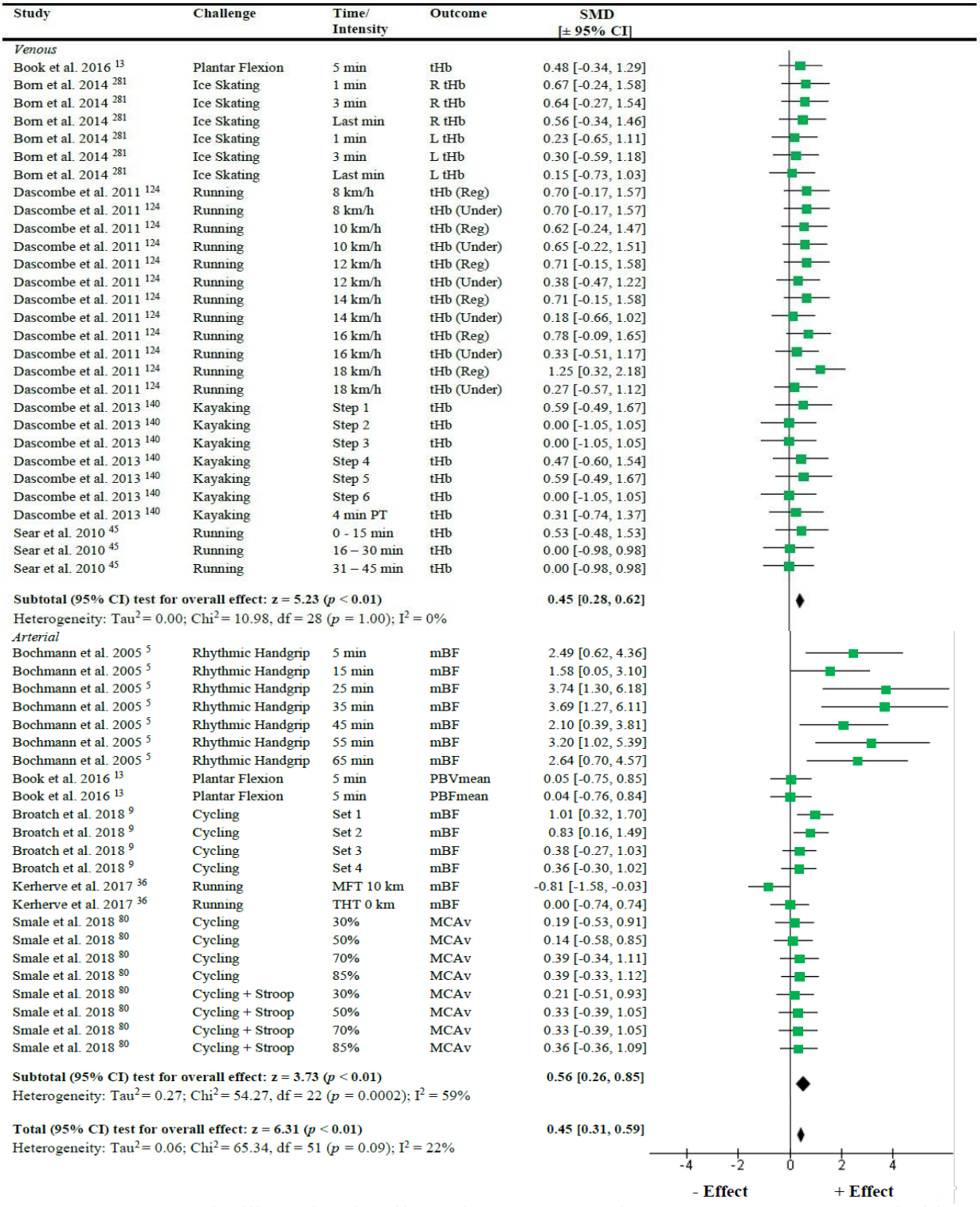

Figure 2-4: Forest plot illustrating the effects of sports compression garments (SCG) compared with a control on peripheral blood flow measures during a physiological challenge. *Square boxes* represent the standardised mean effect for each study, with *lines* representing 95% CIs. A *diamond* represents the overall SMD, with its width representing 95% CIs. *ABF* arterial blood flow, *CI* confidence interval, *L* left leg, *MCAv* middle cerebral artery blood flow velocity, *MFT* moderately flat terrain, *mBF* muscle blood flow, *PT* performance test, *PBVmean* mean popliteal artery blood velocity, *PBFmean* mean popliteal artery flow rate, *Reg* regular-sized compression garment, *R* right leg, *SMD* standardised mean difference, *THT* technical and hilly terrain, *TAMV* time-averaged mean velocity, *tHb* total haemoglobin, *Under* undersized compression garment.

$p < 0.01$). High heterogeneity amongst studies assessing venous blood flow were observed (Cohran's Q = 65.63, $I^2 = 83\%$, $Tau^2 = 1.23$, $p < 0.01$). Conversely, low heterogeneity was observed for studies assessing arterial measures of blood flow (Cohran's Q = 5.73, $I^2 = 0\%$, $Tau^2 = 0.00$, $p = 0.45$).

Study	Challenge	Outcome	SMD [± 95% CI]
Venous			
Castilho Junior et al. 2018 [297]	Running	L VFI	0.54 [-0.35, 1.44]
Castilho Junior et al. 2018 [297]	Running	R VFI	1.08 [0.12, 2.03]
Castilho Junior et al. 2018 [297]	Running	L EF	-0.45 [-1.34, 0.44]
Castilho Junior et al. 2018 [297]	Running	R EF	0.64 [-0.26, 1.54]
Castilho Junior et al. 2018 [297]	Running	L RVF	1.09 [0.13, 2.04]
Castilho Junior et al. 2018 [297]	Running	R RVF	1.19 [0.22, 2.15]
Oficial-Casado et al. 2020 [295]	Running	L Popliteal VBF (MC)	-1.01 [-1.96, -0.07]
Oficial-Casado et al. 2020 [295]	Running	R Popliteal VBF (MC)	-1.62 [-2.65, -0.58]
Oficial-Casado et al. 2020 [295]	Running	L Popliteal VBF (HC)	-2.76 [-4.05, -1.46]
Oficial-Casado et al. 2020 [295]	Running	R Popliteal VBF (HC)	-2.31 [-3.50, -1.13]
Partsch et al. 2014 (a) [386]	Walking	EF	0.02 [-0.78, 0.82]
Partsch et al. 2014 (b) [386]	Walking	EF	0.31 [-0.83, 1.45]
Subtotal (95% CI) test for overall effect: z = 0.66 ($p = 0.51$)			**-0.23 [-0.92, 0.46]**
Heterogeneity: $Tau^2 = 1.23$; $Chi^2 = 65.63$, df = 11 ($p < 0.01$); $I^2 = 83\%$			
Arterial			
Dorey et al. 2018 [130]	HUT	MCAv	0.31 [-0.58, 1.19]
Dorey et al. 2018 [130]	Cycling	MCAv	0.00 [-0.88, 0.88]
Dorey et al. 2018 [130]	HUT Post Cycle	MCAv	0.49 [-0.40, 1.38]
Kerherve et al. 2017 [36]	Running	mBF	-0.10 [-0.84, 0.64]
Mann et al. 2016 [296]	Running	ABF	0.57 [0.06, 1.09]
Mann et al. 2016 [296]	Running	AR	0.72 [0.20, 1.25]
Morrison et al. 2014 [387]	Supine to Stand	MCAv	0.00 [-0.72, 0.72]
Subtotal (95% CI) test for overall effect: z = 2.84 ($p < 0.01$)			**0.37 [0.12, 0.63]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 5.73$, df = 6 ($p = 0.45$); $I^2 = 0\%$			
Total (95% CI) test for overall effect: z = 0.02 ($p = 0.99$)			**-0.00 [-0.41, 0.40]**
Heterogeneity: $Tau^2 = 0.60$; $Chi^2 = 77.01$, df = 18 ($p = 0.00$); $I^2 = 77\%$			

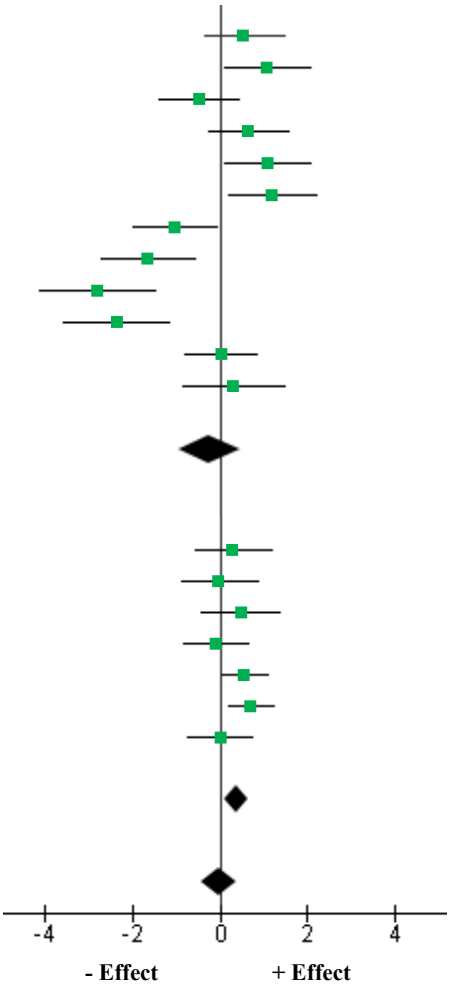

Figure 2-5: Forest plot illustrating the effects of sports compression garments (SCG) compared with a control on peripheral blood flow measures immediately post a physiological challenge. *Square boxes* represent the standardised mean effect for each study, with *lines* representing 95% CIs. A *diamond* represents the overall SMD, with its width representing 95% CIs. *ABF* arterial blood flow, *AR* arterial reserve, *CI* confidence interval, *EF* ejection fraction, *HUT* head up tilt test, *HC* high-pressure compression garments, *L* left leg, *MC* medium-pressure compression garments, *MCAv* middle cerebral artery blood flow velocity, *mBF* muscle blood flow, *RVF* residual volume fraction, *R* right leg, *SMD* standardised mean difference, *VBF* vein blood flow, *VFI* venous filling index.

Study	Challenge	Time	Outcome	SMD [± 95% CI]
Venous				
Book et al. 2016 [13]	Plantar Flexion	5 min	tHb	0.26 [-0.54, 1.06]
Menetrier et al. 2015 [12]	Cycling	3 min	EDV	0.59 [-0.14, 1.33]
Menetrier et al. 2015 [12]	Cycling	5 min	EDV	0.79 [0.05, 1.54]
Menetrier et al. 2015 [12]	Cycling	7 min	EDV	0.93 [0.17, 1.69]
Menetrier et al. 2015 [12]	Cycling	9 min	EDV	1.22 [0.43, 2.01]
Venckunas et al. 2014 [10]	Running	3 – 10 min	VRV	-0.25 [-1.02, 0.52]
Venckunas et al. 2014 [10]	Running	30 min	VRV	-0.26 [-1.03, 0.51]
Venckunas et al. 2014 [10]	Running	3 – 10 min	VER	0.35 [-0.43, 1.12]
Venckunas et al. 2014 [10]	Running	30 min	VER	0.94 [0.12, 1.75]
Subtotal (95% CI) test for overall effect: z = 2.91 ($p < 0.01$)				**0.51 [0.17, 0.85]**
Heterogeneity: $Tau^2 = 0.12$; $Chi^2 = 14.01$, df = 8 ($p = 0.08$); $I^2 = 43\%$				
Arterial				
Book et al. 2016 [13]	Plantar Flexion	5 min	PBVmean	-0.16 [-0.96, 0.64]
Book et al. 2016 [13]	Plantar Flexion	5 min	PBFmean	-0.12 [-0.93, 0.68]
Menetrier et al. 2015 [12]	Cycling	3 min	ABF	2.76 [1.72, 3.80]
Menetrier et al. 2015 [12]	Cycling	5 min	ABF	2.73 [1.70, 3.76]
Menetrier et al. 2015 [12]	Cycling	7 min	ABF	5.14 [3.57, 6.71]
Menetrier et al. 2015 [12]	Cycling	9 min	ABF	4.32 [2.94, 5.69]
Menetrier et al. 2015 [12]	Cycling	3 min	TAMV	2.67 [1.65, 3.69]
Menetrier et al. 2015 [12]	Cycling	5 min	TAMV	2.71 [1.69, 3.74]
Menetrier et al. 2015 [12]	Cycling	7 min	TAMV	3.57 [2.37, 4.78]
Menetrier et al. 2015 [12]	Cycling	9 min	TAMV	3.26 [2.12, 4.40]
Menetrier et al. 2015 [12]	Cycling	3 min	PSV	4.96 [3.43, 6.48]
Menetrier et al. 2015 [12]	Cycling	5 min	PSV	3.48 [2.30, 4.67]
Menetrier et al. 2015 [12]	Cycling	7 min	PSV	5.12 [3.55, 6.68]
Menetrier et al. 2015 [12]	Cycling	9 min	PSV	4.86 [3.36, 6.36]
Menetrier et al. 2015 [12]	Cycling	3 min	RI	4.86 [3.36, 6.37]
Menetrier et al. 2015 [12]	Cycling	5 min	RI	2.92 [1.85, 3.99]
Menetrier et al. 2015 [12]	Cycling	7 min	RI	2.92 [1.85, 3.99]
Menetrier et al. 2015 [12]	Cycling	9 min	RI	2.92 [1.85, 3.99]
Sperlich et al. 2013 [16]	Cycling	10 min	Superficial mBF	-1.42 [-2.75, -0.10]
Sperlich et al. 2013 [16]	Cycling	10 min	Deep mBF	-1.70 [-3.11, -0.30]
Venckunas et al. 2014 [10]	Running	3 – 10 min	ABF	-0.02 [-0.79, 0.75]
Venckunas et al. 2014 [10]	Running	30 min	ABF	0.04 [-0.73, 0.81]
Subtotal (95% CI) test for overall effect: z = 5.77 ($p < 0.01$)				**2.49 [1.65, 3.34]**
Heterogeneity: $Tau^2 = 3.73$; $Chi^2 = 275.37$, df = 21 ($p < 0.01$); $I^2 = 92\%$				
Total (95% CI) test for overall effect: z = 6.13 ($p < 0.001$)				**1.87 [1.27, 2.47]**
Heterogeneity: $Tau^2 = 2.59$; $Chi^2 = 354.18$, df = 30 ($p = 0.00$); $I^2 = 92\%$				

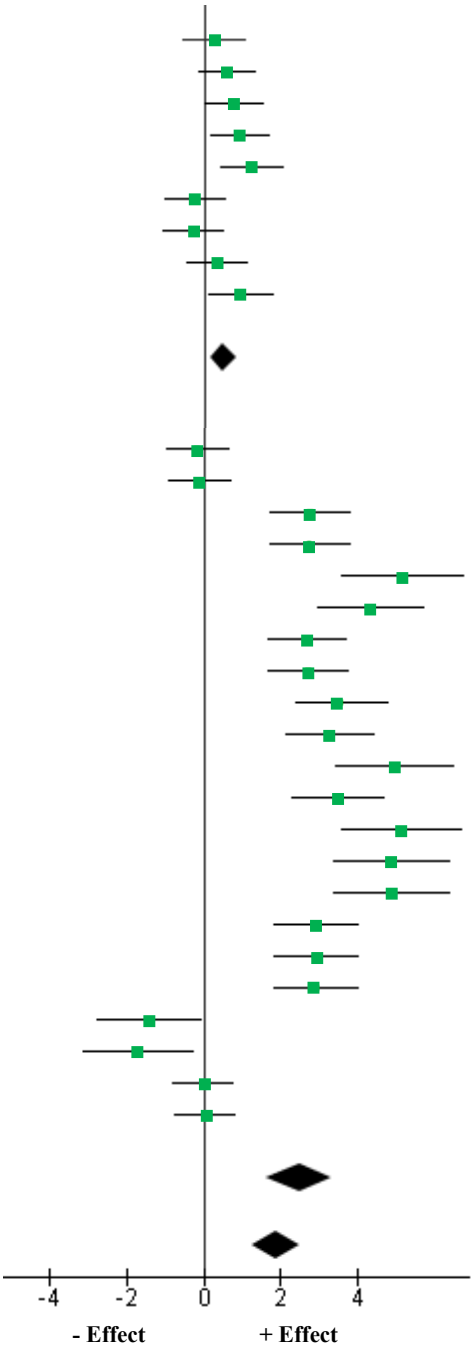

Figure 2-6: Forest plot illustrating the effects of sports compression garments (SCG) compared with a control on peripheral blood flow measures in recovery. *Square boxes* represent the standardised mean effect for each study, with *lines* representing 95% CIs. A *diamond* represents the overall SMD, with its width representing 95% CIs. *ABF* arterial blood flow, *CI* confidence interval, *EDV* end-diastolic velocity, *mBF* muscle blood flow, *PSV* peak systolic velocity, *PBVmean* mean popliteal artery blood velocity, *PBFmean* mean popliteal artery flow rate, *RI* resistance index, *SMD* standardised mean difference, *TAMV* time-averaged mean velocity, *tHb* total haemoglobin, *VER* venous emptying rate, *VRV* venous reserve volume.

A total of four studies measured peripheral blood flow during recovery from a physiological challenge (Fig 2-6). A large positive effect was evident for SCG versus control (SMD = 1.87, 95% CI: 1.27, 2.47, z = 6.13, $p < 0.01$). High heterogeneity amongst studies was observed (Cohran's Q = 354.18, $I^2 = 92\%$, $Tau^2 = 2.59$, $p = 0.00$). There were 12 different measures of peripheral blood flow including four venous (tHb,[13] EDV,[12] VRV,[10] VER[10]) and eight arterial (PBVmean,[13] PBFmean,[13] ABF,[10,12] TAMV,[12] PSV,[12] RI,[12] superficial mBF,[16] deep mBF[16]). For subgroup analysis, SCG had a medium positive effect on venous (SMD = 0.51, 95% CI: 0.17, 0.85, z = 2.91, $p < 0.01$) and a large effect on arterial (SMD = 2.49, 95% CI: 1.65, 3.34, z = 5.77, $p < 0.01$) measures of blood flow. Moderate and high heterogeneity was observed for studies assessing venous (Cohran's Q = 14.01, $I^2 = 43\%$, $Tau^2 = 0.12$, $p = 0.08$) and arterial (Cohran's Q = 275.37, $I^2 = 92\%$, $Tau^2 = 3.73$, $p < 0.01$) measures of blood flow, respectively.

2.4 Discussion

The main findings from this systematic review with meta-analysis were that SCG enhanced measures of peripheral blood flow during (SMD = 0.45; $p < 0.01$) and in the recovery from (SMD = 1.87; $p < 0.01$) a physiological challenge. Also, at these time points, SCG had positive effects on venous (during: SMD = 0.45; $p < 0.01$, recovery: SMD = 0.51; $p < 0.01$) and arterial measures (during: SMD = 0.56; $p < 0.01$, recovery: SMD = 2.49; $p < 0.01$) of blood flow. Although, SCG did not improve overall peripheral blood flow immediately post a physiological challenge, there was a positive effect for measures of arterial blood flow (SMD = 0.37; $p < 0.01$). Conversely, no effects of SCG were observed on peripheral blood flow at rest.

Regarding changes in peripheral blood flow at rest, our results showed no overall effect of SCG to alter peripheral blood flow (Fig 2-2). At rest, skeletal muscle requires approximately 20% of overall cardiac output, with most blood flow directed to the brain, kidney, and liver.[215] Further, peripheral blood flow is tightly coupled to the metabolic demand of the muscles.[217] Thus, the magnitude of potential change in peripheral blood flow with compression at rest might be difficult to detect due to the lack of overall blood flow distribution to the compressed areas (i.e., the limbs). Also, resting blood flow is influenced by several factors, including time of day,[388,389] environmental conditions,[390–392] nutrient

intake,[393–395] posture,[396,397] and the rest time before data collection.[398,399] Therefore, to quantify the SCG effect on resting blood flow it is vital to control these factors. Some studies failed to address these potential confounders, which may help explain the variability in resting peripheral blood flow in the analysed studies (Fig 2-2). For example, 50% of the studies analysed did not provide information on the duration of fasting before collecting resting blood flow measures.[5,6,9,36,80,295] Research has shown that the composition of a meal (i.e., mixed nutrient, high glucose, high fat) can either increase[394,400] or decrease[393,395,401] measures of peripheral blood flow. Further, in the studies that did provide fasting durations, they were between 2[10,387] and 3 h[16,130] before measuring blood flow. These times might not be sufficient as alterations in blood flow can be evident for up to 4 h postprandial.[395,401–403] In support of the current findings, a recent meta-analysis concluded that compression garments do not alter resting haemodynamic variables, including heart rate, cardiac output, blood pressure, and systemic vascular resistance.[288] The authors proposed that the lack of disturbance to central haemodynamics at rest (i.e., low metabolic demand of skeletal muscle) may explain these findings. Additionally, they suggest the efficacy of compression is dependent on the degree of physiological challenge and alterations to central haemodynamics. These proposed mechanisms are relevant to and help explain the lack of compression-induced changes in peripheral blood flow at rest in this review (Fig 2-3).

The results from our review indicate that SCG enhances peripheral blood flow during a physiological challenge. During exercise, skeletal muscle contraction compresses the intramuscular veins and effectively enhances venous flow.[188,404] In turn, the maintenance of venous return is due to the increases in intramuscular pressure from the rhythmic muscle contraction (skeletal muscle pump).[188] The application of external compression (i.e., SCG) may further augment the skeletal muscle pump and subsequently increase venous flow. Compression-induced increases in venous return could enhance stroke volume and cardiac output via increased end-diastolic filling.[287] Our findings of enhanced venous flow during exercise, combined with previous reports of increased cardiac output[38,63,107] and stroke volume[38,107,405] with compression, support this mechanism. As stroke volume is a key factor underlying endurance performance,[406] the augmentation of venous blood flow during exercise with compression may serve to improve exercise performance. However, this mechanism warrants further investigation as contradictory findings have been reported for

changes in stroke volume[13,38] and endurance performance[33,159] with compression. Also, enhanced venous blood flow with compression is suggested to assist in clearing circulating metabolites from the skeletal muscle during exercise.[313] For example, reduced blood lactate levels have been reported with SCG use during cycling,[170] double-poling sprints,[103] and maximal[30,293] or submaximal[313] running. As lactate accumulation and the associated acidosis can be a limiting factor in maximal exercise,[312] SCG may increase exercise capacity at higher intensities and thus improve exercise performance. However, contrasting results are also reported with compression to have no effect[9,77,291] or a negative effect (i.e., increase blood lactate levels)[82,314,407] during exercise. Therefore, the relationship between compression-induced increases in venous flow and blood lactate levels is not fully understood. Additionally, the reduced lactate levels with compression may result from vessel constriction and decreased lactate perfusion from the muscle.[30]

Our subgroup analysis also highlight enhanced arterial blood flow during exercise with SCG (Fig 2-4). Exercise is associated with a significant rise in skeletal muscle blood flow, by almost 100-fold,[216] which is necessary to match the metabolic demand for oxygen in the contracting muscles.[215,217] Additionally, the energy requirements of skeletal muscle are fueled by blood-borne nutrients (i.e., blood glucose, free fatty acids), with increased muscle blood flow essential for their supply during exercise.[315,317] Therefore, compression-induced increases in arterial and muscle blood flow may enhance exercise performance via improved oxygen and nutrient delivery to the muscle. For example, Sear et al.[45] reported increased muscle oxygenation during intermittent high-intensity running when wearing SCG, resulting in an 8.5% improvement in total distance covered. However, research demonstrating an improvement in nutrient delivery to the muscle during exercise with SCG is lacking and requires further investigation. Compression may also provide an ergogenic benefit on cerebral blood flow, as measured by MCAv.[80] Smale et al.[80] showed beneficial effects of SCG on MCAv at higher exercise intensities (70 and 85% maximal aerobic power) in conjunction with enhanced cognitive performance, but not for cycling time-trial performance. Alterations in mean arterial pressure, influenced by changes in cardiac output and total peripheral resistance,[408] are an important stimulus to elicit changes in cerebral blood flow.[409] Although Smale et al.[80] observed no changes in mean arterial pressure with SCG, previous work has highlighted positive changes in cardiac output[38,63] and total peripheral

resistance[12] with compression. Thus, changes in mean arterial pressure due to compression might contribute to the observed benefits in MCAv with SCG. However, as findings are limited to this single study,[80] more research is warranted.

It is also important to acknowledge the constraints in achieving accurate measures of peripheral blood flow during exercise. Although NIRS allows for the continuous assessment of tHb, it is limited in the information it can provide on peripheral blood velocity, flow, and vessel structure. On the other hand, a limitation of more robust methods to assess alterations in peripheral blood flow, such as Doppler ultrasound or venous occlusion plethysmography, is that participants are required to stop exercising to obtain accurate measurements. Nonetheless, despite the methodological differences between studies (i.e., exercise intervention, garment style, measurement of blood flow), there was an overall effect of SCG to improve venous and arterial blood flow during exercise.

The subgroup analysis for peripheral blood flow at the immediately post time point showed that SCG improve arterial, but not venous, measures of blood flow. Although consistent with the data observed at rest, the lack of an effect of SCG on venous return immediately post a physiological challenge is inconsistent with the large improvements reported during the subsequent recovery period (Fig 2-5). In addition, this finding contrasts with those of a recent meta-analysis that concluded stroke volume after a physiological challenge is increased with compression garments due to enhanced venous flow.[288] Our contradictory findings likely stem from the combination of only three studies analysed, the observed large negative effects of SCG on venous flow post-running,[295] and the variability in blood flow measurement techniques (i.e., MRI and air plethysmography). Still, caution is advised in interpreting the findings from Oficial-Casado.[295] Specifically, the pressure applied was not measured but only reported as medium or high-pressure garments. The pressure exerted in these garments may have reduced venous blood flow by applying excess pressure. In support of this, a greater reduction in venous blood flow was evident with the high-pressure garments (Fig 2-5). Additionally, compression shorts exerting high pressure (37 mmHg) have been reported to reduce peripheral blood flow.[16] Although speculative, it highlights the importance of SCG research to measure the degree of pressure, or, at the very minimum, report the manufacturer values.

In contrast to venous blood flow, the subgroup analysis revealed SCG improved arterial blood flow immediately after a physiological challenge (Fig 2-5). A hyperemic response (arterial vasodilation) is present immediately post-exercise due to the vasodilator signals contributing to increased blood flow during exercise.[399] Despite no changes in venous blood flow with compression at immediately post (Fig 2-5), a carry-over effect from the enhanced venous flow during exercise (Fig 2-4) might contribute to the increased arterial flow. A proposed mechanism of increased arterial flow with compression is venular-arteriolar communication.[5] In essence, compression of the venous vessels during exercise (as evident with enhanced venous blood flow; Fig 2-4) may increase shear stress in the vein walls and trigger the release of endothelial dilators.[234,410] These compounds, which are proposed to diffuse to neighbouring arterial vessels and result in arterial vessel dilation,[237] are likely still circulating at the cessation of exercise (i.e., immediately post a physiological challenge). This mechanism may synergise with the proposed myogenic response of compression[5] to increase arterial blood flow; however, further study is needed to determine this relationship.

The findings from this meta-analysis support that SCG enhance peripheral blood flow in recovery, with subgroup analysis showing benefits for venous and arterial blood flow. The aim of recovery techniques following a physiological challenge, such as exercise, is to return the body to a homeostatic state.[370] A frequently proposed mechanism attributed to restoring indices of exercise recovery (i.e., exercise performance, muscle soreness) is increased blood flow.[411–413] Augmented venous flow is hypothesised to facilitate the removal of metabolic by-products from the previously active muscles,[411] which would otherwise likely contribute to the formation of exercise-induced oedema.[414] As this review has shown SCG to augment venous flow in recovery, this mechanism is further supported by lower concentrations of metabolic by-products including (e.g., CK[7,39,53] and LDH[7,83]) when SCG are worn post-exercise. Additionally, these findings were coupled with improved recovery of exercise performance[7,39] and reduced levels of muscle soreness.[7,53,83] Compression-induced increases in venous return may also serve as a protective mechanism against post-exercise hypotension, which can persist for several hours[415] and if individuals remain in a supine position (i.e., recovery after exercise).[107] Post-exercise hypotension, as observed in trained[416,417] and untrained[418,419] individuals, is characterised by a reduction in blood pressure and occurs due to a combination of an inactive skeletal muscle pump,[420] pooling of blood in

previously active muscles,[417] decreased end-diastolic filling,[421] and reduced stroke volume.[417] The benefit of SCG on venous flow described in this review, combined with reports of improved stroke volume[38,107,288] and blood pressure[104,107] with compression garments, highlights the beneficial effects SCG may have in preventing post-exercise hypotension.

Compression appears to improve the sustained post-exercise hyperaemic response present in the recovery from exercise,[420] as our analysis shows beneficial effects of SCG on arterial and muscle blood flow (Fig 2-6). The observed increases in muscle blood flow may be associated with the parallel increase in venous return. Increased venous return causes venous pressure to decrease,[20] which may consequently enhance muscle blood flow via increases in the arteriovenous pressure gradient.[422] However, caution is advised in interpreting these increases in arterial/muscle blood flow as the benefits observed were primarily from a single study that included four different measures of arterial blood flow.[12] Nonetheless, an enhanced muscle blood flow may improve oxygen and nutrient delivery in recovery, which could aid phosphocreatine[423] and glycogen resynthesis.[424] However, this is yet to be supported in compression research as studies investigating muscle oxygenation with SCG in recovery are limited, with contradictory findings.[10,304] Also, only one study has investigated the effect of SCG on nutrient delivery during recovery, with no change in muscle glucose uptake observed with compression.[16] This finding also coincided with reduced superficial and deep muscle blood flow[16] with compression (Fig 2-6). The high degree of pressure exerted by the sports compression shorts (37 mmHg),[16] higher than reported in other compression studies,[9,10,80,124,281] likely mechanically hindered muscle blood flow. Although a positive correlation exists between increased arterial blood flow and improved exercise recovery,[411] no SCG research is currently available to support this mechanism. In addition, our review highlights that no research has investigated the effect of SCG on measures of peripheral blood flow beyond 30 min of use post a physiological challenge. Considering the inflammatory response initiates in the early hours (1-4 h)[269] following exercise, further assessment of compression-induced changes in blood flow during this time is warranted. In turn, this will provide valuable insight into the proposed mechanism (i.e., increased blood flow) attributed to the effectiveness of SCG as a post-exercise recovery strategy.

2.5 Limitations

Although this meta-analysis highlighted changes in peripheral blood flow with SCG, limitations of this review must be considered when interpreting these findings. Firstly, the overall quality of the studies included was moderate (5.8 arbitrary units). Another major issue with compression research is the lack of blinding participants and researchers. The difficulty here lies in the high degree of pressure exerted by SCG, as the participant can quickly identify if receiving the SCG intervention. This is highlighted in the current review as none of the 19 studies incorporated blind allocation, blinding of subjects, or blinding of the researchers who administered the intervention. With the inadequate blinding in compression research, the placebo effect for participants, and the increased risk of bias and interpretation for researchers, cannot be discounted. Similar concerns have been highlighted in previous SCG reviews.[51,68,69,138,376,425] Future compression research should incorporate a placebo intervention (e.g., sham drink with reported benefits similar to SCG) and the blinding of researchers when analysing data (i.e., unaware if data is from placebo, control or SCG intervention). These recommendations would serve to improve the quality of SCG research in determining the potential effects of SCG on exercise performance and recovery.

The high heterogeneity observed in this review might be explained by methodological variations, particularly in the SCG details. For example, the garment types included upper- and lower-body garments, with lower-body garments divided even further with compression socks, tights, and shorts. In addition, some participants may not have received adequate pressure, with only 12 studies measuring exact pressures applied. Other studies reported pressure values indicated by the garment manufacturer[12,130,297] or failed to report any pressure values.[140,295,296] This is problematic as differences in limb dimensions may lead to wide inter-individual variations in pressure and could result in individuals receiving insufficient or excessive levels of pressure.[27] In addition, manufacturer sizing guidelines are typically acquired from crude anthropometric measurements (i.e., height, mass, limb circumference), and these can result in large pressure ranges exerted by a single garment size.[27] The level of pressure exerted by SCG is a crucial consideration and should be measured in future studies as pressure and gradient distribution are critical for the garments effectiveness.[71,134]

Another limitation to consider is the different physiological challenges in this review, which included an orthostatic test,[387] rhythmic movement exercises,[5,13] walking,[386] running,[10,36,124,295–297] cycling,[9,12,130] kayaking,[140] and ice skating.[281] The assessment of peripheral blood flow also varied with different techniques used, including NIRS,[6,9,13,36,124,140,281] Doppler ultrasound,[12,13,80,130,387] plethysmography,[5,10,296,297,386] MRI,[295] and PET.[16] Considering the divergent effects of SCG on macro and microvascular blood flow,[373] and the limitation of techniques in assessing changes in vessel structure (i.e., NIRS, plethysmography), future research should aim to use more accurate techniques (e.g., CEU, Doppler ultrasound, MRI) to quantify compression-induced changes in peripheral blood flow. Finally, the range of participants described in the included studies varied from healthy individuals[5,13,130,387] to recreationally trained/physically active[9,10,16,296,297] and to elite/trained athletes.[6,12,36,80,124,281,295] As differences in peripheral blood flow exist between trained and untrained participants,[426–429] some individuals might be more susceptible to compression-induced blood flow changes. However, research with compression garments is required to support this theory.

2.6 Conclusion

Sports compression garments appear to enhance venous and arterial measures of peripheral blood flow during and in the recovery from a physiological challenge (Fig 2-7). In addition, at immediately post, compression benefited arterial blood flow measures only. However, additional high-quality research that addresses the limitations of compression research highlighted in this review (i.e., the pressure of garments, blinding of participants, blood flow in recovery etc.) is warranted.

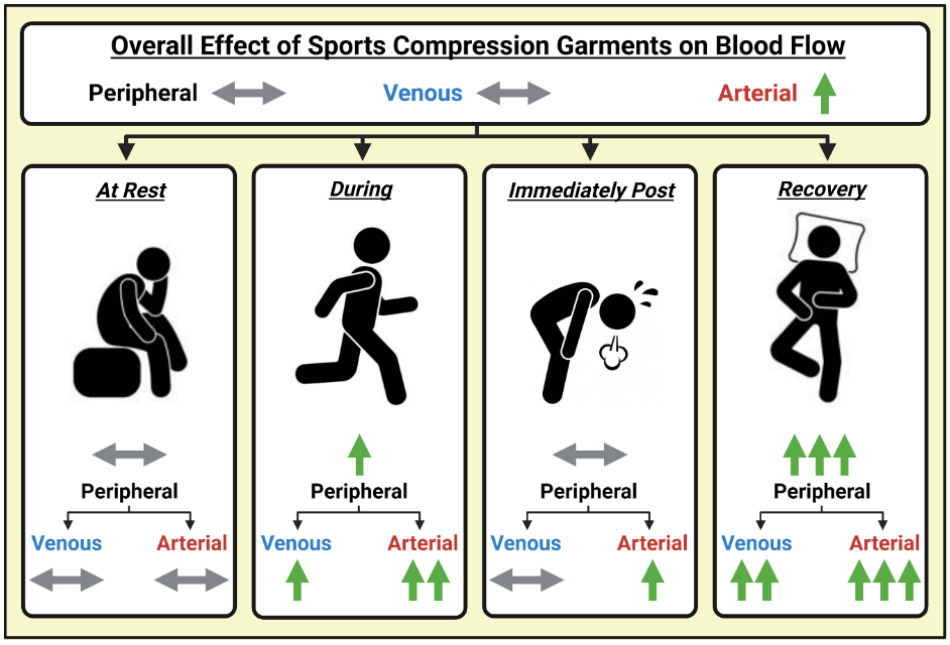

Figure 2-7: Summary of the effects of sports compression garments on peripheral blood flow. Created with Biorender.com. * neutral arrow: no effect, one up arrow: a small positive effect, two up arrows: a medium positive effect, three up arrows: a large positive effect.

CHAPTER THREE

Sports compression garments improve resting markers of venous return and muscle blood flow in male basketball players.

The findings from Chapter 2 highlight the high methodological heterogeneity in SCG research, particularly in the SCG details and techniques used to assess peripheral blood flow. Therefore, Chapter 3 is presented as the first in a series of related studies investigating the effects of sports compression garments on lower-limb blood flow. The purpose of this study was to identify the influence of three different types of sports compression garments, when fitted to targeted pressures, on markers of venous return, muscle blood flow, and muscle oxygenation at rest. In addition, this study also aimed to identify any potential differences in blood flow between sports compression garment types.

This chapter has been published as:

O'Riordan, S. F., McGregor, R., Halson, S. L., Bishop, D. J., and Broatch, J. R. (2021). Sports compression garments improve resting markers of venous return and muscle blood flow in male basketball players. *Journal of Sport and Health Science.* https://doi.org/10.1016/j.jshs.2021.07.010

JSHS, Q1; Impact Factor (2021): 7.179

Abstract

Background: The benefits associated with sports compression garments are thought to be closely related to enhanced blood flow. However, findings are equivocal, possibly due to heterogeneity in techniques used for measuring blood flow, garment types used, and pressures applied. This study combined Doppler ultrasound and near-infrared spectroscopy technologies to provide the first comprehensive assessment of the effects of three sports compression garment types on markers of venous return and muscle blood flow at rest.

Methods: Resting lower-limb blood flow measures (markers of venous return, muscle blood flow, muscle oxygenation) of 22 elite, junior, male basketball players (age, 17.2 ± 0.9 y, mean ± SD) were assessed in four separate conditions: no compression (CON), compression tights (TIGHTS), compression shorts (SHORTS), and compression socks (SOCKS). Markers of venous return (cross-sectional area, time-averaged mean and peak blood flow velocity, and venous blood flow) were measured via Doppler ultrasound at the popliteal and common femoral veins. Muscle blood flow and muscle oxygenation were measured in the gastrocnemius medialis and vastus lateralis using near-infrared spectroscopy.

Results: Popliteal markers of venous return were higher in TIGHTS compared to CON ($p < 0.01$) and SHORTS ($p < 0.01$), with SOCKS values higher compared with CON ($p < 0.05$). Common femoral vein markers of venous return were higher for all conditions compared to CON ($p < 0.05$), with TIGHTS values also higher compared to SOCKS ($p < 0.05$). Gastrocnemius medialis blood flow was higher for TIGHTS compared to CON ($p = 0.000$), SOCKS ($p = 0.012$) and SHORTS ($p = 0.000$), with SOCKS higher compared to SHORTS ($p = 0.046$). Vastus lateralis blood flow was higher for TIGHTS compared to CON ($p = 0.028$) and SOCKS ($p = 0.019$), with SHORTS also higher compared to CON ($p = 0.012$) and SOCKS ($p = 0.005$). Gastrocnemius medialis oxygenation was higher for TIGHTS compared to CON ($p = 0.003$), SOCKS ($p = 0.033$) and SHORTS ($p = 0.003$), with SOCKS higher compared to CON ($p = 0.044$) and SHORTS ($p = 0.032$). Vastus lateralis oxygenation was higher for TIGHTS compared to CON ($p = 0.02$) and SOCKS ($p = 0.006$).

Conclusion*:* Markers of venous return, muscle blood flow, and muscle oxygenation are increased with sports compression garments. TIGHTS were most effective, potentially due to the larger body area compressed.

Keywords: Arterial perfusion, lower-limb compression, pressure, venous flow.

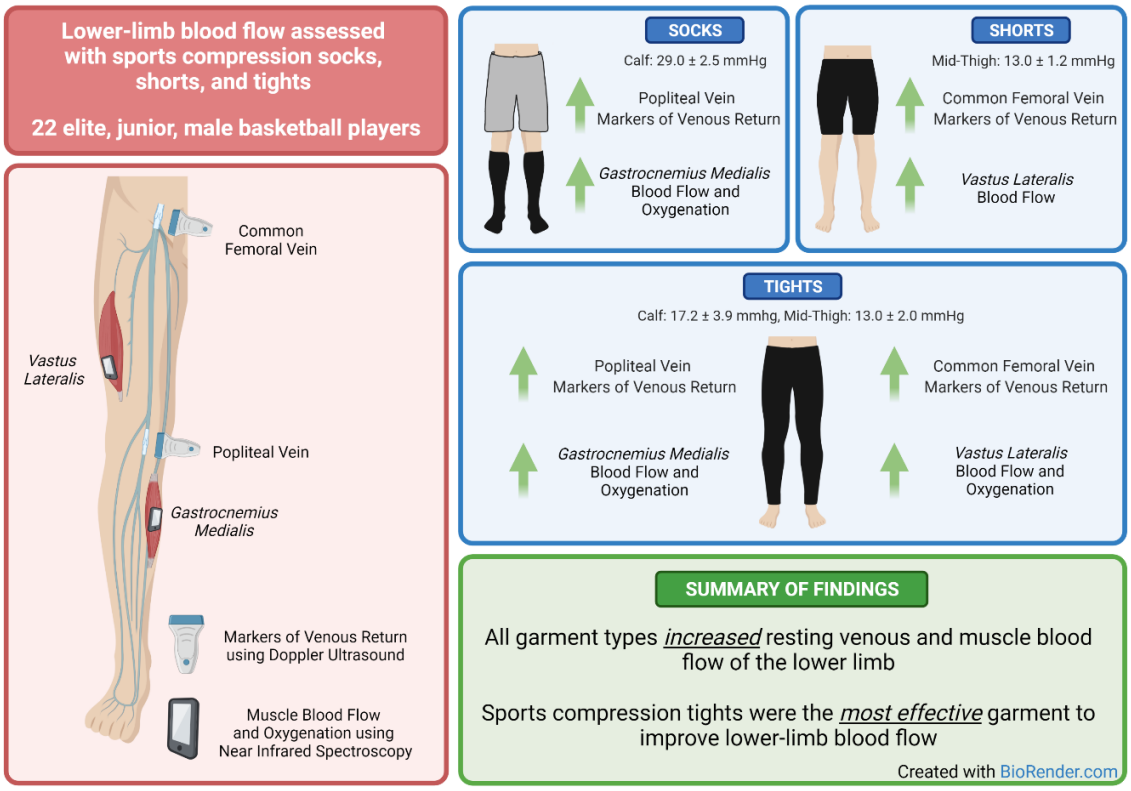

Figure 3-1: Graphical abstract for *Journal of Sport and Health Science* publication. Created with Biorender.com.

3.1 Introduction

Sports compression garments are commonly used in an attempt to improve exercise performance and recovery.[51] However, the underlying mechanisms of action are yet to be established, and a better understanding will help optimise the use of compression as an ergogenic aid. The compression-induced benefits are thought to be closely related to alterations in blood flow, consistent with that reported in therapeutic medicine.[21,195,203] Medical compression garments, which apply a higher level of pressure than SCG,[134] decrease vein diameter, improve valve competence, and reduce venous reflux.[137] As a result, blood is diverted from superficial veins, through perforator veins, and into deep veins, leading to an increase in deep venous velocity, reduced venous pooling, and improved venous return.[15,21,195] The mechanisms by which compression improves arterial and/or muscle blood flow is less clear. Due to the thick-walled structure of the arterioles, compression-induced changes in arterial blood flow are not related to a mechanical reduction in arteriole vessel size.[5] Instead, compression is commonly proposed to reduce arteriolar transmural pressure, resulting in a reflex increase in arteriole vessel size (i.e., vasodilation).[5,373] This myogenic response[5] will lead to a decrease in arterial flow resistance and subsequently improve muscle blood flow.[5,9] Other mechanisms underlying the compression-induced increased muscle blood flow could be a result of venular–arteriolar communication and/or skin vasomotor reflexes[5]; however, these mechanisms remain speculative. Alterations in blood flow with compression have primarily been reported in individuals with circulatory issues who were using high-pressure medical compression (> 30 mmHg)[203]; however, there are little available data on the effect of sports compression on venous and muscle blood flow in healthy or athletic individuals.

Research assessing changes in blood flow with SCG have reported increases,[9,12] no effects,[13,305] or even decreases[16] in various measures of blood flow. A potential explanation for these contradictory findings is the large heterogeneity in techniques used in measuring blood flow. For instance, alterations in muscle oxygenation, limb volume, stroke volume, cardiac output, blood pressure, and heart rate have all been used as indirect markers of compression-induced changes to blood flow.[9,63,104,123] Although these measures provide important information regarding circulatory and cardiac parameters, the use of more direct

measurement techniques for assessing venous return and muscle blood flow is warranted. Doppler ultrasound, regarded as a criterion standard,[430] provides reliable and real-time information about venous structure and flow in the lower extremities.[302,303] However, Doppler ultrasound has yet to be used in sports compression research to assess markers of venous return. Similarly, very few studies have investigated the effects of sports compression on muscle blood flow.[9,36,305] Although commonly used as an indicator of muscle oxygenation and/or overall limb blood volume,[6,13] NIRS with venous occlusion can also provide a non-invasive and reliable measurement of localised (i.e., muscle) blood flow.[308] Previous research has utilised this technique to measure the effects of sports compression on muscle blood flow during exercise.[9,36,305] Our study combines Doppler ultrasound and NIRS (with venous occlusion) technologies to provide a holistic assessment of the effects of SCG on resting markers of venous return and muscle blood flow.

Another important gap in the literature is that no study has directly assessed the effects of garment characteristics (i.e., pressure and type) on blood flow. The level of pressure and the gradient distribution (i.e., the difference between two points) applied to the limbs, and the body area compressed (e.g., calf, thigh, leg, arm, or upper body), has varied in available sports compression research to date[27]; and pressure values are often not reported.[55] This is a crucial omission because pressure and gradient distribution are considered critical for the garments effectiveness.[71,134] Sports compression garment sizing guidelines are typically acquired from crude anthropometric measurements such as height, mass, and limb circumference. In addition, large variations exist in these measurements, with ranges varying by up to 40 cm for height, 25 kg for mass, and 7 cm for calf circumference for the same garment size (2XU, Melbourne, Australia). These non-specific guidelines can result in compression that elicits pressures less than the minimum suggested to improve venous return (thigh, 15 mmHg; calf, 17.3 mmHg).[27,71] Therefore, SCG fitted to target pressure ranges previously shown to alter blood flow measures,[9,71,210] or to enhance exercise performance and recovery[8,9,39] as opposed to manufacturer guidelines, may provide greater insight to fully understand the underlying mechanisms associated with the beneficial effects of SCG Furthermore, despite the range of sports compression garment types available (e.g., socks, shorts, and tights), no study has directly compared the effects of sports compression garment type on resting lower-limb blood flow measures. Compression-induced changes in lower-

limb blood flow might differ between garment types because garments only apply pressure to the limb and the underlying blood vessels they are covering (e.g., compression socks apply pressure to the lower-leg only). Insight from compression-induced changes in blood flow away from (markers of venous return) and to the muscle may have important implications during recovery post-exercise, when athletes are typically resting after competition or training.

We aim to elucidate the potential reasons for equivocal findings in the efficacy of SCG in altering blood flow by addressing measurement techniques, garment types, and the level of pressure applied. The aim of our study, therefore, was to assess for the first time the influence of different SCG, when fitted to target pressures, on markers of venous return and muscle blood flow. It was hypothesised that sports compression garments would alter measures of blood flow. In addition, a further hypothesise was that these alterations would be dependent on the type of SCG used due to differences in the total area of the lower-limb exposed to compression.

3.2 Methods

3.2.1 Participants

Twenty-two elite, junior, male basketball players from the Australian Centre of Excellence Men's Basketball and National Basketball Association Global Academy teams (age, 17.2 ± 0.9 y; height, 199.8 ± 9.3 cm; body mass, 90.0 ± 9.9 kg; mean ± SD) completed our study. This sample size was powered to detect a moderate difference in calf blood flow with and without compression ($d = 0.65$),[6] with an α value of 0.05 and 80% statistical power (G*Power Version 3.1.9.2; Universität Düsseldorf, Düsseldorf, Germany). Written informed consent was obtained prior to participation, and all participants were screened for cardiovascular risk factors associated with exercise and specific risk factors associated with blood flow, including blood pressure, peripheral arterial disease, and diabetes. All procedures were approved by the Victoria University Human Research Ethics Committee (HRE18-087). The experimental approach was a randomised controlled study with a within-subject cross-over design, in which all participants completed the testing protocol under 4 conditions: (1) a non-garment control (CON), (2) compression socks (SOCKS), (3) compression shorts (SHORTS), and (4) compression tights (TIGHTS).

3.2.2 Overview

Participants reported to the laboratory on two separate occasions. The first session familiarised them with the Doppler ultrasound and venous occlusion techniques. The pressure of each sports compression garment (SOCKS, SHORTS, and TIGHTS) was also measured. Approximately 48 h after the familiarisation session, participants reported to the laboratory for the experimental session. The trial was set up during an initial 10 min of supine rest that included fitting the NIRS oximeters, locating and marking the Doppler ultrasound sites, and collecting a fingertip capillary blood sample. Participants were assigned to one of the four conditions (CON, SOCKS, SHORTS, or TIGHTS) in a randomised order. With four conditions, there were 24 possible condition orders. Once a participant was randomly assigned to one of the 24 different condition orders, that condition order was not available for other participants. This process was repeated until all 22 participants were assigned their condition order. Following 5 min of supine rest, markers of venous return, muscle blood flow, and muscle oxygenation measures of the right limb were collected in a supine position. This process was repeated three additional times (i.e., four conditions in total), with 5 min of supine rest between conditions, as previously described.[6,13] A supine position was chosen because it closely replicates the recovery position performed following exercise. Participants arrived at the laboratory following an overnight fast (> 8 h) and were asked to refrain from strenuous exercise (< 24 h) and caffeine (< 12 h) prior to testing sessions.

3.2.3 Sports Compression Garments

A total of three different types of SCG were tested; SOCKS (Recovery Compression Socks; 2XU), SHORTS (Accelerate Compression Shorts; 2XU), and TIGHTS (Refresh Recovery Tights; 2XU). The pressure of the SCG was measured via the Kikuhime pressure monitor device (MediGroup EBI, Melbourne, Australia) at six different landmarks along the leg (Fig 3-2).[139] The desired target pressures were 23–32 mmHg at Landmark C and 12–17 mmHg at Landmark E. These target pressures were chosen because they have previously been shown to either alter blood flow[9,71,210] or to have resulted in enhanced exercise performance or recovery.[8,9,39] The pressure exerted at each landmark was measured in both standing and supine positions, as previously described.[139] In the event that target pressure was not achieved in the supine position with manufacturer sizing guidelines (height and body

mass), another sports compression garment size was tested until the desired pressure was achieved. TIGHTS was fitted according to manufacturer guidelines because pilot data showed it was not possible to simultaneously achieve these target pressures on both Landmark C and Landmark E. As a result, target pressure in TIGHTS was not achieved at Landmark C for 19 participants nor was it achieved at Landmark E for 3 participants.

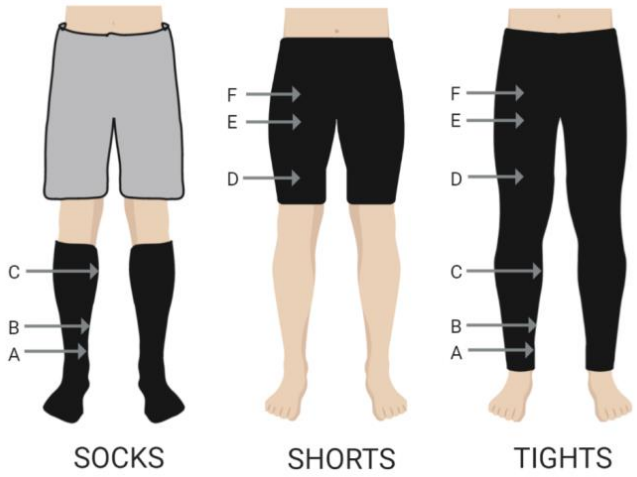

Figure 3-2: Landmarks where garment pressures were measured for SOCKS (A–C), SHORTS (D–F), and TIGHTS (A–F). A: 5 cm proximal to the distal border of the medial malleolus); B: 5 cm proximal to A); C: medial aspect of the maximal calf circumference); D: anterior aspect of the thigh 10 cm below landmark E); E: midpoint between the inguinal crease and the superior-posterior border of the patella); and F: 5 cm proximal to landmark E.[139] Created in Biorender.com. SHORTS = compression shorts; SOCKS = compression socks; TIGHTS = compression tights.

3.2.4 Venous Return

Markers of venous return were measured at the popliteal and common femoral veins via Doppler ultrasound. The ultrasound examinations were performed using an Aplio 500 (Canon Corporation, Tokyo, Japan), with a 5–14 MHz linear transducer and venous presets. A single experienced sonographer performed flow studies in a temperature-controlled (20°C) environment after 5 min of rest. All measurements were obtained in a supine position. Transverse and longitudinal images of the popliteal and common femoral veins were obtained using copious gel and minimal transducer pressure to avoid vein compression for each sports compression garment and control condition. The measurements for inner vessel transverse cross-sectional area (CSA(cm^2)), time-averaged mean blood flow velocity (V_{mean} (cm/s)), and time-averaged peak blood flow velocity (V_{peak} (cm/s)) were obtained for each participant. Previous research has reported that the coefficient of variation (CV) for

these measures when conducted by an experienced sonographer is 4.8% ± 1.3%.[431] Angles of insonation between 55º and 60º between the transducer and the vessels were used to obtain appropriate colour and spectral Doppler signals. Spectral Doppler waveforms were recorded in longitudinal image acquisation from a large sampling volume that included the whole-vessel diameter. Manual venous blood flow (mL/min) was calculated as (CSA (mm^2) × V_{mean} (cm/s)) × 60/100.[432] The common femoral veins were examined 2 cm above the saphenofemoral junction, with SCG (TIGHTS and SHORTS) turned down slightly to gain access. The popliteal veins were examined at the level of the knee crease. Prior to participants wearing TIGHTS in the experimental session, a small incision was made in the garment at the knee crease to create a small window for the transducer to access the popliteal vein. Pilot data confirmed that the pressure of TIGHTS was not altered with a small incision.

3.2.5 Muscle Blood Flow and Oxygenation

Muscle blood flow and muscle oxygenation were assessed in the lower-leg muscles in a supine position using NIRS. This technique provides continuous, non-invasive measurement of concentration changes in O_2Hb and HHb. Oximeters (Oxymon MKIII Near-Infrared Spectrophotometer, Artinis Medical Systems, The Netherlands) at the *gastrocnemius medialis* (calf) and *vastus lateralis* (thigh) muscles were set up as previously described,[9,36] with data acquired using Oxysoft software (V3.0.53, Artinis Medical Systems, The Netherlands). Pilot data confirmed that the pressure was not altered by the oximeter placement under the garment. Muscle oxygenation was calculated via the tissue saturation index (expressed as a percentage and calculated as $[O_2Hb]/([O_2Hb]+[HHb]) \times 100$.[103] Muscle blood flow was assessed using multiple venous occlusions as previously described.[9] Blood flow into the muscle, presented as millilitres of blood per minute, per 100 grams of muscle tissue (mL/min/100 g),[9] was estimated from the following equation:

$$\text{Muscle blood flow} = \left(\frac{(\text{tHb}/1000) \times 6}{[\text{Hb}]} \right) \times 1000$$

where the slope of the rise in tHb (O_2Hb + HHb) was measured during three 20-s venous occlusions separated by 45 s of rest.[36] A single capillary blood sample (approximately 100 µL) was obtained from the participant's fingertip and immediately analysed (OSM-3 Hemoximeter, Blood Gas Analyser, Radiometer, Copenhagen, Denmark) to measure relative

Hb concentration in g/dL. A conversion factor of 0.6206 was used to calculate absolute Hb concentration (mmol/L).[9,308] Venous occlusions were performed immediately following markers of venous return measures for each condition, with the average of the 3 occlusions (coefficient of variation: 12.1% ± 7.3%) used for data analysis.

3.2.6 Statistical Analyses

Data are presented as mean ± SD and were analysed using IBM SPSS Statistics (Version 19.0; IBM Corp., Chicago, IL, USA). A one-way repeated measures analysis of variance (ANOVA) was used to analyse markers of venous return, muscle blood flow, and muscle oxygenation. Normality of distribution was confirmed using the Sharipo–Wilk test. For validation of repeated measurements, Mauchly's sphericity test was used, and the Greenhouse–Geisser correction was applied if necessary. Where significant condition effects were observed, a Fisher Least-Significant Difference post hoc analysis was used. Differences in SCG pressure values between garment types and postures were analysed using a one-way ANOVA. Significance was set at $p < 0.05$. Data in the results section are expressed as the percentage of change relative to the comparative compression garment. To complement the statistical testing, effect sizes (ES) were calculated to assess the magnitude of observed condition effects in markers of venous return, muscle blood flow, and muscle oxygenation. All ESs were log-transformed before analysis, and magnitude of effects were determined by standardisation of the log-transformed variable. Cohen's conventions for ESs (with 95% CI) were used for interpretation. ES values were defined as small (0.20 to 0.49), medium (0.50 to 0.79), and large (≥ 0.80),[384] and were only reported when there was a ≥ 75% likelihood of the effect being equal to or greater than the smallest worthwhile change (ES = 0.20).

3.3 Results

3.3.1 Markers of Venous Return

3.3.1.1 Popliteal CSA

No condition effect was detected for popliteal CSA (p = 0.134; ES = 0.33 ± 0.34 (CON *vs.* TIGHTS); Fig 3-3A and Appendix B).

3.3.1.2 Popliteal V_{mean}

There was a condition effect for popliteal V_{mean} (p = 0.014), with V_{mean} increased in TIGHTS as compared with CON (57.3% ± 90.1%, p = 0.007; ES = 0.58 ± 0.42) and SHORTS (41.5% ± 67.7%, p = 0.009; ES = 0.53 ± 0.39). In addition, popliteal V_{mean} was increased in SOCKS as compared with CON (50.4% ± 109.5%, p = 0.042; ES = 0.43 ± 0.56) but not significantly different in SOCKS as compared with SHORTS (35.3% ± 93.8%, p = 0.092; ES = 0.38 ± 0.48; Fig 3-3B and Appendix B).

3.3.1.3 Popliteal V_{peak}

There was a condition effect for popliteal V_{peak} (p = 0.008), with V_{peak} increased in TIGHTS as compared with CON (58.9% ± 84.4%, p = 0.004; ES = 0.62 ± 0.42) and SHORTS (47.2% ± 64.5%, p = 0.003; ES = 0.55 ± 0.38). In addition, popliteal V_{peak} was increased in SOCKS as compared with CON (57.9% ± 122.5%, p = 0.038; ES = 0.46 ± 0.58) but not significantly different in SOCKS as compared with SHORTS (46.2% ± 112.0%, p = 0.067; ES = 0.40 ± 0.50; Fig 3-3C and Appendix B).

3.3.1.4 Popliteal Venous Blood Flow

There was a condition effect for popliteal venous blood flow (p = 0.013), with increases in TIGHTS as compared with CON (98.6% ± 161.7%, p = 0.009; ES = 1.06 ± 0.56) and SHORTS (47.9% ± 77.5%, p = 0.009; ES = 0.82 ± 0.56). Popliteal venous blood flow was not significantly different in TIGHTS compared with SOCKS (21.7% ± 85.5%, p = 0.246; ES = 0.51 ± 0.69) and in SOCKS compared with CON (63.1% ± 176.8%, p = 0.109; ES = 0.55 ± 0.74; Fig 3-3D and Appendix B).

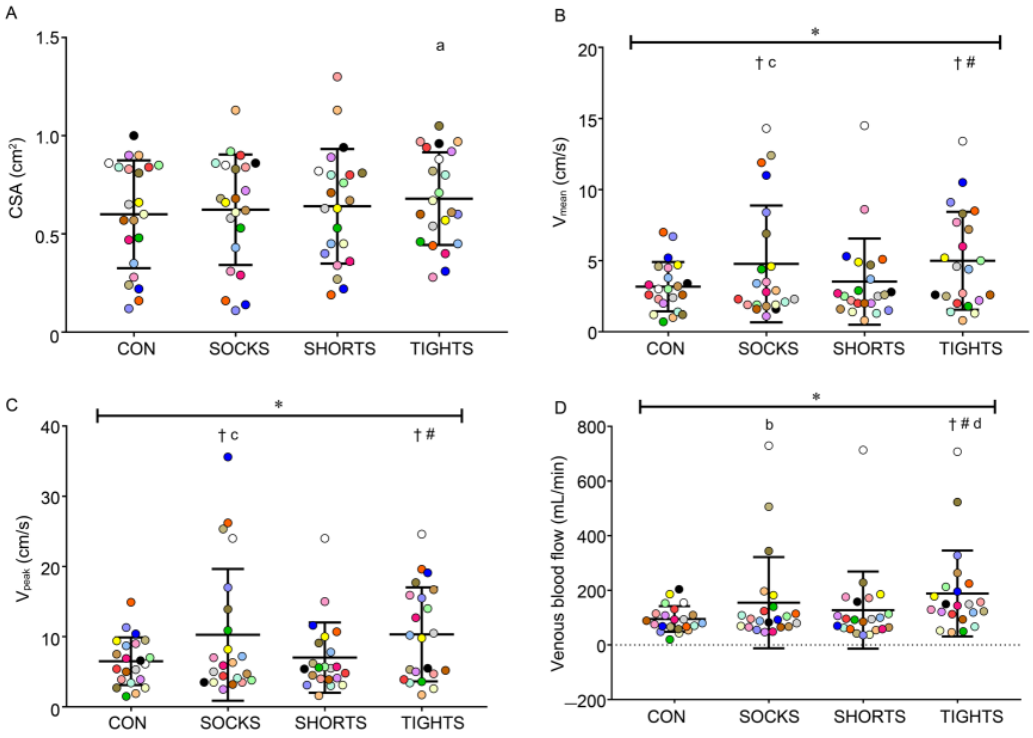

Figure 3-3: Popliteal vein markers of venous return for each sports compression garment condition. Markers measured include (A) CSA, (B) V_{mean}, (C) V_{peak}, and (D) venous blood flow. Bars are the mean ± SD. Individual coloured data points indicate individual participants. * $p < 0.05$, significant condition effect; # $p < 0.01$, significant effect compared to SHORTS; † $p < 0.05$, significant effect compared to CON. [a] denotes small effect compared to CON; [b] denotes medium effect compared to CON; [c] denotes small effect compared to SHORTS; [d] denotes medium effect compared to SOCKS. CON = no compression; CSA = cross-sectional area; SHORTS = compression shorts; SOCKS = compression socks; TIGHTS = compression tights; V_{mean} = mean flow velocity; V_{peak} = peak flow velocity.

3.3.1.5 Femoral CSA

No condition effect was detected for femoral CSA ($p = 0.807$; Fig 3-4A and Appendix B).

3.3.1.6 Femoral V_{mean}

There was a condition effect for femoral V_{mean} ($p = 0.007$), with increased V_{mean} in TIGHTS when compared with CON (45.4% ± 69.4%, $p = 0.006$; ES = 0.63 ± 0.35) and SOCKS (22.4% ± 48.3%, $p = 0.042$; ES = 0.35 ± 0.32). In addition, femoral V_{mean} was increased in SOCKS (18.8% ± 39.2%, $p = 0.035$; ES = 0.28 ± 0.34) and SHORTS (42.4% ± 78.5%, $p = 0.019$; ES = 0.47 ± 0.37) as compared with CON (Fig 3-4B and Appendix B).

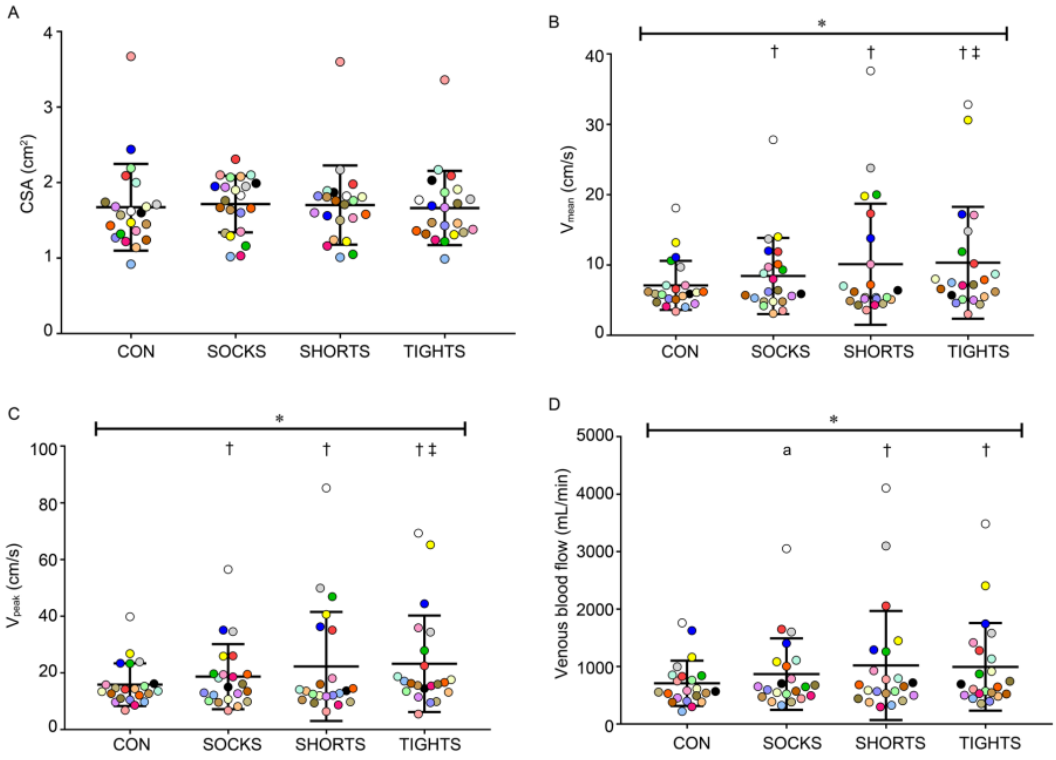

Figure 3-4: Common femoral vein markers of venous return for each sports compression garment condition. Markers measured include (A) CSA, (B) V_{mean}, (C) V_{peak}, and (D) venous blood flow. Bars are the mean ± SD. Individual coloured data points indicate individual participants. * $p < 0.05$, significant condition effect; † $p < 0.05$, significant effect compared to CON; ‡ $p < 0.05$, significant effect compared to SOCKS. [a] denotes small effect compared to CON; CON = no compression; CSA = cross-sectional area; SHORTS = compression shorts; SOCKS = compression socks; TIGHTS = compression tights; V_{mean} = mean flow velocity; V_{peak} = peak flow velocity.

3.3.1.7 Femoral V_{peak}

There was a condition effect for femoral V_{peak} ($p = 0.006$). Specifically, V_{peak} was increased in TIGHTS as compared with CON (46.4% ± 68.1%; $P = 0.004$, ES = 0.66 ± 0.37) and SOCKS (24.1% ± 50.7%, $p = 0.036$; ES = 0.38 ± 0.34). Femoral V_{peak} was also increased in SOCKS (17.9% ± 40.1%, $p = 0.048$; ES = 0.27 ± 0.38) and SHORTS (40.5% ± 78.7%, $p = 0.025$; ES = 0.42 ± 0.39) as compared with CON (Fig 3-4C and Appendix B).

3.3.1.8 Femoral Venous Blood Flow

There was a condition effect for femoral venous blood flow ($p = 0.033$), with femoral venous blood flow increased in TIGHTS (40.3% ± 65.2%, $p = 0.009$; ES = 0.51 ± 0.30) and SHORTS (43.9% ± 97.6%, $p = 0.047$; ES = 0.43 ± 0.34) as compared with CON. Femoral

venous blood flow was not significantly different in SOCKS when compared with CON (22.6% ± 53.2%, p = 0.060; ES = 0.31 ± 0.31; Fig 3-4D and Appendix B).

3.3.2 Muscle Blood Flow

3.3.2.1 Calf Muscle Blood Flow

There was a condition effect for calf muscle blood flow (p < 0.0001). Specifically, calf muscle blood flow was increased in TIGHTS as compared with all other conditions (CON: 82.4% ± 80.6%, p < 0.0001; ES = 1.34 ± 0.53; SOCKS: 35.4% ± 60.0%, p = 0.012; ES = 0.78 ± 0.51; SHORTS: 73.9% ± 72.1%, p < 0.0001; ES = 1.24 ± 0.45) and when SOCKS was compared with SHORTS (28.4% ± 62.8%, p = 0.046; ES = 0.46 ± 0.43). Calf muscle blood flow was not significantly different in SOCKS when compared with CON (34.7% ± 82.4%, p = 0.062; ES = 0.56 ± 0.59; Fig 3-5 and Appendix B).

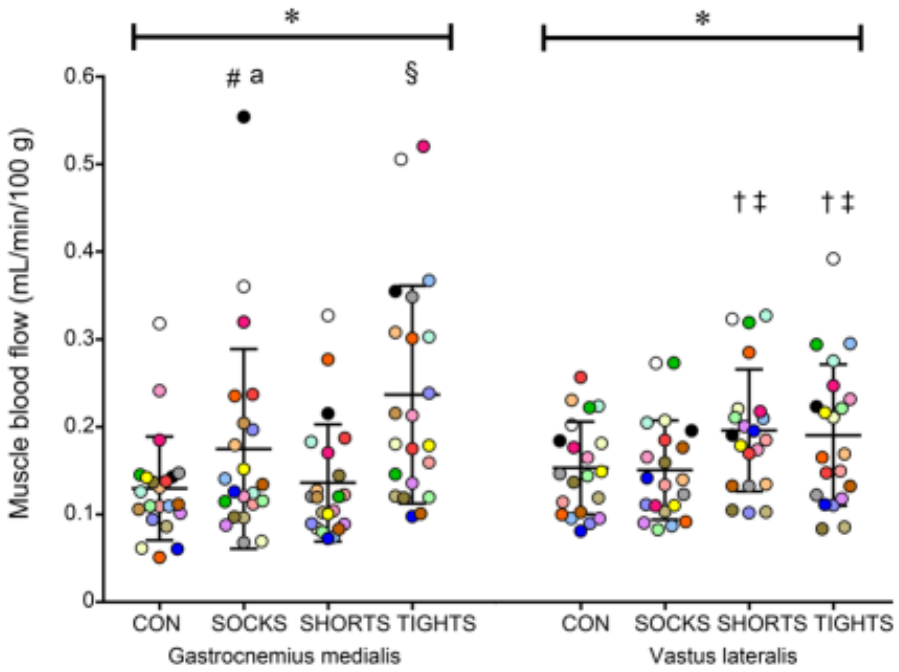

Figure 3-5: Muscle blood flow (mL/min/100 g) to the *gastrocnemius medialis* (calf) and *vastus lateralis* (thigh) muscles for the CON and sports compression garment conditions (SOCKS, SHORTS, and TIGHTS). Bars are the mean ± SD. Individual coloured data points indicate individual participants. * p < 0.01, significant condition effect; $^{\#}$ p < 0.05, significant effect compared to SHORTS; † p < 0.05, significant effect compared to CON; ‡ p < 0.05, significant effect compared to SOCKS; § p < 0.05, significant effect compared to all other conditions. ^{a} denotes medium effect compared to CON. CON = no compression; SHORTS = compression shorts; SOCKS = compression socks; TIGHTS = compression tights.

3.3.2.2 Thigh Muscle Blood Flow

There was a condition effect for thigh muscle blood flow ($p = 0.001$), with thigh muscle blood flow increased in TIGHTS as compared with CON (24.4% ± 47.3%, $p = 0.028$; ES = 0.54 ± 0.51) and SOCKS (26.5% ± 47.3%, $p = 0.019$; ES = 0.61 ± 0.59). In addition, thigh muscle blood flow was increased when SHORTS was compared with CON (28.0% ± 46.3%, $p = 0.012$; ES = 0.70 ± 0.54) and SOCKS (30.1% ± 43.2%, $p = 0.005$; ES = 0.76 ± 0.55; Fig 3-5 and Appendix B).

3.3.3 Muscle Oxygenation

3.3.3.1. Calf Muscle Oxygenation

There was a condition effect for calf muscle oxygenation ($p = 0.002$). Specifically, calf muscle oxygenation was increased in TIGHTS as compared with all other conditions (CON: 3.0% ± 4.2%, $p = 0.003$; ES = 0.55 ± 0.33; SOCKS: 1.6% ± 3.0%, $p = 0.033$;

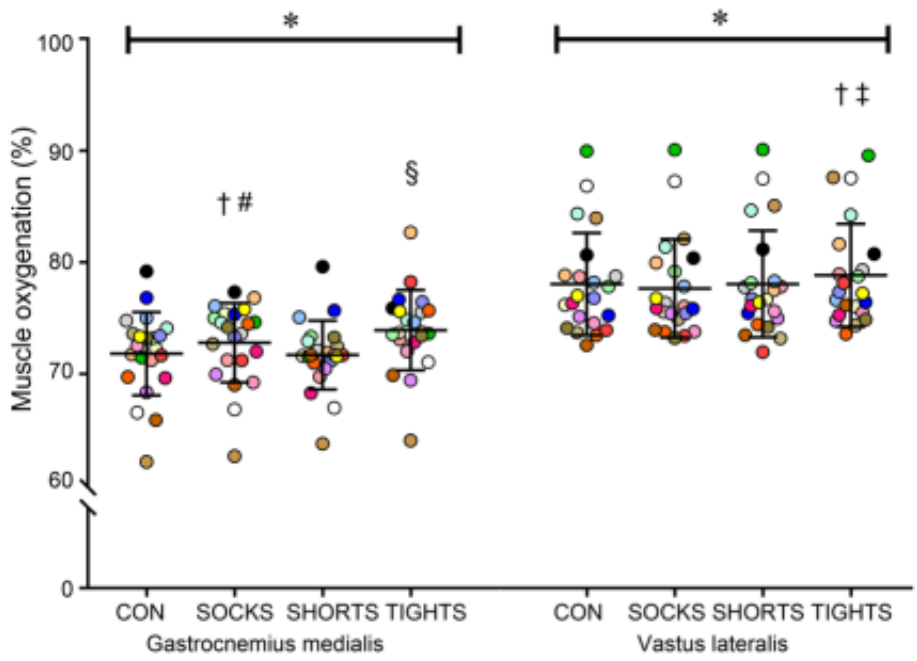

Figure 3-6: Muscle oxygenation (%) of the g*astrocnemius medialis* (calf) and *vastus lateralis* (thigh) muscles for the CON and sports compression garments conditions (SOCKS, SHORTS, and TIGHTS). Bars are the mean ± SD. Individual coloured data points indicate individual participants. * $p < 0.01$, significant condition effect; # $p < 0.05$, significant effect as compared with SHORTS; † $p < 0.05$, significant effect as compared with CON; ‡ $p < 0.05$, significant effect as compared with SOCKS; § $p < 0.05$, significant effect as compared with all conditions. CON = no compression; SHORTS = compression shorts; SOCKS = compression socks; TIGHTS = compression tights.

ES = 0.29 ± 0.26; SHORTS: 3.1% ± 4.0%, p = 0.003; ES = 0.57 ± 0.35). Calf muscle oxygenation was also increased in SOCKS as compared with CON (1.4% ± 3.0%, p = 0.044; ES = 0.26 ± 0.25) and SHORTS (1.5% ± 3.0%, p = 0.032; ES = 0.28 ± 0.25; Fig 3-6 and Appendix B).

3.3.3.2 Thigh Muscle Oxygenation

There was a condition effect for thigh muscle oxygenation (p = 0.009), with thigh muscle oxygenation increased in TIGHTS as compared with CON (1.0% ± 1.8%, p = 0.020; ES = 0.18 ± 0.15) and SOCKS (1.5% ± 2.0%, p = 0.006; ES = 0.26 ± 0.18; Fig 3-6 and Appendix B).

3.3.4 Pressure Profiles

A supine posture resulted in lower pressures at Landmarks B through F for all garments, as compared with standing ($p < 0.05$). In addition, pressure readings at Landmarks A, B, and C were increased for SOCKS as compared with TIGHTS ($p < 0.05$), irrespective of posture (Table 3-1).

Table 3-1: Pressure profiles of each sports compression garment in the supine and standing positions (mean ± SD).

Garment (Posture)	Pressure profiles landmarks (mmHg)					
	A	B	C	D	E	F
SOCKS (supine)	25.9 ± 4.5$^{\#}$	25.8 ± 4.1$^{\#}$	29.0 ± 2.5$^{\#}$			
SOCKS (stand)	26.6 ± 5.4$^{\#}$	29.6 ± 4.2*$^{,\#}$	38.1 ± 4.6*$^{,\#}$			
SHORTS (supine)				13.6 ± 1.6	13.0 ± 1.2	11.63 ± 1.8
SHORTS (stand)				16.1 ± 2.5*	15.2 ± 2.3*	13.9 ± 2.1*
TIGHTS (supine)	15.1 ± 3.8	17.2 ± 3.7	17.2 ± 3.9	13.6 ± 2.4	13.0 ± 2.0	12.2 ± 2.3
TIGHTS (stand)	15.2 ± 4.7	20.2 ± 5.2*	21.8 ± 6.1*	17.1 ± 3.1*	16.3 ± 3.0*	15.5 ± 3.1*

* $p < 0.05$, significant posture effect compared to supine. $^{\#}$ $p < 0.05$, significant condition effect compared to TIGHTS. Abbreviations: SHORTS = compression shorts; SOCKS = compression socks; TIGHTS = compression tights.

3.4 Discussion

This study provides the first comprehensive assessment of the effects of different sports compression garment types on markers of venous return and muscle blood flow. The main findings were that lower-limb SCG, fitted to target pressures (SOCKS and SHORTS) and worn according to manufacturer guidelines (TIGHTS), increased resting markers of venous return and muscle blood flow. Additionally, the increase in muscle blood flow with SOCKS and TIGHTS was coupled with an increase in muscle oxygenation. When comparing garments, TIGHTS elicited the greatest enhancement in resting blood flow measures of the lower limbs. Taken together, these results support the notion that SCG are effective in improving markers of venous return and muscle blood flow and are most pronounced in garments covering the whole leg (i.e., compression tights).

A novel component of this study was the use of Doppler ultrasound to determine the effect of SCG on markers of venous return. This technique, which is the criterion standard for measuring venous structure and flow,[430] has yet to be utilised in studies related to SCG. The current study is, therefore, the first to compare the effect of different sports compression garment types on markers of venous return, including venous blood velocity and venous blood flow, with all 3 compression garments having a positive effect on these markers. The changes in venous blood flow occurred with limited changes in the deep venous cross-sectional area, suggesting that the increase in venous blood flow observed with sports compression is primarily a result of increased mean flow velocity. This may result from compression of the superficial venous system, thereby shunting blood into the deep venous system and increasing blood volume for the skeletal muscle pump to eject.[203]

The positive effects observed in our study are supported by previous research reporting compression-induced increases in similar markers of venous return in healthy individuals with medical compression, as measured by Doppler ultrasound.[56,71,210] However, one study has reported no effect of medical compression on the same markers of venous return.[15] Potential explanations for these differing results include the manner in which ultrasound measurements were collected (i.e., supine *vs.* standing), as well as the level of pressure being applied to the limb. Standing requires the contraction of postural muscles, which may reduce the influence of compression due to muscle contraction (i.e., skeletal

muscle pump).[139] In a study by Stein et al.,[15] the levels of pressure applied, when standing, at the calf (14 mmHg) and mid-thigh (10 mmHg) were considerably lower than those measured for TIGHTS in our study (standing values: 21 mmHg and 16 mmHg, respectively). However, the pressure values reported in Stein et al.[15] were based on manufacturer guidelines only (i.e., not directly measured), highlighting that measuring compression pressure is essential when determining the effectiveness of compression garments in altering blood flow. Notably, the pressure exerted by SCG in our study (calf: ~29 mmHg; thigh: ~13 mmHg) is comparable to the level achieved in previous studies (calf: ~26 mmHg; thigh: ~12 mmHg) that showed compression-induced changes in markers of venous return[56,71,210] and/or muscle blood flow.[9,12,36,195]

Our study is the first to compare different sports compression garment types on muscle blood flow, and the results identified TIGHTS as the most effective garment for improving resting muscle blood flow of the calf and thigh musculature. In support of the proposed mechanisms for muscle blood flow (i.e., myogenic response, venule–arteriolar communication, and skin vasomotor reflexes),[5] all compression garments increased muscle blood flow in the underlying musculature. For example, TIGHTS improved calf and thigh muscle blood flow, whereas SOCKS (calf only) and SHORTS (thigh only) increased muscle blood flow in the compressed muscle only. Similarly, compression was previously reported to increase muscle blood flow (as measured by venous occlusion with NIRS) in the thigh with compression tights[9] and in the calf with compression socks[36] but to have no effect on thigh muscle blood flow with compression socks.[305] Thus, our study's results support the notion that TIGHTS may be the most appropriate garment for improving resting blood flow in the entire lower limb, which may have implications for recovery from exercise that incorporates large lower-body muscle recruitment (e.g., running, jumping, resistance exercise).

By combining Doppler ultrasound and NIRS with venous occlusion to measure compression-induced changes in blood flow, our study provides novel evidence that enhanced markers of venous return are coupled with an increase in muscle blood flow. The observed increases in muscle blood flow may be associated with the parallel increase in venous return. Increased venous return causes venous pressure to decrease[20] which may

enhance muscle blood flow through increases in the arteriovenous pressure gradient.[422] In addition, greater venous return with compression may lower heart rate[9] and cardiovascular stress via improved stroke volume, cardiac output, and heart rate variability,[107] subsequently leading to enhanced muscle blood flow. In support of this, TIGHTS were the most effective compression garment for increasing both markers of venous return and muscle blood flow of the entire lower limb (i.e., in the popliteal and common femoral veins and in the calf and thigh muscles). The enhanced markers of venous return with TIGHTS likely contributed to the greater compression-induced increases in muscle blood flow with TIGHTS. Although SOCKS and SHORTS were beneficial in enhancing markers of venous return in the popliteal and common femoral veins, respectively, ours is the first study to find that TIGHTS were more effective in enhancing these markers. Furthermore, the concurrent increase in muscle blood flow may lead to improved blood flow in the capillary bed and therefore increase the amount of oxygen delivered to the muscle.

The association between greater muscle blood flow and enhanced muscle oxygenation was evident in our study. Increased muscle blood flow to the calf and thigh musculature in TIGHTS was coupled with enhanced muscle oxygenation. Similarly, enhanced muscle blood flow to the calf with SOCKS resulted in improved muscle oxygenation. These results are in agreement with previous studies showing that compression enhanced muscle oxygenation at rest, with reduced venous pooling (i.e., increased venous return) and increased muscle blood flow also evident.[5,6] Conversely, muscle oxygenation was not improved at the thigh with SHORTS, despite increased muscle blood flow. The level of pressure exerted by SHORTS (~13 mmHg) may not have been sufficient to enhance muscle oxygenation because compression is frequently reported to enhance muscle oxygenation with exerted garment pressures > 13 mmHg[36,304] or garments covering the entire lower limb.[45,124] The higher level of pressure with SOCKS (~29 mmHg) and greater surface area covered with TIGHTS may help explain the increased muscle oxygenation with SOCKS and TIGHTS only. However, the exact mechanism for this lack of enhanced muscle oxygenation with SHORTS remains unclear since no other study has investigated the effect of compression shorts on muscle oxygenation. Ours is the first study to identify TIGHTS as the most effective garment for enhancing muscle oxygenation to the lower limb (i.e., thigh and calf

musculature). This is likely due to the greater effect of TIGHTS on markers of venous return and muscle blood flow in the lower limb compared to the other garment styles.

When comparing pressure between garments, TIGHTS had a lower pressure than SOCKS at all landmarks on the lower leg (i.e., Landmarks A, B, and C shown in Fig 3-2). However, TIGHTS was superior at increasing popliteal markers of venous return (Fig 3-3), calf blood flow (Fig 3-5), and oxygenation (Fig 3-6). A potential explanation for this is that the surface area of the lower limb compressed by TIGHTS is greater than that of SOCKS (i.e., entire lower limb *vs.* lower leg), thus compressing more superficial veins and increasing venous return. These findings are supported by Benko et al.,[56] who reported stockings covering the entire lower limb were more effective in improving venous return compared with stockings covering the lower leg only. In our cohort of elite male junior basketball players, manufacturer sizing guidelines were appropriate for providing sufficient pressure to improve blood flow measures, particularly in the TIGHTS condition. The interface pressure changes observed with posture changes (Table 3-1) are attributed to the muscles' contraction upon standing,[139] which is supported by the lack of difference in pressure observed between postures at the ankle (i.e., Landmark A). In general, manufacturer sizing guidelines were appropriate for achieving the target pressures for SOCKS and SHORTS. However, caution is advised in regard to sizing because some participants (SOCKS: $n = 3$; SHORTS: $n = 4$) did require a sports compression garment one size smaller than the manufacturer's recommended size in order to achieve target pressures. For TIGHTS, the use of manufacturer guidelines achieved simultaneous target pressures at Landmarks C and E in only three participants. Considering that the level of pressure applied is critical for the effectiveness of SCG,[71] these data highlight the importance of garment style, as well as posture, when prescribing SCG.

Research to date investigating SCG have often failed to report a pressure profile,[55] while those studies that have reported it frequently only measure pressure at the calf and mid-thigh.[12,83] The pressure differences between these two sites create the impression of a graduated profile[139] (decreasing pressure values from distal to proximal) in TIGHTS. However, the use of additional pressure landmarks (Fig 3-2) shows that compression applied to the upper leg (SHORTS and TIGHTS) is graduated in nature, with no graduated profile

for the lower leg (Table 3-1). Similar to findings by Brophy-Williams et al.,[139] SOCKS and TIGHTS exerted a higher interface pressure at maximal calf girth (Landmark C) than at the lower leg (Landmark B) and upper ankle (Landmark A), creating a progressive (increasing pressure from distal to proximal) pressure gradient[137] in the lower leg. Traditionally, a graduated profile is recommended for effective compression treatment due to regular distal pooling of blood and fluid as a result of gravity in clinical populations.[20,21] However, young athletic populations are less likely to suffer from venous issues that result in pooling around the ankles (e.g., chronic venous insufficiency, deep vein thrombosis, etc.). In addition, in our study, markers of venous return were collected in the supine position, potentially limiting any pooling in the ankles that may occur when standing or in seated postures. Increased pressure applied to the muscle belly has previously been shown to enhance venous pump function,[137] which is similar to the observations in our study. A potential explanation for this is that higher blood volumes will pool at the muscle belly (i.e., the calf musculature) compared with the distal parts of the leg (i.e., the ankle).[137] Thus, to maximise the effect of SCG on skeletal muscle pump function and venous return, the highest level of external pressure should be applied to the underlying musculature.

3.5 Conclusion

Compression tights were the most effective garment for increasing markers of venous return and muscle blood flow in the lower limbs at rest, although compression shorts and compression socks also had a positive effect. These improvements in blood flow were coupled with an improvement in muscle oxygenation for compression tights and socks. Manufacturer guidelines were appropriate for most participants in exerting pressures required to alter measures of blood flow. Therefore, SCG may be a practical intervention for enhancing markers of venous return and muscle blood flow in the lower limbs while at rest.

CHAPTER FOUR

Compression-induced improvements in post-exercise recovery are associated with enhanced blood flow, and are not due to the placebo effect.

The findings from Chapter 3 highlight that sport compression tights, compared to socks and shorts, were the most effective garment in increasing measures of venous return and muscle blood flow. Also, Chapter 2 revealed that a major limitation of SCG research is the inadequate blinding of participants and that the potential placebo effect of SCG cannot be discounted. Therefore, Chapter 4 aimed to investigate the effects of sports compression tights on blood flow post-exercise and aspects of muscle recovery (i.e., muscle damage, exercise performance recovery) compared to a placebo condition. It was hypothesised that sports compression tights worn post-exercise would improve blood flow during this period, subsequently improving indices of muscle recovery, and that these benefits would not be the result of a placebo effect.

The manuscript for this study is in final stages of preparation:

O'Riordan, S. F., Bishop, D. J., Halson, S. L., Clark, S., and Broatch, J. R. (2020). Compression tights enhance post-exercise blood flow and compression induced benefits in muscle recovery are not due to the placebo effect. *Scientific Reports* (in preparation).

Sci. Rep., Q1; Impact Factor (2020): 4.379

Abstract

Introduction: The ergogenic benefits associated with compression garments in post-exercise recovery are likely associated with improvements in blood flow. However, research investigating the effects of compression on post-exercise blood flow is lacking. This study examined the physiological merit of compression tights on blood flow following eccentric resistance exercise induced muscle damage, and assessed if the placebo effect is responsible for any acute performance or psychological benefits.

Methods: Twenty-two resistance-trained participants completed a lower-body resistance exercise session (leg press; 8 sets of 6 reps with 4 s eccentric for each rep) followed by a 4 h recovery period. Participants were assigned a recovery intervention of either compression tights applied for 4 h (COMP, n = 7), placebo tablet (PLA, n = 8) consumed every hour for 4 h, or control (CON, n = 7). Physiological (markers of venous return, muscle blood flow, blood metabolites, thigh girth), performance (countermovement jump, isometric mid-thigh pull) and psychological measures (perceived muscle soreness, total quality of recovery) were collected pre-exercise, immediately post-exercise, during 4 h recovery, and 24 h and 48 h post-exercise. Comparisons between recovery interventions were analysed using a two-way linear mixed model (ANOVA). Also, effect sizes (ES) were calculated to assess the magnitude of observed condition effects.

Results: No significant (p > 0.05) differences were observed between interventions. From ES analysis, COMP enhanced markers of venous return (ES range: 0.49 to 2.21) and muscle blood flow (ES range: 0.44 to 1.15) during the 4 h recovery period. Recovery of performance measures were greater with COMP at 4 h (ES range: 0.27 to 0.76), 24 h (ES range: 0.29 to 0.99) and 48 h (ES range: 0.29 to 0.66) post-exercise. Thigh girth was reduced with COMP (ES range: 0.24 to 0.35) during the 4 h recovery period. Perceptual measures of recovery were improved with COMP during 4 h recovery period (ES range: 0.64 to 2.41), and at 24 (ES range: 0.86 to 3.21) and 48 h (ES range: 0.96 to 4.05) post-exercise. There were no group differences in blood metabolites.

Conclusion: Compression tights worn after resistance exercise enhanced blood flow and indices of recovery from exercise. These benefits of compression were not due to a placebo effect.

Keywords: venous return, arterial perfusion, muscle damage, compression garments

4.1 Introduction

Exercise-induced damage to the muscle frequently occurs following unaccustomed exercise,[249] particularly if it is comprised of a large eccentric component. The etiology of EIMD is characterised by structural damage to the myofibrils during the initial exercise insult, followed by secondary inflammation from leukocyte infiltration into the damaged tissue.[271,272] The signs and symptoms associated with EIMD include muscle soreness, muscle swelling, reduced muscle function, and elevated concentrations of myofibrillar proteins in the blood (e.g., CK, LDH).[173,257,269–272] These can become evident within a few hours after exercise[271] and can persist for several days.[272] Although EIMD is an important process for the adaptive response to exercise training,[173] reducing the symptoms associated with EIMD is beneficial for individuals aiming to maintain short-term exercise performance and training quality.[1] Post-exercise recovery strategies are commonly utilised to alleviate the symptoms of EIMD,[433] with one of the most prevalent techniques being SCG.[68]

The mechanisms by which SCG enhance recovery following exercise remain unclear but may be closely associated with venous and muscle blood flow alterations. Compression-induced increases in venous blood flow[56,71,210] is linked with accelerating the removal of myofibrillar proteins from the muscle.[51,434] For example, lower concentrations of plasma CK have been reported with compression garment use during post-exercise recovery.[7,53,172] Compression may also reduce exercise-induced oedema by limiting the space available for swelling to form and by promoting lymphatic outflow, thus attenuating the inflammatory response and preventing further muscle damage.[68,70] In addition, compression may improve blood flow to the muscle following exercise and aid recovery by increasing nutrient delivery post-exercise. Nonetheless, a limitation with compression research performed to date is that most studies have focused on blood flow responses during exercise,[9–13,16,36] and within a short period (< 1 h) post-exercise.[10,12,16] Considering the inflammatory response begins in the early hours (1-4 h)[269] during exercise recovery, the use of compression garments beyond the first hour post-exercise may serve to reduce the symptoms of EIMD. The assessment of compression-induced changes in blood flow during this time will provide valuable insight into the proposed mechanism (i.e., increased blood flow) attributed to the effectiveness of SCG as a post-exercise recovery strategy.

A further limitation of the compression research to date is that the contribution of psychological factors to the ergogenic effects of compression on exercise performance and recovery outcomes is currently unknown. Considering many studies report favourable psychological outcomes (e.g., perceived muscle soreness, quality of recovery) with a concomitant lack of effect on physiological and/or performance measures,[43,65,119,141,284,287] it is possible that psychological factors may contribute, at least in part, to the benefits associated with compression. In further support of this, participants' positive perception and belief in SCG are suggested to improve exercise performance and recovery.[77,161,284,286] Research in other recovery techniques, including massage[435] and cold water immersion,[436] suggest enhanced exercise recovery might occur via psychophysiological mechanisms (i.e., placebo effect)[436]; however, this has not been appropriately investigated with SCG.

Due to the high level of pressure exerted on the limb with compression garments, a challenge with compression research is the inability to blind participants. Previous research has attempted to blind participants using similar-looking garments with a low level of pressure.[75,79,150] Alternatively, compression research has used 'sham' placebo interventions (e.g., drink[41] and ultrasound[39,43,74]), in which participants were deceived into thinking these interventions are beneficial for exercise performance and/or recovery. However, a limitation of these studies is that belief in the placebo intervention (as compared with compression) was not assessed, meaning the presence of a placebo effect is still unable to be discounted.[39,41,43,74] In addition, no study has incorporated a placebo intervention promoting the beneficial effect on blood flow, despite the general consensus that the ergogenic effects associated with SCG are closely related to improvements in blood flow.[51,68,288] In order to determine the effectiveness of SCG on exercise recovery, it is crucial to try and limit this placebo effect. Controlling for the placebo effect was achieved by matching belief between compression and placebo conditions.

This study aimed to investigate the influence of sports compression tights on post-exercise recovery, as well as compare the effects of compression on markers of post-exercise blood flow, to those of a placebo condition that participants were informed was as effective as compression for the recovery from exercise. It was hypothesised that sports compression tights would enhance post-exercise blood flow and subsequently improve indices of muscle

recovery, and that these benefits would not be related to the placebo effect – i.e., compression would elicit superior benefits, due to increased blood flow, when compared with the placebo and control conditions.

4.2 Methods

4.2.1 Participants

Thirteen males (mean ± SD: age, 24.9 ± 5.9 y; height, 179.5 ± 7.8 cm; body mass, 85.6 ± 10.7 kg) and nine females (mean ± SD: age, 27.3 ± 2.9 y; height, 167.4 ± 7.0 cm; body mass, 62.5 ± 11.8 kg) completed the study. Participants were required to be performing a minimum of two lower-body resistance exercise sessions a week, for a minimum of 6 months, to be eligible to participate. Written informed consent was obtained before participation. All participants were screened to ensure no contraindications were present for study participation, including cardiovascular risk factors (i.e., personal or family history of cardiovascular disease) and exercise capacity (e.g., musculoskeletal injury or joint pain). All procedures were approved by the Victoria University Human Research Ethics Committee (HRE18-227). The experimental approach was a between-subject parallel-group design. Participants were assigned one of three recovery conditions in a randomised fashion, matched on belief in the interventions (as assessed during the familiarisation session). These conditions were sport compression tights [COMP, 4 males and 3 females (n = 7)], placebo by deception [PLA, 5 males and 3 females (n = 8)] or a passive control [CON, 4 males and 3 females (n = 7)]. A parallel-group design was chosen to avoid a repeated bout effect that would be present in a cross-over design. Participant characteristics are described in Table 4-1.

Table 4-1: Descriptive characteristics of participants in experimental groups (mean ± SD).

	COMP (n = 7)	PLA (n = 8)	CON (n = 7)
Age (y)	26.6 ± 5.2	26.9 ± 5.8	24.9 ± 5.1
Height (cm)	177.8 ± 3.5	172.6 ± 10.9	174.6 ± 11.5
Body Mass (kg)	74.3 ± 14.2	76.2 ± 13.7	73.8 ± 19.3
Leg Press 1 RM (kg)	260.0 ± 115.2	242.1 ± 78.8	244.6 ± 94.7
Quadriceps Skinfold (mm)	8.8 ± 3.1	11.9 ± 5.8	11.2 ± 2.1

4.2.2 Overview

Participants reported to the laboratory on four separate occasions (Fig 4-1). Session one involved leg press 1RM testing, and familiarisation of the performance tests, blood flow measurements, and perceptual questionnaires. Anthropometric measurements of height, body mass, and quadriceps' skinfold of the right leg were also taken. Following the reading of individual information sheets that highlighted the benefits of the COMP and PLA conditions for exercise recovery, participants completed belief questionnaires for both recovery interventions. Session one was conducted a minimum of 10 days before session two.

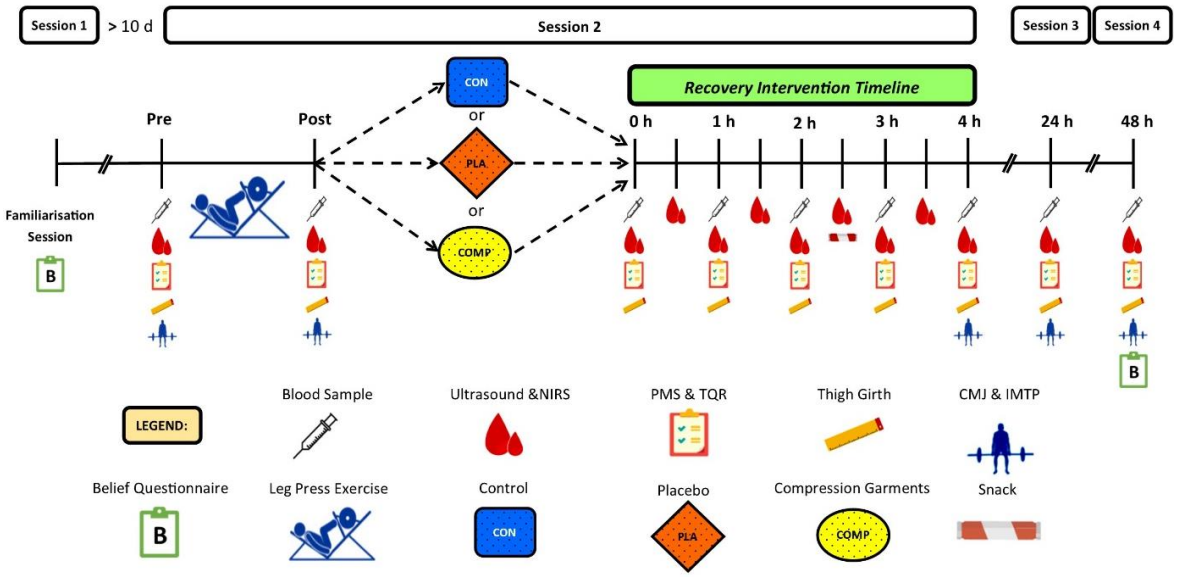

Figure 4-1: Schematic diagram of testing sessions.

Following a period of refraining from strenuous (< 48 h) or unaccustomed (< 7 d) exercise, participants reported to the laboratory for three experimental sessions. Participants

were also asked to refrain from other exercise or recovery interventions (e.g., massage, water immersion) until the final testing session (session four) was complete. Session two started with pressure measurements of SCG (COMP only), followed by a 20-min supine rest period during which the sites for blood flow and thigh girth measurements were identified and prepared. Immediately after this, baseline measures of blood flow, perceptual questionnaires, thigh girth, and performance tests, as well as a venous blood sample, were collected. Participants then completed the leg press exercise protocol, and all baseline measures were repeated immediately after exercise. Following the post-exercise measures, participants performed their assigned recovery intervention (i.e., CON, PLA, or COMP) while supine for 4 h, and measurements were repeated at 30 (blood flow) or 60 (blood samples, perceptual questionnaires, thigh girth) min intervals. Performance tests were repeated at the end of 4 h supine rest only. Sessions three and four involved re-testing of baseline measures at 24 and 48 h post-exercise, respectively. At the end of the 48-h testing session, participants repeated the belief questionnaires in their completed recovery intervention. Testing sessions two, three, and four, started at the same time of day to minimise diurnal variations.

4.2.3 Recovery Information and Belief Questionnaires

During the familiarisation session, participants were given an information sheet on the efficacy of two recovery interventions (Appendix F), SCG and L-Arginine supplementation. These information sheets illustrated peer-reviewed data on the effectiveness of either SCG[52] or L-Arginine[362] in enhancing recovery post-exercise, with a particular focus on their capacity to improve blood flow and reduce the symptoms of EIMD. The benefits of L-Arginine[362] were used to create a placebo by deception, with participants assigned to PLA group falsely led to believe they were receiving L-Arginine tablets (detailed below) during 4 h recovery post-exercise. A 'belief' questionnaire[436] was used to assess the participants anticipated effectiveness of SCG and L-Arginine for exercise recovery. Participants were instructed to mark an 'X' on a 5-point likert scale, with 0 representing 'not effective at all' and 5 representing 'extremely effective'. From this questionnaire, participants were assigned their recovery intervention (CON, PLA, or COMP). A participant was randomly assigned to either COMP or CON if they answered a higher belief in COMP than L-Arginine (PLA) after reading the information sheets, and vice versa for a higher belief

in L-Arginine (PLA) (i.e., participant was randomly assigned to either PLA or CON). If a participant rated both interventions equally, they were then randomly assigned to one of the three recovery interventions. A similar 'belief' questionnaire was used at the end of testing to measure the participants' perceived effectiveness of their completed recovery intervention (i.e., COMP or PLA).

4.2.4 One Repetition Max Testing

Prior to testing of 1RM, participants performed a standardised warm-up consisting of 5 min of cycling at 1 W per kg body mass, 10 repetitions of bodyweight squats, 10 repetitions on each leg of bodyweight walking lunges, high knee run over 20 m, heel kick run over 20 m, 3 submaximal counter-movement jumps (CMJ), and 1 maximal CMJ. Following the warm-up, participants performed two warm-up sets of the leg press protocol, with each set consisting of 10 reps with no weight and 5 reps at 50% of a participant's self-estimated 1RM. Participants then performed a repetition at an estimated 90% of 1RM. If the repetition was completed successfully with the correct technique, participants performed another repetition effort with gradually increasing resistance. This process was repeated until failure or loss of technique, with 3 min of rest allowed between max effort attempts. A successful 1RM was the greatest mass lifted with correct form through a complete range of motion.[368,437] This 1RM was used to prescribe the workload for the lower-body resistance exercise session.

4.2.5 Dietary Control

Participants completed a 24-h diet diary before session two, and were asked to replicate this diet for the 24 h before sessions three and four. Participants were asked to refrain from caffeine and alcohol consumption (< 12 h) before all testing sessions. A snack (Aussie Bodies, Protein FX Super Bar, New Zealand) containing 25.6 g protein and 18.4 g carbohydrate was provided to the participant at 2 h and 30 min into recovery. The same snack was provided after session 3 to help maintain nutrition adherence post-testing.

4.2.6 Venous Return

Markers of venous return were measured at the popliteal and common femoral veins via Doppler ultrasound. The ultrasound examinations were performed using a CX50 Ultrasound System (Philips, USA), L12-3 MHz linear transducer and venous presets. Flow

studies were performed in a temperature-controlled (22°C) environment. All measurements were obtained in a supine position. Transverse and longitudinal images of the popliteal and common femoral veins were obtained using copious gel and minimal transducer pressure to avoid vein compression. The inner vessel transverse cross-sectional area (CSA; cm^2), time-averaged mean blood flow velocity (V_{mean}; cm/s) and time-averaged peak blood flow velocity (V_{peak}; cm/s) measurements for popliteal and common femoral veins were obtained for at each time point (Fig 4-1). Angles of insonation between 55-60º between the transducer and the vessels were used to obtain appropriate colour and spectral Doppler signals. Spectral Doppler waveforms were recorded in longitudinal from a large sampling volume that included the whole vessel diameter. Manual venous blood flow (mL/min) was calculated as ((CSA (mm^2) x V_{mean} (cm/s)) x 60/100).[432] The common femoral veins were examined 2 cm above the saphenofemoral junction, with the garment turned down slightly to gain access. The popliteal veins were examined at the level of the knee crease. Prior to participants wearing the garment, a small incision was made in the garment at the knee crease to create a small incision (5 x 3 cm) for the transducer to access the popliteal vein. Pilot data confirmed pressure of the garment was not altered with this small incision.

4.2.7 Muscle Blood Flow

Muscle blood flow was assessed in the *vastus lateralis* muscle using NIRS. This technique provides continuous, non-invasive measurement of concentration changes in O_2Hb and HHb.[308] These changes were monitored using an oximeter (Oxymon MKIII Near-Infrared Spectrophotometer, Artinis Medical Systems, The Netherlands) with data acquired using Oxysoft software (V3.0.53, Artinis Medical Systems, The Netherlands). An oximeter was fixed on the lowest third of the *vastus lateralis*, approximately 10-15 cm from the femur's lateral epicondyle, parallel to the long axis.[9,438] Oximeter placement site was shaved of excess hair and cleaned with an alcohol swab to ensure good signal quality, with each oximeter attached to the skin surface using double-sided tape. Pilot data confirmed pressure was not altered by the oximeter placement under the garment. Skinfold thickness was measured at the site of oximeter during session one using Harpenden skinfold callipers to determine subcutaneous fat to be less than 35 mm.

To assess muscle blood flow, multiple venous occlusions were performed. The venous occlusion technique required the inflation of a pressure cuff, applied to the upper right thigh near the inguinal crease (compression of the femoral vein), to 70 mmHg using an automated rapid cuff inflation system (Hokanson, Washington, USA). This technique restricts venous outflow, while still allowing arterial inflow. Blood flow into the muscle, presented as millilitres of blood per minute, per 100 grams of muscle tissue ($mL \cdot min^{-1} \cdot 100\ g^{-1}$),[9] was estimated from the following equation:

$$\text{Muscle Blood Flow} = \left(\frac{(tHb/1000)\ x\ 6}{[Hb]} \right)\ x\ 1000$$

where the slope of the rise in tHb (O_2Hb + HHb) was measured during three 20-s venous occlusions separated by 45 s of rest,[36] and the absolute value of Hb concentration was measured from a baseline blood sample and immediately analysed (KX-21N; Sysmex, Japan). Venous occlusions were performed immediately following markers of venous return measures at each time point (Fig 4-1), with the average of the three occlusions (coefficient of variation (CV); 14.9 ± 10.9%) used for data analysis.

4.2.8 Perceptual Measures

Participants assessed their level of perceived muscle soreness via self-manual palpation of the gluteal and thigh muscles followed by rating their level of soreness using a visual analogue scale (0 = no soreness, 10 = extremely high soreness; Appendix H).[439] Each participant's level of perceived recovery and fatigue was assessed using the total quality of recovery (TQR) scale (Appendix I), which is a scale from 6 (no recovery) to 20 (maximal recovery).[440]

4.2.9 Thigh Girth

Girth measurements were taken at the midpoint of the right thigh to evaluate potential swelling of muscles resulting from exercise. In a standing position, the thigh midpoint was determined and marked as 4 cm distal to halfway between the greater trochanter and lateral epicondyle.[436] For the COMP group, the thigh midpoint was also determined with participants wearing the garments prior to 4 h supine rest, and the site marked with tape. Thigh circumference was measured around the thigh while the participant lay supine on the

table, with the foot flat on the table surface and the knee at 90º.[436] Measurements were repeated twice at each time point (Fig 4-1), with the average value used for analysis.[8]

4.2.10 Blood Analyses

A 22-gauge indwelling venous catheter (Optiva IV Catheter 22G X 1", Smiths Medical, USA) was inserted into the antecubital vein. The catheter was kept patent with 0.9% saline (~3 mL; Pfizer, Australia) after each blood draw in session two. Blood samples at 24 and 48 h post-exercise were drawn via venepuncture (Winged Infusion Set 21G X 0.75", Smiths Medical, USA). Blood samples (~10 mL each) were collected into an EDTA tube (K2EDTA, Smiths Medical, USA) at each time point (Fig 4-1). A portion (100 μL) of blood from baseline, 24 and 48 h blood samples were analysed immediately for tHb concentration (KX-21N; Sysmex, Japan). The remaining whole blood was centrifuged at 1,000 *g* and 4ºC for 10 min. The acquired plasma was stored at -80º C for subsequent analysis. All samples were analysed using commercially available kits for CK (Creatine Kinase Activity Assay Kit, Abcam, Melbourne, Australia) and LDH (Lactate Dehydrogenase Assay Kit, Abcam, Melbourne, Australia). All samples were analysed in duplicate. The intra-assay coefficients of variation were 2.6 % for CK and 3.8 % for LDH.

4.2.11 Exercise Performance Testing

The CMJ and isometric mid-thigh pull (IMTP) performance tests were performed on a force platform (400S, Fitness Technology, Adelaide, Australia). Prior to all performance testing, participants performed the same standardised warm-up as completed before 1RM testing during session one. The CMJ test was chosen as it is a valid[441] and reliable[441,442] test for assessing the fatigue levels of lower body power.[443] Participants performed CMJ with feet at hip-width. Each CMJ consisted of a quick downward movement to approximately 90º knee flexion, followed by a fast upward vertical jump as high as possible. Upon landing, both feet were required to be within the frames of the force plate. When performing the CMJ, hands were placed on a wooden dowel across the participants' shoulders to eliminate the influence of arm swing on jump performance.[442] Each participant completed five maximal jumps, separated by 10 s of rest,[444] and the average of the five maximal jumps[445] was used to derive jump height (m), relative peak force (N/kg), relative peak power (W/kg), and total duration (s).

The IMTP test is commonly used to assess fatigue and changes in maximum strength and rate of force development capabilities.[446–448] The IMTP protocol required participants to pull upward on an immovable bar for 3 s while standing on the force platform.[444] The mid-thigh position for each participant was determined by marking the midpoint between the top of the patella and the inguinal crease of the front thigh. The site was marked with a permanent marker to ensure re-test reliability. Participants self-selected their hip and knee angles for the test,[449] with the barbell's height adjusted to be in contact with the marked mid-thigh position.[450] Two repetitions were performed, separated by a 2-min rest. A third repetition was performed if a > 250 N difference was observed between peak forces of the first two efforts.[451,452] Force-time variables calculated from IMTP included absolute peak force (N), relative peak force (N/kg), force at 100 ms (N), force at 200 ms (N), rate of force development (RFD; ΔForce/ΔTime) from 0 – 100 ms (N/s), and RFD from 0 – 200ms (N/s).[450,452] The average value reported across the two trials was used for analysis.

The raw force-time data for both CMJ and IMTP, sampled at 600 Hz, was collected using Ballistic Measurement System software (Fitness Technology, Adelaide, Australia). Raw force-time data was exported to and analysed in Microsoft Excel using spreadsheets specifically formulated for analysing CMJ[453] and IMTP.[454]

4.2.12 Exercise Intervention

An eccentric focused leg press exercise protocol, consisting of 8 sets of 6 repetitions at 85% of 1RM, was used to induce lower-limb muscle damage. Participants assumed a seated position on the leg press machine (Hammer Strength Linear, Schiller Park, IL, USA) and placed feet shoulder-width apart and flat on the platform. Prior to the beginning of 8 sets, participants performed a total of two warm-up sets, 10 repetitions with no weight on the leg press machine and 8 repetitions at 50% of 1RM. Participants lowered the resistance platform slowly for a duration of 4 s (time recorded by the investigator), and then pushed the platform back to its starting position as quickly as possible by extending the legs for each repetition. A 3-min rest period was provided between each set.

4.2.13 Recovery Intervention

For the COMP group, lower-body sports compression tights (Refresh Recovery Tights, 2XU, Melbourne, Australia) were assigned to participants based on height and weight (manufacturer guidelines), with garments pressure measured at the beginning of session two via the Kikuhime device (mediGroup, Australia) at six different landmarks along the lower limb. The landmarks were 5 cm proximal to the distal border of the medial malleolus (A), 5 cm proximal to A (B), medial aspect of maximal calf girth (C), anterior aspect of the thigh 10 cm below landmark E (F), midpoint between the inguinal crease and the superior-posterior border of the patella (E) and 5 cm proximal to landmark E (F).[139] The PLA group were given a sugar-free tablet (Hermesetas, Stevia Sweet 220 Tablets, Woolworths) at 0, 1, 2, and 3 h following post-exercise performance testing. Participants assigned to CON did not participate in any recovery intervention but remained supine for 4 h.

4.2.14 Statistical Analysis

Data are presented as mean ± SD and were analysed using IBM SPSS Statistics (Version 19, IBM Corp., Chicago, IL, USA). Normality was confirmed using the Sharipo-Wilk test. Belief effect (COMP vs. PLA) was assessed using independent sample t-tests. Comparisons between recovery interventions were analysed using a two-way linear mixed model (ANOVA) with repeated measures for time, where the between-subject factor is the recovery intervention (CON vs. COMP vs. PLA), and the within-subject factor is time. Significance was set at $P < 0.05$. Where significant time or interaction (time x condition) effects were found, a Fisher Least-Significant Difference post-hoc analysis was used. Also, ES were calculated to assess the magnitude of observed condition effects on markers of venous return, muscle blood flow, perceptual measures (muscle soreness, TQR), thigh girth, blood plasma measures (CK, LDH) and performance tests (CMJ, IMTP). All ES were log-transformed before analysis, and the magnitude of condition effects was determined by standardisation of the log-transformed variable. Cohen's conventions for ES (with 95% CI) were used for interpretation. Due to the smaller than originally planned sample size, ES analysis were incorporated as these are independent of sample size[455] and help the readers to understand the magnitude of the differences with SCG.[456] ES values were defined as small (0.20 to 0.49), medium (0.50 to 0.79) and large (≥ 0.80), and were only reported when there

was a ≥ 75% likelihood of the effect being equal or greater than the smallest worthwhile change (ES = 0.20).

4.3 Results

A detailed summary of statistical data for all between-group effects for blood flow measures (markers of venous return and muscle blood flow), performance measures (CMJ and IMTP), and perceptual/swelling measures (muscle soreness, TQR, and thigh girth) are presented in Tables 4-2, 4-5, and 4-7, respectively.

4.3.1 Garment Details

The compression tights applied 14 ± 2.2 mmHg, 17.4 ± 2.6 mmHg, 20.1 ± 2.5 mmHg, 13.9 ± 2.5 mmHg, 13.9 ± 2.5 mmHg and 12.6 ± 2.4 mmHg of pressure to the lower-limb of COMP group at landmarks A (upper ankle) to F (upper thigh), respectively.

4.3.2 Belief Questionnaires

The average belief in the interventions for all participants was 3.3 ± 0.7 for COMP, and 3.3 ± 0.9 for PLA. Participants assigned to COMP had a baseline belief in their intervention of 3.0 ± 0.6, which was significantly lower ($p < 0.05$) than participants in the PLA condition (3.9 ± 0.8). Belief in the COMP intervention (3.9 ± 0.8) was significantly higher ($p < 0.05$) than that of the PLA intervention (3.0 ± 0.5) at the end of the study.

4.3.3 Popliteal Markers of Venous Return

There were no interaction effects for popliteal CSA ($p = 1.000$; Fig 4-2A), V_{mean} ($p = 0.543$; Fig 4-2B), V_{peak} ($p = 0.766$; Fig 4-2C) and venous blood flow ($p = 1.000$; Fig 4-2D) or main effects of time for popliteal CSA ($p = 1.000$) and venous blow flow ($p = 0.110$). There were main effects of time for elevated popliteal V_{mean} ($p < 0.001$; Fig 4-2B) and V_{peak} ($p < 0.0001$; Fig 4-2C) post-exercise. ES analysis revealed medium to large effects for increased popliteal V_{mean} during 4 h post-exercise recovery in the COMP group compared to the CON and PLA groups, respectively (Table 4-2).

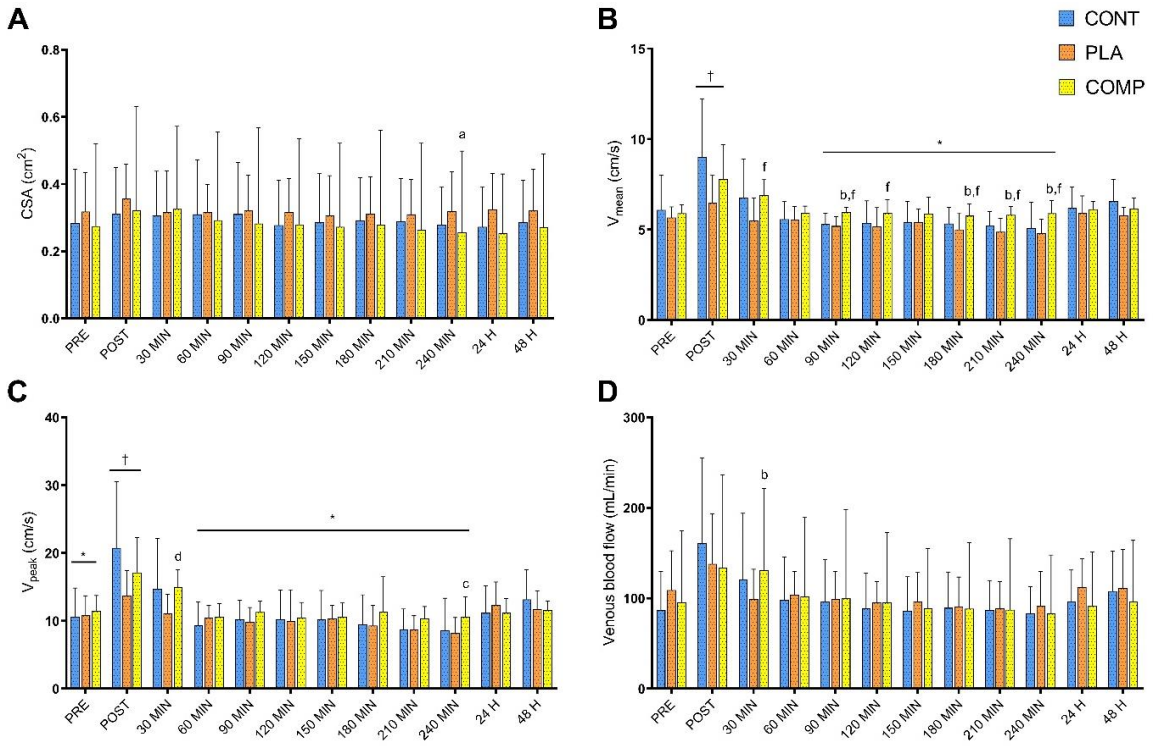

Figure 4-2: Popliteal vein markers of venous return for CON, PLA, and COMP conditions. Markers measured include A; cross-sectional area (CSA), B; mean flow velocity (V_{mean}), C; peak flow velocity (V_{peak}) and D; venous blood flow. Time points are before exercise (PRE), immediately post-exercise (POST), 4 h recovery (30 min – 240 min), and 24 and 48 h post-exercise. All data presented as mean ± SD. † significant time effect as compared with all other time points. * significant time effect as compared with 30 min post-exercise. [a] small effect as compared with CON. [b] medium effect as compared with CON. [e] medium effect as compared with PLA. [f] large effect as compared with PLA.

4.3.4 Femoral Markers of Venous Return

There were no interaction effects for femoral CSA (p = 1.000; Fig 4-3A), V_{mean} (p = 1.000; Fig 4-3B), V_{peak} (p = 1.000; Fig 4-3C) and venous blood flow (p = 0.966; Fig 4-3D) or main effects of time for femoral CSA (p = 0.984). There were main effects of time for elevated femoral V_{mean} (p < 0.001; Fig 4-3B), V_{peak} (p < 0.0001; Fig 4-3C) and venous blood flow (p < 0.001; Fig 4-D) post-exercise. ES analysis revealed medium to large effects for increased V_{mean} and venous blood flow during 4 h post-exercise recovery in the COMP group compared to the CON and PLA groups (Table 4-2).

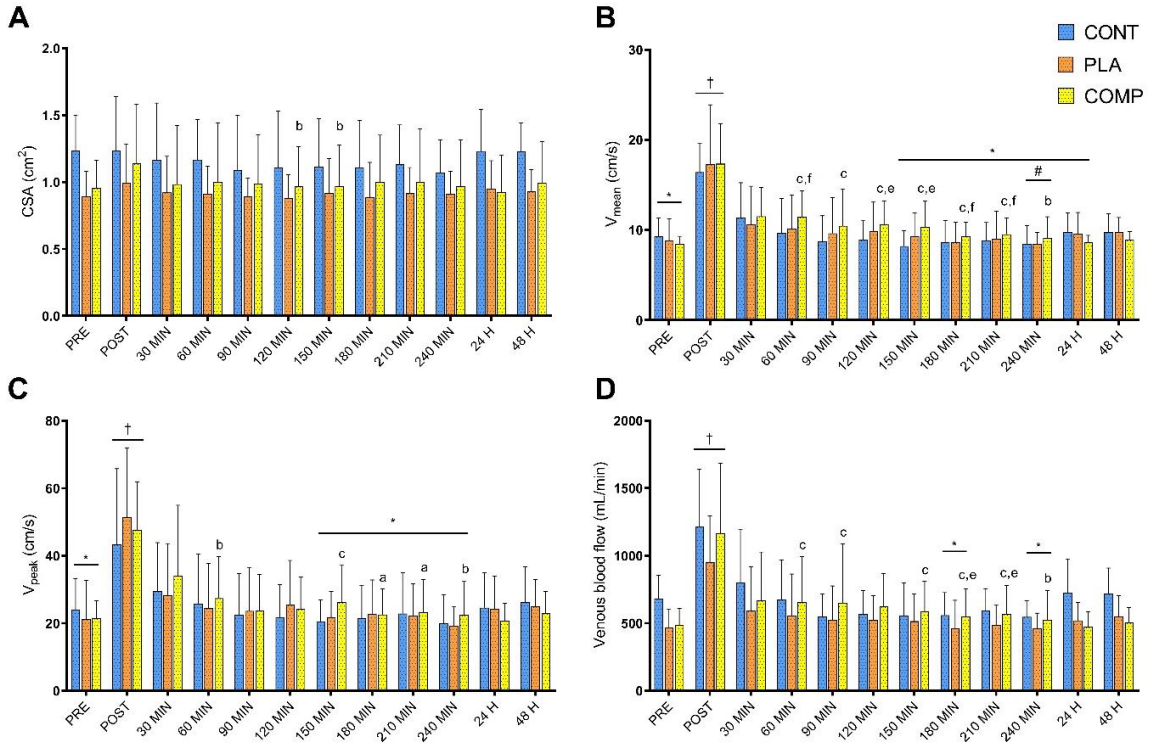

Figure 4-3: Common femoral vein markers of venous return for CON, PLA, and COMP conditions. Markers measured include A; cross-sectional area (CSA), B; mean flow velocity (V_{mean}), C; peak flow velocity (V_{peak}) and D; venous blood flow. Time points are before exercise (PRE), immediately post-exercise (POST), 4 h recovery (30 min – 240 min), and 24 and 48 h post-exercise. All data presented as mean ± SD. † significant time effect as compared with all other time points. * significant time effect as compared with 30 min post-exercise. # significant time effect as compared with 60 min post-exercise. [a] small effect as compared with CON. [b] medium effect as compared with CON. [c] large effect as compared with CON. [e] medium effect as compared with PLA. [f] large effect as compared with PLA.

4.3.5 Muscle Blood Flow

There was no interaction effect for muscle blood flow (*P*p= 1.000). There were main effects of time ($p < 0.001$) for muscle blood flow (Fig 4-4). Specifically, muscle blood flow was elevated post-exercise compared to all other time points ($p < 0.001$), and elevated at 30 min as compared with baseline and 120 min, 150 min, 180 min, 210 min, 240 min, 24 h, and 48 h post-exercise ($p < 0.05$). ES analysis revealed small to large effects for increased in muscle blood flow during 4 h post-exercise recovery in the COMP group compared to the CON and PLA groups (Table 4-2).

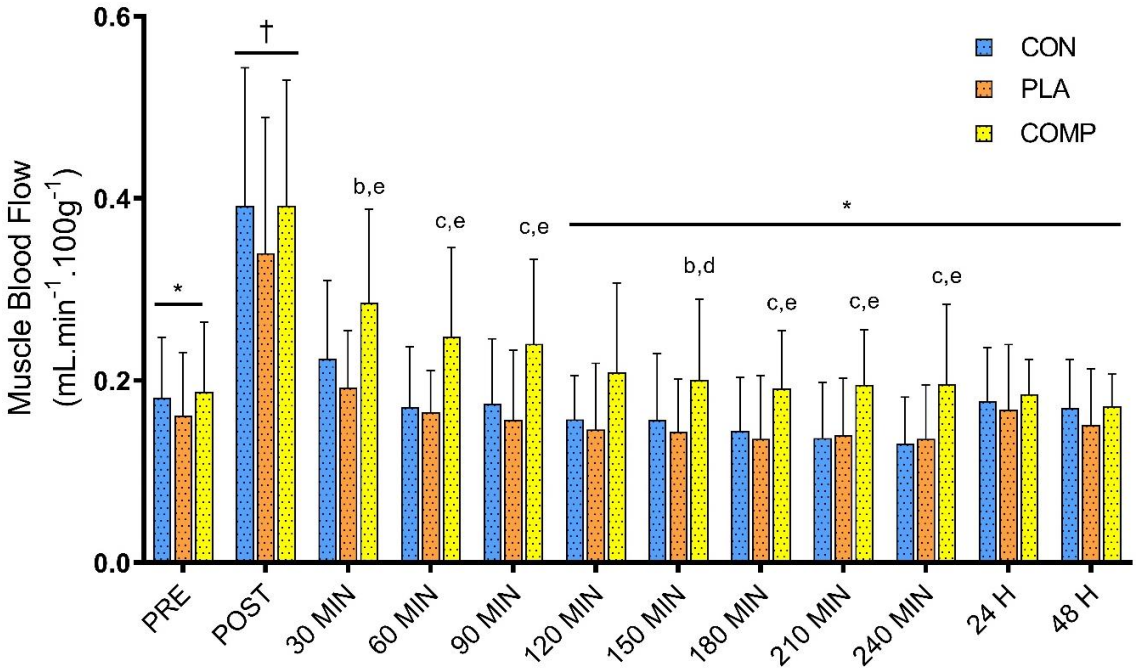

Figure 4-4: Muscle blood flow (millilitres of blood per min per 100 grams of tissue) for CON, PLA, and COMP conditions. Time points are before exercise (PRE), immediately post-exercise (POST), 4 h recovery (30 min – 240 min), and 24 and 48 h post-exercise. All data presented as mean ± SD. † significant time effect as compared with all other time points. * significant time effect as compared with 30 min post-exercise. [b] medium effect as compared with CON. [c] large effect as compared with CON. [d] small effect as compared with PLA. [e] medium effect as compared with PLA.

4.3.6 Performance

There were no interaction ($p > 0.05$) or main effects of time ($p > 0.05$) for all CMJ (Table 4-3) and IMTP (Table 4-4) variables measured. For CMJ variables, there was small to large effects for improved performance post-exercise in the COMP group compared to the CON and PLA groups (Table 4-5). There were also medium effects for improved IMTP performance at 4 h post-exercise in the COMP group compared to the CON and PLA groups (Table 4-5).

Table 4-2: Summary of all between-group effects considered substantial in magnitude for muscle blood flow and markers of venous return.

Measure	Group Comparison	Change Between	Mean Difference in Change		Standardised ES		Effect Magnitude
			Absolute Difference	± 95% CI	ES	± 95% CI	
Popliteal CSA (cm^2)	COMP vs. CON	PRE - 240 min	0.05	0.04	0.49	0.39	Small
Popliteal Vmean (cm/s)	COMP vs. CON	PRE - 90 min	0.85	1.66	0.58	1.17	Medium
		PRE - 180 min	1.02	1.61	0.71	1.08	Medium
		PRE - 210 min	0.76	1.72	0.52	1.28	Medium
		PRE - 240 min	0.73	2.17	0.62	1.65	Medium
	COMP vs. PLA	PRE - 30 min	1.17	1.25	2.21	2.88	Large
		PRE - 90 min	0.53	0.69	1.05	1.29	Large
		PRE - 120 min	0.48	1.23	1.05	2.34	Large
		PRE - 180 min	0.59	1.11	1.35	2.39	Large
		PRE - 210 min	0.78	1.02	1.69	2.07	Large
		PRE - 240 min	0.89	0.93	1.95	1.91	Large
Popliteal Vpeak (cm/s)	COMP vs. PLA	PRE - 30 min	3.26	4.58	0.98	1.64	Large
		PRE - 240 min	1.60	4.35	0.73	1.65	Medium
Popliteal Blood Flow (mL/min)	COMP vs. PLA	PRE - 30 min	45.31	53.85	0.64	0.79	Medium
Femoral CSA (cm^2)	COMP vs. CON	PRE - 120 min	0.14	0.29	0.54	1.05	Medium
		PRE - 150 min	0.14	0.25	0.56	0.92	Medium
Femoral Vmean (cm/s)	COMP vs. CON	PRE - 60 min	2.56	3.52	1.50	1.77	Large
		PRE - 90 min	2.52	3.75	1.28	1.79	Large
		PRE - 120 min	1.89	2.07	0.94	1.77	Large
		PRE - 150 min	2.93	2.83	1.55	1.51	Large
		PRE - 180 min	1.80	2.02	1.09	1.20	Large
		PRE - 210 min	2.04	1.99	1.15	1.05	Large
		PRE - 240 min	1.42	1.86	0.72	1.11	Medium
	COMP vs. PLA	PRE - 60 min	1.64	3.48	1.02	1.93	Large
		PRE - 120 min	1.09	2.37	0.60	1.33	Medium
		PRE - 150 min	1.33	2.98	0.65	1.59	Medium
		PRE - 180 min	1.32	1.69	0.80	2.14	Large
		PRE - 210 min	1.46	3.02	0.91	1.90	Large
Femoral Vpeak (cm/s)	COMP vs. CON	PRE - 60 min	4.26	12.19	0.60	1.31	Medium
		PRE - 150 min	8.27	8.64	0.82	1.06	Large
		PRE - 180 min	4.01	6.56	0.49	0.92	Medium
		PRE - 210 min	3.89	10.7	0.47	1.05	Medium
		PRE - 240 min	5.07	8.44	0.52	1.03	Medium
Femoral Blood Flow (mL/min)	COMP vs. CON	PRE - 60 min	229.55	444.11	1.01	1.65	Large
		PRE - 90 min	258.03	399.59	0.94	1.65	Large
		PRE - 120 min	200.49	178.56	0.87	0.93	Large
		PRE - 150 min	223.14	249.86	1.24	1.24	Large
		PRE - 180 min	211.04	198.19	1.07	0.96	Large
		PRE - 210 min	215.80	217.91	1.03	0.95	Large
		PRE - 240 min	150.10	158.46	0.61	0.79	Medium
	COMP vs. PLA	PRE - 180 min	97.16	170.47	0.76	0.95	Medium
		PRE - 210 min	110.86	220.43	0.61	1.22	Medium
Muscle Blood Flow ($mL \cdot min^{-1} \cdot 100\ g^{-1}$)	COMP vs. CON	PRE - 30 min	0.07	0.08	0.79	0.96	Medium
		PRE - 60 min	0.07	0.07	0.93	0.75	Large
		PRE - 90 min	0.07	0.06	1.01	0.94	Large
		PRE - 150 min	0.05	0.05	0.78	0.85	Medium
		PRE - 180 min	0.05	0.04	0.88	0.86	Large
		PRE - 210 min	0.06	0.05	1.15	0.80	Large
		PRE - 240 min	0.07	0.04	1.03	0.53	Large
	COMP vs. PLA	PRE - 30 min	0.07	0.08	0.55	0.97	Medium
		PRE - 60 min	0.06	0.07	0.54	0.81	Medium
		PRE - 90 min	0.06	0.06	0.78	0.87	Medium
		PRE - 150 min	0.04	0.06	0.44	0.68	Small
		PRE - 180 min	0.04	0.05	0.65	0.71	Medium
		PRE - 210 min	0.04	0.05	0.60	0.70	Medium
		PRE - 240 min	0.04	0.04	0.56	0.50	Medium

Table 4-3: Countermovement jump (CMJ) measures for CON, PLA, and COMP conditions. Measures include jump height, relative peak force, relative peak power and total duration. Time points are before exercise (PRE), immediately post-exercise (POST), and 4, 24, and 48 h post-exercise.

Variable	Condition	Time point				
		PRE	POST	4 h	24 h	48 h
Jump Height (m)	CON	0.28 ± 0.04	0.26 ± 0.03	0.25 ± 0.02	0.27 ± 0.03	0.27 ± 0.03
	PLA	0.28 ± 0.07	0.25 ± 0.06	0.25 ± 0.06	0.26 ± 0.07	0.27 ± 0.07
	COMP	0.31 ± 0.06	0.29 ± 0.06	0.30 ± 0.06 [a,d]	0.31 ± 0.06 [a]	0.31 ± 0.06 [a]
Relative Peak Force (N/kg)	CON	22.8 ± 1.6	21.8 ± 1.9	21.4 ± 1.3	21.7 ± 1.7	21.7 ± 1.6
	PLA	23.0 ± 3.1	22.4 ± 3.8	22.2 ± 2.5	22.1 ± 2.2	22.5 ± 2.3
	COMP	21.6 ± 1.0	21.2 ± 1.3	21.0 ± 0.9 [b]	21.8 ± 0.8 [c,d]	21.5 ± 1.0 [b]
Relative Peak Power (W/kg)	CON	43.7 ± 3.8	41.4 ± 3.1	40.5 ± 2.9	41.9 ± 2.5	42.8 ± 2.9
	PLA	47.4 ± 9.0	44.6 ± 7.9	44.3 ± 7.4	45.4 ± 7.6	46.6 ± 7.1
	COMP	48.3 ± 5.5	46.1 ± 6.5	46.6 ± 5.3 [a]	48.5 ± 5.7 [a,d]	48.4 ± 5.7
Total Duration (s)	CON	0.638 ± 0.036	0.682 ± 0.086	0.663 ± 0.080	0.654 ± 0.087	0.650 ± 0.075
	PLA	0.632 ± 0.074	0.652 ± 0.098	0.663 ± 0.077	0.650 ± 0.080	0.647 ± 0.087
	COMP	0.641 ± 0.070	0.669 ± 0.09	0.657 ± 0.080 [b,e]	0.635 ± 0.072 [c,f]	0.642 ± 0.075 [e]

All data presented as mean ± SD. [a] small effect as compared with CON. [b] medium effect as compared with CON. [c] large effect as compared with CON. [d] small effect as compared with PLA. [e] medium effect as compared with PLA. [f] large effect as compared with PLA.

Table 4-4: Isometric mid-thigh pull (IMTP) measures for CON, PLA, and COMP conditions. Measures include peak force, relative peak force, force at 100 ms and 200 ms, and rate of force development (RFD) at 100 ms and 200 ms. Time points are before exercise (PRE), immediately post-exercise (POST), and 4, 24, and 48 h post-exercise.

Variable	Condition	Time point				
		PRE	POST	4 h	24 h	48 h
Peak Force (N)	CON	1467 ± 447	1309 ± 314	1329 ± 337	1305 ± 364	1304 ± 382
	PLA	1241 ± 374	1228 ± 444	1202 ± 397	1149 ± 382	1148 ± 442
	COMP	1621 ± 290	1615 ± 380	1535 ± 292	1513 ± 267	1462 ± 444
Relative Peak Force (N/kg)	CON	19.6 ± 3.3	17.9 ± 3.9	18.0 ± 3.2	17.7 ± 3.8	17.5 ± 3.6
	PLA	16.3 ± 3.9	15.8 ± 4.1	15.7 ± 4.0	14.9 ± 3.9	14.9 ± 5.1
	COMP	21.5 ± 1.4	21.2 ± 2.1	20.4 ± 2.2	20.2 ± 1.9	19.1 ± 3.6
Force at 100 ms (N)	CON	353 ± 204	323 ± 136	348 ± 78	352 ± 125	284 ± 73
	PLA	285 ± 148	287 ± 98	342 ± 233	317 ± 184	292 ± 149
	COMP	358 ± 196	381 ± 109	495 ± 102 [b,e]	436 ± 127	378 ± 148
Force at 200 ms (N)	CON	658 ± 251	618 ± 185	665 ± 179	640 ± 176	559 ± 135
	PLA	595 ± 248	588 ± 233	595 ± 347	579 ± 260	547 ± 232
	COMP	752 ± 244	771 ± 175	930 ± 215 [b,e]	804 ± 180	705 ± 232
RFD 0 - 100 ms (N/s)	CON	3096 ± 2043	2819 ± 1359	3064 ± 787	3090 ± 1250	2422 ± 739
	PLA	2455 ± 1480	2425 ± 989	2987 ± 2305	2735 ± 1814	2539 ± 1437
	COMP	3123 ± 1964	3309 ± 1141	4402 ± 1132 [b,e]	3840 ± 1289	3295 ± 1436
RFD 0 - 200 ms (N/s)	CON	3075 ± 1254	2884 ± 926	3117 ± 896	2987 ± 876	2585 ± 677
	PLA	2777 ± 1245	2717 ± 1165	2759 ± 1722	2681 ± 1285	2545 ± 1129
	COMP	3534 ± 1222	3601 ± 887	4364 ± 1120 [b,e]	3761 ± 915	3282 ± 1135

All data presented as mean ± SD. [b] medium effect as compared with CON. [e] medium effect as compared with PLA.

Table 4-5: Summary of all between-group effects considered substantial in magnitude for CMJ and IMTP variables.

Measure	Group Comparison	Change Between	Mean Difference in Change		Standardised ES		Effect
			Absolute Difference	± 95% CI	ES	± 95% CI	Magnitude
CMJ Jump Height (m)	COMP vs. CON	PRE - 4 h	0.02	0.02	0.45	0.32	Small
		PRE - 24 h	0.01	0.02	0.29	0.27	Small
		PRE - 48 h	0.02	0.01	0.29	0.19	Small
	COMP vs. PLA	PRE - 4 h	0.02	0.02	0.27	0.21	Small
CMJ Relative Peak Force (N/kg)	COMP vs. CON	PRE - 4 h	0.80	1.07	0.56	0.78	Medium
		PRE - 24 h	1.27	1.11	0.94	0.83	Large
		PRE - 48 h	0.97	0.99	0.71	0.74	Medium
	COMP vs. PLA	PRE - 24 h	1.11	1.47	0.48	0.63	Small
CMJ Relative Peak Power (W/kg)	COMP vs. CON	PRE - 4 h	1.62	2.15	0.37	0.41	Small
		PRE - 24 h	1.99	1.97	0.39	0.39	Small
	COMP vs. PLA	PRE - 24 h	2.40	2.17	0.31	0.26	Small
CMJ Duration (s)	COMP vs. CON	PRE - 4 h	0.04	0.06	0.76	1.17	Medium
		PRE - 24 h	0.06	0.07	0.99	1.33	Large
	COMP vs. PLA	PRE - 4 h	0.05	0.04	0.69	0.58	Medium
		PRE - 24 h	0.06	0.04	0.81	0.55	Large
		PRE - 48 h	0.05	0.05	0.66	0.63	Medium
IMTP Force @ 100ms (N)	COMP vs. CON	PRE - 4 h	166.28	246.75	0.69	1.02	Medium
	COMP vs. PLA	PRE - 4 h	80.55	199.99	0.60	0.97	Medium
IMTP Force @ 200ms (N)	COMP vs. CON	PRE - 4 h	209.86	331.12	0.70	1.36	Medium
	COMP vs. PLA	PRE - 4 h	168.43	307.87	0.66	1.08	Medium
IMTP RFD @ 100ms (N/s)	COMP vs. CON	PRE - 4 h	1152.04	2497.88	0.57	1.31	Medium
	COMP vs. PLA	PRE - 4 h	746.72	2040.61	0.56	0.99	Medium
IMTP RFD @ 200ms (N/s)	COMP vs. CON	PRE - 4 h	983.69	1670.42	0.64	1.38	Medium
	COMP vs. PLA	PRE - 4 h	801.69	1555.90	0.63	1.09	Medium

4.3.7 Perceptual Measures

There were no interaction effects for muscle soreness ($p = 0.720$) or TQR ($p = 0.914$). There were main effects of time for muscle soreness ($p < 0.0001$) and TQR ($p < 0.0001$). Specifically, muscle soreness was higher ($p < 0.005$), and TQR lower ($p < 0.05$), at every time point as compared with baseline (Table 4-6). For muscle soreness, there was medium to large effects for lower ratings post-exercise in the COMP group compared to CON and PLA groups (Table 4-7). There were also large effects for increased TQR at all time-points post-exercise in the COMP group compared to the CON and PLA groups (Table 4-7).

4.3.8 Blood Analyses

There were no interaction effects for plasma LDH ($p = 0.99$) or CK ($p = 0.965$), and no main effect of time for CK ($p = 0.254$). There were main effects of time ($p = 0.009$) for LDH. Specifically, LDH was increased at 60 min, 120 min, 180 min and 240 min as compared with baseline, 24 h and 48 h ($p < 0.05$; Table 4-6).

4.3.9 Thigh Girth

There were no interaction effects ($p = 1.000$) or main effects of time ($p = 0.985$) for thigh girth circumference (Table 4-6). ES analysis revealed small effects for reduced thigh girth during 4 h post-exercise recovery in the COMP group compared to the CON and PLA groups (Table 4-7).

Table 4-6: Muscle soreness, total quality of recovery (TQR), thigh girth, lactate dehydrogenase (LDH) and creatine kinase (CK) for CON, PLA, and COMP conditions. Time points are before exercise (PRE), immediately post-exercise (POST), 4 h recovery (60 min – 240 min), and 24 and 48 h post-exercise.

Variable	Condition	Time point							
		PRE †	POST	60 min $§	120 min **$§	180 min **$§	240 min **$§	24 h	48 h
Muscle Soreness (AU)	CON	0.9 ± 0.9	4.4 ± 1.4	3.4 ± 1.1	3.0 ± 0.6	2.7 ± 1.3	2.6 ± 1.0	5.3 ± 1.6	5.9 ± 1.6
	PLA	0.8 ± 1.0	3.9 ± 1.9	3.4 ± 1.8	3.0 ± 2.0	3.0 ± 2.0	3.4 ± 2.4	6.5 ± 1.5	5.5 ± 2.1
	COMP	0.6 ± 0.8	3.3 ± 2.4	3.3 ± 2.4	2.0 ± 1.9 [b,e]	1.9 ± 1.6 [c,e]	1.4 ± 1.6 [c,f]	4.0 ± 1.5 [f]	3.2 ± 1.9 [c,f]
		PRE †	POST	60 min **$	120 min **$	180 min **#$§	240 min **#$§	24 h	48 h **
TQR (AU)	CON	17.9 ± 1.2	12.6 ± 1.1	13.6 ± 1.4	14.7 ± 1.4	15.3 ± 1.7	15.6 ± 2.1	12.0 ± 1.8	12.6 ± 2.5
	PLA	18.8 ± 1.5	13.0 ± 3.4	15.1 ± 2.7	15.6 ± 2.3	16.4 ± 2.2	16.6 ± 2.1	12.9 ± 2.2	14.8 ± 2.4
	COMP	17.9 ± 1.2	13.4 ± 1.3	16.0 ± 2.5 [c,f]	16.7 ± 3.0 [c,f]	17.3 ± 2.9 [c,f]	17.7 ± 2.8 [c,f]	14.7 ± 1.4 [c,f]	16.2 ± 1.9 [c,f]
		PRE	POST	60 min	120 min	180 min	240 min	24 h	48 h
Thigh Girth (cm)	CON	53.9 ± 5.9	54.9 ± 6.1	54.6 ± 5.9	54.5 ± 5.9	54.4 ± 5.9	54.3 ± 5.9	55.3 ± 6.1	55.0 ± 6.1
	PLA	56.2 ± 4.2	57.3 ± 4.4	57.0 ± 4.3	56.8 ± 4.2	56.7 ± 4.1	56.7 ± 4.1	57.6 ± 4.4	57.4 ± 4.4
	COMP	54.5 ± 5.4	55.5 ± 5.5	53.6 ± 5.2 [a,d]	53.6 ± 5.2 [a,d]	53.6 ± 5.2 [a,d]	53.6 ± 5.2 [a,d]	55.1 ± 5.5	54.8 ± 5.4
		PRE	POST	60 min *$§	120 min *$§	180 min *$§	240 min *$§	24 h	48 h
LDH ($U.L^{-1}$)	CON	81.2 ± 19.4	83.6 ± 15.3	88.9 ± 14.6	95.5 ± 18.4	91.3 ± 16.5	89.5 ± 21.8	77.3 ± 9.0	74.9 ± 17.3
	PLA	82.5 ± 19.9	93.9 ± 28.3	95.2 ± 25.9	101.7 ± 23.7	94.6 ± 31.2	95.4 ± 26.3	80.9 ± 19.6	73.9 ± 17.0
	COMP	73.3 ± 17.8	78.2 ± 13.4	92.8 ± 32.6	88.9 ± 15.1	91.8 ± 11.4	88.2 ± 9.4	73.7 ± 5.4	77.9 ± 15.9
		PRE	POST	60 min	120 min	180 min	240 min	24 h	48 h
CK ($U.L^{-1}$)	CON	558 ± 172	572 ± 329	661 ± 234	669 ± 255	501 ± 162	603 ± 250	424 ± 118	460 ± 329
	PLA	794 ± 368	577 ± 288	786 ± 342	894 ± 439	752 ± 397	668 ± 367	612 ± 338	615 ± 439
	COMP	686 ± 401	557 ± 125	589 ± 200	709 ± 200	696 ± 180	835 ± 308	511 ± 242	689 ± 282

All data presented as mean ± SD. † significant time effect as compared with all other time points. * significant time effect as compared with PRE. ** significant time effect as compared with POST. # significant time effect as compared with 60 min. $ significant time effect as compared with 24 h. § significant time effect as compared with 48 h. [a] small effect as compared with CON. [b] medium effect as compared with CON. [c] large effect as compared with CON. [d] small effect as compared with PLA. [e] medium effect as compared with PLA. [f] large effect as compared with PLA.

Table 4-7: Summary of all between-group effects considered substantial in magnitude for muscle soreness, TQR and thigh girth.

Measure	Group Comparison	Change Between	Mean Difference in Change		Standardised ES		Effect
			Absolute Difference	± 95% CI	ES	± 95% CI	Magnitude
Muscle Soreness (AU)	COMP vs. CON	PRE - 120 min	0.71	1.50	0.68	1.30	Medium
		PRE - 180 min	0.57	2.01	1.13	2.83	Large
		PRE - 240 min	0.86	1.82	0.84	1.65	Large
		PRE - 48 h	2.50	2.26	0.99	1.40	Large
	COMP vs. PLA	PRE - 120 min	0.82	1.97	0.64	1.30	Medium
		PRE - 180 min	0.96	1.99	0.70	1.32	Medium
		PRE - 240 min	1.77	2.34	1.16	1.49	Large
		PRE - 24 h	2.42	1.61	0.86	1.10	Large
		PRE - 48 h	2.25	2.30	0.96	1.34	Large
TQR (AU)	COMP vs. CON	PRE - 60 min	2.43	1.76	2.41	1.75	Large
		PRE - 120 min	2.00	2.16	1.78	2.10	Large
		PRE - 180 min	2.00	2.25	1.76	2.11	Large
		PRE - 240 min	1.86	1.99	1.55	1.81	Large
		PRE - 24 h	2.43	2.02	2.75	2.04	Large
		PRE - 48 h	3.57	3.19	4.05	3.49	Large
	COMP vs. PLA	PRE - 60 min	2.77	1.82	2.13	1.49	Large
		PRE - 120 min	2.73	2.23	1.98	1.80	Large
		PRE - 180 min	2.93	2.20	2.11	1.71	Large
		PRE - 240 min	3.23	1.96	2.33	1.52	Large
		PRE - 24 h	3.63	1.95	3.21	1.59	Large
		PRE - 48 h	2.89	2.25	2.34	1.81	Large
Thigh Girth (cm)	COMP vs. CON	PRE - 60 min	1.57	0.32	0.29	0.05	Small
		PRE - 120 min	1.47	0.24	0.27	0.04	Small
		PRE - 180 min	1.40	0.24	0.25	0.04	Small
		PRE - 240 min	1.33	0.21	0.24	0.03	Small
	COMP vs. PLA	PRE - 60 min	1.68	0.33	0.35	0.06	Small
		PRE - 120 min	1.47	0.27	0.31	0.05	Small
		PRE - 180 min	1.35	0.28	0.28	0.05	Small
		PRE - 240 min	1.36	0.25	0.29	0.05	Small

4.4 Discussion

This study aimed to assess the effects of sports compression tights on post-exercise blood flow, and to determine if the placebo effect was responsible for any acute performance or psychological benefits during the recovery from an eccentric lower-body resistance exercise session. The main findings were that compression tights increased blood flow during the 4 h post-exercise recovery period, and that this increase coincided with enhanced recovery of exercise performance and improved subjective ratings of soreness and recovery. Additionally, these findings suggest that compression was more effective in improving blood flow, exercise performance, and subjective ratings of soreness and recovery as compared with both the placebo and control conditions. These results highlight that the ergogenic benefits associated with compression garments are closely linked to physiological alterations

(e.g., increased blood flow), and the compression-induced improvements in exercise recovery are not explained by the placebo effect.

A novel component of this study was to monitor the effects of wearing sports compression tights for 4 h post-exercise on markers of venous return and muscle blood flow. The external pressure applied by sports compression is suggested to assist muscle pump action and enhance venous return by decreasing vein diameter, increase venous flow velocity, and reduce venous pooling in the lower limbs.[21,137,195] Although no changes in venous diameter were present in the current study, there was medium to large effects for compression tights to enhance venous flow velocity during the 4-h recovery period. The increase in venous flow velocity is likely due to the shunting of blood from superficial veins to the deep venous system (i.e., popliteal and common femoral veins).[21,137,195] Previous findings have observed compression-induced increases in similar markers of venous return at rest.[56,71,210] However, this is the first study to investigate the effect of compression tights on these markers of venous return post-exercise, and our findings suggest that these effects are maintained for up to 4 h post-exercise.

Our findings of enhanced markers of venous return coinciding with large effects of attenuated EIMD symptoms (e.g., reduced muscle soreness and improved muscle recovery), thus justifying that compression use for 4 h post-exercise is beneficial for recovery. Furthermore, compression-induced increases in venous return may also serve as a protective mechanism against post-exercise hypotension, which can persist for several hours[415] and if individuals remain in a supine position (i.e., recovery after intense exercise).[107] Post-exercise hypertension, observed in trained[416,417] and untrained[418,419] individuals, is characterised by a reduction in blood pressure, and occurs due to a combination of an inactive muscle pump,[420] pooling of blood in previously active muscles,[417] decreased end-diastolic filling[421] and reduced stroke volume.[417] The increase in venous velocity observed in this study, combined with compression garments resulting in a pronounced increase in stroke volume,[288] highlights the beneficial effects compression may have in preventing post-exercise hypertension. Furthermore, the enhanced venous return observed with compression may also serve to increase muscle blood flow via increases in arteriovenous pressure gradient and/or endothelial shear stress.[20,71,422,457]

Similar to markers of venous return, effects of compression to enhance muscle blood flow were evident throughout the 4-h recovery period. Previous research has highlighted compression to enhance muscle blood flow during exercise,[9,36] and immediately post-exercise.[11,12] From ES analysis, the current study is the first to show that increased muscle blood flow is still present for 4 h post-exercise while wearing sports compression tights. Although the underlying mechanisms associated with compression-induced increases in muscle blood flow are less clear, and may be attributed to enhanced venous return,[5,71,457] it is frequently suggested that a myogenic response may provide an explanation.[5,220,458] The garment's compressive effect is proposed to increase extravascular tissue pressure, subsequently reducing arteriolar transmural pressure and resulting in a reflex increase in arteriole vessel size (i.e., vasodilation).[5,373] In turn, this leads to a decrease in arterial flow resistance, thus improving muscle blood flow.[5,220,458] Considering muscle blood flow is positively correlated with glucose uptake[347] and rates of MPS,[359] compression may enhance the delivery of nutrients to the muscle, consequently enhancing the recovery and restoration process.[9,39,83,434] The only study to investigate the effect of compression garments on post-exercise nutrient delivery reported no effect of compression on glucose uptake reported,[16] likely due to the high level of pressure (37 mmHg) exerted to the limb (i.e., mechanically reduced muscle blood flow). Other post-exercise strategies promoting increases in limb (femoral artery) blood flow, such as hot water immersion,[353] have been reported to improve glucose metabolism[459] and key markers of MPS and muscle hypertrophy.[351] However, these findings are not consistent,[460,461] and future research is required to investigate the effect of SCG on post-exercise nutrient uptake and rates of MPS due to their correlations with muscle blood flow.

A crucial component of this study, and the first in compression research, was the effective deception of participants administered the placebo intervention. To achieve this, participants in the PLA were given information sheets that highlighted similar benefits and mechanisms that are associated with compression (i.e., improved blood flow and reduced muscle damage/inflammation). After reading the information sheets, the PLA group had a higher belief rating for this intervention (3.9 ± 0.8) than the COMP group (3.0 ± 0.6). Thus, in support of our hypothesis, this study highlights that compression's performance and perceptual benefits are likely due to compression-induced physiological alterations and not a

placebo effect. This is also supported by the increase in blood flow (i.e., venous flow velocity and muscle blood flow) coinciding with medium to large effects of improved performance and perceptual indices of recovery in the COMP group. Additionally, these benefits were not present in the PLA or CON groups.

In the present study, the use of sport compression tights during recovery did not affect CK or LDH at any time point, in line with previous studies.[42,66,74,127,330] However, except for a small increase in LDH concentrations during the 4-h recovery period, there were no significant increases in the measured blood parameters following exercise in all three groups. It is not uncommon for blood markers to remain unchanged following resistance exercise,[54,55,462] with the reliability of blood markers as an indicator of muscle damage questioned.[463] Several factors may explain the high variability in blood markers of EIMD and lack of effect reported in this study. For example, blood markers reflect relative amounts released, degree of enzyme activity, rate of clearance,[464] and may not accurately represent the level of EIMD. A potential explanation for the lack of change in blood markers is that participants muscle were already in an exercise-induced damaged state, as evident in the high LDH and CK values pre-exercise. Although participants were asked to refrain from strenuous exercise 48 h prior to testing Session 2, an earlier exercise session (i.e., 72 h prior to testing Session 2) could be responsible for the elevated LDH and CK values pre-exercise. These blood markers can reach a peak level from 24 to 96 h following an exercise bout[465] and may remain elevated for up to 7 d post-exercise.[249,464] Also, considering the magnitude of change in blood biomarkers of EIMD are typically greater in untrained than trained individuals,[332] as well as trained individuals possessing a more efficient mechanism of myofibrillar protein clearance following exercise,[333] the exercise intervention in the current study may not have been sufficient to elicit a significant response[462] in this resistance-trained cohort. In addition, the inclusion of both male and female participants may have masked any impact of the exercise protocol on blood biomarkers, as females are reported to exhibit lower muscle damage marker activity following damaging exercise.[334] Despite the limited changes in blood markers, the exercise protocol resulted in elevations in muscle soreness and fatigue, and performance decrements.

The applied pressure from compression showed small effects in reducing thigh girth circumference during the 4-h recovery period, and potentially limiting the space available for fluid accumulation and swelling to occur.[53] Attenuating muscle swelling post-exercise may reduce the secondary inflammatory response and soreness.[86] The changes in muscle soreness and TQR reported in this study support this mechanism and are consistent with previous research.[43,55,65,127] In comparison, this is the first study to highlight that these benefits of compression garments on perceptual measures are not due to a placebo effect or prior belief in the efficacy of compression. The reduction in muscle soreness with COMP in this study, further highlights that compression tights used post-exercise may help limit muscle damage and decrease inflammation, thus improving exercise performance recovery.

Compression tights used for 4 h after an eccentric lower-body resistance exercise session appears to enhance (small to large effects) the recovery of CMJ and IMTP performance. Damage to the contractile elements of muscle following resistance exercise leads to oedema formation, resulting in muscle soreness and decrements in exercise performance.[173,269] The improved recovery of CMJ variables with COMP, observed in this study and consistent with previous research,[55,86,321] has been attributed to the enhanced repair of the muscle contractile elements.[74] In support of this, improved ratings of muscle soreness and exercise performance recovery were evident with COMP. Regarding IMTP, COMP was beneficial at 4 h post-exercise only (Force at 100 ms, Force at 200 ms, RFD 0 to 100 ms, RFD 0 to 200 ms). The application of compression is suggested to positively influence muscle fibre recruitment[342] and muscle contraction efficiency[106] due to reduced muscle movements.[50,59] Although speculative, the enhanced motor unit activation, important for maximising force development (i.e., RFD measures),[466,467] may explain the enhanced RFD at 4 h post-exercise for COMP in the current study. However, this proposed mechanism requires further investigation.

4.5 Conclusion

Sports compression tights used for 4 h post an eccentric lower-body resistance exercise session appear to increase blood flow and improve perceptual and performance indices of exercise recovery (Fig 4-5). Furthermore, the addition of a successful placebo by deception in this study highlights that the benefits observed in the current study with

compression were likely not due to a placebo effect. Therefore, sports compression tights might be a beneficial strategy to improve recovery when used for 4 h following an eccentric lower-body resistance exercise session.

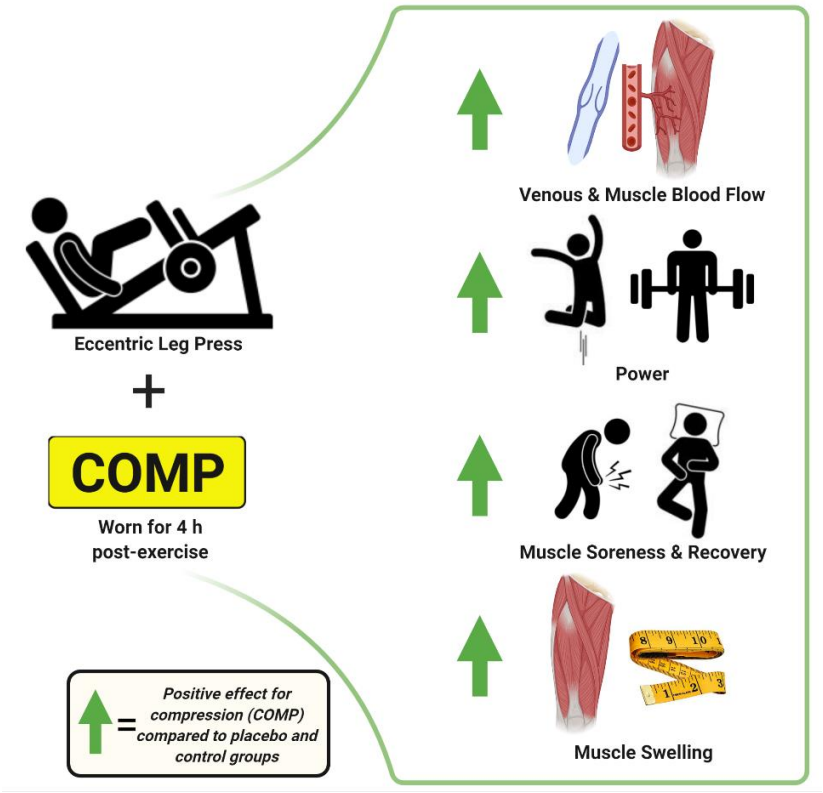

Figure 4-5: Summary of the effects of sports compression tights worn for 4 h post eccentric leg press exercise on blood flow and indices of muscle recovery. Created with Biorender.com.

CHAPTER FIVE

Reduced post-exercise muscle microvascular perfusion with compression is offset by increased muscle oxygen extraction: Assessment by contrast-enhanced ultrasound

The main findings from Chapter 4 were that sports compression tights enhanced lower limb blood flow when worn during the post-exercise recovery period. Compression-induced increases in muscle blood flow may increase oxygen and nutrient delivery to the muscle, potentially improving exercise performance and muscle recovery. The microvascular system (capillaries) is important for delivering and exchanging nutrients and hormones within the muscle (e.g., oxygen, glucose and insulin), and whether SCG alter microvascular blood flow is currently unknown. Although the previous chapters have shown sports compression tights to increase muscle blood flow as measured via NIRS with venous occlusion, this method does not identify if SCG affect microvascular blood flow. Therefore, the aim of Chapter 5 was to investigate whether sport compression tights enhance skeletal muscle microvascular blood flow.

This chapter has been published as:

Broatch, J. R.*, **O'Riordan, S. F.*,** Keske, M. A., Betik, A.C., Bishop, D. J., Halson, S. L., and Parker, L. (2021). Reduced post-exercise muscle microvascular perfusion with compression is offset by increased muscle oxygen extraction: Assessment by contrast-enhanced ultrasound. *The Federation of American Societies for Experimental Biology Journal*. 35(5), e21499. *indicates equal contribution and shared first authorship.

https://doi.org/10.1096/fj.202002205RR

The FASEB Journal, Q1; Impact Factor (2021): 4.966

Abstract

Purpose: The microvasculature is important for both health and exercise tolerance in a range of populations. However, methodological limitations have meant changes in microvascular blood flow are rarely assessed in humans during interventions designed to affect skeletal muscle blood flow. The aim of this study is, for the first time, to use contrast-enhanced ultrasound to directly measure the effects of compression on muscle microvascular blood flow alongside measures of femoral artery blood flow and muscle oxygenation following intense exercise in healthy adults. It was hypothesised that both microvascular and femoral artery blood flows would be augmented with compression garments as compared with a control condition.

Methods: Ten recreationally active participants completed two repeated-sprint exercise sessions, with and without lower-limb compression tights. Muscle microvascular blood flow, femoral arterial blood flow (2D and Doppler ultrasound), muscle oxygenation (near-infrared spectroscopy), cycling performance, and venous blood sampling were measured/taken throughout exercise and the 1 h post-exercise recovery period.

Results: Compared with control, compression reduced muscle microvascular blood volume and attenuated the exercise-induced increase in microvascular velocity and flow immediately after exercise and 1 h post-exercise. Compression increased femoral artery diameter and augmented the exercise-induced increase in femoral arterial blood flow during exercise. Markers of blood oxygen extraction in muscle were increased with compression during and after exercise. Compression had no effect on blood lactate, glucose, or exercise performance.

Conclusion: These findings provide new evidence that lower-limb compression attenuates the exercise-induced increase in skeletal muscle microvascular blood flow following exercise, despite a divergent increase in femoral artery blood flow. Decreased muscle microvascular perfusion is offset by increased muscle oxygen extraction, a potential mechanism allowing for the maintenance of exercise performance.

Keywords: Capillary-myocyte interface, ergogenic, microvasculature, NIRS, sprint-interval exercise.

5.1 Introduction

Blood flow plays a vital role in the delivery of nutrients and hormones to many tissues in the body including skeletal muscle.[215,218,219] During exercise, total limb and microvascular (capillary) blood flow increases to augment oxygen delivery and uptake to the contracting muscle — a phenomenon that has been known for over 100 years.[215,468] Oxygen uptake increases in skeletal muscle in an exercise intensity-dependent fashion to meet the increased metabolic demand of the contracting muscle.[375,469,470] Thus, it is expected that exercise with a higher metabolic demand (e.g., repeated-sprint exercise) will concurrently demand larger volumes of blood flow distribution to the working muscles to maintain exercise performance.[215,471] However, it is the microvasculature that lies downstream of the cardiovascular and arterial vascular networks that is in direct contact with the myocyte and is therefore ultimately responsible for nutrient and hormone exchange including the delivery and uptake of oxygen and substrates. In support, microvascular dysfunction is a hallmark feature of many clinical populations who suffer from exercise intolerance including type 2 diabetes,[472,473] heart failure,[474,475] and peripheral arterial disease.[476] Thus, it is not surprising that the extent of microvascular blood flow in response to exercise is considered a rate limiting step for exercise capacity, at least in clinical populations characterised by microvascular dysfunction.[472–476] However, the link between microvascular blood flow and exercise performance in recreationally active and healthy people is less clear, a likely consequence of the indirect methods used to estimate or measure muscle blood flow.[5,9,16,36,220,230,305]

Compression garments have previously been assessed as a potential method to augment exercise-induced increases in limb blood flow and/or skeletal muscle perfusion, with mixed results.[5,11,16,36,195,220,230,305] This may be important considering the proposed role of limb blood flow in moderating muscle regeneration,[399] and exercise capacity in both healthy[477–479] and clinical populations that exhibit vascular dysfunction.[472–476] As such, compression-induced alterations in blood flow may be a potential strategy for improving exercise capacity and post-exercise recovery. It is thought that the external compression applied by the garment reduces arteriolar transmural pressure by an amount approximately equivalent to the level of pressure applied,[220] subsequently causing a reflex vasodilation of

the arterioles and increased blood supply to the capillary network.[5] Additionally, compression may improve blood supply to the microvasculature via increased arterial blood flow,[12] greater venous return,[71] and a subsequent increase in stroke volume.[405,480] In support of these mechanisms, a previous study reported that lower-limb compression tights increase muscle blood flow by ~18% during exercise in healthy individuals, as measured by NIRS during brief venous occlusion.[9] Similarly, compression garments have been reported to increase limb perfusion both at rest and during exercise as measured by strain-gauge plethysmography,[5,11] nuclear magnetic resonance flowmetry,[220,230] and radioactive ^{133}Xe isotope clearance.[195] Conversely, compression garments have also been reported to have either no effect on limb perfusion as measured by NIRS,[36,305] or to even reduce limb perfusion as measured by PET.[16] These contradictory reports likely stem not only from variations in exercise protocol, the application of compression, and population demographics, but also variations in techniques used to measure limb perfusion.

The vast majority of techniques used to measure compression-induced changes in blood flow are unable to distinguish between macrovasculature flow responsible for feeding the capillary network (i.e., large arteries, feed arteries and arterioles), and the microvasculature flow feeding the muscle bed (i.e., capillaries) that is responsible for nutrient and hormone exchange. This is important, as it has been shown that macro and microvascular blood flow responses to muscle contraction,[472,481] insulin infusion,[482,483] and meal ingestion,[393,484] can be altered independent of each other. One of the most common methods for estimating muscle microvascular perfusion is NIRS. However, NIRS measurements represent a weighted average of the O_2 saturation of the haem compounds,[485] including arterial, capillary and venous haemoglobin and skeletal muscle myoglobin.[298] Furthermore, the distribution of haem units among these vascular beds is largely unknown.[298] In addition, the NIRS signal is influenced by factors like adipose tissue thickness,[486] skin melanin content,[487] and cutaneous blood flow/volume[488]; all of these will affect NIRS-derived measures of blood flow. More sophisticated blood flow measurement techniques like nuclear magnetic resonance flowmetry and PET provide high-resolution measurements of regional blood flow, but are unable to spatially distinguish the microvasculature from larger conduit and feed arteries within the muscle.[489] With these limitations in mind, it is unknown if previously reported compression-induced changes in blood flow are representative of muscle

microvascular blood flow occurring at the capillary-tissue interface, or whether they are due to changes in macrovascular blood flow supplying the microvascular network.

Our team, along with our collaborators, have optimized a technique known as real-time CEU to directly measure microvascular blood volume, velocity, and flow in human skeletal muscle.[393,473,483,484,490,491] This technique measures microvascular haemodynamics via the intravenous infusion of a contrast agent composed of haemodynamically inert lipid microspheres, which are echogenic and sufficiently small in size to perfuse capillaries. This is a widely used method for the evaluation of microvascular blood flow (perfusion) in various human tissue,[492] including skeletal muscle in vivo.[218,219,490] The three main features of CEU that makes it unique from other techniques is that it can quantify changes in: (i) the number of capillaries that are active/open (i.e., microvascular blood volume), (ii) the filling rate of blood through the capillary bed (i.e. capillary flow velocity), and (iii) the overall extent of blood flow through the capillary bed (i.e., microvascular blood flow) which is the product of volume and velocity. While this technique has been used in the context of muscle contraction and exercise,[472,473,490] no research to date has utilised it to assess the effects of compression on microvascular blood flow.

The aim of this study was to use modern ultrasound techniques to comprehensively assess, for the first time, the effects of compression garments on both macro (femoral artery) and microvascular (capillary) blood flow in skeletal muscle following intense exercise and throughout the post-exercise recovery period. Considering the divergent roles of the macro- (i.e., supplying the microvasculature) and microvasculature (i.e., capillary-muscle nutrient and hormone exchange), these assessments will provide novel information to better characterise the effects of compression on the different vascular networks. It was hypothesised that both femoral artery and muscle microvascular blood flow would be augmented with compression garments compared to control immediately after and 1 h post-exercise.

5.2 Methods

5.2.1 Participants and Experimental Design

The study employed a within-subject crossover design, in which participants completed two exercise sessions under two separate conditions: 1) wearing full-length, lower-limb compression tights (2XU Elite MCS Tights, Melbourne, Australia; COMP), and 2) wearing normal loose-fitting exercise shorts (control; CON). Ten (8 male and 2 female) recreationally active participants, performing at least 90 min of moderate- to high-intensity aerobic exercise per week, completed the study (mean ± SD: age, 27.4 ± 6.3 y; height, 1.81 ± 0.06 m; body mass, 74.5 ± 14.0 kg; body-mass index, 22.6 ± 3.5 kg/m^2). Written informed consent was obtained prior to participation. Participants were screened for contraindications for study participation including smoking, personal or family history of type 2 diabetes and cardiovascular disease, critical limb ischaemia (including peripheral artery disease), microvascular disease, and other factors limiting exercise capacity (e.g., arthritis or other musculoskeletal complications). All procedures were approved by the Deakin University Human Research Ethics Committee (2018-177) and were conducted in accordance with the Declaration of Helsinki.

5.2.2 Familiarization and Experimental Sessions

Participants reported to the laboratory on three separate occasions. The first session involved a familiarisation session where participants underwent two full sets of the exercise protocol and were familiarized with the ultrasound equipment and blood flow measurement methods. The study utilized a repeated-sprint exercise (RSE) protocol in an attempt to maximise the effects of compression on blood flow. For example, supra-maximal intensity exercise (< 60 s) recovery period places considerable metabolic stress on components of aerobic metabolism, including blood flow and oxygen uptake and delivery.[9,215,471,493]

A minimum of 48 h after the familiarisation session, participants reported to the laboratory for their first randomised experimental session (CON or COMP). Participant preparation included mark-up of ultrasound probe location and NIRS placement on the thigh, insertion of a catheter into a forearm antecubital fossa vein, and fitting/pressure assessment of the compression tights (COMP condition only) as previously described.[9] Garment pressure

was assessed (Kikuhime Pressure Monitor; mediGroup, Melbourne, Australia) at the medial aspect of the maximal calf girth, and on the anterior aspect of the thigh at the mid-point between the inguinal crease and superior-border of the patella.[9,139] Specifically, the garments in the COMP condition elicited 20.6 ± 3.7 mmHg of pressure at the maximal calf, and 11.1 ± 3.1 mmHg of pressure at the mid-thigh. After 30 min of rest on a bed, baseline blood samples were collected and baseline vascular measures were taken. Participants then completed the RSE protocol, which was followed by 60 min of rested recovery on a bed. Muscle microvascular blood flow was measured at baseline, immediately after completion of the RSE protocol (immediate transfer to bed), and after 60 min of post-exercise recovery in the Semi-Fowler's position (supine with the head and trunk raised to 30˚). Femoral arterial blood flow was measured at baseline, after RSE sets 1, 2 and 3, and at 60 min post-exercise. Due to potential Doppler interference associated with intravenous microsphere infusion, femoral arterial blood flow could not be measured after RSE set 4. Venous blood samples were acquired at baseline, after RSE sets 1, 2 and 3, and at 15, 30, 45 and 60 min post-exercise (Fig 5-1). Due to intravenous infusion of the ultrasound contrast agent, a venous blood sample could not be taken after RSE set 4.

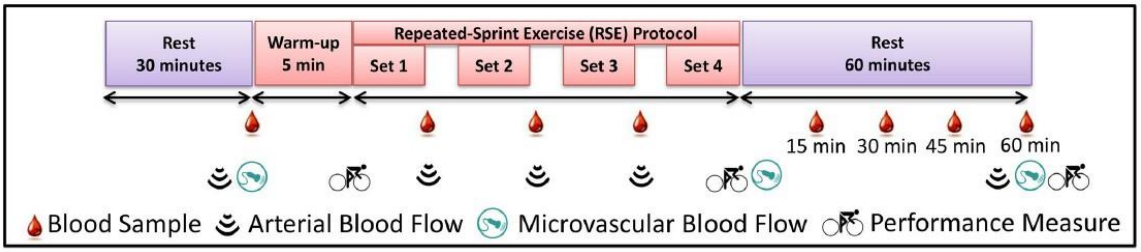

Figure 5-1: Experimental Design. In a randomised, cross-over, repeated-measures design, participants completed the experimental session twice; once wearing loose clothes, and once wearing lower-limb compression garments. Venous blood and vascular measures were taken before, during, and after the repeated-sprint exercise protocol, and throughout the 60-min post-exercise recovery period.

Within 2 to 7 d after completing the first experimental session, participants attended the research laboratory to undergo their second alternative experimental session. The order in which participants performed the CON and COMP sessions was randomised, counter-balanced, and performed at the same time of day to minimise diurnal variation. All participants were asked to be well fed (last meal 2-3 h prior to testing), hydrated, and refrain from strenuous exercise (24 h) and caffeine (12 h) prior to each testing session. Participants

completed a 24 h diet diary in the lead up to their first experimental session which they were then asked to replicate prior to their second session.

5.2.3 Repeated-Sprint Exercise (RSE) Protocol

Prior to the RSE protocol, participants performed a warm-up procedure consisting of a 5-min self-selected warm-up (134 ± 41 W), and three practice sprints at 75%, 90%, and 100% of perceived maximal effort. Participants then performed 4 sets of 10 x 6-s maximal sprints on a wind-braked cycle ergometer (Wattbike Pro/Trainer, Wattbike Ltd, UK). Each 6-s sprint was interspersed by 24 s of passive recovery and each set interspersed by 2 min of seated recovery. Approximately 5 s before starting each sprint, participants were asked to assume the ready position (dominant foot slightly above parallel to the ground) and to wait for the start signal to be announced by the researcher. The flywheel was required to be motionless before each sprint, such that each effort commenced from a stationary start. Verbal encouragement was given consistently during the protocol by the same tester, and participants were reminded of the number of intervals remaining in each RSE set at regular intervals. Subjective RPE were assessed at the end of each RSE set using Borg's 6 - 20 scale.[494] The peak power and average power achieved during each sprint was used as a measure of exercise performance. In addition, participants performed a single 6-s maximal cycling sprint immediately after the 60-min post-exercise microvascular measurement (and a repeat of the warm-up procedure), which was used as a measure of post-exercise recovery performance. The heart rate was measured throughout the RSE protocol and recovery period using a heart rate strap (Polar H10, Polar, USA).

5.2.4 Vastus Lateralis Muscle Microvascular Blood Volume, Velocity and Flow

Microvascular blood flow in the *vastus lateralis* was measured using real-time CEU during intravenous infusion of a commercially available ultrasound contrast agent (Definity, Lantheus Medical Imaging, USA), as previously performed.[393] The *vastus lateralis* muscle was chosen as the predominant and preferred site for measuring skeletal muscle microvascular blood flow due to its accessibility (i.e., it is superficial and provides a large region of interest for analysis), which affords a clear uninterrupted ultrasound image, and importantly its correlative role in force production during repeated-sprint cycling exercise.[495] A steel measuring tape was used to create a line between the anterior superior iliac spine

(ASIS) and the superior border of the patella. A linear array ultrasound probe (L9-3) interfaced to an ultrasound machine (iU22 Philips, Bothell, WA, USA) was then initially placed in cross-section over the *vastus lateralis* muscle approximately two thirds distal along the ASIS-patella line. The contrast enhanced ultrasound image of the *vastus lateralis* muscle was checked during the first two minutes of contrast agent infusion, and if necessary minor adjustments were made to the probe location to avoid interference from substantial arterioles and fascia artefacts. The precise probe location was marked on the skin with a permanent marker and measured with a steel tape measure (relative to the ASIS-patella) to ensure accurate replication within and between testing sessions. Depth and focus were adjusted for each participant in their first testing session to maximise the *vastus lateralis* region of interest and kept consistent for their subsequent testing session. For the compression session, the probe location and mark-up were completed prior to participants adorning the compression garments. A small incision (~ 6 cm) was then made in the garment over the marked probe position to ensure the probe was in direct contact with the participant's skin. Pilot data confirmed that this incision had no measurable impact on the level of compression applied to the participant's skin by the garment.

The contrast agent solution (1 mL of Definity suspended in 29 mL of saline solution [0.9% NaCl]) was intravenously infused at a rate of 192 $mL.min^{-1}$ using a standard syringe pump (TE-311, Terumo, Japan). Infusion of the contrast agent was commenced 4 min before each time point to allow the blood pool microsphere concentration to reach steady state. To ensure steady-state whole-body equilibrium of the contrast agent for the post-exercise measure, infusion commenced between sprints 4 and 5 of the last sprint set for this time point. After 4 min of infusion, six 45-s digital captures were acquired. All digital recordings were preceded by a high mechanical index flash to disrupt all microspheres within the probe line of sight to measure muscle microsphere re-appearance kinetics. Settings for gain (75-76%) and mechanical index (0.11 for continuous and 1.30 for flash) were kept identical for all participants and testing sessions.

To calculate muscle microvascular blood volume, velocity and flow, all digital images were analysed offline using Qlab software (QLAB, Philips Healthcare, Andover, MA, USA). The background acoustic intensity (0.5-s frame for the baseline and 60-min post-

exercise time points, and 0.25-s frame for the post-exercise time point) was subtracted from the raw data to eliminate signal from larger vessels and tissue artefacts.[393] The acoustic intensity measured from a region of interest was exported for each individual 45-s video capture. The average of the six 45-s captures for each time point was then plotted over time and curve fitted using the equation $y = A(1-e^{-\beta(t-tb)})$, where "y" is acoustic intensity, "tb" is the background time, "t" is time, "β" is the rate constant (a measure of microvascular capillary refilling rate), and "A" is the plateau of acoustic intensity (a measure of microvascular blood volume). The muscle microvascular blood flow was calculated by $A \times \beta$. Due to the specialised nature and training required to accurately, reliably, and consistently analyse and process CEU images, the same individual analysed all ultrasound files.

5.2.5 Superficial Femoral Artery Diameter, Velocity and Flow

A high frequency L12-5 linear array transducer was used to measure the diameter and blood velocity of the superficial femoral artery, as previously described.[393] The diameter was assessed using 2D ultrasound and measured at the peak of the QRS complex using a three-lead electrocardiograph system interfaced to the ultrasound machine. This was completed to ensure that all femoral artery diameter measurements were taken at the same phase within the cardiac cycle. Blood velocity (time-averaged mean velocity) was assessed by Doppler ultrasound. The femoral artery blood flow ($mL.min^{-1}$) was calculated as Πr^2 x mean velocity x 60 min, where the radius (r) is cm and the mean velocity is in $cm.s^{-1}$. Femoral artery ultrasound measurements were taken in triplicate. All settings were recorded and kept consistent within and between sessions.

5.2.6 NIRS-derived Muscle Oxygen Extraction

Markers of muscle oxygen extraction were assessed using the NIRS technique[496] continually during the entire experimental session (i.e., baseline, warm-up, RSE protocol, and 60-min recovery period). This technique provides continuous, non-invasive monitoring of the relative changes in O_2Hb and HHb concentration. Changes in O_2Hb and HHb of the right *vastus lateralis* were monitored using NIRS oximetry (Oxymon MKIII Near-Infrared Spectrophotometer, Artinis Medical Systems, The Netherlands) with data transmitted simultaneously to a personal computer and acquired using the Oxysoft software (V3.0.53,

Artinis Medical Systems, The Netherlands). The oximeter's optodes were housed in a plastic holder to ensure their position is fixed, and then secured on the cleaned (hair shaved off and skin swabbed with an alcohol swab) skin surface with tape. The oximeter was positioned at the same location on the contralateral leg to the ultrasound muscle microvascular blood flow measurements. Muscle oxygen extraction was calculated as changes in O_2Hb and HHb, relative to a 60-s average taken during passive bed rest prior to exercise. To account for muscle blood volume changes following exercise and recovery which may influence NIRS-derived measures of muscle oxygen extraction, changes in muscle O_2Hb and HHb were normalized to changes in total tHb, i.e., O_2Hb – tHb, and HHb – tHb, respectively. This was performed as NIRS-derived measures of tHb are indicative of changes in regional blood volume.[300] All NIRS measures were calculated at baseline (average of last 60 s of bed rest prior to exercise), during RSE (average of each RSE set including all exercise and rest periods), and at 15, 30, 45 and 60-min post-exercise (average of the 60 s preceding each time point). A 3-s moving average was applied to smooth all NIRS signals before analyses.[438]

5.2.7 Blood Collection and Analysis

Venous blood samples were collected at baseline, immediately after RSE sets 1, 2 and 3, and at 15, 30, 45, and 60 min post-exercise. Venous blood was collected using safePICO Blood Gas syringes containing EDTA (Radiometer Medical, Denmark) and analysed immediately for blood lactate and glucose (ABL800 FLEX Blood Gas Analyzer, Radiometer, Denmark).

5.2.8 Statistical Analyses

Data were checked for normality and analysed using Prism statistical analysis software (Graphpad Prism 8.4.3). Non-normally distributed data was first log-transformed to approximate normal distribution prior to statistical analysis. Comparisons of multiple means were analysed using a two-factor repeated measures mixed model analysis of variance (ANOVA) with Time (before, during and after exercise) and Condition (CON and COMP) as the within-subjects factors. Significant interaction and main effects were explored post-hoc with Fisher's Least Significant Difference test. Average sprint data was analysed using a two-tailed paired t-test. Statistical analysis was conducted at the 95% level of significance ($p \leq 0.05$).

5.3 Results

5.3.1 Muscle Microvascular Blood Volume, Velocity, and Flow

Main effects of time ($p < 0.001$) and condition ($p = 0.023$) were detected for muscle microvascular blood volume (Fig 5-2A). Compared with baseline, microvascular blood volume increased in both conditions immediately post-exercise ($p < 0.001$) and remained elevated above baseline at 60 min post-exercise ($p = 0.002$). When data are averaged over the time points measured, microvascular blood volume was lower in the COMP condition as compared with the CON condition (main condition effect of ~ 14%). There was no interaction effect for microvascular blood volume ($p = 0.215$).

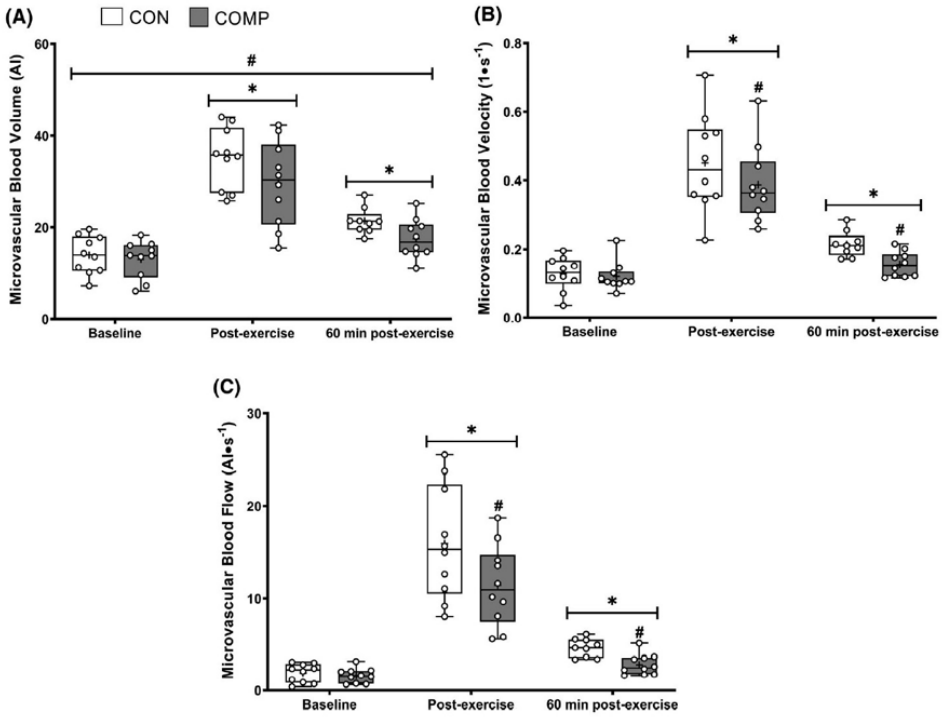

Figure 5-2: The effects of compression garments on repeated-sprint, exercise-induced muscle microvascular blood volume (A), velocity (B) and flow (C). Data are presented as box and whisker plots. The box represents the interquartile range alongside the median (line) and mean (plus symbol). The whiskers represent the minimum and maximum range of the data. n = 10 participants. *$p < 0.05$ compared to baseline. #$p < 0.05$ compared to the same time-point in the CON session or indicates a main effect of condition. Microvascular blood volume is expressed as acoustic intensity (AI); microvascular filling rate, or microvascular blood velocity, is expressed as $1 \cdot s^{-1}$; Microvascular blood flow is expressed as acoustic intensity/s ($AI \cdot s^{-1}$).

Interaction effects were detected for muscle microvascular blood velocity ($p = 0.025$; Fig 5-2B) and flow ($p = 0.026$; Fig 5-2C). Compared with baseline, muscle microvascular blood velocity and flow increased immediately post-exercise and remained elevated at 60 min post-exercise in both conditions (all $p < 0.01$). However, the increase in microvascular blood velocity occurred to a lesser extent in the COMP condition as compared with the CON condition immediately after exercise (-14% lower peak blood velocity, $p = 0.004$) and 60 min post-exercise (-27% lower peak blood velocity, $p < 0.001$). Likewise, the increase in muscle microvascular blood flow was lower in the COMP condition as compared with the CON condition immediately after exercise (-29% lower peak blood flow, $p = 0.009$) and 60 min post-exercise (-40% lower peak blood flow, $p < 0.001$).

Representative CEU images of muscle microvascular perfusion and microsphere flow dynamics are presented in Figures 5-3 and 5-4, respectively. The average background acoustic intensity of all ultrasound images in contrast enhanced mode was similar between the CON and COMP conditions (25.4 ± 6.7 versus 24.3 ± 6.4 AI units; $p = 0.307$), indicating that the background tissue and artefact signal for the analysed regions of interests were similar between conditions.

5.3.2 Femoral Artery Diameter, Blood Velocity and Flow

Main effects of condition ($p = 0.014$) and time ($p < 0.001$) were detected for femoral artery diameter (Fig 5-5A). Compared with baseline, femoral artery diameter increased in both conditions after the RSE sets and remained dilated at 60-min post-exercise ($p < 0.001$). Femoral artery diameter was greater in the COMP condition as compared with the CON condition when data was averaged over the entire session (main condition effect of ~2%). There was no interaction effect for artery diameter ($p = 0.109$).

A main effect of time ($p < 0.001$) was detected for femoral artery blood velocity (Fig 5-5B). Femoral artery blood velocity increased above the baseline in both conditions after the RSE sets and remained elevated above baseline, although to a lesser extent, at 60 min post-exercise (all $p < 0.001$). There was a non-significant increase for velocity in the COMP condition as compared with the CON condition over the entire session (main condition effect of ~11%, $p = 0.063$). There was no interaction effect ($p = 0.335$) for femoral artery blood velocity.

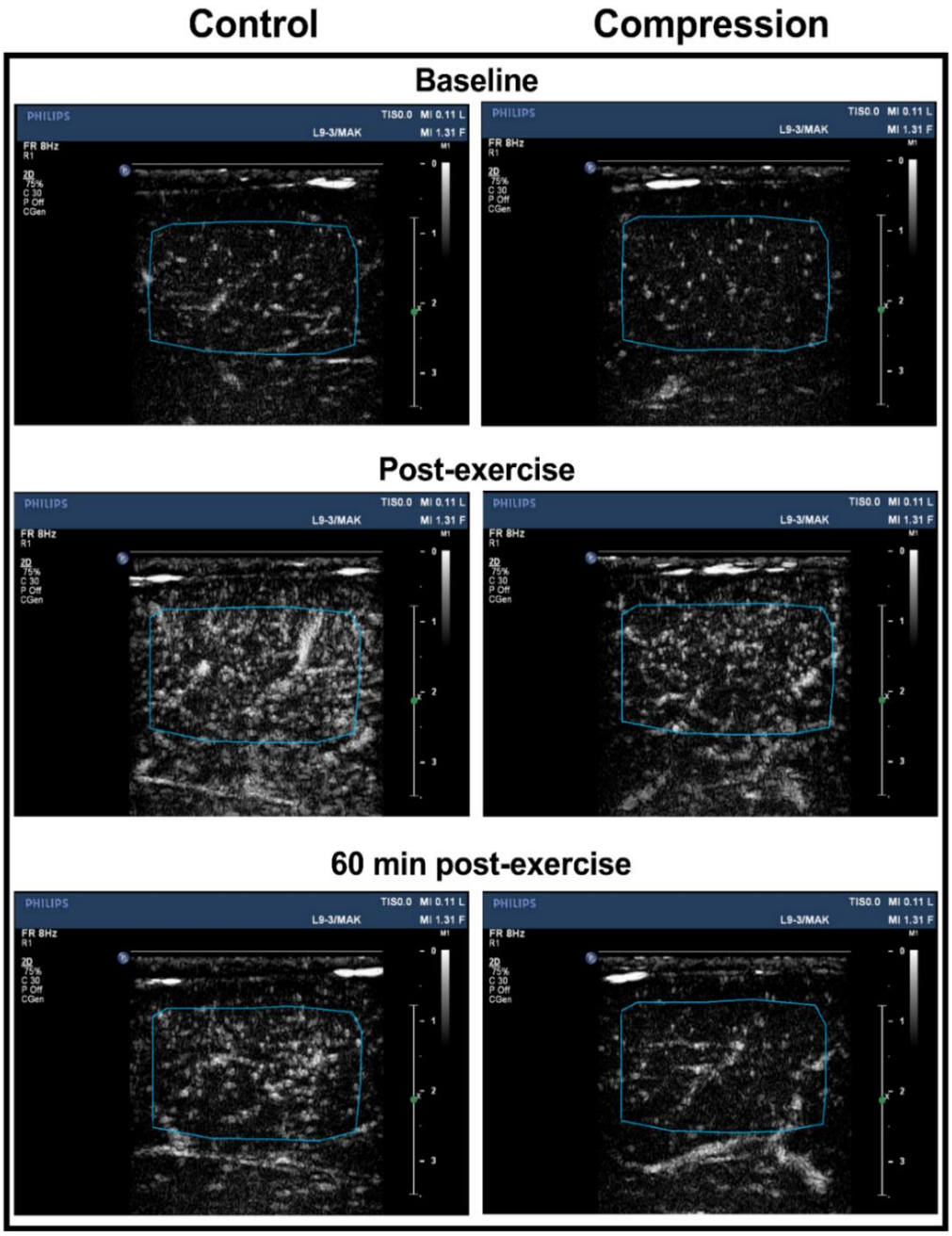

Figure 5-3: Representative contrast enhanced ultrasound images of skeletal muscle microvascular perfusion in cross-section of the *vastus lateralis* from a single participant at baseline, immediately after repeated-sprint exercise, and 60 min post-exercise with and without compression garments. The infused contrast agent contains echogenic microspheres which circulate within the muscle microvasculature and can be measured by contrast enhanced ultrasound. The blue box indicates the selected region of interest used to measure microspheres within the muscle microvasculature. The number of microsphere can be seen increase after RSE with both CON and COMP, and remains elevated above baseline at 60 min post-RSE. However, the exercise-induced increase in the number of microspheres immediately after RSE and 60 min post-RSE is attenuated with COMP.

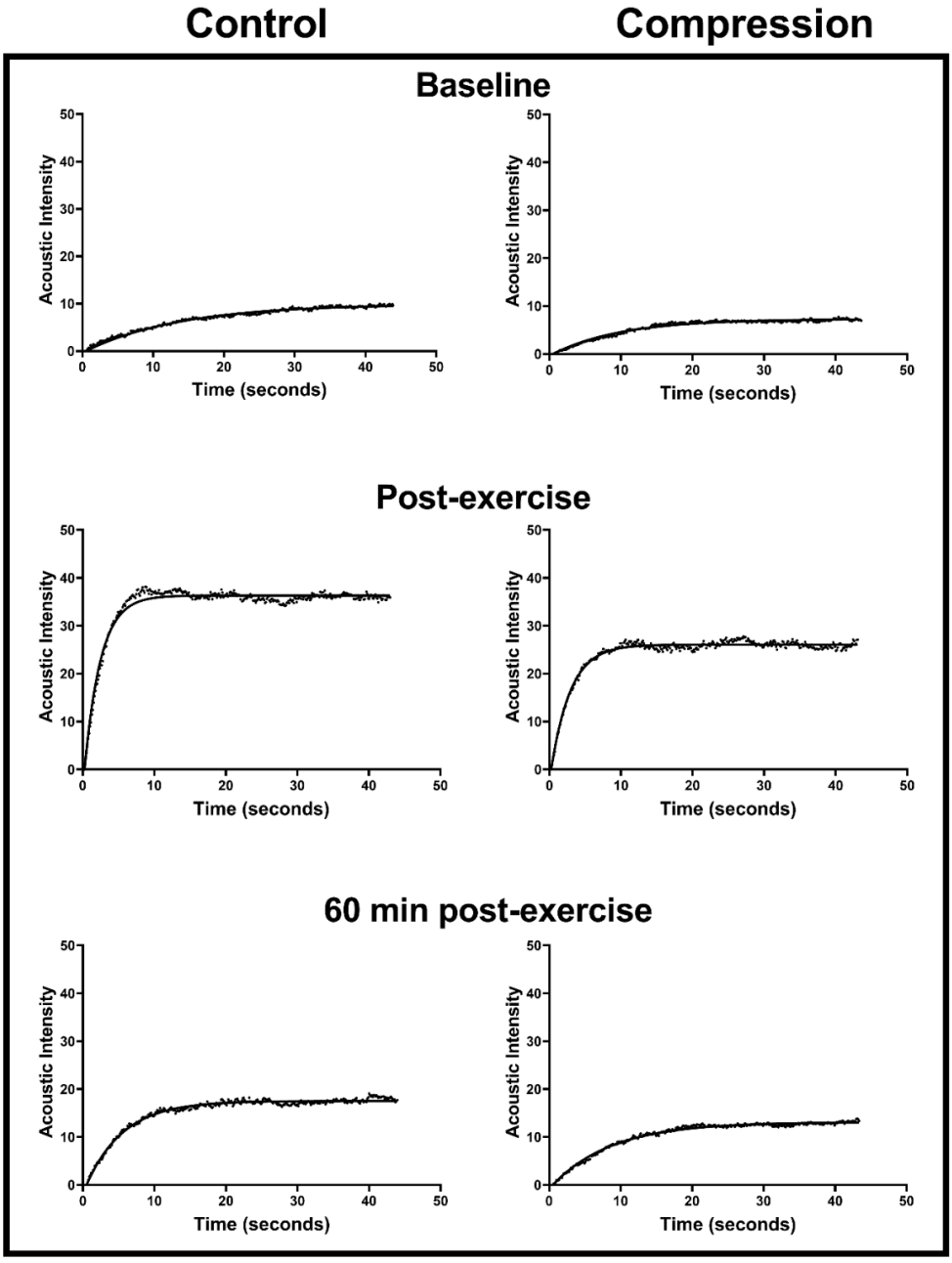

Figure 5-4: Representative curve fits for skeletal muscle microvascular perfusion from a single participant at baseline, immediately after RSE, and 60 min post-exercise with and without compression garments. A high-mechanical index flash from the ultrasound probe is used to destroy all current microspheres within the ultrasound probe line of sight. The reappearance kinetics of the microspheres, and their magnitude, are used to calculate muscle microvascular blood volume, velocity and flow.

An interaction effect (p = 0.031) was detected for femoral artery blood flow (Fig 5-5C). Compared with baseline, femoral artery blood flow was elevated in both conditions after the RSE sets and remained elevated to a lesser extent at 60 min post-exercise (all $p < 0.001$). The increase was greater in the COMP condition as compared with the CON condition after Set 1 (p = 0.009) and Set 2 (p = 0.001), but not Set 3 (p = 0.101) or 60 min post-exercise (p = 0.930).

Femoral artery diameter, blood velocity and flow data when averaged over the three RSE sets were elevated in the COMP condition as compared with the CON condition (p = 0.027, p = 0.080, and p = 0.025; Fig 5-5A, 5-5B, and 5-5C, respectively).

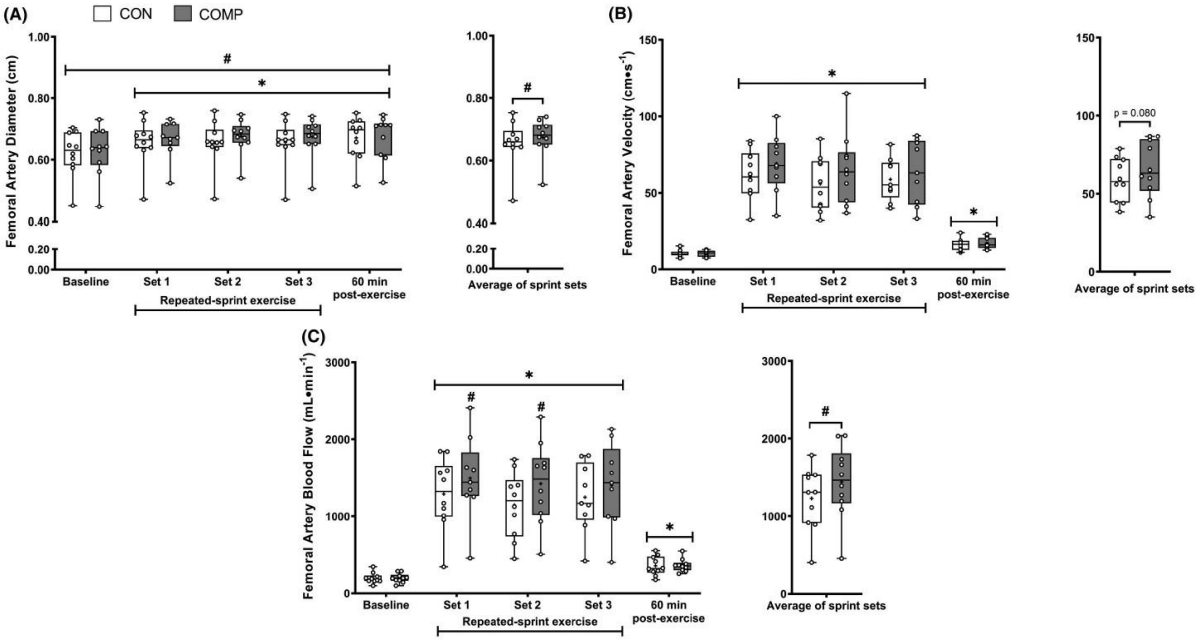

Figure 5-5: The effects of compression garments and repeated-sprint exercise on femoral artery diameter (A), blood velocity (B), and blood flow (C). Data are presented as box and whisker plots. The box represents the interquartile range alongside the median (line) and mean (plus symbol). The whiskers represent the minimum and maximum range of the data. n = 10 participants. *p < 0.05 compared to baseline. #p < 0.05 compared to the same time-point in the CON session or indicates a main effect of condition.

5.3.3 NIRS-derived tHb, O_2Hb, and HHb

An interaction effect (p = 0.026) was detected for muscle tHb (Fig 5-6A). Compared with baseline, tHb was elevated after the RSE sets and post-exercise time-points in both conditions (all $p < 0.01$). Muscle tHb was lower in the COMP condition as compared with the CON condition after set 1 (p = 0.053) and sets 2 - 4 (all $p < 0.05$).

An interaction effect (p = 0.025) was detected for normalized muscle O_2Hb (Fig 5-6B). Compared with baseline, normalized O_2Hb was lower after the RSE sets in both conditions (all $p < 0.001$). Compared with the CON group, normalized O_2Hb was lower with the COMP condition throughout the post-exercise recovery period (all $p < 0.05$).

An interaction effect (p = 0.041) was detected for normalized muscle HHb (Fig 5-6C). Compared with baseline, normalized muscle HHb was higher after the RSE sets with COMP only (all $p < 0.01$) and lower throughout the recovery period in both conditions (all $p < 0.001$). Compared with the CON group, normalized muscle HHb was higher in the COMP condition after the RSE sets (all $p < 0.05$) and at 60 min post-exercise ($p < 0.05$).

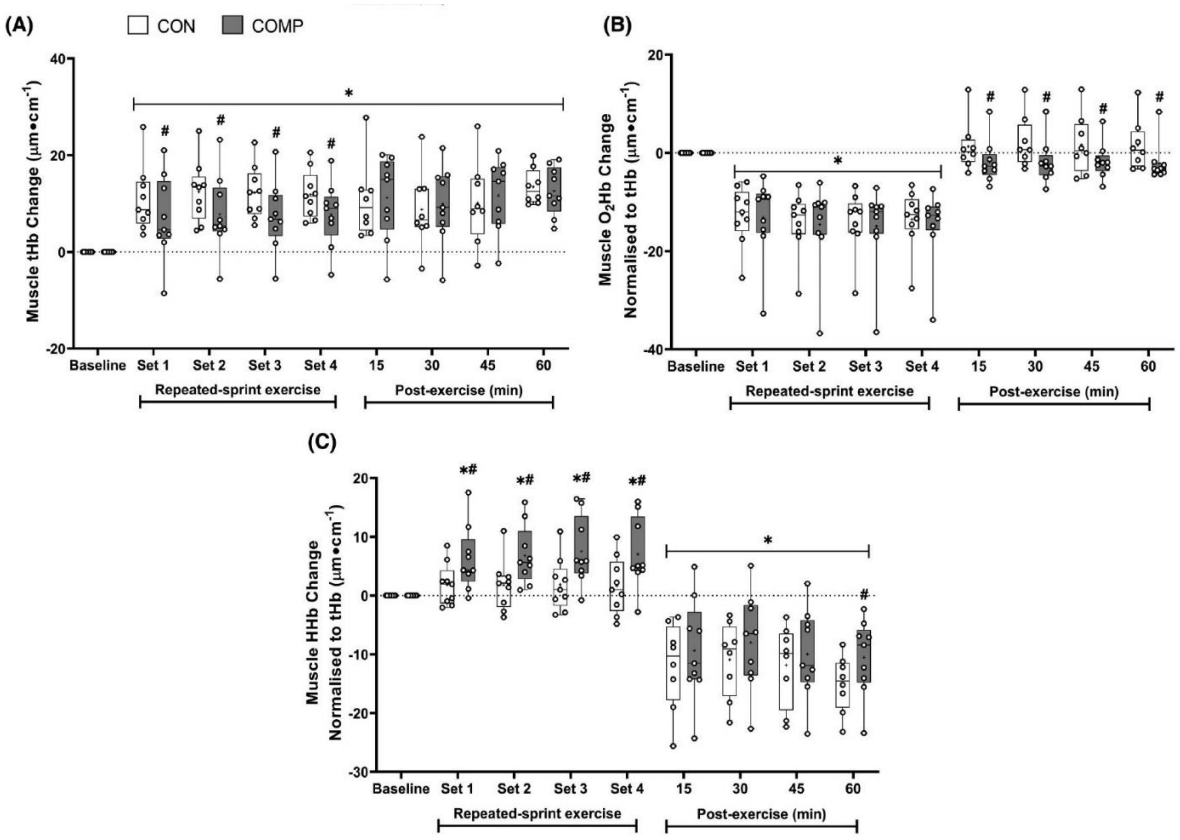

Figure 5-6: The effects of compression garments on repeated-sprint exercise-induced muscle total haemoglobin (tHb; A), oxyhaemoglobin (O_2Hb) normalized to tHb (B), and deoxyhaemoglobin (HHb) normalized to tHb (C). Data are presented as box and whisker plots. The box represents the interquartile range alongside the median (line) and mean (plus symbol). The whiskers represent the minimum and maximum range of the data. n = 9 participants. *$p < 0.05$ compared to baseline. #$p < 0.05$ compared to the same time-point in the CON session.

5.3.4 Forearm Venous Blood Lactate and Glucose

An interaction effect ($p = 0.012$) was detected for blood lactate (Fig 5-7A). Compared with baseline, blood lactate was elevated after each RSE set and remained elevated above baseline throughout the 60-min post-exercise recovery period in both conditions (all $p < 0.01$). Blood lactate was lower after the first set in COMP as compared with CON ($p = 0.002$), and similar between the two conditions at all other time points (all $p > 0.171$).

A main effect of time ($p < 0.001$) was detected for blood glucose (Fig 5-7B). Compared with baseline, blood glucose levels were elevated after RSE sets 2 and 3 ($p < 0.001$) in both conditions, which remained elevated 15 and 30 min post-exercise ($p < 0.05$). No condition ($p = 0.696$) or interaction effects ($p = 0.477$) were detected for blood glucose.

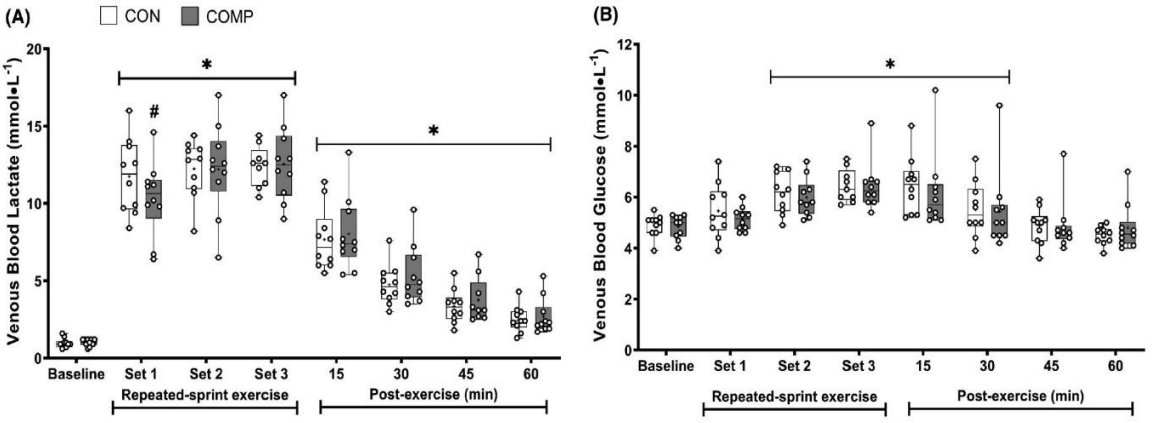

Figure 5-7: The effects of compression garments on repeated-sprint exercise-induced venous blood lactate (A) and glucose (B) concentrations. Data are presented as box and whisker plots. The box represents the interquartile range alongside the median (line) and mean (plus symbol). The whiskers represent the minimum and maximum range of the data. n = 10 participants. *$p < 0.05$ compared to baseline. #$p < 0.05$ compared to the same time-point in the CON session.

5.3.5 Repeated-Sprint Exercise (RSE) Performance, RPE and Heart Rate

A main effect of time was detected for peak power, mean power, RPE, and heart rate ($p < 0.001$). Compared with RSE set 1, peak and mean power were lower, and RPE was higher, after RSE sets 2 - 4 in both conditions (Fig 5-8A, 5-8B, all $p < 0.001$; Fig 5-8C, all $p < 0.01$). Compared with baseline, heart rate was elevated after each RSE set and remained elevated above baseline throughout the 60-min post-exercise recovery period (Fig 5-8D,

$p < 0.001$). There were no condition (all $p > 0.257$) or interaction (all $p > 0.310$) effects for peak power, mean power, RPE, or heart rate.

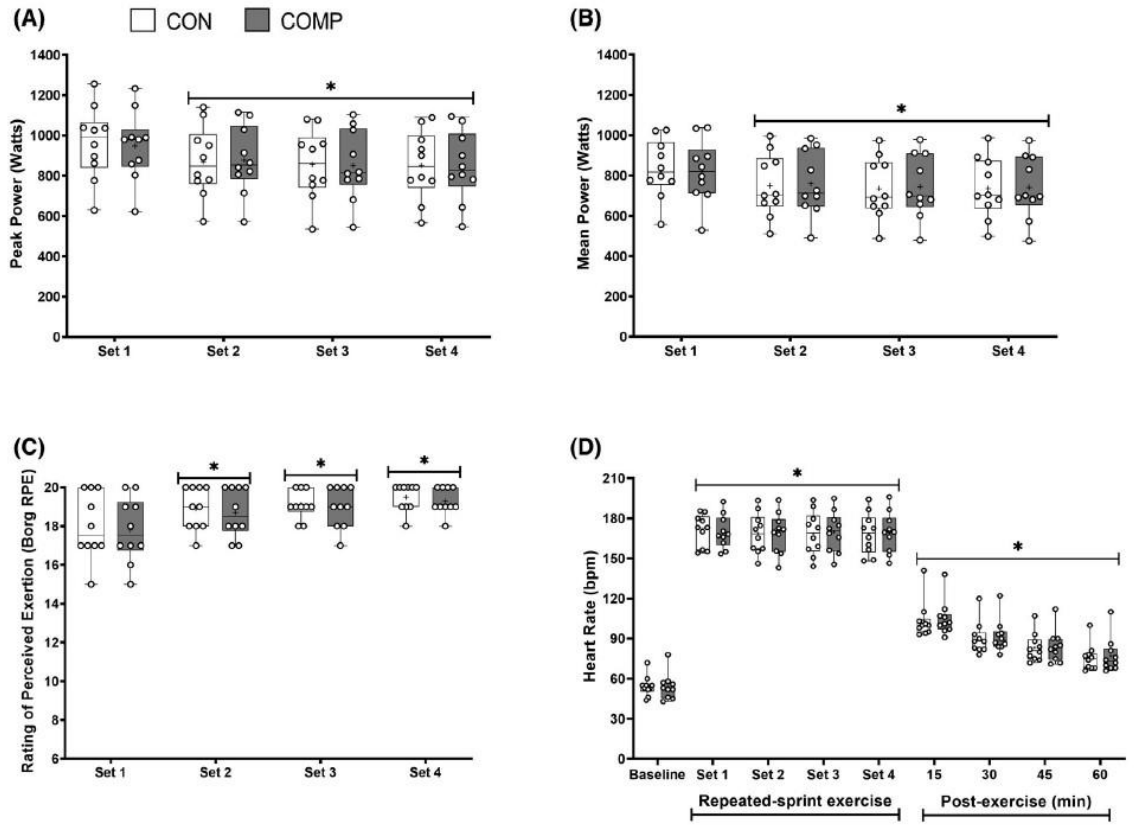

Figure 5-8: The effects of compression garments on repeated-sprint exercise peak power (A), mean power (B), RPE (C) and heart rate (D). Displayed power values represent average peak power and average mean power from the 10 sprints in the corresponding set. Data are presented as box and whisker plots. The box represents the interquartile range alongside the median (line) and mean (plus symbol). The whiskers represent the minimum and maximum range of the data. n = 10 participants. *p < 0.05 compared to set 1 (panels A, B and C) or baseline (panel D).

5.3.6 Sprint Performance (Single 6-S Sprint) Before, Immediately After, and 60 Minutes After the RSE Protocol

Main effects of time ($p < 0.001$) were detected for single-sprint performance peak power, mean power, and peak heart rate (Table 5-1). Peak and mean power were lower, and peak heart rate higher, for the last RSE sprint as compared with both the first RSE sprint and recovery sprint (60 min post-RSE) in both conditions. There were no condition (all $p > 0.888$) or interaction effects (all $p > 0.486$).

Table 5-1: The effects of compression garments on single sprint performance before and after repeated-sprint exercise.

	First RSE sprint		Final RSE Sprint		Recovery Sprint	
	CON	COMP	CON	COMP	CON	COMP
Mean power (Watts)	994 ± 204	994 ± 204	739 ± 142*	738 ± 153*	983 ± 204	997 ± 202
Peak power (Watts)	1116 ± 233	1125 ± 230	862 ± 154*	839 ± 183*	1100 ± 242	1095 ± 216
Peak heart rate (bpm)	158 ± 18	156 ± 16	174 ± 15*	173 ± 15*	160 ± 16	163 ± 16

Note: Multiple means were analysed using a two-way linear mixed model (ANOVA) with Time and Condition (CON vs COMP) as the within-subjects' factors. Data are presented as Mean ± SD. * $p < 0.001$ compared to both the first repeated-sprint exercise (RSE) sprint and recovery sprint (60 min post-RSE).

5.4 Discussion

These findings provide novel evidence that lower-limb compression tights attenuate the exercise-induced increase in skeletal muscle microvascular blood flow following repeat-sprint exercise (RSE), and that these reductions persist for up to 1 h post-exercise. This attenuation of microvascular blood flow occurred despite an increase in femoral artery blood flow, indicating for the first time that there are divergent effects of compression on leg macro- and microvascular blood flow during and following exercise. The compression-induced attenuation in muscle microvascular perfusion did not influence exercise performance. However, compression led to an increase in measures of blood oxygen extraction, which may indicate a compensatory mechanism to conserve exercise capacity in healthy individuals during conditions of reduced muscle microvascular blood flow. These findings highlight that the microvasculature in skeletal muscle has considerable built-in redundancy (i.e., a large capacity to adapt to attenuation in blood flow to maintain adequate gas and nutrient exchange) in healthy, recreationally active people such that RSE performance is not impaired when microvascular blood flow is reduced with lower-limb compression garments.

This study demonstrates, for the first time, that compression exerts divergent effects on macrovascular and microvascular blood flow following exercise. Consistent with previous reports of an increase in femoral arterial blood velocity and flow,[12] as well as total-limb blood flow,[5,9,11,195,220,230] compression tights augmented the exercise-induced increase in femoral artery diameter, velocity, and blood flow in the current study. This has been hypothesized to occur due to a compression-induced reduction in transmural pressure and a subsequent arterial/arteriolar vasodilatory response.[220] While confirming an increase in upstream large

artery blood flow, these findings add the novel observation that compression attenuated the exercise-induced increase in muscle microvascular blood velocity, volume, and flow. These findings were supported by a decrease in NIRS-derived muscle tHb, suggesting a decrease in exercise-induced muscle (regional) blood volume with compression. Decreased muscle microvascular perfusion may be the result of a mechanical hindrance in muscle blood flow, as reported by others using PET imaging.[16] Capillaries are more susceptible to compression than larger blood vessels, due to their lack of vascular smooth muscle and connective tissue. As such, compression may reduce microvascular blood flow through an elevation in interstitial fluid pressure and subsequent microvascular compression. Collectively, compression may cause a vasodilation of the major 'feed' arteries/arterioles and subsequently increases limb arterial blood flow, but concurrently compresses the microvasculature. Others have also reported divergent responses of arterial and microvascular blood flow to muscle contraction and other pharmacological, hormonal and metabolic stimuli.[393,481–484] These observations may reflect redistribution of blood within the limb to other non-myocyte tissues such as adipose tissue, skin, bone, fascia and connective tissue.

The regulation and co-ordination of vascular tone and blood flow within and between the cardiac, macrovascular, and microvascular systems, is critical for the moderation of exercise capacity, performance, and recovery.[399,477–479] In support, impaired muscle microvascular perfusion in type 2 diabetes patients is associated with reduced exercise capacity, independent of cardiac functional reserve.[473] Others have similarly linked muscle microvascular dysfunction to reduced exercise capacity in heart failure patients[474,475] and peripheral arterial disease.[476] In sedentary rodents, decreasing skeletal muscle nutritive microvascular blood flow with serotonin in the constant-flow perfused rat hind limb markedly impaired skeletal muscle oxygen consumption and force production during muscle contraction elicited by sciatic nerve stimulation despite total leg blood flow remaining constant.[497] In healthy adults, the influence of muscle microvascular blood flow alongside the maintenance of exercise capacity and performance is less clear. However, the observation of decreased muscle microvascular blood flow alongside the maintenance of exercise capacity suggests there is considerable redundancy built in to the muscle capillary-myocyte interface system. This muscle microvascular blood flow reserve likely allows for the maintenance of exercise performance during conditions of reduced muscle microvascular

blood flow, at least in healthy individuals. Indeed, total limb perfusion does not seem to be the rate-limiting factor for oxygen transport, even during intense exercise.[498] Furthermore, basic measures of exercise metabolism (glucose and lactate), heart rate, and RPE, were all similar between compression and control. This suggests alternative haemodynamic or metabolic compensatory mechanisms may be involved in maintaining exercise performance during conditions of decreased muscle perfusion.

To elucidate potential compensatory mechanisms, the effects of lower-limb compression tights on NIRS-derived indicators of muscle oxygen extraction (i.e., O_2Hb and HHb) relative to changes in regional flow (i.e., tHb) were measured. Muscle HHb normalised to changes in regional blood volume was higher with compression, as compared with control during the RSE sets and at 60 min post-exercise. This suggests that, in the presence of decreased muscle microvascular blood flow and blood volume during exercise and recovery, blood oxygen extraction is increased to maintain oxygen delivery and availability to the myocyte. The mechanism of a compression-induced increase in oxygen extraction is unclear; however, it may relate to the observed reduction in microvascular blood flow and volume that results in the muscle extracting more oxygen (per unit of blood). In support of this, oxygen[499,500] and glucose[501] extraction have been reported to increase when limb blood flow is decreased via nitric oxide and/or cyclooxygenase inhibition. Thus, compression garments may compress low-resistance capillaries allowing flow to be carried by high-resistance capillaries, which improves flow homogeneity and oxygen extraction. Isolated constant-flow muscle systems show that increasing perfusion pressure with certain vasoconstrictors improves flow homogeneity and enhances oxygen delivery and uptake by skeletal muscle during rest or contraction.[502–504] However, considering the paucity of research that has directly measured microvascular blood flow with compression garments, the precise mechanism behind the observed increase in measures of muscle oxygen extraction during and after exercise with compression garments, and the potential link to microvascular blood flow, warrant further investigation.

Muscle blood flow is also critical for aspects of muscle recovery and exercise training adaptations, including MPS and angiogenesis. Muscle blood flow is positively associated with rates of MPS,[17,18] and as such, repeated transient reductions in skeletal muscle

microvascular blood flow may impair MPS. This may have implications for resistance training adaptations, including strength and skeletal muscle mass.[358,505] Blood flow to the microvasculature has also been implicated in angiogenesis, which may contribute to increases in skeletal muscle microvasculature capillarisation and endothelial enzyme content, and improved insulin sensitivity and glycaemic control.[427,491,506,507] The signals prompting such vascular remodelling responses are not entirely clear but are linked to haemodynamic stimuli, including vascular shear stress and transmural pressure.[427,506,508] As such, a potential implication of compression attenuating the exercise-induced increase in microvascular flow could be an impairment in muscle vascular remodelling, which may ultimately compromise long-term training adaptations that otherwise lead to improved muscle oxygen delivery and aerobic exercise capacity. Considering the relationship between muscle microvascular dysfunction and exercise intolerance in diseased populations,[473–476] this may have important implications for longer-term, vascular-related exercise training adaptations in healthy individuals. Research investigating the long-term effects of compression garments on muscle microvascular remodelling and function are warranted.

The post-exercise reduction in microvascular blood flow with compression reported in the current study is comparable to those reported in clinical populations. For example, clinical populations such as those with type 2 diabetes and peripheral arterial disease display a ~ 25% to 60% lower microvascular blood flow response to exercise as compared with controls when assessed with CEU. Specifically, exercise-intolerant type 2 diabetes participants are reported to have ~ 25% lower exercise-stimulated microvascular blood flow (stress testing on treadmill) compared with exercise tolerant type 2 diabetes participants.[473] Peripheral arterial disease patients with type 2 diabetes display ~ 60% reduction in exercise-stimulated microvascular blood flow (plantar-flexion exercise) as compared with healthy controls.[509] Exercise-mediated increases in microvascular blood flow (forearm contraction) is ~ 60% lower in people with type 2 diabetes and microvascular disease (neuropathy or retinopathy) when compared with healthy controls, despite a similar stimulation in brachial artery blood flow.[472] In the current study, there was a ~ 29% reduction in exercise-stimulated microvascular blood flow when recreationally active healthy participants wore compression. However, this reduction in microvascular blood flow is the result of mechanical compression,

whereas reductions in microvascular blood flow in clinical populations during exercise are mostly driven by a lower capillary density in skeletal muscle.[510]

Both muscle contraction and exercise have been reported to increase microvascular blood flow in skeletal muscle.[490,501,511] Forearm skeletal muscle contraction (hand grip exercise at 80% maximal handgrip strength) in healthy adults humans increases forearm microvascular blood volume by ~ 46% when measured after a short, 12-min, intermittent contraction protocol.[490] Peak microvascular perfusion measured by CEU in the *gastrocnemius* muscle also increases in healthy adults by ~ 57% after walking treadmill exercise (60% heart rate reserve for 10 min).[476] Also, light-intensity knee extensor exercise (3-min intermittent contraction protocol at 25% 1RM) is reported to increase microvascular blood flow in vastus lateralis muscle of healthy adults,[512] which readily returns to basal levels within minutes post-contraction. These findings contribute to the literature by providing evidence that an intense RSE protocol leads to a substantial increase in muscle microvascular blood flow in the vastus lateralis muscle of healthy adults immediately after exercise (~ 889%), which remains elevated for up to at least 1 h post-exercise (~ 146%). These observations reflect similar findings of elevated muscle microvascular blood flow for up to 3 h after moderate-intensity cycling exercise in healthy adults (1 h at ~ 75% VO_{2peak}),[510] for up to 1 h after moderate-intensity treadmill exercise in healthy young and older adults (45 min at ~ 40% VO_{2peak}),[511] and for up to 4 h after intense single-legged knee extensor exercise in healthy adults (1 h of contractions at 80% W_{peak}, with three 5-min intervals at 100% W_{peak}).[501] As such, RSE is a potent stimulus for increasing muscle microvascular blood flow in healthy young adults.

This study provides an indirect comparison between CEU and other techniques aimed at measuring skeletal muscle microvascular blood flow. For example, using an identical RSE exercise protocol and similar cohort (i.e., young and recreationally active adults), lower-limb compression tights increased muscle blood flow by ~ 11% immediately post-exercise,[9] as measured by NIRS during venous occlusion. In contrast, this study reports a decrease of ~ 29% in microvascular blood flow as measured directly by CEU. Although NIRS is thought to only measure [Hb] in blood vessels < 1 mm,[511] our current findings support the notion that NIRS-derived measures of microvascular blood flow are likely influenced by factors like

haem distribution and/or skin and adipose tissue blood flow.[298] This is further supported by the lack of effect of lower-limb compression garments on NIRS-derived measures of blood flow following long-distance trail running,[36,305] whereby any potential effect may have been masked by the inability of NIRS to measure muscle microvascular perfusion. In the only study to use PET to investigate the effect of compression garments on muscle blood flow, compression shorts (high-level of compression of ~ 37 mmHg) reduced *quadriceps femoris* blood flow by ~ 50% when measured 10 min after a high-intensity cycling session.[16] This is consistent with the reduction in microvascular perfusion reported in the current study, and the difference in magnitude may be explained by the level of compression pressure applied (i.e., ~ 37 mmHg vs ~ 11 mmHg) and/or the timing of the post-exercise measurement of microvascular blood flow (i.e., 10 min post-exercise vs immediately post-exercise). Furthermore, although PET provides a direct measurement of muscle perfusion, it is unable to differentiate between capillaries and arterioles/venules that reside within the muscle.[489] The findings of this study contribute new knowledge by demonstrating that muscle femoral artery blood flow is increased, whereas microvascular perfusion in muscle is reduced from external compression as low as ~11 mmHg at the mid-thigh. Future research should aim to employ more sensitive techniques to measuring muscle microvascular blood flow, such as CEU, than can better compartmentalise macro and microvascular blood flow in skeletal muscle.

The finding that performance was unchanged with compression garments contradicts the ~5% increase in repeated-sprint cycling power reported in our previous study using the same RSE protocol.[9] This is not unexpected given the equivocal findings of previous research investigating the effects of compression garments on exercise performance.[68,286] Performance has numerous psychological determinants, in that any potential effect of compression may have been masked by factors like external motivation, priming, mental fatigue, and the placebo effect.[436,512] This may be further exacerbated by the nature of the exercise protocol chosen, as performance during supra-maximal exercise relies heavily on participant motivation.[513] Another potential explanation for these discordant findings is the different methods used to calculate power. The Wattbike ergometer used in the current study calculates power via a load cell located next to the chain, whereas the SRM power meter used in Broatch et al.[9] calculates power using strain gauges located between the crank axle and chain rings.[514]

Although the Wattbike provides close agreement in power as compared with the 'gold-standard' SRM power meter, it has been reported to be less accurate at high power outputs (> 700 W),[514] which may have contributed to the differences observed between studies. Regardless, performance was not reduced when wearing compression tights in the current study, despite the lower microvascular blood flow. Mean power was ultimately maintained between conditions, suggesting that the compression-induced attenuation in microvascular blood flow has minimal effect on exercise performance, at least at supra-maximal intensities in the conditions tested. It is also important to note that due to logistical limitations with the equipment used, microvascular blood flow and arterial blood flow measures were collected immediately after exercise, as opposed to dynamic measures taken during exercise, which may not directly reflect what is occurring during muscle contraction.[215]

This study aimed to assess and differentiate the effects of compression garments on macro and microvascular blood flow in skeletal muscle following RSE. Contrary to our hypothesis, lower-limb compression tights impaired the exercise-induced increase in muscle microvascular blood flow immediately following RSE, which was also evident 1 h into the post-exercise recovery period. Conversely, compression tights increased macrovascular blood flow as assessed at the femoral artery, which is consistent with the majority of research reporting compression-induced increases in total-limb blood flow.[5,9,11,195,220,230] As such, our findings highlight a novel divergence between post-exercise macro and microvascular blood in muscle with compression garments (Fig 5-9), further highlighting the necessity to distinguish between macrovascular and microvascular blood flow in future exercise physiology and sports science research. Despite the lack of effect on high-intensity exercise performance and the recovery, the observed compression-induced reduction in microvascular blood flow may have important implications for glucose disposal and exercise capacity in pathological populations (e.g., type 2 diabetes and cardiovascular disease), as well as long-term skeletal muscle adaptations reliant on adequate muscle perfusion (e.g., MPS and angiogenesis). The authors also acknowledge the specificity of the cohort and exercise protocol used in the current study, which may limit the translation of findings to certain cohorts (e.g., elderly, sedentary, and clinical populations) and more conventional exercise interventions (e.g., moderate-intensity continuous exercise and resistance exercise). Future research investigating the effects of compression garments on these factors is warranted.

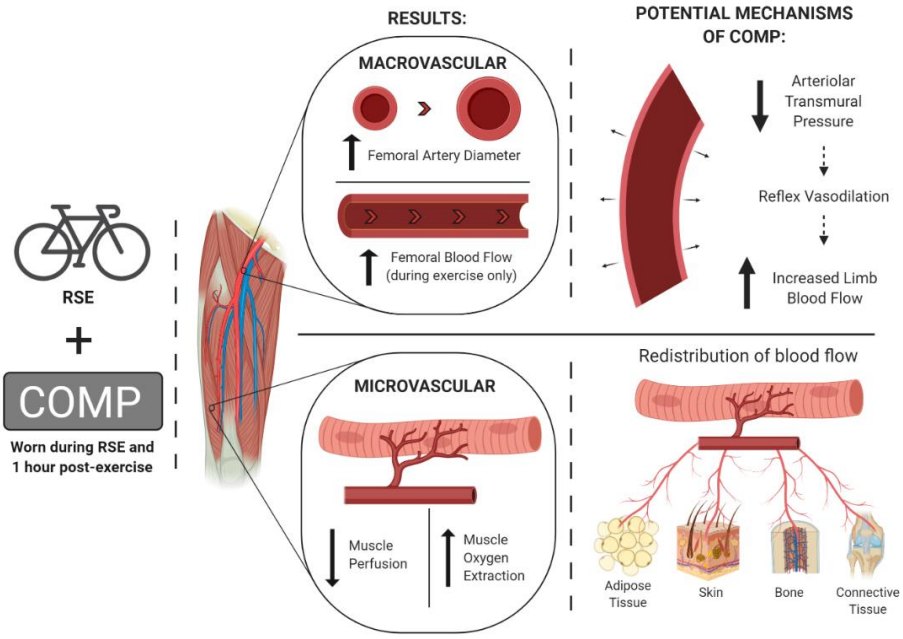

Figure 5-9: Potential mechanisms by which lower-limb compression garments (COMP) may alter femoral artery macrovascular blood flow, and skeletal muscle microvascular blood flow, during repeated-sprint exercise (RSE) and the 1-h post-exercise recovery period. Created with Biorender.com.

CHAPTER SIX

Thesis Summary and Discussion

This thesis aimed to investigate the influence of SCG on blood flow, exercise performance, and exercise recovery. The current chapter summarises the key findings, highlights practical recommendations, discusses limitations and considerations, and provides recommendations for future research.

6.1 Summary of Key Findings

- A systematic review with meta-analysis (Chapter 2) of the available compression literature identified that SCG alter peripheral measures of blood flow (Fig 6-1A). Specifically, beneficial effects of compression were observed during, immediately post, and in recovery from a physiological challenge. This review also highlighted that compression benefited arterial blood flow measures, and not venous blood flow, immediately after a physiological challenge.

- Sports compression socks, shorts, and tights increased resting venous and muscle blood flow of the lower limb (Fig 6-1B; Chapter 3). When comparing garments, sports compression tights were the most effective garment at improving resting blood flow in the lower limb. For example, compression tights enhanced venous flow at the popliteal and common femoral veins and increased muscle blood flow of the calf and thigh musculature. In contrast, compression socks and compression shorts increased blood flow measures in the underlying veins and muscles only (i.e., popliteal vein and calf musculature for socks, common femoral vein and thigh musculature for shorts).

- The results of Chapter 4 suggest that sports compression tights enhance venous and muscle blood flow for up to 4 h post-exercise (Fig 6-1C). In addition, this compression-induced increase in blood flow coincided with improved indices of muscle recovery, as compared with control and placebo conditions. Also, the benefits of SCG for exercise recovery were likely not due to a placebo effect.

- Using modern ultrasound techniques (CEU), the results of Chapter 5 demonstrate a divergent effect of SCG on macro and microvascular blood flow (Fig 6-1D). These findings may have implications for mechanisms and adaptations reliant on adequate muscle perfusion (e.g., nutrient delivery, exercise capacity, angiogenesis, and MPS).

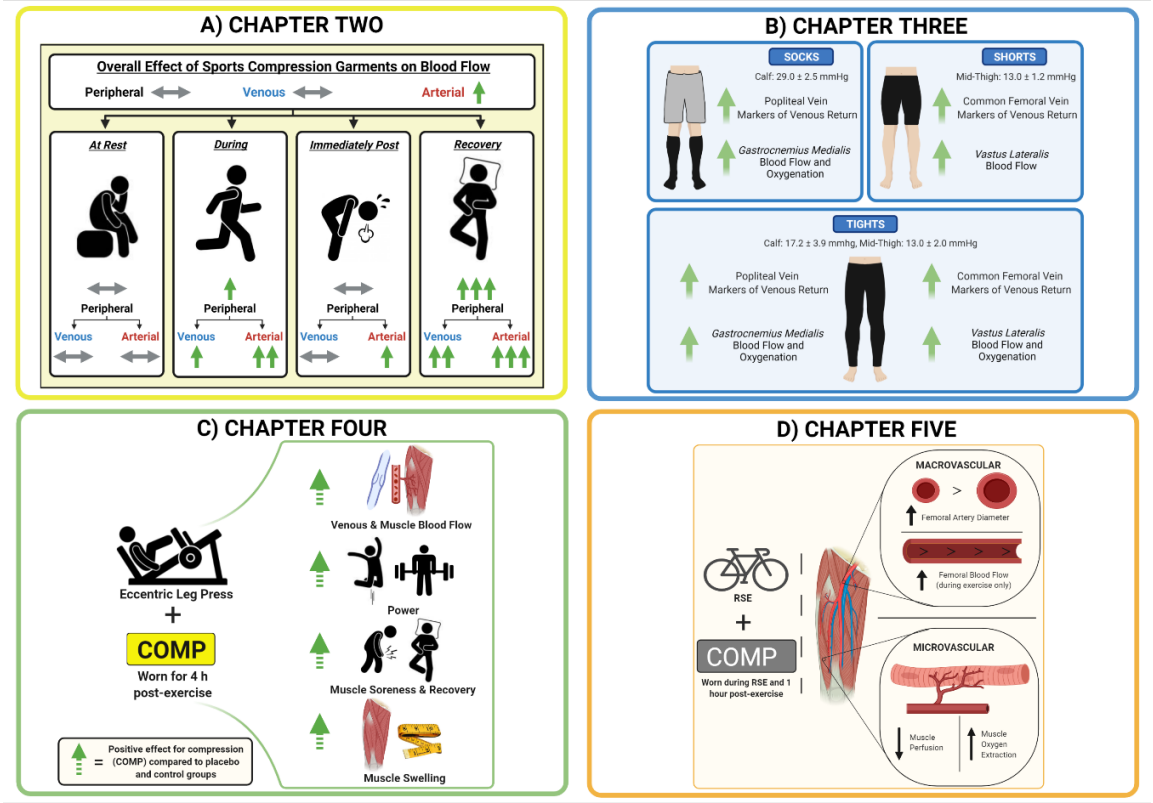

Figure 6-1: Summary of thesis findings. Created with Biorender.com.

Sports compression garments improve peripheral blood flow in a time-dependent manner:

A systematic review and meta-analysis were conducted to determine the influence of SCG on peripheral measures of blood flow (Chapter 2). Most reviews to date have focused on exercise performance and/or recovery outcomes with compression.[68–70,138,286,376] This is a crucial omission as the mechanism of action for compression-induced benefits has been attributed to haemodynamics and blood flow alterations.[68,138] Despite a recent review highlighting SCG benefits on central haemodynamic responses (i.e., heart rate, stroke volume),[288] the influence of SCG on peripheral blood flow (i.e., venous and arterial blood flow) was yet to be established. This chapter aids our understanding of the effects of SCG on venous and arterial blood flow.

The main finding of this systematic review and meta-analysis was that SCG positively altered measures of peripheral blood flow. However, these positive findings were time-dependent, and variations existed between venous and arterial measures of blood flow. Indices of venous blood flow were enhanced during, and in recovery from, a physiological

challenge, but no changes were evident at rest or immediately post. Compression increased arterial blood flow during, immediately post, and in recovery from a physiological challenge. Similar to venous blood flow, there was no effect of SCG on arterial blood flow at rest.

The findings from this review suggest SCG would be most beneficial in altering peripheral blood flow when utilised either during, or in the recovery from, a physiological challenge (e.g., exercise). Although the findings from this chapter support the notion that SCG improve blood flow, it also highlighted several limitations of sports compression research. For example, there is high heterogeneity between studies in regards to the level of pressure applied, type of garment used (e.g., lower-body vs upper-body), physiological challenge implemented (e.g., endurance vs resistance vs orthostatic challenge), and participant training status (trained vs untrained). Of particular relevance to this review, there was variability in the techniques used to assess changes in peripheral blood flow, including NIRS,[6,9,13,36,124,140,281] Doppler ultrasound,[12,13,80,130,387] plethysmography,[5,10,296,297,386] MRI[295] and PET.[16] These variations may help explain the inconsistencies between studies in regards to their effects on peripheral blood flow. This chapter also noted that no research has investigated the effects of SCG on peripheral blood flow beyond 30 min of use post a physiological challenge.

Compression tights are more effective than compression socks or shorts for increasing lower limb blood flow:

Chapter 3 aimed to investigate the effects of three types of SCG (socks, shorts, or tights) on markers of venous return and muscle blood flow at rest, as measured by Doppler ultrasound and NIRS technologies. Considering garments only apply pressure to the underlying blood vessels they are covering, it was hypothesised that blood flow might differ between garment types. Therefore, this study was the first to investigate potential differences between SCG styles on measures of lower-limb blood flow at rest.

The main findings were that all garment types increased resting markers of venous return and muscle blood flow. However, when comparing garment types, sport compression tights elicited the greatest overall increase in resting blood flow measures of the entire lower limb. For example, compression tights improved markers of venous return at the popliteal and common femoral veins. Whereas, compression socks and shorts were only beneficial in

enhancing markers of venous return in the popliteal and common femoral veins, respectively. Similarly, compression tights enhanced calf and thigh muscle blood flow. In contrast, compression socks (calf muscle only) and shorts (thigh muscle only) increased blood flow to the underlying musculature only.

This study provides the first comprehensive assessment of the effects of different SCG types on markers of venous return and muscle blood flow. Data from this study highlight the importance of garment type when prescribing SCG. These findings from Chapter 3 confirm that SCG can positively alter markers of venous return and muscle blood flow in the lower limbs at rest, with these benefits greatest in sport compression tights.

Compression-induced improvements in markers of exercise recovery are likely associated with increased blood flow, and not due to a placebo effect:

Although the results of Chapter 3 demonstrate that compression-induced increases in resting venous and muscle blood flow, it is unknown if SCG alter blood flow during post-exercise recovery. Therefore, Chapter 4 aimed to investigate the effects of SCG on post-exercise blood flow. Also, given the difficulty in blinding participants to wearing compression garments, it is currently unknown if the ergogenic benefits associated with SCG on exercise performance and recovery indices are related to a placebo effect.[76,161,284] Previous SCG research has attempted to blind participants via different techniques, including low-level pressure garments and 'sham' placebo drinks. However, belief in the placebo intervention was not assessed. As such, this study also aimed to assess the placebo effect of compression. This was achieved by matching belief between sports compression tights and placebo conditions.

The main finding of Chapter 4 was that sports compression tights appear to enhance measures of blood flow (venous and muscle blood flow) for up to 4-h following lower-body resistance exercise. In addition, enhanced indices of recovery (exercise performance, perceptual measures) were evident with compression compared with placebo and control conditions. Also, the placebo by deception was effective, as participants in the placebo group had a greater belief in their intervention as compared with the compression group.

Chapter 4 is the first study in compression research to monitor the effects of SCG, for a duration longer than 30 min post-exercise, on markers of venous return and muscle blood flow during exercise recovery. As the inflammatory response begins in the early hours post-exercise, and muscle blood flow is positively associated with muscle nutrient delivery, augmented blood flow for up to 4-h post-exercise may enhance the recovery process. Furthermore, by measuring the belief effect in both compression and placebo interventions, an effective placebo by deception was incorporated to determine the effectiveness of SCG on exercise recovery; this is another first in compression research. Finally, as the increase in blood flow with compression coincided with enhanced exercise recovery, these results suggest that the benefits of compression may be closely associated with physiological alterations (e.g., increased blood flow), and not a placebo effect.

Divergent effects of compression tights on macro-and microvascular blood flow:

The findings from Chapters 3 and 4 demonstrated the benefits of SCG to augment venous and muscle blood flow. However, the question remained whether these benefits translated to improved microvascular blood flow. Therefore, the final study of this thesis investigated the effects of sports compression tights on both macro (femoral artery) and microvascular (capillary) blood flow following intense exercise and throughout the post-exercise recovery period. As compression is shown to enhance muscle blood flow,[5,9] it was hypothesised that sports compression tights would enhance macro and microvascular blood flow. Using modern ultrasound techniques (CEU), this study provided insight into the effects of SCG on microvascular blood flow.

The main finding from this study was that sports compression tights attenuated lower-limb skeletal muscle microvascular blood flow following RSE, despite increased femoral artery blood flow. However, an attenuation in microvascular blood flow had no influence on the measured exercise performance (repeated sprint cycling power), which may be explained by an increase in blood oxygen extraction. These findings provide the first evidence that SCG have divergent effects on lower-limb macro and microvascular blood flow.

In support of the hypothesis that sports compression tights would enhance macrovascular blood flow, an increase in upstream large artery blood flow was observed. This increase likely occurred due to a reduction in transmural pressure, leading to an arterial

vasodilatory response (i.e., a myogenic response).[220] However, the compression-induced changes in microvascular flow were contrary to the initial hypothesis. Sports compression tights attenuated muscle microvascular blood velocity, volume, and flow. As capillaries lack the vascular smooth muscle and connective tissue of larger blood vessels (i.e., femoral artery), compression may have mechanically hindered muscle perfusion. Despite these divergent effects of compression, it did not affect exercise performance and recovery. Also, the increase in muscle oxygen extraction suggests a built-in redundancy to compensate for the attenuated muscle perfusion and maintain exercise performance. Nonetheless, these novel findings may have implications in other settings. For example, processes important for skeletal muscle adaptation, such as MPS, rely on adequate muscle perfusion. Consequently, the attenuation of muscle perfusion with compression, could be hypothesised to negatively impact long-term adaptations to exercise training (Fig 6-2). The novel findings from this study highlight that future research investigating the effects of regular SCG use on training adaptations is warranted.

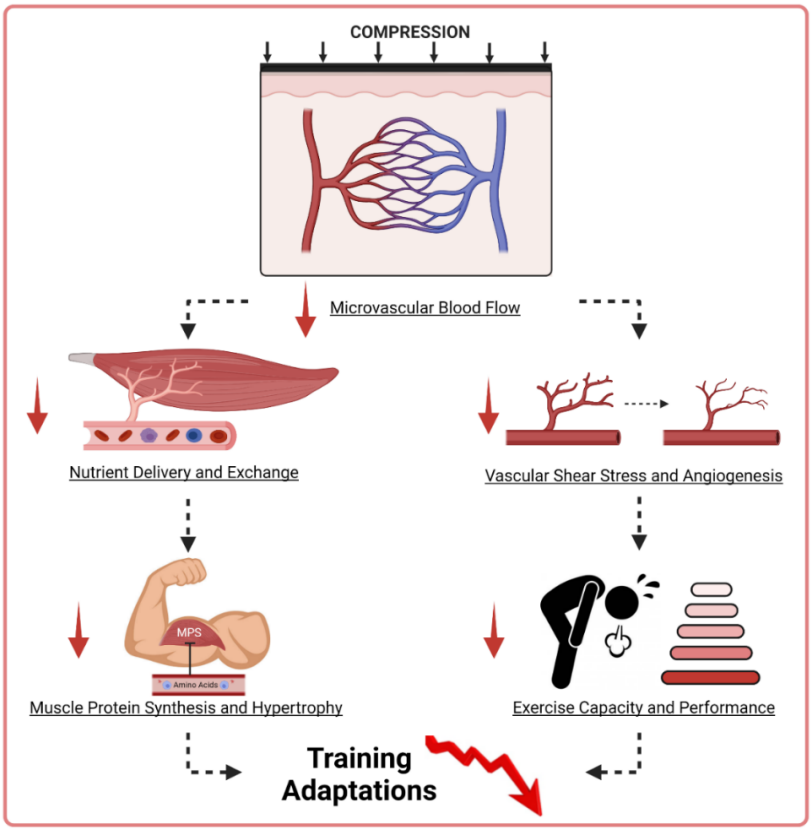

Figure 6-2: Updated potential mechanisms for sports compression garments to alter training adaptations. Created with Biorender.com.

6.2 Practical Applications

The studies in this thesis investigated the effects of SCG on measures of blood flow at rest (Chapter 3), during exercise (Chapter 5), and post-exercise (Chapter 4 and 5). In addition, the potential benefits of SCG on exercise performance (Chapter 5) and indices of recovery (Chapter 4 and 5) were assessed. Collectively, the mechanistic and performance focus of these studies help enhance our knowledge of the underlying mechanism whilst providing practical recommendations for the use of SCG.

- Despite all lower-body SCG (i.e., sock, shorts, and tights) enhancing venous and muscle blood flow measures at rest, tights had the greatest effect. Therefore, individuals aiming to maximise the ergogenic benefits of SCG are encouraged to choose garments that cover and apply pressure to most of the limb.

- As the pressure level can vary between SCG brands[59,515] and between individuals prescribed the same size garment,[27] ensuring adequate pressure can be challenging. However, it is essential for their effectiveness.[134] The three studies in this thesis used sports compression tights (brand: 2XU), with improvements shown in macrovascular measures of blood flow (i.e., femoral artery flow, common femoral vein flow, popliteal vein flow). The pressure level across the three studies at the maximal calf and mid-thigh were approximately 19 mmHg and 12.5 mmHg, respectively. Thus, athletes should aim for similar levels of pressure.

- The application of compression for 4 h after exercise appears beneficial for enhancing performance and perceptual recovery indices. These findings may prove useful for athletes with twice a day training (i.e., morning and evening sessions) or those in competition environments with minimal rest between events.

- Finally, due to the reduced microvascular blood flow observed with SCG in Chapter 5, a cautious approach to using SCG during or after every exercise session is advised as the potential compression-induced effects on training adaptations are currently unknown (Fig 1-6 and Fig 6-2).

6.3 Limitations and Considerations

Although the studies described in this thesis have produced novel findings regarding alterations in blood flow with SCG, the potential limitations of this research also need to be acknowledged - as discussed below.

- Given that recovery is essential for maintaining exercise performance in athletes, translating the findings from this thesis to practical settings (i.e., athletes) should be done with caution. Although athletes (high-level basketball players) were recruited for the study described in Chapter 3, only compression-induced changes in blood flow at rest were assessed. In addition, the studies that assessed SCG effect on exercise performance and recovery (Chapter 4 and 5) were performed in recreationally trained individuals (i.e., non-athletes). As training status influences exercise capacity[516] and the ability to recover,[517] future studies should aim to recruit an athletic population to further delineate the ergogenic benefits of SCG for this cohort.

- The parallel-group design used in Chapter 4 may have masked any potential condition effects, which may have been evident in a cross-over study design (i.e., if participants acted as their own control). However, a parallel-group design was chosen to avoid any repeated bout effect associated with eccentric exercise.[518] Considering the repeated bout effect is reported to last for up to 6 months post exercise,[519] numerous factors (e.g., participant drop-out due to a long washout period, time constraints with a PhD, etc.) limited our ability to incorporate a cross-over study design. Also, a parallel-group study design eliminated an order effect regarding participant belief in the recovery intervention.

- Caution is advised when interpreting the findings from Chapter 4. Although moderate to large effects were present, the enhanced indices of recovery and blood flow observed with SCG were not statistically significant. Therefore, it could be argued that sports compression tights, when worn for 4 h post-eccentric resistance exercise, do not alter blood flow or improve indices of recovery. A potential reason for these non-significant findings is the underpowered analysis, as I initially planned to recruit

10 participants per group. However, due to continued COVID-19 restrictions, I was unable to complete all the testing. Despite the statistically non-significant findings, the inclusion of ES analysis helps the readers to understand the magnitude of the differences with SCG and quantify the practical significance of the research.[520]

- The studies in this thesis utilised only one brand of SCG (i.e., 2XU). As such, it is worth noting the use of other SCG brands (e.g., Skins, Nike, UnderArmour etc.) may result in different findings due to variations in the level of pressure applied between SCG brands.[59]

- Due to the global impact of COVID-19, I was unable to conduct a longitudinal study to determine the effect of SCG use on the adaptive responses to resistance training (Appendix A). As blood flow and nutrient uptake are positively correlated,[490] I had also hoped to perform an acute arm of this study as a compromise, which aimed to determine the effect of SCG on post-exercise markers of glycogen replenishment and MPS. Unfortunately, as restrictions/lockdowns continued in Victoria, Australia, the difficult decision was made to omit this study completely. To compensate, Chapter 2 and Chapter 5 were included.

6.4 Future Directions

Collectively, the studies included in this thesis have improved the understanding regarding the effects of SCG on markers of blood flow. In particular, the novel findings of this thesis highlight that SCG appear to improve blood flow during and in recovery from exercise (Chapter 2), differences in blood flow exist between SCG styles (Chapter 3), compression enhances blood flow for up to 4-h post-resistance exercise (Chapter 4), improved indices of recovery with SCG are not due to a placebo effect (Chapter 4), and that SCG have divergent effects on lower-limb macro and microvascular blood flow (Chapter 5). However, these findings also expose topics for future research.

- This thesis reported differences in compression-induced changes in blood flow across three lower-body garments styles. Future research should consider and investigate the

effects of other garment styles, including upper-body garments (e.g., sleeves, t-shirts) in altering blood flow.

- Due to COVID-19 restrictions, I could not determine the effects of regular SCG use on the adaptive response to resistance training (Appendix A). Therefore, future work should endeavour to answer this question while also conducting similar research across different exercise modalities (e.g., steady-state exercise, RSE).

- Again, due to constraints beyond my control (COVID-19), I could not investigate the effect of SCG on important molecular mechanisms for adaptation and recovery from exercise (i.e., MPS and glycogen replenishment; Appendix A). Given the importance of muscle perfusion for nutrient exchange, the novel findings of reduced microvascular blood flow (contrary to the original hypothesis) highlight the importance and necessity for future research to investigate the effect of compression on nutrient delivery and underlying molecular mechanisms.

- Future research should incorporate a placebo condition to adequately determine the beneficial effects of compression on exercise performance and recovery, similar to the methods described in Chapter 4 (i.e., matched by belief).

- More studies in high-level athletes are essential to determine if the findings from Chapters 4 and 5 are transferrable to this cohort.

- Lastly, with advances in fitting technology and individualisation of SCG, future work should incorporate custom-fitted garments. Given the variation of pressure from 'off the shelf' garments, properly controlling for this variable will lead to more robust study designs and help to definitively determine the efficacy of SCG for exercise performance and recovery. Furthermore, a classification system similar to that used with medical compression (Table 1-2) should be explored to identify if specific pressure ranges are more beneficial for different settings (e.g., during or post-exercise).

CHAPTER SEVEN

References

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APPENDICES

Appendix A: Information on cancelled sports compression and training study

Title: The effect of regular sports compression garment use on muscle adaptive responses to eight weeks of resistance training in males.

Approved Ethics No: HRE19-094

The first cohort of participants were due to begin this study in March 2020, with 12 of 20 required participants successfully recruited. However, due to COVID-19 restrictions in Victoria, Australia, for the majority of 2020, it was not possible to begin any data collection. There was hope to include the acute arm of this study (i.e., data collection from the first training session and 'acute biopsy trial') as part of my thesis, but as lockdowns continued beyond 2020 (six in total), the difficult decision was made to omit this study from my PhD. Outlined below is the methodology submitted as part of the ethics application.

Methods:

The experimental design and timeline are outlined Fig 1. Participants will first report to the laboratory (Muscle Function Lab, Building P, Room PB145, Victoria University, Footscray Park) for muscle strength testing (1RM). This session will also be a familiarisation session to the testing protocols used in this study, including Doppler ultrasound, near-infrared spectroscopy (NIRS), and performance measures (countermovement jump (CMJ), isometric mid-thigh pull (IMTP)). Approximately 10 to 14 days after the baseline 1RM testing, participants will report to the laboratory again for testing of baseline measures (second visit), including anthropometric measurements (height and weight), muscle mass (dual-energy x-ray absorptiometry (DXA)), garment pressure (COMP only), CMJ and IMTP. Exactly 24 h after the second visit, participants will be begin an eight-week resistance training intervention, while either wearing sports compression garments (SCG) after each training session (Compression; COMP) or no recovery (Control; CON). The first resistance training session will be an 'Acute Trial' in which muscle biopsies, blood samples, blood flow measures (Doppler ultrasound, NIRS), and perceptual information (muscle soreness (MS), total quality of recovery (TQR)) will be collected immediately pre, 1 h post, 5 h post and 48 h post the first resistance training session (Acute Trial). Participants will complete three resistance training sessions per week for the next 8 weeks. Garment pressure, performance

(IMTP/CMJ) and perceptual (PMS/TQR) measures will be assessed weekly. Baseline measures, 1RM and a final muscle biopsy will be collected 48 h post the final resistance training session. For all sessions in this study (pre-testing, eight-week training intervention, post-testing) participants will report to the Exercise Physiology Laboratory, Building P, Room PB145-PB151, Victoria University, Footscray Park.

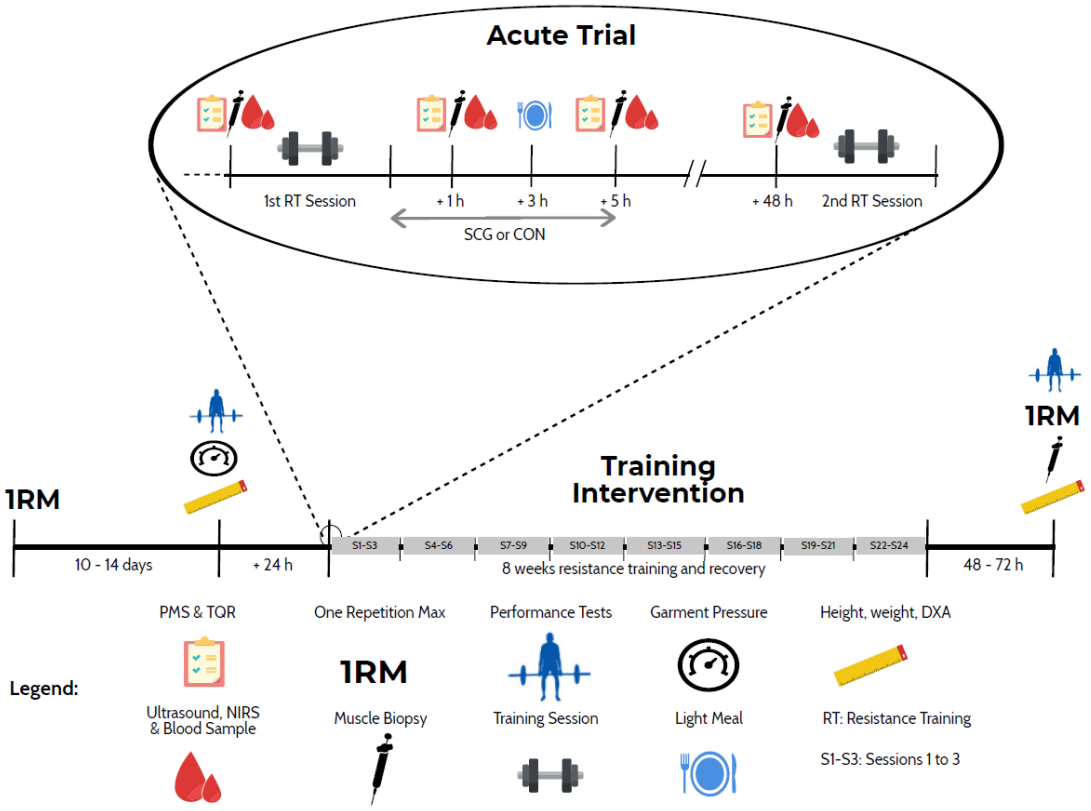

Figure 1: Experimental design and timeline.

One Repetition Max Testing:

Participants will be tested to determine their 1RM for both the leg press and bench press. This 1RM data will be used to set an individual workload for the resistance training sessions. Prior to testing of 1RM for leg press, subjects will perform a standardized warm-up consisting of 5 min cycling at 1 W per kg body mass, 10 repetitions of body weight squats, 10 repetitions on each leg of bodyweight walking lunges, high knee runs over 20 m, heel kick runs over 20 m, 3 submaximal CMJs and 1 maximal CMJ. Following the warm-up, participants will perform a total of three warm up sets, 10 reps with no weight (leg press machine for leg press

and barbell for bench press), 5 reps at 50% of estimated 1RM, and 2-3 reps at 75% estimated 1RM (1). Participants will then perform a repetition at an estimated 90% of 1RM. If a repetition is completed successfully, and with correct technique, participants will perform another one repetition effort with gradually increasing resistance until failure or loss of technique. A 3-min rest period will be allowed between maximum effort attempts. A successful 1RM will be the greatest mass lifted with correct form through a complete range of motion (2,3). The 1RM leg press will be conducted before the 1RM bench press with a 5-minute rest period between tests (1). An additional warm-up will be completed immediately prior to warm-up sets for 1RM bench press testing including 10 arm swings forward, 10 arm swings backwards and 10 body weight push ups.

Kikuhime Pressure Monitor:

The garment pressure (COMP group only) will be assessed using a Kikuhime pressure monitor at the time points depicted in Fig 1. This device contains a small air-filled piece of plastic that is placed between the garment and the skin. The pressure applied by the garment is then displayed on a monitor in real time, and to the nearest mmHg. Pressure will be measured at six sites on the right lower-limb. In addition, garment pressure will be assessed each week (the beginning of sessions 4, 7, 10, 13, 16, 19 and 22) at landmarks B and D to ensure the same level of pressure from visit 2 is still being applied. In the event the level of pressure has changed by ± 2 mmHg, new SCG applying original pressure will be assigned to the participant. This method has previously been approved by the VUHREC as per application ID: HRE18-227.

Anthropometry Measures:

An anthropometric profile including height and weight will be performed during the second visit. Skinfold thickness at the sites of NIRS oximeter placement (*vastus lateralis* and *gastrocnemius medialis* muscles of the right lower-limb) will be measured during the second visit using Harpenden skinfold callipers, as subcutaneous fat (> 35 mm) can influence the quality of the NIRS signal (4).

Dual-energy X-ray Absorptiometry (DXA):

Body composition will be assessed by DXA at time points depicted in Fig 1. DXA is a quick and non-invasive method for estimating total and regional body fat and lean mass. The procedure involves exposure to a very small amount of radiation (less than 0.01 millisievert (mSv) per examination) (5). This is less than the radiation experience during a standard x-ray or during a 7-hour plane flight. The effective dose of radiation the participants will be exposed to across the two DEXA scans in this study is less than 0.02 mSv. DXA scans will follow standard operating procedures and participants will be measured after an overnight fast to minimise measurement error (5). This study has been assessed by a Medical Physicist and the radiation dose determined to be of minimal risk. A Victorian Specific Module has been completed as per requirements of the Department of Health. All scans will be performed at Building P, Victoria University, Footscray Park. A qualified technician will perform these scans in the first instance, whilst the student investigator is being accredited and trained ((Bone Mineral Densitometry course; Radiation Use License; TLD badge; local area induction; VU training for DXA).

Performance Tests:

To assess performance recovery following resistance training session 1, performance tests including CMJ and IMTP will be performed at the time points depicted in Fig 1. In addition, CMJ and IMTP will be assessed weekly before sessions 4, 7, 10, 13, 16, 19 and 22.

Prior to all performance tests, participants will perform a standardized warm-up consisting of 5 min of cycling at 1 W per kg body mass, 10 repetitions of body weight squats, 10 repetitions on each leg of bodyweight walking lunges, high knee runs over 20 m, heel kick runs over 20 m, 3 submaximal CMJs and 1 maximal CMJ.

The CMJ is a valid and reliable test for estimating explosive power of the lower limb (6). The CMJ test will be performed with subjects standing on a force place with feet in a hip wide position. Participants will be required to perform a quick downward movement to approx. 90^{o} knee flexion, followed by a fast upward vertical jump as high as possible. Upon landing, both feet will be required to be within the frames of the force plate. When performing the CMJ, hands will be placed on hips to eliminate the influence of arm swing on jump

performance (7). A set of 5 CMJs will be completed, with 8 seconds of rest between repetitions. Vertical ground reaction forces (N) and jump height (cm) will be used for analysis.

The IMTP is a reliable assessment of whole-body maximum force generating capacity (8), and is regularly used to monitors athletes' training progression (9). The test will be performed on a Smith Machine while standing on a force platform. The mid-thigh position will be determined by marking the midpoint between the top of the patella and the inguinal crease of the front thigh. This site will be marked with a permanent marker, along with feet position, to ensure retest reliability. Participants will self-select their hip and knee angles for the test with the height of the barbell adjusted to be in contact with the marked mid-thigh position. Participants will be instructed to pull upward on an immovable bar for 3 seconds while standing on the force platform. Two repetitions will be performed separated by 2 min rest, with a third repetition performed if a greater than 250 N difference is seen between peak forces of the first two efforts. Peak force (N) and rate of force development (N/s) will be used for analysis. These methods have previously been approved by the VUHREC as per application ID: HRE18-227.

Perceptual Questionnaires:

Participants will be asked to answer the following perceptual questionnaires at the time points depicted in Fig 1 and before resistance training sessions 4, 7, 10, 13, 16, 19 and 22.

- Total quality of recovery (TQR) - This will be assessed by participants rating their perceived recovery on a scale from 6 (no recovery) to 20 (maximal recovery) (10).
- Perceived muscle soreness (MS) - This will be assessed via self-palpation of the exercised muscle, where the participant will be asked to rate their level of soreness using a visual analogue scale (0 = nothing at all, 10 = extremely high) (11).

Muscle Biopsies:

Muscle will be sampled by a trained physician (Dr. Andrew Garnham) from the *vastus lateralis* (VL) muscle of the quadriceps using the modified Bergström needle technique (12,13). Under local anaesthesia (1% Xylocaine), a small incision will be made through the skin, subcutaneous tissue and fascia overlying the VL, using sterilised equipment and aseptic techniques. A 5-mm needle will be

inserted into the muscle and a small (~50-400 mg) portion of muscle tissue removed. Muscle samples will be obtained immediately before and 1, 5 and 48 h after exercise on the Acute Trial day. The muscle samples obtained will be promptly placed into liquid nitrogen in order to snap freeze, and transferred to cryotubes for later analysis. Muscle samples will be analysed for changes in muscle glycogen levels and markers of muscle protein synthesis (e.g, phosphorylated p70S6 kinase, mammalian target of rapamycin (mTOR), ribosomal protein S6 (rps6)) and muscle protein degradation (e.g., atrogin-1, MuRF1 and myostation). Analysis of gene and protein expression will be performed via real-time PCR and Western blotting respectively. A final resting muscle sample will be collected 48 h after the final resistance training session. This sample will be used to compare changes in muscle fibre cross-sectional area and composition from the sample collected at the beginning of the first resistance training session. The muscle biopsy procedure has been undertaken previously by the involved investigators (See VU HRE15-292, HRE19-011).

Doppler Ultrasound:

Doppler ultrasound will be used to measure markers of venous return (venous cross-sectional area, venous peak flow velocity and venous mean flow velocity) for the popliteal (behind the knee) and common femoral (upper-thigh) veins at each time point depicted in Fig 1. Each site will be marked with a permanent marker to ensure consistency at each collection time point. Lubricating jelly will be applied to the skin at each site to help transmit the signal. Measures at the common femoral vein will be accessed with the garments folded down slightly. A small window will be cut in the garments, before each participant is asked wear to the SCG, to allow probe access to the popliteal vein. The angle of the transducer relative to the skin will be between 45 and 60 degrees, with the depth adjusted to insonate the total width of the veins. The ultrasound signal will be measured for approximately 60s at each site in order to obtain measures of venous return previously mentioned. Personnel trained in the use of ultrasound for venous measures will collect all measures. This method has previously been approved by the VUHREC as per application ID: HRE18-227.

NIRS:

Muscle blood flow and muscle oxygenation will be measured at the *vastus lateralis* and *gastrocnemius medialis* muscles. An oximeter will be positioned on the lowest third of the *vastus lateralis* muscle, parallel to the long axis of the leg (14). A second oximeter will be

positioned on the *gastrocnemius medialis* muscle belly, parallel to the major axis of the shin of the same leg (15). Each placement site will be shaved of excess hair to help ensure a good quality signal. The NIRS device provides continuous, non-invasive measurement of concentration changes in oxyhemoglobin (O2Hb), HHb and total haemoglobin (tHb) (15,16). Changes in muscle oxygenation will be monitored using an oximeter (Oxymon MKIII Near-Infrared Spectrophotometer, Artinins Medical Systems, The Netherlands), with data transmitted simultaneously to a personal computer and acquired using (Oxysoft V3.0.53, Artinins Medical Systems, The Netherlands) software. Changes in muscle oxygenation will be calculated via the tissue saturation index (expressed as a percentage and calculated as ([O2Hb]/([O2Hb] + [HHb]) x 100)) (17). To assess muscle blood flow, multiple venous occlusions (70 mmHg) will be performed (18). This technique requires the inflation of a pressure cuff, applied to the upper thigh, using an automated rapid cuff inflation system (Hokanson, Washington, USA). Blood flow into the muscle is then calculated by the rise in tHb (O2Hb + HHb) (18). Three 20-s venous occlusions, separated by 45 s of rest (19), will be performed at each time point depicted in Fig 1. The average of these three measurements will be used for data analysis. This method has previously been approved by the VUHREC as per application ID: HRE18-227.

Blood Samples:

An indwelling cannula will be inserted into an antecubital vein for the collection of 10-mL blood samples. Blood samples will be collected at the time points depicted in Fig 1. Blood samples will be analysed for levels of glucose, insulin and growth-related hormones (growth hormone (GH), Insulin growth like factor 1 (IGF1)) using commercially available kits (R&D Multiplex ELISA Kit). Samples will be collected, stored, and prepared as per manufacturer guidelines. Cannulations and blood collections will be undertaken by trained personnel under sterile conditions and following standard Victoria University Exercise Physiology operating procedures. The total volume of blood collected from each participant during this study will be 40-mL.

Resistance Training Sessions:

The resistance training sessions (Table 1) will be performed three times per week on non-consecutive days, for a duration of eight weeks. Weeks 1, 3, 5 and 7 schedules will be ordered

program 1, program 2 and program 1 for the three sessions. Weeks 2, 4, 6 and 8 schedule will be program 2, program 1 and program 2. Training loads will progressively increase to maintain relative loading. For each training session, both groups will perform a standardised warm up and cool down. All training session will be supervised to ensure training load and intensity are adhered to.

Table 1. Resistance training program.

Program 1				**Program 2**			
Exercise	**Reps**	**Sets**	**Rest (s)**	**Exercise**	**Reps**	**Sets**	**Rest (s)**
Leg Press	8-10	3	120	Leg Press	8-10	3	120
Bench Press	8-10	3	120	DB Shoulder Press	8-10	3	120
Seated Row	8-10	3	120	Lat Pulldown	8-10	3	120
DB Lunges	8 L+R	3	120	DB Split Squat	8 L+R	3	120
Knee Flexion	8-10	3	120	DB Romanian Deadlift	8-10	3	120

Recovery Intervention:

Participants will undertake one of two recovery interventions, SCG (COMP) or a passive control (CON). For both interventions, participants will be seated on a laboratory bed with legs supine for 5 h post-training session 1 (Fig 1 – 'Acute Trial). For the COMP recovery intervention, lower body SCG tights (2XU Recovery Compression Tights, Melbourne, Australia) will be worn for the duration of the 5 h recovery period only. The SCG tights will be assigned to participants based on height and weight (manufacturer guidelines), and pressure applied to the limb will be measured using the kikuhime pressure monitor. Following each training session (excluding session 1), the COMP group will be required to wear SCG for a duration of 2 hours after resistance training sessions only. Participants will receive a reminder via text message to remove SCG after 2 hours. Participants in the CON group will not receive any intervention after training sessions.

Controls Procedures:

Nutrition: A standardised diet (energy intake ~36kcal/kg, carbohydrate ~ 5.1 g/kg, protein ~1.3 g/kg, and fat ~1.2 g/kg) will be provided to each participant 24 h prior to each testing session requiring biopsy collection. In addition, a light meal will also be provided at 3 h post-exercise. During the 8-week training program, standardised meals will not be provided. Participants will arrange their own meals, and asked to maintain their habitual diet. However,

participants will be provided with a shake before and after each training sessions in an attempt to control nutritional intake around training. The shake will contain 0.4 g.kg.bw of protein and 0.4 g.kg.bw of carbohydrate.

Exercise: Participants will be asked to refrain from other resistance training workouts and recovery interventions (e.g. water immersion, massage) for the duration of the study, and other exercise 24 h prior to muscle function testing and muscle biopsies. Participants will also record any additional exercise performed outside of the study using a training diary. This diary will record session details, duration and RPE, and will be provided to participants to complete before each supervised resistance training session.

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Appendix B: Chapter Three – Supplementary Table

Supplementary Table: Differences between CON and sports compression garments conditions for all variables.

Variable		Sports compression garment		
	CON	SOCKS	SHORTS	TIGHTS
Calf muscle blood flow (mL/min/100 g)	0.13 ± 0.06	0.05 (± 0.05)	0.01 (± 0.03)	0.11 (± 0.05) *
Thigh Calf muscle blood flow (mL/min/100 g)	0.15 ± 0.05	0.00 (± 0.02)	0.04 (± 0.03) *	0.04 (± 0.03) *
Calf Muscle oxygenation (%)	71.8 ± 4.2	1.0 (± 0.9) *	-0.1 (± 0.8)	2.1 (± 1.3) *
Thigh Muscle oxygenation (%)	78.0 ± 4.6	-0.4 (± 0.6)	0.0 (± 0.4)	0.8 (± 0.7) *
Popliteal CSA (cm^2)	0.6 ± 0.3	0.0 (± 0.1)	0.0 (± 0.1)	0.1 (± 0.1)
Popliteal Vmean (cm/s)	3.2 ± 1.7	1.6 (± 1.5) *	0.4 (± 1.9)	1.8 (± 1.3) *
Popliteal Vpeak (cm/s)	6.5 ± 3.4	3.8 (± 3.5) *	0.5 (± 2.2)	3.8 (± 2.4) *
Popliteal venous blood flow (mL/min)	94.9 ± 46.9	59.9 (± 74.4)	32.5 (± 56.9)	93.6 (± 68.0) *
Femoral CSA (cm^2)	1.7 ± 0.6	0.0 (± 0.3)	0.0 (± 0.2)	0.0 (± 0.2)
Femoral Vmean (cm/s)	7.1 ± 3.5	1.3 (± 1.2) *	3.0 (± 2.5) *	3.2 (± 2.2) *
Femoral Vpeak (cm/s)	15.9 ± 7.5	2.8 (± 2.8) *	6.4 (± 5.5) *	7.4 (± 4.8) *
Femoral venous blood flow (mL/min)	708.4 ± 393.3	160.2 (± 167.2)	310.8 (± 306.5) *	285.3 (± 204.8)*

Notes: Values for CON presented as mean ± SD. All other data presented as mean difference from CON (± 95%CI). Calf stands for gastrocnemius medialis; Thigh stands for vastus lateralis. * significant effect as compared with CON. CSA = cross-sectional area; SHORTS = compression shorts; SOCKS = compression socks; TIGHTS = compression tights; V_{mean} = mean flow velocity; V_{peak} = peak flow velocity;.

Appendix C: Chapter Three - Information to Participants

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate

You are invited to participate in a research project entitled:

"SPORT COMPRESSION GARMENTS INFLUENCE ON BLOOD FLOW"

This project is being conducted by Mr Shane O'Riordan from the Institute for Health and Sport (IHES), Victoria University, and the Australian Institute of Sport.

Project explanation

This project, funded by 2XU, aims to investigate the effectiveness of sports compression garments (SCG), fitted to target pressures, in altering blood flow at rest. As detailed below, the testing session will involve a number of conditions, three with and one without SCG, during which a number of measures will be taken to assess compression-induced changes in blood flow. The results of this research will have a significant and direct application to current sporting practice, and will be relevant to all athletes for the prescription of SCG.

What will I be asked to do?

We will first ask you to complete a cardiovascular screening questionnaire to determine your eligibility to participate in this study. If you are eligible for the study, and give your consent to participate, you will be asked to visit the Physiology Laboratory at the Australian Institute of Sport on two separate occasions:

- 1 x 1 h familiarisation session
- 1 x 1.5 h testing session

Session 1 – Familiarisation:
For the first session, you will be required to wear three different types of SCG (socks, shorts and tights), during which we will measure the pressure exerted by each garment via a pressure monitoring device (detailed below). You may be required to try various sizes of each garment until a pre-defined target pressure is achieved. The garment size that achieves the target pressure will be used for testing. During this session, you will also be familiarised with the Doppler ultrasound and near-infrared spectroscopy (NIRS) testing procedures. Several anthropometric measures will also be taken at this session. Details of all these procedures are outlined below.

Session 2 – Testing Session:
During this session, you will complete all testing procedures (detailed below) with four different testing conditions (i.e., no garment, socks, shorts, and tights). Upon arrival to the lab, a capillary blood sample (approximately 100µL) will be taken from your fingertip. You will then be required to lie down for 20 min, after which you will change into the first of your assigned conditions. Following another 5 min of lying down, the Doppler ultrasound and NIRS testing procedures, as well as a simple questionnaire, will be collected/completed. This process will be repeated 3 additional times (i.e., 4 conditions total). You will also be asked to refrain from strenuous exercise (<24 h) prior to the testing session, as this may influence some of the experimental measures.

What will I gain from participating?

As a result of participating in this study you can expect to increase your understanding of physiological assessments used by sport scientists, which will be performed in a state-of-the-art and purpose-built facility. You will also gain the experience of participating in a science experiment investigating the effectiveness of SCG in altering blood flow. Furthermore, upon completion of the trial, you will be allowed to keep the compression garments used during testing.

How will the information I give be used?

Your data will be stored under alphanumeric codes (i.e., without your name or personal details) and only the researchers will be able to connect the data to you. The data that will be collected during the study will be used/published in peer-reviewed journals, conference presentations, and a research report to 2XU. No personal details will be revealed without your written consent.

What are the potential risks of participating in this project?

Before you volunteer to this study, make sure you read carefully the items below:

1. Your choice to be involved or not in this study will not impact your relationship with your basketball coaches and teammates i.e. team selection, performance reviews, etc., and with Mr O'Riordan in providing services as your recovery physiologist. Furthermore, you are free to withdraw from this study at any time without any consequences or need for explanation.
2. For the application of NIRS, the sites will require shaving some hair to ensure a good signal. This may result in a slight abrasion of your skin.
3. For any medical emergencies a call to 000 will be made. The researchers will also commence appropriate resuscitation methods while waiting for an emergency team to arrive.
4. There is a small risk of bruising or infection (e.g. tenderness and/or redness) from the capillary blood sampling procedure. This risk will be minimised with capillary blood sampling undertaken by trained personnel under sterile conditions.
5. To minimise the risk of any psychological stress, your results will remain confidential. Should you experience any adverse or unusual psychological changes, you will have access to AIS medicine/psychology for debriefing if necessary. With this safeguard in place, you will have access to counselling, free of charge in the case of any psychological event.

How will this project be conducted?

Pre-experiment screening:

All testing will be conducted in accordance with current guidelines for testing in the Physiology Laboratory at the Australian Institute of Sport. You will initially be screened for cardiovascular risk factors and any health issues of relevance to the study. If you answer "Yes" to any of the 10 questions on the Cardiac Screening Questionnaire, you will be asked to seek guidance from you GP or appropriate allied health professional prior to undertaking physical activity/exercise. If you are suffering from severe pulmonary disorders, have high blood pressure, diabetes and arrhythmias, or have risk of an adverse event from conditions (e.g., musculoskeletal injuries), you will be excluded from participating in this study. If you are deemed healthy and at low risk of any adverse events, we will then request you to complete the two sessions involved in this study.

Familiarisation session:

During this session you will be asked to try on three different types of lower-limb SCG (socks, shorts, tights), and may be asked to try a number of sizes until target pressure in each garment is achieved. In addition, you will be familiarised with the equipment used during the testing session.

Testing session:

This session will be conducted as follows:

- Capillary blood sample.
- 20 min lying down rest prior to testing.
- Randomised assignment to one of four conditions, and 5 min of lying down rest.
- Assessment of venous return (Doppler ultrasound) and muscle blood flow/muscle oxygenation (NIRS).
- This process will be repeated 3 additional times (i.e., 4 conditions total), with 5 min of lying down quiet between conditions.

Testing Protocols:

- Compression Garments: Changes in blood flow will be measured under one of four conditions; with one of three lower-leg SCG, (2XU Elite MCS shorts, tights or socks), and without (control) compression. The extent of pressure that the garment applies to your skin will be assessed using a pressure monitor, and this will determine the size of SCG that you will wear for each condition.

- Anthropometry Measures: Your height and weight will be measured during the familiarisation session. Skinfold measurements will be performed on your right leg at the mid-thigh and mid-calf.

- Kikuhime Pressure Monitor: For each SCG condition, the pressure exerted by the garment will be measured using the kikuhime device. This device contains a small air-filled piece of plastic that is placed between the garment and your skin. Garment pressure will be measured in both standing and lying down positions on your right limb at the mid-thigh and mid-calf.

- Capillary Blood: A single capillary blood sample will be taken from your fingertip via pinprick prior to the start of testing on your second visit. Approximately 100µL of blood will be collected in a capillary tube and immediately analysed for haemoglobin concentration.

- Doppler Ultrasound: This technique will be used to measure markers of venous return (blood flow) in the popliteal (behind the knee) and femoral (inner-thigh) veins. Lubricating jelly will be applied to each site to help transmit the signal. In addition, for the control condition, lubricating jelly will be applied to the skin at each site to help prevent friction from the ultrasound transducer. Ultrasound signals will be measured for 60 s in order to obtain measures of venous return. This technique will be performed for each condition following 5 min of supine rest. A qualified sonographer will perform all ultrasound measurements.

- NIRS: Non-invasive oximeters will be placed on your right leg at the mid-thigh and mid-calf. A venous occlusion will be performed to measure your blood flow. This will require inflation of a pressure cuff applied to your upper thigh for 20s. The level of pressure exerted (70 mmHg) is roughly one-third of that exerted during a standard blood pressure test. Following 45s rest, this will be repeated two more times. This procedure allows us to investigate muscle blood flow and oxygenation for each condition.

- Comfort Rating of SCG: You will be asked to provide a comfort rating of each garment using an 11-point scale.

Who is conducting the study?

The study is conducted by the College of Sport and Exercise Science, Victoria University, Footscray Park Campus. The main investigators are:

Principal Investigators:
Mr Shane O'Riordan, Mobile: 0414 703 872, email: shane.oriordan@live.vu.edu.au
Dr James Broatch, Mobile: 0422 050 361, email: james.broatch@vu.edu.au

Associate Investigators:
Prof David Bishop
Dr Shona Halson
Dr Sally Clark

Any queries about your participation in this project may be directed to the principal investigators, Mr Shane O'Riordan or Dr James Broatch, with contact details above. If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001, email researchethics@vu.edu.au or phone (03) 9919 4781 or 4461.

Appendix D: Chapter Three - Informed Consent

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

INFORMATION TO PARTICIPANTS:

We would like to invite you to be a part of a study entitled:

"SPORT COMPRESSION GARMENTS INFLUENCE ON BLOOD FLOW"

(a) AIMS OF THE STUDY:

- This project aims to investigate the efficacy of lower-limb sport compression garments (SCG), fitted to target pressures, in altering blood flow.

(b) PROCEDURES INVOLVED AND NATURE OF THE PROJECT:

- Participants will be requested to attend the Physiology Laboratory at the Australian Institute of Sport, Bruce, ACT (Sport Science and Sport Medicine Building) on two separate occasions; a familiarisation session, and the main testing session.

- Familiarisation Session: This will take approximately 45 – 60 min, in which you will be familiarised with testing measures including Doppler ultrasound, near-infrared spectroscopy (NIRS) and kikuhime pressure monitor device. Several anthropometric measures will also be taken at this session. Details of all these procedures are below.

- Compression Garments: Changes in blood flow will be measured under one of four conditions; with one of three lower-leg SCG, (2XU Elite MCS shorts, tights or socks), and without (control) compression. The extent of pressure that the garment applies to your skin will be assessed using a pressure monitor. The size of SCG you will wear for each trial will be determined by the level of pressure applied and determined during the familiarisation session.

- Anthropometry Measures: Your height and weight will be measured during the familiarisation session. Skinfold measurements will be performed on your right lower limb at the mid-thigh and mid-calf.

- Kikuhime Pressure Monitor: For each SCG condition, the pressure exerted by the garment will be measured using the kikuhime device. This device contains a small air-filled piece of plastic that is placed between the garment and your skin. Garment pressure will be measured in both standing and lying down on your back positions on your right leg at the mid-thigh and mid-calf.

- Capillary Blood: A single capillary blood sample will be taken from your fingertip via pinprick prior to the start of testing. Approximately 100µL of blood will be collected in a capillary tube and immediately analysed for haemoglobin concentration. Trained personnel will conduct this technique under sterile conditions to minimise risk of bruising or infection.

- Doppler Ultrasound: This technique will be used to measure markers of venous return (blood flow) for the popliteal (behind the knee) and femoral (inner-thigh) veins. This technique will be performed for each condition following 5 min of lying down rest. A qualified sonographer will perform all ultrasound measurements.

- NIRS: This procedure allows us to investigate changes in muscle blood flow and oxygenation for each condition. A venous occlusion will be performed, which requires inflation of a pressure cuff applied to your upper thigh for 20s. Following 45s rest, this will be repeated two more times.

- Comfort Rating of SCG: You will be asked to provide a comfort rating of each garment using an 11-point scale.

CERTIFICATION BY PARTICIPANT

I, _____ (Phone No:) _____

of _____

certify that I am voluntarily giving my consent to participate in the study:

"SPORT COMPRESSION GARMENTS INFLUENCE ON BLOOD FLOW"

I certify that the objectives of the study, together with any risks and safeguards associated with the procedures listed hereunder to be carried out in the research, have been fully explained to me by **Mr Shane O'Riordan and/or Dr James Broatch** and that I freely consent to participation involving the above mentioned procedures:

Participants will be requested to attend the Physiology Laboratory at the Australian Institute of Sport, Bruce, ACT (Sport Science and Sport Medicine Building) on two separate occasions.

I certify that I have had the opportunity to have any questions answered and that I understand that I can withdraw from this study at any time and that this withdrawal will not jeopardise me in any way.

I have been informed that the information I provide will be kept confidential.

Signature of individual: _____ **Date:** _____

Signature of parent/guardian: _____ **Date:** _____
(Required if the individual is under 18 years of age)

Any queries about your participation in this project may be directed to the principal researchers:

Mr Shane O'Riordan
Telephone number: 0414 703 872
Email: shane.oriordan@live.vu.edu.au

Dr James Broatch
Telephone number: 0422 050 361
Email: james.broatch@vu.edu.au

If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001, email Researchethics@vu.edu.au or phone (03) 9919 4781 or 4461.

Appendix E: Chapter Three - Cardiac Screening Questionnaire

CARDIAC SCREENING QUESTIONNAIRE

Personal Details:

Name: _____

Date of Birth: _____ Gender: Male ☐ Female ☐

Name of person to be contacted in an emergency: _____

Contact Number: Home: _____ Mobile: _____

Screening Questionnaire:

This questionnaire aims to identify any cardiac issues which may restrict your participation in this study. This is self-administered and self-evaluated. Please circle either 'Yes' or 'No' to the following questions.

1. Has a doctor ever told you that you have a heart condition or have you ever suffered a stroke? Yes No
2. Do you have any heart condition(s)? Yes No
3. Are you taking any drugs/medication for you heart? Yes No
4. Have you ever been told that you have:
   a) High blood pressure? Yes No
   b) Heart Infection? Yes No
   c) Heart Murmur? Yes No
5. Have you ever had heart tests carried out by a doctor? Yes No
6. Have you ever had very rapid heart beating that has begun and ended for no apparent reason? Yes No
7. Has anyone in your family died before the age of fifty from a heart condition? Yes No
8. Does anyone in your family suffer from any form of heart disease/issues? Yes No
9. Are you currently taking a prescribed medication(s) for any medical condition? Yes No
   If 'Yes', please provide details: _____
   _____
10. Do you have any other medical condition(s) that may make it dangerous for you to participate in this study? Yes No
    If 'Yes', please provide details: _____
    _____

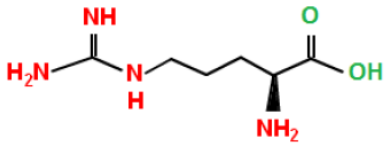
If you answered 'Yes' to any of the 10 questions, please seek guidance from your GP or appropriate allied health professional prior to undertaking physical activity/exercise.

I believe that to the best of my knowledge, all of the information I have supplied within this tool is correct.

Signature of individual: _____ **Date:** _____

Appendix F: Chapter Four - Recovery Information Sheets

L-Arginine Supplementation



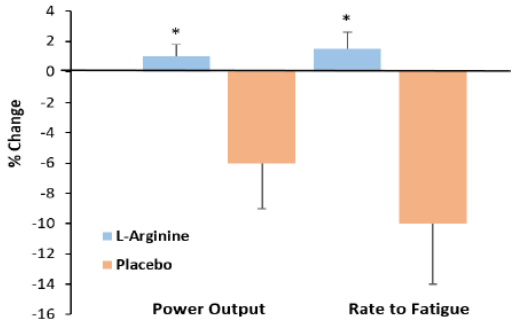
L - Arginine

How does it work?

By enhanced vasodilation and thus blood flow, L-arginine can enhance the rate of recovery following training by promoting waste product removal and minimising symptoms of exercise-induced muscle damage. In addition, it can improve blood flow to the working muscles to enhance nutrition and oxygen delivery both during and post-exercise.

It can help.....

Reduce:	Prevent:	Improve:
Inflammation	Fatigue	Blood Flow
Swelling	Muscle Damage	Muscle Power
Soreness	Muscle Aches	Performance



Adapted from Campbell et al. (2006) – Nutrition; 22; 872-881.

Background

L-arginine supplementation has typically been used in clinical populations to enhance blood flow through vasodilation. L-arginine has also been used in exercise settings to enhance blood flow both during and post-exercise with the aim of reducing exercise-induced muscle damage including inflammation, muscle soreness and swelling.

L-Arginine and Sport

L-Arginine is quickly becoming a common supplement to enhance performance and recovery following exercise. With improved blood flow, it has the potential to enhance the rate of physiological restoration following exercise while attenuating reductions in performance, such muscle strength and power output.

Improved Performance

Literature supports the use of L-arginine for enhancing performance and recovery. Research has shown power output and rate to fatigue remained unchanged with L-arginine supplementation, but reduced by 6% and 10% respectively, with no supplementation.

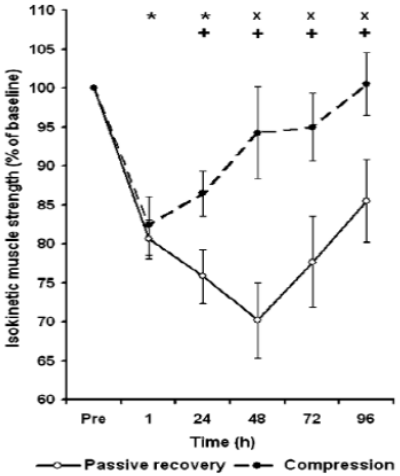
Sports Compression Garments

How does it work?

By improving venous return and thus promoting waste product removal and minimise symptoms of exercise-induced muscle damage, sports compression can enhance the rate of recovery following training. In addition, they can improve blood flow to the working muscles to enhance nutrition and oxygen delivery both during and post-exercise.

It can help.....

Reduce:	Prevent:	Improve:
Inflammation	Fatigue	Blood Flow
Swelling	Muscle Damage	Muscle Strength
Soreness	Muscle Aches	Performance



Jakeman et al. (2010) – Eur J Appl Physiol; 109; 1137-1144.

Background

Compression is traditionally utilised in clinical settings for the treatment of various circulatory issues, with the aim to improve venous return and reduce lower-limb venous pooling. Sports compression garments are used as a recovery strategy post-exercise with the aim of reducing exercise-induced muscle damage including inflammation, muscle soreness and swelling.

Sports Compression and Sport

Sports compression garments are typically used by athletes to improve performance and enhance recovery. They have the potential to enhance the rate of physiological restoration following exercise while attenuating reductions in performance, such as muscle strength and jump height.

Improved Performance

Literature supports the use of sports compression garments as a recovery technique for improving performance. A recent study showed wearing sports compression during the recovery period following exercise, attenuated reductions in muscle strength by almost 25% compared to no recovery.

Appendix G: Chapter Four - Belief Effect Questionnaires

Participant Name: _____ Date: _____ Time: _____

Directions: Indicate on the line how you feel RIGHT NOW in response to each question.

1. How often do you perform recovery after exercise or competition?

Never 1 2 3 4 5 *Always*

What recovery techniques have you used (if any)?

_____

_____

2. How effective do you think post-exercise recovery techniques are in general?

Not effective at all 1 2 3 4 5 *Extremely effective*

3. How effective do you think the recovery technique L-Arginine will be?

Not effective at all 1 2 3 4 5 *Extremely effective*

4. Do you think the recovery technique L-Arginine will be more effective than no recovery?

Not at all 1 2 3 4 5 *Most definitely*

Participant Name: _____ Date: _____ Time: _____

Directions: Indicate on the line how you feel RIGHT NOW in response to each question.

1. How often do you perform recovery after exercise or competition?

Never — 1 — 2 — 3 — 4 — 5 — *Always*

What recovery techniques have you used (if any)?

_____

_____

2. How effective do you think post-exercise recovery techniques are in general?

Not effective at all — 1 — 2 — 3 — 4 — 5 — *Extremely effective*

3. How effective do you think the recovery technique compression garments will be?

Not effective at all — 1 — 2 — 3 — 4 — 5 — *Extremely effective*

4. Do you think the recovery technique compression garments will be more effective than no recovery?

Not at all — 1 — 2 — 3 — 4 — 5 — *Most definitely*

Participant Name: _____ Date: _____ Time: _____

Directions: Indicate on the line how you feel RIGHT NOW in response to each question

1. How effective do you think post-exercise recovery techniques are in general?

Not effective at all — 1 — 2 — 3 — 4 — 5 — *Extremely effective*

2. How effective was the recovery technique you used?

Not effective at all — 1 — 2 — 3 — 4 — 5 — *Extremely effective*

3. How effective do you think this recovery technique would have been as compared to no recovery technique at all?

Not effective at all — 1 — 2 — 3 — 4 — 5 — *Extremely effective*

4. Would you consider using this recovery technique in the future?

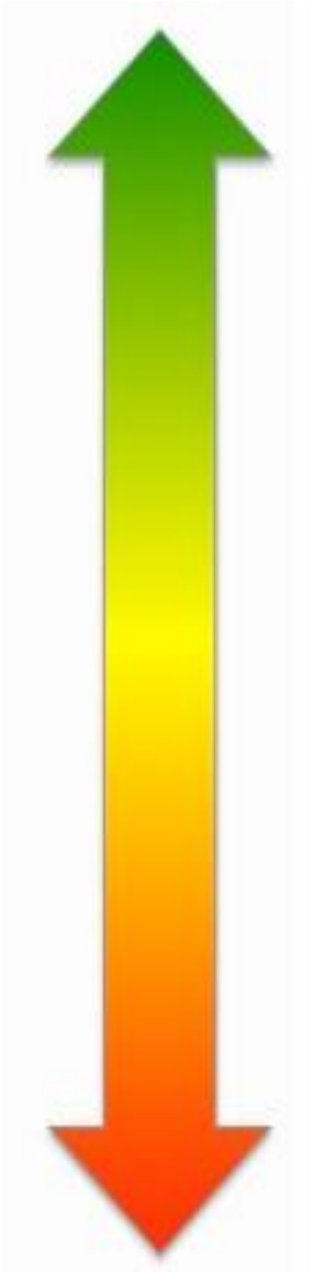
Never again — 1 — 2 — 3 — 4 — 5 — *Most definitely*

Appendix H: Chapter Four – Muscle Soreness Scale

AIS

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

Perceived Muscle Soreness



0 No soreness

1

2 Minimal soreness

3

4 Moderate soreness

5

6 Sore

7

8 Very Sore

9

10 Extremely High Soreness

Appendix I: Chapter Four - Total Quality of Recovery Scale

AIS

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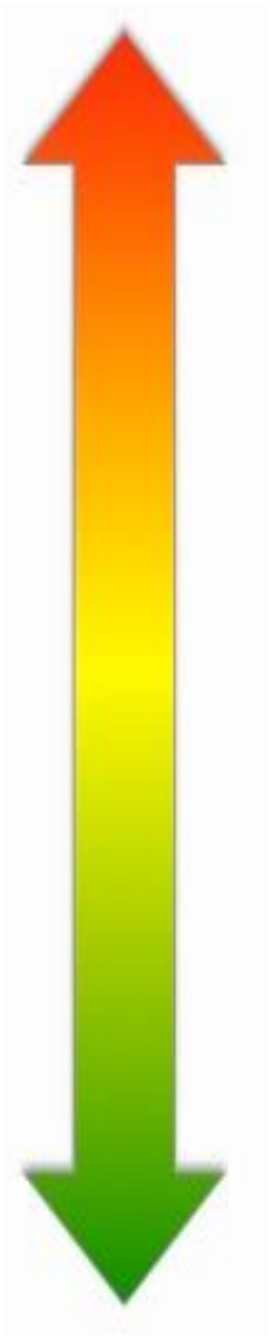
Total Quality of Recovery

Please choose the number on the scale below which best describes your current feeling of recovery.



6

7 Very, very poor recovery

8

9 Very poor recovery

10

11 Poor recovery

12

13 Reasonable recovery

14

15 Good recovery

16

17 Very good recovery

18

19 Very, very good recovery

20

Appendix J: Chapter Four - Participants Information Sheet

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate in a research project entitled:

"COMPARISON OF TWO DIFFERENT RECOVERY STRATEGIES ON POST-EXERCISE BLOOD FLOW AND RECOVERY"

This project is being conducted by Mr Shane O'Riordan, under the supervision of Dr James Broatch, from the Institute for Health and Sport (IHES), Victoria University, Melbourne.

Project explanation

This project aims to compare the influence of two recovery interventions, sports compression garments (SCG) and L-arginine supplementation, on post-exercise blood flow and recovery. As detailed below, you will be required to complete an exercise protocol followed by one of three post-exercise recovery interventions. We are investigating a number of variables through the observations we are taking, and will disclose these, in more detail, at the completion of the study. Testing measures will be collected pre and post-exercise to assess the effectiveness of your intervention in enhancing recovery and altering blood flow. The results of this research will have a significant and direct application to current sporting practice, and will be relevant to all athletes wishing to maximise recovery post-exercise.

What will I be asked to do?

We will first ask you to complete a pre-exercise screening questionnaire about your family medical history and exercise habits to determine your eligibility to participate in this study. If you are eligible for the study, and give your consent to participate, you will be asked to visit the Exercise Physiology Laboratory, Building P, Room PB151, Victoria University, Footscray Park Campus, VIC on four separate occasions to take part in:

- 1 x 1 h familiarisation session and one repetition max testing
- 1 x 5 h testing session
- 2 x 30 min testing session at 24 and 48 h post-exercise

Visit 1 – Familiarisation:
For the first visit, you will also be familiarised with testing measures used in this study, including Doppler ultrasound, near-infrared spectroscopy (NIRS), countermovement jump (CMJ), isometric mid-thigh pull (IMTP), and one repetition max (1RM) testing of leg press. Several anthropometric measures will also be taken at this session. Details of all these procedures are outlined below. In addition, you will be asked to answer a recovery intervention questionnaire for both SCG and L-arginine.

Visit 2 – Testing Session:
For the compression group, sizing of SCG will be done at the beginning of this session. Following 10 min of lying down rest, baseline testing measures will be collected (blood samples, Doppler Ultrasound, NIRS, questionnaires, thigh girth, CMJ, IMTP). You will then complete a lower-body resistance training session (outlined below). Baseline testing measures will be repeated immediately post-exercise. You will then perform your allocated recovery intervention (SCG, L-arginine, or control). You will be required to remain in a resting lying down position for 4 h, with Doppler ultrasound and NIRS measures repeated every 30min, and blood samples, questionnaires and thigh girth repeated every hour. A snack will be provided at 2 h 30 min into recovery. You will be required to perform CMJ and IMTP at the end of your 4 h recovery period. You will be asked to refrain from strenuous exercise (< 48 h) or unaccustomed exercise (< 7 d), prior to each testing session, as these may influence some of the experimental measures.

Visit 3 and 4 – Re-testing Session:
Visits 3 and 4 will require you to return to the laboratory for the re-testing of baseline measures at 24 and 48 h, respectively.

What will I gain from participating?

As a result of participating in this study you can expect to increase your understanding of physiological assessments used by sport scientists, which will be performed in a state-of-the-art and purpose-built facility. You will also gain the experience of participating in an exercise science experiment investigating the effectiveness of different recovery interventions on blood flow and post-exercise recovery. Furthermore, upon completion of the trial, you will receive a pair of 2XU compression tights (RRP AU$175).

How will the information I give be used?

Your data will be stored under alphanumeric codes (i.e. without your name or personal details) and only the researchers will be able to connect the data to you. The data that will be collected during the study will be used/published in peer-reviewed journals, conference presentations, and a research report to 2XU. No personal details will be revealed without your written consent.

What are the potential risks of participating in this project?

Before you volunteer to this study, make sure you read carefully the items below:

1. You are free to withdrawn from this study at any time without any consequences or need for explanation.
2. For any medical emergencies a call to 000 will be made. The researchers will also commence appropriate resuscitation methods while waiting for an emergency team to arrive.
3. There is a small risk of bruising or infection (e.g. tenderness and/or redness) from the blood sampling procedures. This risk will be minimised with blood sampling undertaken by trained personnel under sterile conditions.
4. For the application of NIRS, the sites will require shaving some hair to ensure a good signal. This may result in a slight abrasion of your skin.
5. All exercise activity carries a risk of injury, fainting and risks of sudden death due to myocardial infarction and/or stroke. It is important that you tell us if you have any medical condition. The risk of such events is in reality very low.
6. There is a small risk of nausea, abdominal pain, and worsening of allergies and asthma from L-arginine supplementation. This risk is minimal as the total L-arginine ingested in this study is 2.2 g, with 20 g per day considered safe.
7. There is a risk of muscle soreness as a result of the exercise protocol (lower-body resistance training). This is a normal response to this type of exercise, and while uncomfortable, it poses no health risk to you and passes after several days.
8. Furthermore, exercise can be accompanied in rare cases by the possibility of mood changes such as irritability and depression. These changes are however short term and can be reversed with a maximum of two to three weeks of recovery. To minimise the risk of any psychological stress, your results will remain confidential. Should you experience any adverse or unusual psychological changes, you will be immediately removed from the study and "debriefed" by speaking with the psychologist associated with this study, Dr Glen Hosking (Victoria University Psychologist). Dr Glen Hosking can be contacted on (03) 9919 2266. With this safeguard in place, you will have access to counselling, free of charge in the case of any psychological event.

How will this project be conducted?

Pre-experiment screening:

All testing will be conducted in accordance with current guidelines for testing in the Exercise Physiology Laboratory, Building P, Room PB151, Victoria University, Footscray Park Campus, VIC. You will initially be screened for cardiovascular risk factors and any health issues of relevance to the study. If you are suffering from severe pulmonary disorders, have high blood pressure, diabetes and arrhythmias, or have risk of an adverse event from conditions (e.g. musculoskeletal injuries), you will

be excluded from participating in this study. If you are deemed healthy and at low risk of any adverse events, we will then request you to complete the four sessions involved in this study.

Familiarisation session and 1RM Testing (visit 1):

During this session you will be familiarised with the testing measures used during the testing sessions, 1RM testing and answering a recovery intervention questionnaire about both SCG and L-arginine. Further information for these tests are detailed below. The 1RM test will require you to lift the maximum amount of weight possible for one repetition of leg press. This will require you to perform one repetition of leg press, with weight gradually increasing until failure or loss of technique. You will be allowed 3 min of rest between each maximal attempts. Your successful 1RM will be the greatest weight lifted for one repetition with correct form through a complete range of motion. Further information for these tests are detailed below.

Testing session 1 (visit 2):

This session will be conducted as follows:

- Sizing of SCG (compression group only).
- 10 min lying down rest required prior to testing.
- Following lying down rest, blood samples, Doppler ultrasound, NIRS, questionnaires, thigh girth, CMJ and IMTP measures will be collected in this order.
- Lower-body resistance training session.
- Re-testing of baseline measures.
- You will then undertake one of three interventions (SCG, L-arginine, or control).
- Lying down rest for 4 h.
- Re-testing of Doppler ultrasound and NIRS every 30 min, with re-testing of blood samples, questionnaires and thigh girth every 1 h. Finally, CMJ and IMTP will be performed at the end of 4 h lying down rest.

Testing session 2 (visit 3) and 3 (visit 4):

These sessions will be conducted as follows:

- 10 min lying down rest required prior to testing.
- Re-testing of baseline measures, in same order as visit 2.

Testing Protocols:

- Anthropometry Measures: Your height and weight will be measured during the familiarisation session. Thigh girth will be measured on your right thigh. Skinfold measurements will be performed on your right lower limb at the mid-thigh and mid-calf.

- Interventions: You will be allocated one of three interventions, SCG, L-arginine, or control. SCG intervention will require you to wear SCG (2XU Recovery Tights) for a duration of 4 h, while lying down after post-exercise measures. L-arginine supplement will require you to lie down for 4 h and ingest a tablet at 0, 1, 2 and 3 h after post-exercise measures. Control group will be required to lie down for 4 h after post-exercise measures.

- Kikuhime Pressure Monitor: For the SCG intervention, the pressure exerted by the garment will be measured using the kikuhime device. This device contains a small air-filled piece of plastic that is placed between the garment and your skin. Garment pressure will be measured in both standing and lying down positions on your right limb at the mid-thigh and mid-calf.

- Nutritional Controls: Prior to visit 2, you will be asked to compete a 24 h nutritional record. It will be returned to you, and you will be asked to replicate the diet as closely as possible before visits 3 and 4. In addition, you will be asked to refrain from caffeine and alcohol ingestion (< 12 h) prior to visits 2, 3 and 4. You will be provided a snack (Aussie Bodies, Protein FX Super Bar, New Zealand) containing 25.6 g protein and 18.4 g carbohydrate at 2 h 30 min after post-exercise measures. The same snack will be given to you to consume after visit 3.

- Blood Samples: During your second visit, a cannula will be inserted in your forearm, which will remain in place for the duration of your second visit. This cannula will allow us to collect blood samples (10 mL) without the need to insert a new needle every time a sample is required. Blood samples for visits three and four will be collected using a standard venepuncture technique. In addition, at the beginning of visits two, three and four, a single capillary blood sample (100 µL) will be taken from your fingertip via pinprick, collected in a capillary tube and immediately analysed for haemoglobin concentration. Trained personnel will conduct all cannulations and blood collections under sterile conditions.

- Doppler Ultrasound: This technique will be used to measure markers of venous return (blood flow) in your popliteal (behind the knee) and femoral (upper-thigh) veins. Lubricating jelly will be applied to each site to help transmit the signal. Ultrasound signals will be measured for 60 s in order to obtain measures of venous return.

- NIRS: Non-invasive oximeters will be placed on your right leg at the mid-thigh and mid-calf. A venous occlusion will be performed to measure your blood flow. This will require inflation of a pressure cuff applied to your upper thigh for 20 s. The level of pressure exerted (70 mmHg) is roughly one-third of that exerted during a standard blood pressure test. Following 45 s rest, this will be repeated two more times. This procedure allows us to investigate muscle blood flow and oxygenation for each condition.

- Perceptual Questionnaires:
  - *Total Quality of Recovery Questionnaire*: You will be asked to provide a quality of recovery rating on a scale from 6 (no recovery) to 20 (maximal recovery).

  - *Perceived Muscle Soreness Questionnaire:* You will be asked to provide a muscle soreness rating, via self-palpation of the exercised muscle using a visual analogue scale (0 = nothing at all, 10 = extremely high).

  - *Recovery Intervention Questionnaire:* You will be asked to rate the anticipated effectiveness of both recovery interventions on a 0 to 5 point Likert scale, with 0 representing 'not effective at all' and 5 representing 'extremely effective' following visit 1. You will also be asked to rate the perceived effectiveness of the completed recovery intervention on a similar Likert scale after visit 4.

- Countermovement Jump: Prior to performing CMJs, you will be required to perform a standardized warm-up of 5 min cycling, 10 repetitions of body weight squats, 10 repetitions on each leg of bodyweight walking lunges and 3 submaximal CMJs. For the CMJ test, you will be required to perform a quick downward movement, followed immediately by a fast vertical jump, with your hands placed on your hips. You will be asked to complete 5 CMJs, with 8 seconds rest between repetitions. This will allow us to investigate the effects of your intervention on performance recovery.

- Isometric Mid-Thigh Pull: You will be required to pull upward as hard as possible on an immovable bar for 3 seconds. Two repetitions will be performed separated by 2 min rest, with a third repetition performed if a 250N difference is seen between peak forces of the first two efforts. This will allow us to investigate the effects of your intervention on performance recovery.

- Lower-Body Resistance Training Session: Following the performance tests (CMJ and IMTP) you will be required to do a lower-body resistance training session. You will assume a seated position in the leg press machine, and place feet shoulder-width apart and flat on the platform. You will lower the platform slowly for a duration of 4s and then push the platform back to starting position by extending your legs until knees are slightly bent. This will be one rep. You will be required to perform 8 sets of 6 reps of leg press. The weight you will be required to lift for 6 reps will be approximately 85% of your 1RM testing during visit 1. You will receive 3 min of rest between each set.

Who is conducting the study?

The study is conducted by the Institute for Health and Sport (IHES), Victoria University, Footscray Park Campus. The main investigators are:

Principal Investigators:
Mr Shane O'Riordan, Mobile: 0414 703 872, email: shane.oriordan@live.vu.edu.au
Dr James Broatch, Mobile: 0422 050 361, email: james.broatch@vu.edu.au

Associate Investigators:
Prof David Bishop
Dr Shona Halson
Dr Sally Clark

Any queries about your participation in this project may be directed to the principal investigators, Mr Shane O'Riordan or Dr James Broatch, with contact details above. If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001, email researchethics@vu.edu.au or phone (03) 9919 4781 or 4461.

Appendix K: Chapter Four - Informed Consent

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

INFORMATION TO PARTICIPANTS:

We would like to invite you to be a part of a study entitled:

"COMPARISON OF TWO DIFFERENT RECOVERY STRATEGIES ON POST-EXERCISE BLOOD FLOW AND RECOVERY"

(a) AIMS OF THE STUDY:

- This project aims to investigate the efficacy of two recovery interventions, sport compression garments (SCG) and L-arginine supplementation, as post-exercise recovery modalities and their influence on blood flow.

(b) PROCEDURES INVOLVED AND NATURE OF THE PROJECT:

- Participants will be requested to attend the Exercise Physiology Laboratory, Building P, Room PB151, Victoria University, Footscray Park Campus, VIC on four separate occasions.

- Familiarisation Session and One Rep Max Testing: You will be asked to attend the Exercise Physiology Laboratory, Building P, Room PB151, Victoria University, Footscray Park Campus, VIC for a familiarisation session and one rep max (1RM) testing of leg press. This will take approximately 45min – 60min, in which you will be asked to answer a recovery intervention questionnaire for both SCG and L-arginine. You will also be familiarised with testing measures used in this study, including Doppler ultrasound, near-infrared spectroscopy (NIRS), countermovement jump (CMJ) and isometric mid-thigh pull (IMTP). Several anthropometric measures will also be taken at this session. In addition, you will complete testing to determine your 1RM for leg press. Details of all these procedures are below.

- Testing Sessions: You will be asked to attend the Exercise Physiology Laboratory, Building P, Room PB151, Victoria University, Footscray Park Campus, VIC for testing sessions over three consecutive days. Day 1 will firstly involve the sizing of SCG (compression group only), followed by the collection of all testing measures (blood samples, Doppler ultrasound, NIRS, questionnaires, thigh girth, CMJ, IMTP). You will then be required to perform a lower-body resistance training session (outlined below), with testing measures repeated immediately post-exercise. You will then perform your allocated recovery intervention (SCG, L-arginine or control). You will be required to remain in a lying down position for 4 h, with Doppler ultrasound and NIRS measures repeated every 30 min, and blood samples, questionnaires and thigh girth repeated every hour. A snack will be provided at 2 h 30 min into recovery. You will be required to perform CMJs and IMTP at the end of your 4 h recovery period. You will return to the laboratory 24 and 48 h later to repeat all testing measures.

- Anthropometry Measures: Your height and weight will be measured during the familiarisation session. Thigh girth will be measured on your right thigh. Skinfold measurements will be performed on your right lower limb at the mid-thigh and mid-calf.

- Interventions: You will be allocated one of three interventions, SCG, L-arginine or control. SCG intervention will require you to wear SCG (2XU Recovery Tights) for a duration of 4 h, while lying down after post-exercise measures. L-arginine supplement will require you to ingest a tablet at 0, 1, 2 and 3 h after post-exercise testing. Control group will be required to lie down for 4 h after post-exercise measures.

- Kikuhime Pressure Monitor: For the SCG intervention, the pressure exerted by the garment will be measured using the kikuhime device. This device contains a small air-filled piece of plastic that is placed between the garment and your skin. Garment pressure will be measured in both standing and lying down positions on your right limb at the mid-thigh and mid-calf.

- Nutritional Controls: Prior to visit 2, you will be asked to compete a 24 h nutritional record. It will be returned to you, and you will be asked to replicate the diet as closely as possible before visits 3 and 4. In addition, you will be asked to refrain from caffeine and alcohol ingestion (< 12 h) prior to visits 2, 3 and 4. You will be provided a snack at 2 h 30 min after post-exercise measures, with the same snack given to you to consume after visit 3.

- Blood Samples: During your second visit, a cannula will be inserted in your forearm, which will remain in place for the duration of your second visit. This cannula will allow us to collect blood samples without having to insert a new needle every time a sample is required. Blood samples for visit three and four will be collected using a standard venepuncture technique. Blood samples will be de-identified (e.g., 1A, 1B, 1C corresponds to participant 1 at time points A-C) and stored at -80°C for subsequent analysis. In addition, at the beginning of visits two, three and four, a single capillary blood sample will be taken from your fingertip via pinprick. Trained personnel will conduct all cannulations and blood collections under sterile conditions.

- Doppler Ultrasound: This technique will be used to measure markers of venous return (blood flow) for the popliteal (behind the knee) and femoral (upper-thigh) veins.

- NIRS: This procedure allows us to investigate changes in muscle blood flow and oxygenation. A venous occlusion will be performed, which requires the inflation of a pressure cuff applied to your upper thigh for 20s. Following 45s rest, this will be repeated two more times.

- Perceptual Questionnaires:

  - *Total Quality of Recovery Questionnaire*: You will be asked to provide a quality of recovery rating on a scale from 6 (no recovery) to 20 (maximal recovery).

  - *Perceived Muscle Soreness Questionnaire*: You will be asked to provide a muscle soreness rating, via self-palpation of the exercised muscle using a visual analogue scale (0 = nothing at all, 10 = extremely high).

  - *Recovery Intervention Questionnaire:* You will be asked to rate the anticipated effectiveness of both recovery interventions on a 0 to 5 point Likert scale, with 0 representing 'not effective at all' and 5 representing 'extremely effective' following visit 1. You will also be asked to rate the perceived effectiveness of the completed recovery intervention on a similar Likert scale after visit 4.

- Countermovement Jump: Prior to performing CMJs, you will be asked to perform a standardized warm-up. CMJs involve performing a quick downward movement, followed immediately by a fast vertical jump. This will allow us to investigate the effects of your intervention on performance recovery.

- Isometric Mid-Thigh Pull: This will involve pulling upward on a fixed barbell as quickly as possible and continuing your effort for three seconds. This will allow us to investigate the effects of your intervention on performance recovery.

- 1RM Testing: This will involve you lifting as much weight as possible for 1 repetition of leg press. This will allow us to determine your individual workload (weight lifted) for the lower-body resistance training session during visit 2.

- Lower-Body Resistance Training Session: Following the performance tests (CMJ and IMTP), you will undertake a lower-body resistance training session. You will be required to perform 8 sets of 6 reps of leg press. The weight you will be required to lift for 6 reps will be approximately 85% of your 1RM testing during visit 1. You will receive 3 min of rest between each set.

CERTIFICATION BY PARTICIPANT

I, _____(Phone No:)_____

of _____

certify that I am at least 18 years old and that I am voluntarily giving my consent to participate in the study:

"COMPARISON OF TWO DIFFERENT RECOVERY STRATEGIES ON POST-EXERCISE BLOOD FLOW AND RECOVERY"

I certify that the objectives of the study, together with any risks and safeguards associated with the procedures listed hereunder to be carried out in the research, have been fully explained to me by **Mr Shane O'Riordan and/or Dr James Broatch** and that I freely consent to participation involving the below mentioned procedures:

Participants will be requested to attend the Exercise Physiology Laboratory, Building P, Room PB151, Victoria University, Footscray Park Campus on four separate occasions.

I certify that I have had the opportunity to have any questions answered and that I understand that I can withdraw from this study at any time and that this withdrawal will not jeopardise me in any way.

I consent to further analysis of my tissue samples provided.

I have been informed that the information I provide will be kept confidential.

Signed: _____

Date: _____

Any queries about your participation in this project may be directed to the principal researchers:

Mr Shane O'Riordan
Telephone number: 0414 703 872
Email: shane.oriordan@live.vu.edu.au

Dr James Broatch
Telephone number: 0422 050 361
Email: james.broatch@vu.edu.au

If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001, email Researchethics@vu.edu.au or phone (03) 9919 4781 or 4461.

Appendix L: Chapter Five - Participant Information Sheet

TO: Participants

Plain Language Statement

Title	*Do lower-limb sports compression garments enhance microvascular blood flow?*
Protocol Number	*HREA - JB03486*
Coordinating Principal Investigator/ Principal Investigator	*Dr Lewan Parker*
Associate Investigator(s)	*Dr James Broatch* *A/Prof. Michelle Keske* *Dr Andrew Betik* *Mr Shane O'Riordan* *Prof. David Bishop* *Dr Shona Halson*
Location:	*Deakin University (Burwood Campus)*

1 Your Consent

You are invited to take part in this research project which will investigate whether sports compression garments can increase skeletal muscle microvascular blood flow (small blood vessels).

This Plain Language Statement and Consent Form contains detailed information about the research project. It explains the tests and treatments involved. Knowing what is involved will help you decide if you want to take part in the research or not.

Please read this information carefully. Ask questions about anything that you don't understand or want to know more about. Before deciding whether or not to take part, you might want to talk about it with a relative, friend or your local doctor.

Participation in this research is voluntary. If you don't wish to take part, you don't have to. Your choice to participate, withdraw, or not participate, will have no effect on your academic grades, employment, or memberships.

If you decide you want to take part in the research project, you will be asked to sign the consent section. By signing it you are telling us that you:
- Understand what you have read
- Consent to take part in the research project
- Consent to have the tests and treatments that are described
- Consent to the use of your personal and health information as described.

You will be given a copy of this Plain Language Statement and Consent Form to keep.

2 What is the purpose of this research?

Sports compression garments (SCG) are commonly used by athletes as a means to improve exercise performance and aid muscle recovery. Although the exact mechanisms are unclear, these improvements may be related to improved muscle blood flow. Increased muscle blood flow will increase oxygen and nutrient delivery to the muscle, thereby improving exercise performance and muscle recovery. The microvascular system (small blood vessels/capillaries) is important for the delivery and exchange of nutrients and hormones within the body (e.g., oxygen, glucose and insulin), and whether SCG alter microvascular blood flow is currently unknown. The main aims of this project are:

1: To determine whether SCG improve skeletal muscle microvascular blood flow.

This project is being conducted by Dr Lewan Parker, Dr Andrew Betik, and A/Prof Michelle Keske from Deakin University, as well as Dr James Broatch, Prof David Bishop, Dr Shona Halson, and Mr Shane O'Riordan from Victoria University.

You might be eligible for this study if you meet the following criteria:

- Aged 18–40 years
- Normal weight (BMI 18-27 kg/m^2)
- Performing regular aerobic exercise (i.e., > 90 min of moderate-to-high intensity aerobic exercise per week)
- Do not have high blood pressure
- The absence of cardiometabolic disease or other conditions that may preclude your ability to undergo cycling exercise
- Are not currently smoking
- Are not currently pregnant or breast-feeding
- Have given signed informed consent to participate in the study

There are no additional costs associated with participating in this research project. All tests and equipment required as part of the research project will be provided to you free of charge. You will not be paid for participation in this project, but will be able to keep the compression garment tights used for testing ($200 RRP) once you have completed the study.

3 What does participation in this research involve?

Prior to enrolment in the study you will be asked to complete a set of questionnaires to identify conditions that may exclude you from participating. We may also discuss your participation with your current GP or specialist. If there is evidence of risk, this study may not be suitable for you.

After enrolment into the study, you will be asked to undergo/perform the following sessions and procedures:

- **Visit 1 – Screening and familiarisation session (~1 h).**
  - General health, physical activity and medical history questionnaires
  - Resting heart rate and blood pressure and body composition analysis
  - Repeated-sprint ability and performance measure familiarisations
  - Wear a face mask/mouthpiece to measure your oxygen consumption.

- **Visits 2 and 3– Main testing sessions (~3 h).**
  - High-intensity cycling exercise: 4 sets of 10 x 6-s maximal sprints, with 24 seconds of rest between sprints, and 2 min of rest between sprint sets
  - Wear compression tights for one testing session, and no compression the other
  - Venous blood sampling and infusion of an approved solution
  - Ultrasound measurement of the thigh
  - Non-invasive assessment of muscle oxygenation
  - Wear a face mask/mouthpiece to measure your oxygen consumption

The overall time commitment for this study is around 7 hours, spread across 7-10 days. All testing sessions will take place at the Deakin University (Burwood campus) research facilities, building J, level 5.

4 What do I have to do?

For each testing visit (all 3 visits), you will be asked to avoid exercise (apart from what is prescribed) and alcohol for 48 h prior to attending the Deakin University research facility. You will also be asked to avoid caffeine on the day of the study and fast (no food) for 2 h before coming into the research laboratory.

Visit 1 – Screening and familiarisation session

For this visit you will be asked to attend the Deakin University research laboratory (Burwood Campus, Building J, Level 5). Your resting heart rate, blood pressure, and body composition will be measured. You will then be asked to perform two sets of the repeated-sprint ability protocol (20 x 6-s sprints total) for familiarisation, as well as the performance measure protocol. Your oxygen consumption will be measured (using a mouthpiece) during 6 of these 20 sprints.

- **Body composition.** Your height will be measured while you will stand barefoot on a stadiometer. Your weight will be measured on a standard scale. Your hip and waist circumference will be measured via a standard measuring tape. You will be asked to stand wearing just light clothes.

- **Repeated-sprint ability familiarisation.** The exercise will be performed on a cycle-ergometer. Following a 5-minute cycling warm-up at low-intensity, you will be asked to complete two sets of 10 x 6-s maximal sprints (i.e., 20 sprints in total). Individual sprints will be separated by 24 seconds of rest, and sprint sets will be separated by 2 minutes of rest. During the 1st, 5th, and 9th sprint of each set, we will analyse your body oxygen consumption and fuel metabolism (you will be asked to breathe into a mouthpiece/mask). We will also measure your heart rate and blood pressure throughout.

- **Performance measure familiarisation.** Similar to the repeated-sprint protocol, we will measure your exercise performance during a 6-s maximal sprint on the cycle ergometer. Your performance will be measured by the amount of power you are able to produce during each sprint. During familiarisation, we will ask you to do a single 6-s sprint on two separate occasions; 1) after the 5-minute warm up, and 2) after the 2nd sprint set.

Visits 2 and 3 – Main Testing Sessions.

For this visit you will be asked to attend the Deakin University research laboratory after a 2 h fast. Upon arriving at the laboratory, an intravenous cannula will be inserted into each arm, one for blood sampling and one to infuse a safe microbubble solution (detailed later). After a baseline blood sample the microbubble infusion will commence, and you will be asked to rest on a hospital bed for 30 min. You will then be asked to perform a 5-min cycling warm-up, followed by the full (4 sets of 10 x 6-s sprints) repeated-sprint ability protocol. Whole body oxygen consumption and muscle oxygenation will be measured during the exercise protocol. After the exercise session, you will be asked to lie down on a bed and rest quietly for 1 hour. Blood samples and ultrasound measurements will be taken regularly during visits 2 and 3.

- **Repeated-sprint ability protocol.** The exercise will be performed on a cycle-ergometer. Following a 5-minute cycling warm-up at low-intensity, you will be asked to complete four sets of 10 x 6-s maximal sprints (i.e., 40 sprints in total). Individual sprints will be separated by 24 seconds of rest, and sprint sets will be separated by 2 minutes of rest. During the 1st, 5th, and 9th sprint of each set, we will analyse your body oxygen

consumption and fuel metabolism (you will be asked to breathe into a mouthpiece/mask). We will also measure your heart rate and blood pressure throughout.

- **Performance measure.** Similar to the familiarisation, we will measure your exercise performance during a 6-s maximal sprint on the cycle ergometer. We will ask you to do a single 6-s performance sprint on three separate occasions; 1) after the 5-minute warm up, 2) after the 4th sprint set, and 3) 1 hour after exercise.

- **Blood Sampling.** Research staff qualified to perform cannulation and venepuncture will collect blood samples via intravenous catheter and venepuncture. Catheters are used when several blood samples are needed from one site over a brief duration such as to be used here. Once the catheter is in place, it is a simple and painless procedure to remove further blood samples. It is possible, although unlikely, that some minor bruising may occur around the site of cannulation. For visits 2 and 3, 12 venous blood samples (10 mL each) will be taken in total, for each session. The volume of blood collected at each visit (120 mL), and the combined total blood volume collected over the study (240 mL), is substantially less than the amount provided during a single blood donation (~500 mL). Venous blood samples will be analysed for markers of vascular function and cardiometabolic health (e.g., markers of inflammation and bone, lipid and glucose metabolism), and exercise metabolism (e.g., lactate, pH, and oxygen saturation).

- **Ultrasound measurements.** We will use a specific ultrasound technique to measure how well blood is flowing through the small blood vessels in the muscle of your thigh. This will require infusing a contrast agent (called Definity) into one of your veins so that pictures of these small blood vessels can be taken. To do this a small plastic cannula will be inserted into a vein on your forearm using a needle. The insertion of the needle can be uncomfortable (similar to receiving an injection or donating blood). However, once the catheter is in place the needle is removed and the infusion procedure is painless. We will also measure how blood is moving through your leg by placing a non-invasive ultrasound probe on the surface of the skin of your thigh to image the arteries within the thigh. Ultrasound measurements will be taken at baseline, immediately after the 3rd and 4th sprints sets, and 60 minutes after exercise.

- **Near-infrared Spectroscopy (NIRS).** This technique is used to measure the amount of oxygen present in your muscle. It is a non-invasive and pain-free technique, in which a probe is placed on your skin over the muscle in your thigh, and an infrared light is sent into your muscle. This infrared signal will record the changes in haemoglobin (the oxygen carrying protein in your blood) in your muscle during the exercise protocol and recovery. To ensure a good signal is received, we will need to clean the area on your leg muscle by shaving the hair off and swabbing the skin with an alcohol swab.

- **Compression Garments.** You will be required to complete the exercise protocol under two conditions: 1) whilst wearing compression tights, and 2) without wearing compression tights. The order in which you perform these conditions will be randomised between Visits 2 and 3. For the trial you are wearing compression, we will measure how much pressure the garment is applying to your skin (at three locations on your leg) with a hand-held pressure monitoring device.

5 Do I have to take part in this research project?

Participation in any research project is voluntary. If you do not wish to take part, you do not have to. If you decide to take part and later change your mind, you are free to withdraw from the project at any stage.

Your decision whether to take part or not to take part, or to take part and then withdraw, will not affect your routine treatment, your relationship with those treating you or your relationship with Deakin University.

Before you make your decision, a member of the research team will be available to answer any questions you have about the research project. You can ask for any information you want. Sign the Consent Form only after you have had a chance to ask your questions and have received satisfactory answers.

If you decide to withdraw from this project, please notify a member of the research team. This notice will allow that person or the research supervisor to inform you if there are any health risks or special requirements linked to withdrawing.

6 What are the possible benefits of taking part?

We cannot guarantee or promise that you will receive any direct benefits from this research; however, possible benefits may include gaining a better understanding of your general health and how compression garments may be used to improve blood flow and exercise performance.

7 What are the possible risks and disadvantages of taking part?

Before you volunteer to be part of this study, there are some important things to understand:

- It is important that you do not have one or more of the following conditions;
  i. Previous heart attack or cardiac arrest.
  ii. Heart failure.
  iii. Exercise test that resulted in chest pain, or chest pain at any other time in the past 6 months related to exertion.
  iv. Current muscle and joint pain (e.g., arthritis) and/or nerve pain that will prevent comfortable participation in exercise.
- All exercise activity carries a risk of injury and, in extreme cases, risks of suffering a heart attack or stroke. We will take all reasonable precautions when performing the exercise sessions. All exercise will be supervised by experienced exercise scientists and the microbubble infusions supervised by personnel trained in advance first aid and resuscitation and are familiar with the procedures involved.

Other known risks of this study are possibly:

- Having a drug injected or blood sample taken may cause some discomfort, bruising, minor infection or bleeding. If this happens, it can be easily treated.

- A small number of people (8.4% of people) have side-effects during the infusion of the contrast agent (Definity) during ultrasound imaging. The most common of these side-effects include:
  i) Back pain (1.2% of people)
  ii) Chest pain (0.8%)
  iii) Headache (2.3%)
  iv) Dizziness (0.6%)
  v) Nausea (1.0%)
  vi) Flushing (1.1%)

These symptoms usually go away quickly once the infusion is stopped.

- You may experience hyperventilation (quicker rate of breathing) during the exercise. There is no physical danger involved with this measurement. If you feel uncomfortable at any time, you can easily remove the facemask / mouthpiece

- During the exercise session, you may experience some muscle or other soft tissue soreness. In this case, you will be treated immediately using appropriate sports first aid (e.g., ice treatment). If an injury persists, or the injury needs medical evaluation and/or treatment, you will be referred to appropriate medical or allied health practitioners at no cost to you, and will not return to the study until cleared to do so by the treating practitioner.

- It is important that women participating in this study are not pregnant. It is important to let the researchers know if you think you might be pregnant. If you think you might be pregnant then we cannot enrol you into the study.

There may be additional unforeseen or unknown risks.

We will use every possible safety measure to protect you while performing the activities in this research:

- In the case of medical emergencies, a call to 000 will be made. The researchers and/or research team medical Doctor will commence appropriate resuscitation methods or other appropriate procedures (e.g., administration of adrenalin) while waiting for an emergency team to arrive. In the event of emergencies, you will need to undergo an additional medical review and consent process before you will be permitted to return to the study. The research team medical Doctor will be present during the infusion of microbubbles, and contactable via mobile at all other times during the study.

- For all other adverse events of a physical nature, exercise will be terminated immediately, you will be consulted and reassured and then we will make arrangements for you for appropriate follow-up (e.g., immediate review by a medical practitioner or early referral to an appropriate health professional) at no cost to you.

- In the case of any reportable (e.g., more serious than just muscle soreness in response to new exercise) adverse event (whether described above or not), one of the medical doctors involved in the study will be informed as soon as practicable, and upon review make a decision regarding the safety of continued participation in the study.

If you become upset or distressed as a result of your participation in the research, the study doctor will be able to arrange for counselling or other appropriate support. Any counselling or support will be provided by qualified staff who are not members of the research project team. This counselling will be provided free of charge.

8 What will happen to my test samples?

The collection of venous blood is a mandatory component of the research project and will be utilised for both medical health screening and research purposes. Blood samples and subsequent data will be coded with a re-identifiable ID number and stored for a minimum of 5 years at Deakin University (Burwood Campus). Blood will be analysed for glucose, insulin, and markers of cardiometabolic and vascular health.

9 Can I have other treatments during this research project?

Whilst you are participating in this research project, you may not be able to take some or all of the medications or supplements you have been taking for your condition or for other reasons. It is important to tell the research staff about any treatments or medications you may be taking, including over-the-counter medications, vitamins or herbal remedies, acupuncture or other alternative treatments. You should also tell the researchers about any changes to these during your participation in the research project. The researcher will explain to you which treatments or medications may need to be stopped for the time you are involved in the research project or you may be excluded from participation.

10 What if I withdraw from this research project?

You can withdraw from the study at any time. If you decide to withdraw from the project, please notify a member of the research team.

With your permission, the information already collected will be retained to ensure that the results of the research project can be measured properly and to comply with law. You should be aware that data collected by the research team up to the time you withdraw will form part of the research project results. If you do not want them to do this, you must tell them before you join the research project.

11 What happens when the research project ends?

Following participation in the research project you will be provided with a health report detailing some of the results that have been collected. However, many of the main findings of the research project will not be available until completion of the research project and data analysis of all participants has been completed. Upon finalisation of the results, you will be notified of the main findings of the research project.

We hope that results from this study will be published in a medical journal. Information will be reported as a group data and you will not be individually identified. We will also be happy to provide you, upon request, with the results of the project and/or relevant publications.

Part 2 How is the research project being conducted?

12 What will happen to information about me?

By signing the consent form you consent to the relevant research staff to collect and use personal information about you for the research project. Any information obtained in connection with this research project that can identify you will remain confidential. All information is re-identifiable (coded). Only the research staff will have the code and access to the data. Your information will only be used for the purpose of this research project and it will only be disclosed with your permission, except as required by law. We will also ask your permission to use the data in future studies in the same area of research.

Information about you may be obtained from your health records held at this and other health services for the purpose of this research. By signing the consent form you agree to the study team accessing health records if they are relevant to your participation in this research project.

It is anticipated that the results of this research project will be published and/or presented in a variety of forums. In any publication and/or presentation, information will be provided in such a way that you cannot be identified, except with your permission. All data will be presented as the average of the group.

In accordance with relevant Australian and/or Victoria privacy and other relevant laws, you have the right to request access to your information collected and stored by the research team. Please contact the study team member named at the end of this document if you would like to access your information.

13 Complaints

If you require further information or if you have any problems concerning this project, you can contact the principal researchers:

Dr James Broatch, +61 422 050 361, james.broatch@vu.edu.au
Dr Lewan Parker, +61 3 9246 8740, lewan.parker@deakin.edu.au

If you have any complaints about any aspect of the project, the way it is being conducted or any questions about your rights as a research participant, then you may contact:

The Manager, Office of Research Integrity, Deakin University, 221 Burwood Highway, Burwood Victoria 3125, Telephone: 03 9251 7129, Facsimile: 9244 6581; research-ethics@deakin.edu.au. Please quote the project protocol number: HREA - JB03486

14 Who is organising and funding the research?

This research project is being conducted in by Deakin and Victoria Universities, and funded by 2XU.

By taking part in this research project you agree that samples of your blood or tissue (or data generated from analysis of these materials) may be provided to Deakin University.

You or your family will not benefit financially from your involvement in this research project even if, for example, your samples (or knowledge acquired from analysis of your samples) prove to be of commercial value to Deakin University, Victoria University, or 2XU.

No member of the research team will receive a personal financial benefit from your involvement in this research project (other than their ordinary wages).

15 Who has reviewed the research project and is it approved?

All research in Australia involving humans is reviewed by an independent group of people called a Human Research Ethics Committee (HREC). The ethical aspects of this research project have been approved by the Deakin University Human Research Ethics Committee (DUHREC). This project will be carried out according to the principles of ICH Good Clinical Practice and the National Statement of Ethical Conduct in Human Research (2007) produced by the National Health and Medical Research Council (NHMRC). This statement has been developed to protect the interests of people who agree to participate in human research studies.

16 Further information and who to contact

The person you may need to contact will depend on the nature of your query.

If you want any further information concerning this project or if you have any medical problems which may be related to your involvement in the project (for example, any side effects), you can contact the research staff:

Dr James Broatch, +61 422 050 361, james.broatch@vu.edu.au
Dr Lewan Parker: +61 3 9246 8740, lewan.parker@deakin.edu.au

Research medical doctor

Name	Dr Andrew Garnham
Position	Research team medical doctor
Telephone	+61 4 16246911
Email	Andrew.garnham@deakin.edu.au

If you have any complaints about any aspect of the project, the way it is being conducted or any questions about being a research participant in general, then you may contact:

Complaints contact details

Position	The Manager, Office of Research Integrity
Telephone	(03) 9251 7129
Email	research-ethics@deakin.edu.au

Appendix M: Chapter Five - Informed Consent

Consent Form - *Adult providing own consent*

Title	*Do lower-limb sports compression garments enhance microvascular blood flow?*
Protocol Number	*HREA - JB03486*
Coordinating Principal Investigator/ Principal Investigator	*Dr Lewan Parker*
Associate Investigator(s)	*Dr James Broatch* *A/Prof. Michelle Keske* *Dr Andrew Betik* *Mr Shane O'Riordan* *Prof. David Bishop* *Dr Shona Halson*

Declaration by Participant

I have read the Participant Information Sheet or someone has read it to me in a language that I understand.

I understand the purposes, procedures and risks of the research described in the project, and that I freely consent to participation involving the below mentioned procedures:

- General health, physical activity and medical history questionnaires
- Body composition analysis
- Repeated-sprint ability protocol (4 sets of 10 x 6-s maximal sprints)
- Exercise performance test (single 6-s maximal sprints)
- Ultrasound assessment of the thigh
- Blood sampling and infusion of Definity microbubble solution via intravenous cannula
- Measurement of oxygen consumption
- Measurement of muscle oxygenation via NIRS

I have had an opportunity to ask questions and I am satisfied with the answers I have received.

I freely agree to participate in this research project as described and I understand that I am free to withdraw from the study at any stage without any consequences. If I decide to withdraw from the study, I agree that the information collected about me up to the point when I withdraw may continue to be processed.

I understand that the researchers will not reveal my identity and personal details if information about this project is published or presented in any public form.

I understand that I will be given a signed copy of this document to keep.

Name of Participant (please print) _____

Signature _____ Date _____

Opportunities may arise for tissue samples and data from this study to be incorporated into to future research and publications.

I (the participant) give permission to use the data and tissues collected during the study in future research and/or publications. The future use may include comparison of my data to data from other studies, and the future analysis of blood samples for proteins, enzymes and other factors that are related to muscle function, performance and health.

Name of Participant (please print) _____

Signature _____ Date _____

Declaration by Researcher†

I have given a verbal explanation of the research project, its procedures and risks and I believe that the participant has understood that explanation.

Name of Researcher†
(please print) _____

Signature _____ Date _____

† A senior member of the research team must provide the explanation of, and information concerning, the research project.

Note: All parties signing the consent section must date their own signature.

Form for Withdrawal of Participation - *Adult providing own consent*

Title	*Do lower-limb sports compression garments enhance microvascular blood flow?*
Protocol Number	*HREA - JB03486*
Coordinating Principal Investigator/ Principal Investigator	*Dr Lewan Parker*
Associate Investigator(s)	*Dr James Broatch* *A/Prof. Michelle Keske* *Dr Andrew Betik* *Mr Shane O'Riordan* *Prof. David Bishop* *Dr Shona Halson*

Declaration by Participant

I wish to withdraw from participation in the above research project and understand that such withdrawal will not affect my relationship with Deakin University.

Name of Participant (please print) _____

Signature _____ Date _____

In the event that the participant's decision to withdraw is communicated verbally, the Study Doctor/Senior Researcher will need to provide a description of the circumstances below.

Declaration by Researcher†

I have given a verbal explanation of the implications of withdrawal from the research project and I believe that the participant has understood that explanation.

Name of Study Doctor/
Researcher† (please print) _____

Signature _____ Date _____

† A senior member of the research team must provide the explanation of and information concerning withdrawal from the research project.

Note: All parties signing the consent section must date their own signature.