

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

**PERFORMANCE, PHYSIOLOGICAL, AND PERCEPTUAL EFFECTS OF
WEARING GRADUATED COMPRESSION STOCKINGS DURING RUNNING**

A thesis presented in partial fulfilment of the requirements for a degree of Master of
Science in Sport and Exercise Science at Massey University, Auckland, New Zealand.

ROBERT CREASY

2008

PERFORMANCE, PHYSIOLOGICAL, AND PERCEPTUAL EFFECTS OF WEARING GRADUATED COMPRESSION STOCKINGS DURING RUNNING

Purpose: The aims of these studies were to examine the effects of wearing different grades of graduated compression stockings (GCS) on performance, physiological, and perceptual measures before, during, and after exercise in well-trained runners. **Method:** Two separate running studies were conducted where participants wore different grades of GCS compared with a placebo control stocking in random, counter-balanced order: (1) a field study focussed on a series of 10-km running performances on a 400m track; (2) a laboratory study that examined the effects of 40-min treadmill running on physiological, perceptual, and muscle function responses. Changes in muscle function and damage were determined pre- and post-run by measuring creatine kinase (CK) and myoglobin (Mb) concentrations, counter-movement jump (CMJ) height, muscle soreness, and pressure sensitivity. Physiological measurements of heart rate (HR), oxygen uptake ($\dot{V}O_2$), blood lactate concentration [La], and ratings of perceived exertion (RPE) were measured during running. Pre- and post-run perceptual scales assessed comfort, tightness and pain associated with wearing GCS. **Results:** There were no significant differences in 10-km run time, mean HR, $\dot{V}O_2$, [La], and RPE for participants wearing different GCS in (1) and (2) ($P < 0.05$). Con and Low were rated most comfortable ($P < 0.05$) and Hi were tightest ($P < 0.05$) and induced more pain ($P < 0.05$) when GCS were compared in both studies. CMJ was better in participants wearing Low and Med GCS post-run compared with Con in (1) and for Con and all GCS at 0 h post-exercise in (2). CK and Mb levels were higher ($P < 0.05$) and pressure sensitivity was more pronounced ($P < 0.05$) at 0 h post-run for Con and all GCS (2). Few participants (4/10) reported muscle soreness at any one location in (2). **Conclusions:** Well-trained runners did not experience improved performance, physiological, or perceptual responses when wearing different grades of GCS during 10-km track or 40 min treadmill running compared with a control garment. 40 min treadmill running at 80% $\dot{V}O_2$ max may not be strenuous enough to elicit a loss of muscle function in well-trained runners. Runners felt more comfortable wearing GCS that had less compression.

ACKNOWLEDGEMENTS

Thank you so much to all the athletes who participated in these two studies. Your blood, sweat, energy and time have written these pages. It has been a pleasure to work with all of you.

Thank you very much to Dr Ajmol Ali; initially for offering me the scholarship to study at Massey University, and more importantly for his advice, wisdom and patience in taking me on and leading me through the learning process to complete this research. Without his efforts none of this would have happened.

Thank you to Dr Johann Edge for his advice and assistance during all parts of the study. I have greatly appreciated your opinions and help.

Thank you also to all those who offered their time as research assistants in the lab: Helen Ryan, Stuart Mitchley, Simon Bennetts, and Jasmine Thompson. I enjoyed the time and learning experiences I spent with you all.

Rob Creasy

December 2008

CONTENTS

PERFORMANCE, PHYSIOLOGICAL, AND PERCEPTUAL EFFECTS OF WEARING GRADUATED COMPRESSION STOCKINGS DURING RUNNING	2
ACKNOWLEDGEMENTS	3
LIST OF TABLES	10
LIST OF FIGURES	12
1.0 GENERAL INTRODUCTION	1
2.0 REVIEW OF LITERATURE	5
2.1 Graduated Compression Stockings	5
History	6
2.2 Running Performance	12
Endurance Running	12
Leg Power	13
2.3 Mechanisms of Action	14
Muscle Soreness and Damage	15
Muscle Fatigue	24
Venous Return	26

Blood Lactate Clearance	28
Thermoregulation.....	31
$\dot{V}O_2$ Kinetics	31
Perception	34
2.4 Types of Sport.....	35
Endurance Sports	35
Jumping and Sprinting Sports	36
Team Sports	37
2.5 User Groups	38
Elderly.....	38
Untrained.....	39
2.6 Summary	40
3.0 GENERAL METHODS.....	42
Preliminary Procedures	42
Graduated Compression Stockings	42
Muscle Function.....	46

Physiological Measures	51
Perceptual Measures	56
10-km Time Trial Running	57
Treadmill Running	58
Concurrent $\dot{V}O_2$, max and Lactate Test	58
Statistical Analysis.....	59
 4.0 THE EFFECTS OF GRADUATED COMPRESSION STOCKINGS ON RUNNING PERFORMANCE	 61
4.1 Abstract.....	61
4.2 Introduction.....	62
4.3 Methods.....	65
Participants.....	65
Preliminary Procedures	66
Experimental Procedures	68
Statistical Analyses	71
4.4 Results.....	72
Performance Data.....	73

Physiological Data	75
Perceptual Data	75
4.5 Discussion	80
Conclusion	85
5.0 THE PHYSIOLOGICAL AND PERCEPTUAL EFFECTS OF WEARING GRADUATED COMPRESSION STOCKINGS DURING RUNNING	86
5.1 Abstract	86
5.2 Introduction.....	87
5.3 Methods.....	91
Participants.....	91
Experimental Measurements.....	92
Preliminary Procedures	95
Experimental Procedures	95
Blood sampling and analyses.....	97
Statistical Analyses	97
5.4 Results.....	100
Muscle Function.....	101

Physiological Data	107
Blood Analyses	110
Perceptual Data	112
5.5 Discussion	116
6.0 GENERAL DISCUSSION	123
7.0 REFERENCES	130
8.0 APPENDICES	153
Appendix 1	154
Appendix 2	156
Appendix 3	157
Appendix 4	158
Appendix 5	159
Appendix 6	160
Appendix 7	161
Appendix 8	162
Appendix 9	164
Appendix 10	167

Appendix 11.....	169
Appendix 12.....	174
Appendix 13.....	178
Appendix 14.....	180
Appendix 15.....	182
Appendix 16.....	183

LIST OF TABLES

Table 3.1: Compression applied by GCS at the ankle and below the knee according to manufacturers guidelines when fitted correctly from sizing chart.

Table 4.1: Anthropometric measures and performance characteristics of participants determined by a concurrent $\dot{V}O_2$ max and lactate test.

Table 4.2: Maximum counter-movement jump height (mean \pm SD) achieved over three attempts before and after 10-km time trial running wearing different GCS.

Table 4.3: Changes in blood lactate concentration ($\text{mmol}\cdot\text{L}^{-1}$) from pre- to post- 10-km run and heart rate at each 2-km mark of the time trial run for participants wearing GCS (mean \pm SD).

Table 4.4: Subjective perceptions of exertion (RPE), pleasure-displeasure (Feeling Scale), and activation (Felt Arousal Scale) experienced by participants wearing GCS (mean \pm SD).

Table 5.1: Anthropometric measures and performance characteristics of participants determined by a concurrent $\dot{V}O_2$ max and lactate test.

Table 5.2: Compression applied by GCS at the ankle and below the knee according to manufacturer's guidelines when fitted correctly from sizing chart.

Table 5.3: Subjective perceptions of pleasure/displeasure (Feeling Scale), and perceived activation (Felt Arousal Scale) experienced by participants during each trial (mean \pm SD).

LIST OF FIGURES

Figure 3.1: GCS correctly fitted over legs flush under the knee and smoothed to avoid bunching.

Figure 3.2: Compression level measured at the ankle using a pressure bladder connected to a digital meter.

Figure 3.3: Pressure sensitivity measured at the lateral head of the left gastrocnemius muscle using a pressure algometer.

Figure 3.4: Venous blood sampled from the right antecubital vein for creatine kinase and myoglobin analysis.

Figure 4.1: Experimental protocol for each 10-km time trial run.

Figure 4.2: Performance time for participants completing 10-km time trials wearing different GCS (mean \pm 95% CI).

Figure 4.3: Change in counter-movement jump height (cm) from pre- to post-10-km time trial runs for participants wearing GCS (mean \pm 95% CI).

Figure 4.4: Perceived GCS comfort recorded pre- and post-10-km running time trials for participants wearing different GCS (mean \pm 95% CI).

Figure 4.5: Perceived GCS tightness recorded pre- and post-10-km running time trials for participants wearing different GCS (mean \pm 95% CI).

Figure 4.6: Perceived pain for participants wearing GCS pre- and post-10-km running time trials (mean \pm 95% CI).

Figure 5.1: Breath-by-breath gas analysis and heart rate recorded during 40-min treadmill running wearing GCS.

Figure 5.2: Experimental protocol for 40-min treadmill running

Figure 5.3: Counter-movement jump height measured at pre-, 0 h post-, 24 h post-, and 48 h post-run for each GCS intervention (mean \pm 95% CI).

Figure 5.4: Peak leg power calculated from jump height at pre-exercise and 0, 24, and 48 h post-run for each GCS intervention (mean \pm 95% CI).

Figure 5.5a: Location and frequency of muscle soreness during the Con trial only

Figure 5.5b: Location and frequency of muscle soreness during the Low GCS trial only

Figure 5.5c: Location and frequency of muscle soreness during the Hi GCS trial only

Figure 5.6: Mean pressure sensitivity as measured by pressure algometer during each trial (left and right legs combined for each trial; mean \pm 95% CI).

Figure 5.7: Oxygen uptake ($\dot{V}O_2$) for each 5-min block of treadmill running during each trial (mean \pm 95% CI).

Figure 5.8: Heart rate for each 5-min block of treadmill running during each trial (mean \pm 95% CI)

Figure 5.9: Blood lactate concentration (mmol·L⁻¹) at rest, during treadmill running at each 5-min block and immediately post-exercise (mean \pm 95% CI).

Figure 5.10: Mean (\pm 95% CI) Creatine Kinase levels during each trial; ⁺main effect of time, significantly higher than pre-run P<0.001).

Figure 5.11: Mean (\pm 95% CI) Myoglobin levels during each trial; *main effect of time, significantly higher than all time points P<0.05).

Figure 5.12: RPE at each 5-min block of treadmill running for participants wearing different GCS interventions (mean \pm 95% CI)

Figure 5.13: Ratings of perceived comfort pre- and post-run for participants wearing different GCS (mean \pm 95% CI).

Figure 5.14: Ratings of perceived tightness pre- and post-run for participants wearing different GCS (mean \pm 95% CI).

Figure 5.15: Ratings of perceived pain pre- and post-run for participants wearing different GCS (mean \pm 95% CI).

1.0 GENERAL INTRODUCTION

Graduated compression stockings (GCS) were initially designed in a clinical environment to decrease deep venous dilation and improve venous blood flow (Stanton et al., 1949). They have been used to successfully treat venous deficiencies including varicose veins, deep vein thrombosis (DVT), and venous thromboembolism (Lawrence et al., 1980; Cooke et al., 1996; Byrne, 2001). Compression garments have also been used to treat swelling from lymph deficiencies and acute inflammation (Jonker et al., 2001).

Athletes have experimented with compression garments in various sports as an ergogenic aid. Jumping, power lifting, and running events have received the most attention from athletes wishing to improve their performance. Research has been undertaken to find performance effects and the related physiological mechanisms for over 20 years (Berry et al., 1987; Sciacca et al., 1991; Bringard et al 2006; Ali et al., 2007). Recently, sports apparel companies have marketed a variety of GCS garments to athletes and the general population as having a number of performance and recovery benefits. This has led to a surge in interest from athletes who want measurable performance and recovery improvements. At present minimal research has been undertaken to assess performance improvements or the underlying physiological mechanisms influenced by highly-trained athletes wearing GCS. Furthermore, no studies have compared different compression grades for athletic performance or physiological responses. Despite this, many athletes wear GCS while training and racing as a performance aid.

A number of mechanisms have been proposed to identify why GCS may improve athletic performance during a single event or for multiple events. Potential mechanisms include improved venous return (Mayberry et al 1991), greater blood lactate ([La]) clearance (Berry et al., 1987; Kraemer et al., 1998) and leg power (Kraemer et al., 1998a) and/or reduced post-exercise muscle soreness (Ali et al., 2007). Improved venous return could potentially increase end diastolic volume and improve cardiac output. This would allow an athlete to work at the same intensity with less cardiovascular stress or to increase their exercise intensity and performance. An enhanced lactate clearance could assist an athlete to train or race at a faster speed at lactate threshold intensity. An improved leg power may enhance performance in events utilising the stretch-shortening cycle. Also, as competitive events and training sessions are often interspersed with short recovery periods (hours to days), GCS may enhance maintenance of performance from one event or training session to the next.

In support of some of these mechanisms, recent research has shown that GCS may enhance athletic performance of untrained and moderately trained athletes. Indeed, there was a tendency ($P=0.15$) for moderately trained team sport and endurance athletes to have lower heart rates and faster running times over 10 km wearing a GCS garment compared with a control (Ali et al., 2007). Research with moderately trained athletes has also demonstrated significant improvements in sub-maximal running economy (Bringard et al., 2006) and faster 5 km run times when wearing GCS compared with control (Chatard, 1998). Improvements in leg power have also been reported wearing GCS (Kraemer et al., 1998a). Post-exercise benefits have also been shown from wearing GCS,

with a significant attenuation in delayed onset muscle soreness (DOMS) in the days after upper and lower body exercise (Kraemer et al., 2001; Duffield et al., 2007). However, a number of these previous studies did not use a placebo garment and therefore the validity of these results can be questioned. Furthermore, the participants were untrained to moderately trained athletes, which does not determine whether GCS can improve performance in well-trained athletes. Another important aspect that is unknown is the optimal compression grade required to improve athletic performance. Therefore, there are a number of questions that are yet to be ascertained despite the widespread use of GCS by the athletic population.

Therefore, the aims of the experiments reported in this thesis were (1) to determine the performance effects of wearing different grades of knee-length compression stockings pre, during, and post 10-km running and (2) to compare the physiological and perceptual effects of wearing different GCS grades during three separate 40-min treadmill runs at pre-, during, post-0h, post-24h, and post-48h time points. Running performance was measured by 10-km time trial runs on a 400 m track. Changes in heart rate, oxygen uptake, and blood lactate concentration were measured during 10-km time trial runs and 40-minute treadmill runs to assess different physiological responses to running while wearing GCS. Participants also provided subjective responses to the exercise itself as well as the comfort, level of tightness and any associated pain from wearing GCS. Recovery from time-trial and treadmill running was assessed by measuring changes in muscle function and muscle soreness. The results

from these studies will help to indicate the optimal grade of GCS for training and competition for well-trained runners.

Overview

This thesis is separated into 6 chapters which describe investigations about the performance effects and mechanisms affected by wearing GCS. Chapter 2 reviews the current literature that discusses GCS, physiological mechanisms influenced by GCS and running, and the athletes that may benefit from wearing GCS. Chapter 3 outlines the general methodology used in these studies. Chapter 4 describes the effects of wearing different levels of GCS on 10-km time trial running performance. Chapter 5 describes the physiological and perceptual responses during and following 40 min of treadmill running at 90% of athletes' best 10 km time ($80 \pm 5\% \dot{V}O_2 \text{ max}$). Chapter 6 provides a general discussion of the results from both studies in relation to the current literature.

2.0 REVIEW OF LITERATURE

2.1 Graduated Compression Stockings

Graduated compression stockings (GCS) were originally designed to improve blood flow in the venous system (Lawrence et al., 1980). They are now widely used in vastly different circumstances and are purported to offer considerable beneficial effects to those who wear them. GCS are designed to provide graduated compression at the distal section of an arm or leg that gradually decreases up the limb towards the heart. Clinical patients suffering from venous deficiencies from long periods of forced inactivity are prescribed GCS (Stanton et al., 1949; Mayberry et al., 1991; Jonker et al., 2001; van Geest et al., 2003). Aircraft passengers wear GCS to avoid deep vein thrombosis (DVT) and swelling in the feet and legs experienced on long-haul flights (Byrne, 2001). Workers who spend long periods standing and walking wear GCS to alleviate leg fatigue (Kraemer et al., 2000). Athletes competing in jumping (Kraemer et al., 1998a), running (Bringard et al., 2006), and cycling (Chatard et al., 2004) sports wear GCS to enhance their performance. Wearing GCS may support blood and lymph flow in the venous system (Stanton et al., 1949) and reduce muscle fatigue (Kraemer et al., 1998b). The GCS garment predominantly analysed in this review is a stocking that covers the ankle and finishes just below the knee.

This review summarises the key factors associated with GCS. Specifically this chapter attempts to explain the history of how GCS were originally designed and what they were used for. The potential benefits for athletes using GCS in training and

competition are described. The different designs and mechanisms affected by wearing GCS are defined. The physiological (body) and perceptual (mind) effects of wearing GCS during and after exercise are explained. Further, wearing GCS to improve sport performance is analysed. Finally, the populations who may gain the most benefits from wearing GCS are identified. This chapter also identifies published research to discuss what information is already known and where gaps exist in our knowledge about GCS.

History

Clinical Use

Graduated compression stockings are worn in a medical environment to prevent venous stasis, reduce pulmonary oedema and enhance impaired venous return. Symptoms including DVT (Byrne, 2001) and venous deficiencies (Jonker et al., 2001; van Geest et al., 2003) are alleviated by decreasing the cross sectional area of the leg veins. Compression achieved by wearing elastic stockings was found to increase venous blood flow in patients suffering from venous deficiencies (Stanton et al., 1949). Wilkins et al. (1952) continued the initial research to show that wearing elastic stockings significantly decreased post-operative pulmonary oedema in hospital patients. The next development came from Scurr et al. (1977) who observed that an elastic compression stocking that had graduated pressure that was highest at the ankle and gradually decreased up the leg had significant effects on patients suffering from DVT. The study covered one leg with a GCS garment, the other leg was left bare. The leg covered with a GCS garment decreased DVT by 37% compared with 11% for the leg with no stocking. However, the positive observations in the hospital were not supported by any physiological mechanisms.

Investigations into the mechanisms that alleviated venous deficiencies gave positive results to support clinical observations. Blood and lymph pooling at the skin and muscles was reduced, ensuring that circulation continued to return blood to the heart and assist clearance at damaged tissue, interstitial spaces, and muscle (Mayberry et al., 1991; Kraemer et al., 2000). Byrne (2001) demonstrated that stockings exerting 20 mmHg compressive pressure at the ankle dissipating to 10 mmHg pressure at the calf achieved 75% higher deep venous blood flow velocity in DVT than a control. Compression applied to the knee had the greatest contribution to femoral venous blood flow velocity (Lawrence et al., 1980). However, 30 mmHg compression had negative consequences, causing decreased subcutaneous tissue flow and reduced deep vein blood flow velocity in some patients via a tourniquet effect (Lawrence et al., 1980).

Despite these findings GCS were not widely used to alleviate venous deficiencies in clinical patients (Dalen, 2002) until a meta-analysis of venous deficiency treatments showed that wearing GCS decreased post-operative venous thromboembolism by 69% (Wells et al., 1994). This finding encouraged hospitals to use GCS to treat all patients suspected with venous deficiencies (Dalen, 2002).

Athletic Use

The sport performance effects of wearing GCS were not investigated until Berry et al. (1987) measured changes in blood lactate concentration for athletes wearing GCS

(18-8 mmHg) during $\dot{V}O_2$ max running, treadmill running to exhaustion, and 3 min supra-maximal cycling tests followed by a 60 min recovery period. They found that athletes wearing GCS during running experienced no significant changes in $\dot{V}O_2$ max and run to exhaustion time. However, resting femoral blood flow velocity increased for athletes wearing GCS. Lower blood lactate concentration ([La]) was observed in athletes wearing GCS during and after cycling exercise. This indicated that exercise performance may have been impeded because lactate was retained in muscle beds, inhibiting lactate clearance from muscle rather than assisting lactate clearance via the increased circulation observed by an augmented venous return (Berry et al., 1987). Sciacca et al (1991) measured venous return in highly trained runners at rest and immediately after running 2000 m (middle distance runners) or 6 repetitions of 100 m (sprinters) while wearing GCS (32 mmHg at ankle, 26 mmHg at calf). They found that 2-km running created significant stress on the veins measured in the lower leg and that the GCS significantly inhibited venous return.

New types of compression garments and changes in textile design tailored specifically for athletes encouraged further study. Compression shorts were designed to assist athletes in sports where explosive power was critical to performance – particularly jumping and sprinting. There are a number of studies that have investigated the use of compression leggings, shorts and stockings on parameters such as jump height (Kramer et al., 1996; Doan et al., 2003), repeated jump height (Kraemer et al., 1998a), running performance (Chatard, 1998; Ali et al., 2007), marathon running (Benigni et al., 2001),

sprint performance (Doan et al., 2003), cycling (Chatard et al., 2004), running economy (Bringard et al., 2006), muscle damage after eccentric loading (Trenell et al., 2006), and recovery strategies after rugby union matches (Gill et al., 2006). The summary of this research (using an athletic population) indicates that wearing GCS significantly improves repeated jump height, running economy, and cycling for elderly individuals. However, the research by Berry et al. (1987, 1990) and Sciacca et al. (1991) indicates that GCS may be beneficial to clinical patients, but had no significant benefit for a healthy athletic population.

GCS have become increasingly popular among the athletic population since a number of apparel companies (e.g. Skins, 2XU, Zensah, Kompressorz) released heavily marketed products for consumers. Recreational through to elite athletes wear compression garments as part of warm-up, performance, cool-down, recovery or all parts of their training and racing. Whether GCS improve performance, and specifically enhance an athlete's potential to run faster in endurance events are points of considerable conjecture. The details of these studies and underlying mechanisms will be explained in this chapter.

Types

There are different types of lower limb compression garments: the full-length ankle-to-hip garment, a short that covers the knee to the hip, a tight that covers the ankle to mid-thigh, and a stocking that covers the foot and ankle, finishing at the knee. GCS are effective because they apply static external compression to limb tissues to decrease the

cross-sectional area of the venous system, which increases the linear velocity of blood flowing through veins (Lawrence et al., 1980). The increased venous blood flow prevents venous pooling in the lower leg (Lawrence et al., 1980). Investigations into knee- and thigh-length compression garments has demonstrated that venous return was not significantly ($P < 0.05$) improved by a stocking reaching above the knee (Lawrence et al., 1980; Cooke et al., 1995; Byrne 2001). Below-knee compression was directly compared with whole limb compression using a pneumatic vinyl sleeve divided into individual chambers with different pressure gradients at the ankle, calf, knee, lower thigh, and upper thigh (Lawrence et al., 1980). Compression below the knee has been shown to be the most important region to enhance venous blood flow velocity using pneumatic sleeves in hospital patients in a supine position (Lawrence et al., 1980). The improvement in blood flow found by Lawrence et al. (1980) may not be transferrable to people wearing compression sleeves while standing or when muscles are actively contracting. In a clinical environment below-knee compression stockings have better treatment outcomes for patients simply because they are as effective in improving blood flow velocity as thigh-length stockings and are more likely to fit correctly (Byrne, 2001). Thigh length (and full length) compression stockings may cause bunching around the knee that creates discomfort, skin irritations, and possibly a tourniquet effect that inhibits venous blood flow (Byrne, 2001). Though there are considerable differences between clinical patients and athletes, the issues experienced by patients are equally pertinent to athletes. A thigh-length GCS may slide down the leg and/or bunch around the knee during training for any athlete who requires considerable mobility at the knee joint to exercise effectively. A full length compression garment may not slide down the leg, but may bunch around the knee

joint as well causing discomfort and possibly a tourniquet effect. A knee-length GCS provides all the beneficial effects of enhanced blood flow without any of the disadvantages that thigh-length and full length compression garments may have.

Torso compression garments have recently been developed to complement arm and leg compression clothing (e.g. SkinsTM, 2XUTM) so it is possible to achieve almost full-body compression. Full body compression has been used in power-lifting and swimming as a mechanical ergogenic aid; however, the performance enhancements are currently unproven or unpublished.

Lower limb GCS apply greatest compressive pressure at the ankle, which dissipates gradually to the calf, thigh and hip. This gradual dissipation ensures there is no tourniquet effect (Lawrence et al., 1980). Graduated compression is critical to stocking function however elastic tights are available on the market but they do not provide compressive forces to limbs (Bringard et al, 2006). Research investigating participants wearing elastic tights during exercise has shown no effect on running economy and blood lactate (Bringard et al., 2006) or on blood lactate, heart rate, and oxygen consumption during cycling exercise and subsequent recovery (Berry et al., 1990). This is because they do not apply sufficient pressure to enhance venous blood flow (Berry et al., 1990).

The textiles used to make GCS are usually a combination of lycra, and/or neoprene (www.Skins.net; www.2XU.com.au; www.kompressorz.net; Doan et al., 2003). The different levels of compression that a garment applies to the body may be altered by

the materials used, the weave of the materials, and the dimensions of the garment. A stocking that utilises materials that have less stretch and/or tighter weave apply more compressive force. Because individual leg size and shape varies considerably a large number of sizing options may be required to ensure the correct fit based on anthropometrical measurements (ankle, calf, thigh circumference, and leg length). Despite materials, designs, and levels of compression GCS garments are produced to have the same beneficial effects as the skeletal muscle pump (Kraemer et al., 2000) and increase deep venous velocity while decreasing blood pooling in the calf veins (Sigel et al., 1975).

2.2 Running Performance

Endurance Running

Successful endurance running performance may be determined by three factors: aerobic power ($\dot{V}O_2$) at anaerobic threshold (Kumagai et al., 1982), run speed at $\dot{V}O_2$ max (Roecker et al., 1998), and running economy (Costill et al., 1970). Lactate exchange and the ability to buffer hydrogen ions, while important, were shown to be less critical performance determinants for self-paced time trial running (Messonier et al., 2002).

Running time trials conducted over distances between 3-10 km have high inter-test reliability (Chapman et al., 1998; Gomez et al., 2002; Hopkins et al., 2001; Levine et al., 1997; Stray-Gundersen et al., 1999; Stray-Gundersen et al., 2001). Altitude investigations into the “live high – train low” hypothesis (that has since become widely

accepted) tested highly trained runners using 5-km time trials between groups and found very good repeatability ($17:19.2 \pm 0:15.4$, $CV=3.7\%$: Levine et al., 1997). Hopkins et al. (2001) analysed the race times completed by highly trained runners competing in cross-country and road races. They found the reliability between times by the same runner had a CV ranging from 1.2-1.9%.

Leg Power

Leg power is one of the essential factors required to enhance sprint and jumping performance in athletes. Elite competitors in long jump and triple jump athletics have worn GCS as part of training and international competition, however, this trend has not extended to include track sprint distances. Maintaining leg power may be essential to athletes in team sports such as volleyball, basketball, and netball who perform repeated sprint and jump efforts during exercise that induces considerable muscle fatigue.

Leg power may be inferred by the maximal height achieved from a counter-movement jump (CMJ). A study by Kraemer et al. (1998a) used different exercise modalities (endurance, resistance, isometric) to induce muscle fatigue. This was followed by 10 CMJ wearing either thigh compression shorts or normal gym shorts. The mean repeated jump height was significantly higher for both trained and untrained individuals wearing the compression shorts. The proposed mechanisms causing superior leg power maintenance were diminished muscle oscillation and enhanced proprioception (Kraemer et al., 1998a).

Gomez et al. (2002) observed that CMJ was considerably lower after completing a 10-km track run at race pace. The time required for leg power to recover from hard 10-km running was 48-h (Gomez et al., 2002). This was because CMJ height measured for runners 48-h after a 10-km race were not significantly different to the CMJ measured pre-race, indicating that this length of time allowed leg power to return to normal (Gomez et al., 2002). However, no CMJ measurements were made between 0-h post-run and 48-h post-run to determine how leg power recovered during this period. A maximal effort for a 10-km time trial run may induce considerable loss of muscle function that would affect CMJ height, however, the time points between 0-h and 48-h post-run where this happens have not been investigated.

2.3 Mechanisms of Action

Athletic enhancement using GCS garments may have beneficial indirect performance effects by decreasing muscle oscillations, lowering energy expenditure, lowering blood lactate concentration, improving running economy, reducing muscle damage, enhancing leg power and increasing circulation (Berry et al., 1987; Kraemer et al., 1996; Kraemer et al., 1998a; Kraemer et al., 2001; Doan et al., 2003; Bringard et al., 2006). Whether these physiological alterations cause significant performance benefits for endurance runners remains unclear.

Muscle Soreness and Damage

Muscle soreness is described as a dull and aching pain that makes muscles feel tender and/or stiff (Ebbeling et al., 1989). Muscle soreness accompanied by loss of muscle function after exercise (especially eccentric exercise) is defined as delayed onset muscle soreness (DOMS) (Newham et al., 1987; Clarkson et al., 1988; Trenell et al., 2006). Soreness is usually noted after 24-h in musculo-tendinous junctions, gradually spreading to the muscle bellies by 48 h, peaking between 24- and 48-h (Pyne, 1994) and subsiding to pre-exercise levels 5-7 days later (Ebbeling et al., 1989; MacIntyre et al., 1995). However, decreased force capacity may occur through a combination of muscle injury and muscle fatigue depending on the type of contraction, duration and intensity of exercise (Faulkner et al., 1993). Repeated maximal voluntary contractions may require 24 h to recover (Newham et al., 1983) while maximum isometric strength exercise may require two weeks to recover (Faulkner et al., 1993). The mechanisms causing post-exercise muscle soreness and DOMS are numerous, primarily because the fundamental physiological principles remain ambiguous and different exercise modes may have varying effects on muscle physiology (MacIntyre et al., 1995). The key mechanisms appear to be mechanical or metabolic stress which may occur separately or concurrently (Pyne, 1994).

Mechanical Trauma Theory

Mechanical trauma may cause DOMS by shear forces to contractile or elastic muscular tissue. This theory proposes that the sarcolemmal structure is damaged, upsetting calcium homeostasis and initiating cell necrosis. Tissue swelling and

inflammation follows from immune cells and cellular debris accumulating where muscle damage occurred (Armstrong, 1984). Tissue repair occurs through a three-stage process (Armstrong, 1990; Armstrong et al., 1991). The first is the autogenic phase which may begin during exercise and continues for several hours after exercise where cell structures are degraded, membrane integrity is lost and a phagocytic response initiated. The second phase facilitates inflammation through phagocyte release and breakdown of damaged cell structures and metabolites including prostaglandin E₂ (PGE₂). The process begins four to six hours post-exercise and peaks three-days post-exercise. During the third phase muscle function is inhibited from 6 h to 7 d post-exercise to ensure damaged muscle fibres and tissues are repaired and pre-exercise muscle function is restored (Armstrong et al., 1991). Pain and inflammation may be exacerbated in this phase by tissue swelling, extra-cellular matrix breakdown (MacIntyre et al., 1995), histamine release (Stauber et al., 1988) and increased pain receptor sensitivity (Smith, 1991). These responses protect muscle and tissues from further damage from a loss in muscle function and lower muscle strength when the same exercise mode is undertaken up to 6 months later (repeated bout effect; Nosaka et al., 2001).

Metabolic Stress Theory

Metabolic stress may be aggravated by prolonged endurance exercise at high intensity or by exercise to exhaustion (Pyne, 1994). The proposed mechanism causing metabolic stress states that ATP delivery to contracting muscle is compromised because ATP synthesis cannot replace ATP broken down by hydrolysis (Pyne, 1994). This may occur during intense exercise when insufficient ATP delivery to specific muscles causes

substantial structural damage (Duncan et al., 1987). Other factors that may increase metabolic stress include muscle ischemia, hypoxia, ion concentration changes, and accumulation of metabolic bi-products (Jenkins, 1988; Westerblad et al., 1991; Sahlin, 1992). The mechanisms underlying the metabolic stress theory may occur concurrently or separately to the mechanisms causing mechanical stress (Pyne, 1994). The theory does not sufficiently explain why localised pain occurs from low-intensity and high-impact exercise (e.g. downhill running). This theory suggests that the most extreme muscle damage occurs from exercise to exhaustion. This may occur during run to exhaustion trials at slow running speeds that take more than one hour to complete. However, the theory is limited for short duration high-intensity exercise such as 2,000-m rowing races where rapid ATP turnover requires considerable aerobic and anaerobic glycolysis that deplete muscle and liver glycogen and blood glucose stores. However, rowers do not experience intense muscle soreness or loss of muscle function as they are capable of competing successfully in multiple races on the same day.

Eccentric Load Theory

This theory states that exercise primarily requiring eccentric muscle contraction causes the greatest amount of muscle injury (Faulkner et al., 1993) and muscle fatigue (Newham et al., 1983). Damage may be caused by greater stress to tendon attachments and sarcomeres when fully lengthened causing inflammation, swelling and muscle stiffness (Jones et al., 1989). The repeated eccentric contractions may overstretch sarcomeres causing structural damage to the muscle membrane, sarcoplasmic reticulum, and transverse tubules causing intracellular calcium ion release (Proske et al., 2001). The

damaged sarcomeres are broken down by proteolysis, which attracts macrophages and monocytes to the area and causes localised swelling and oedema (Proske et al., 2001).

GCS Effect on Muscle Soreness and DOMS

Compression garments have been advocated as a recovery modality to alleviate exercise-induced muscle damage (Noonan et al., 1999) but the underlying mechanism for the compression effect on intracellular metabolic function remains ambiguous (Trenell et al., 2006). A number of studies have investigated how GCS garments worn during exercise have influenced post-exercise muscle soreness and DOMS (Chatard, 1998; Trenell et al., 2006; Ali et al., 2007). These studies have related their findings to literature published about muscle damage and repair (mechanical trauma theory, metabolic stress theory, eccentric load theory) to identify the physiological mechanisms that may be enhanced or alleviated by wearing GCS.

Ali et al. (2007) have proposed that a GCS garment may alleviate swelling and inflammation by applying compressive pressure around the muscle. This would minimise mechanical trauma caused by exercise and help to enhance post-exercise recovery. Wearing GCS during exercise may decrease leg and DOMS 24-h post-exercise. Athletes running a paced 10-km course wearing GCS (18-22 mmHg) reported significantly lower DOMS 24-h post-exercise ($P < 0.05$), especially in the hip flexors, hamstrings and gastrocnemius muscle groups. The decrease in muscle soreness and pain was observed when athletes wore GCS despite showing a trend to run faster ($P = 0.15$). This was a conflicting result considering that faster running requires higher exercise intensity

causing greater muscle damage (Ali et al., 2007). However, the participants in this study were paced during all 10-km runs. The athletes involved in this study were team sport athletes who may not have been accustomed to continuous and high intensity running exercise on hard surfaces. Muscle soreness was reported by participants wearing GCS and wearing no GCS (control). A placebo effect from the GCS may have effected the frequency that participants reported muscle soreness.

Trenell et al. (2006) induced substantial DOMS using downhill walking, which had the same effect whether participants wore GCS leggings or no garment. This was achieved using repeated eccentric contractions walking on a treadmill at 6km/h on a 25% downhill gradient. Comparisons were made by randomly cutting out the left or right legging so that one leg was covered by a GCS, the other leg was uncovered. Though participants were randomly assigned based on their dominant leg, subjective bias may have affected the results because no control garment was used and the participants were not blinded to which leg was covered by a GCS. Participants reported significant increases in perceived muscle soreness for both legs 1-hr and 48-h post-exercise compared with baseline data. Metabolic changes were measured in both legs at pre-, 1-h post-, and 48-h post-exercise. Only phosphodiester levels increased significantly in the GCS covered leg compared with the uncovered leg, other measured levels remained unchanged or changed equally between the GCS and uncovered legs. The increased phosphodiester levels were explained by two possible mechanisms: either 1) GCS enhanced the inflammatory and repair response, or 2) GCS reduced the blood flow to skeletal muscles. The results indicate that GCS did not have a protective effect for

uninjured recreational athletes exposed to an acute and repetitive eccentric load that caused muscle damage. The study did not measure changes in creatine kinase or myoglobin levels, which would have objectively determined muscle damage to confirm the subjective perceptions of muscle soreness that participants expressed.

Chatard (1998) found that leg pain sensation was lower in athletes completing 5-km runs wearing elastic compression tights than controls who wore running shorts. However, leg pain was measured using only a three-point scale that was less comprehensive when compared with other pain scales (Chatard, 1998). The three-point pain scale provides an indication for pain perception, but lacks the accuracy to quantify the difference in pain experienced by participants between the treatment and control conditions. Perceived leg pain was reported as 'good' or 'very good' in all 12 participants after wearing elastic tights during 80 min of recovery between two 5-min maximal cycling bouts (Chatard et al., 2004). However, there was no difference in conditions between cycling performance when the same participants wore non-compression cycling shorts (Chatard et al., 2004). This suggests that any difference between wearing a GCS and cycling shorts may have been influenced by a placebo effect rather than any treatment effect because participants in the study knew they wore a different garment between the treatment and control trials.

Muscle soreness and DOMS may be effectively measured using a combination of subjective scales, subjective perceptions from an applied pressure, and CK and myoglobin levels measured from a venous blood sample. Subjective perceptions of

muscle soreness may be identified using an anatomical diagram divided into muscular regions and a scale to determine the severity and location of soreness. Muscle soreness may be quantified using a pressure algometer that measures the force a person can tolerate that is applied to a localised muscle area (Jensen et al., 1986). Muscle damage can be objectively measured by an increase in CK and Myoglobin above baseline levels in venous blood (Byrnes et al., 1985; Suzuki et al., 1999).

Compression garments also decreased post-exercise muscle soreness for individuals with no training history (Kraemer et al., 2001). Untrained participants wore upper body compression for three days after exercise prescribed specifically to cause muscle damage and DOMS. Muscle damage was provoked by two sets of 50 bicep curl repetitions with every fourth rep involving a maximal isometric hold and an opposed maximal eccentric contraction. The compression group (10 mmHg) achieved greater peak torque and power contractions 48- and 72-h post-exercise, had smaller bicep circumferences one and two days post-exercise indicating less localised swelling, and experienced significantly less pain three days post-exercise compared with a group who wore no upper body compression (Kraemer et al., 2001). The investigators concluded that wearing compression after exercise that caused considerable muscle damage had substantially assisted the healing process through three key processes. The first was less muscle damage from the structural support of the garment and improved muscle contractile unit repair. It is unclear what structural support the compression garment may have provided. Greater structural support may be important for leg muscles during running that are exposed to repeated impact. However, the bicep curls did not generate

forces in the direction of muscle fibre contraction that would increase muscle oscillation. Further, the investigators did not state what mechanism may have assisted muscle repair. The second process outlined by the authors was enhanced pressure-induced mechanical and chemical mechanisms that relieved tissue damage. Though compression may provide structural support that prevents muscle damage by decreasing muscle oscillation, the muscle damage and repair theories developed by Armstrong (1990), Armstrong et al. (1991), and Clarkson et al. (1982, 1986, 1988) do not indicate that compression enhances mechanical or chemical processes. The third was that compression facilitated increased hydrostatic pressure to enhance lymph drainage and alleviate swelling. This process may be the most beneficial to clear swelling, inflammation, lymph, and metabolite accumulation where muscle damage is localised. Compression garments may enhance lymph drainage, but a tourniquet effect described by Lawrence et al. (1980) indicates that metabolites such as lactate may remain at the muscle damage site. Though the findings from this study provide considerable support to the effectiveness of wearing upper body compression during resistance training designed to cause muscle damage the underlying mechanisms remain unclear.

Reduced mechanical trauma wearing GCS has been observed as diminished muscle oscillations (Kraemer et al., 1998a), however, physiological indicators of muscle damage (creatine kinase activity and myoglobin concentration in blood or interstitial fluid) were not measured. Further, muscle oscillation was not directly measured. Therefore the concept of reduced mechanical trauma from wearing compression during exercise remains as a theory that requires further investigation.

Reduced leg pain may benefit runners completing high volume training. Anecdotal evidence suggests many distance runners wear GCS during long runs and races as an injury prevention strategy. Benigni et al. (2001) found that runners wearing GCS had decreased leg volume and gastrocnemius vein diameter when measured after completing a half marathon. However, the measurement was made when the stockings were removed after completing the event, so vein diameter may have been different during running and/or once the GCS were removed after running. This agrees with the findings of Kraemer et al. (2001) who found enhanced lymph drainage and decreased swelling after eccentric arm exercise. It also indicates that less blood may have pooled in the legs as the gastrocnemius vein diameter was smaller (Benigni et al., 2001). Based on these findings wearing knee-length GCS may have a circular effect by reducing lymph build-up in the legs and decreasing tissue oscillation during running. Lymph build-up in the legs, especially around and within skeletal muscle would increase the mass of the muscles and leg. This would amplify the ground impact forces during running and increase muscle oscillation.

Many studies investigating the effect of wearing GCS on muscle soreness have methodological flaws or have been unable to prove purported theories (Chatard et al., 1998; Kraemer et al., 1998a; Kraemer et al., 1998b; Doan et al., 2003; Bringard et al., 2006; Trenell et al., 2006; Ali et al., 2007). In many studies a placebo compression garment was not used in the control group when making comparisons with the treatment group that wore GCS or a compression garment. In these studies any beneficial effects

observed in participants wearing a compression garment may have been substantially influenced by the placebo effect. Other studies describe how wearing compression reduces muscle damage by reducing muscle oscillation. However, there is insufficient evidence to support this theory because the experimental protocols do not have the resolution to measure what the theory describes.

Muscle Fatigue

Sedentary Population

Individuals who do not take part in regular physical activity but are employed in occupations where they spend long periods of time on their feet may gain considerable benefits from wearing GCS while they work. Sedentary female workers were asked to simulate a normal 8-h working day wearing either tights without graduated compression (control: ankle=7.7 mmHg, calf=7.6 mmHg, thigh=9 mmHg), low compression graduated tights (low: ankle=7.6 mmHg, calf=6.8 mmHg, thigh=5.2 mmHg) or high compression graduated tights (high: ankle=15.4 mmHg, calf=8.4 mmHg, thigh=8.6 mmHg). Ankle and calf circumference were significantly ($P<0.05$) lower for participants wearing low and high compression tights compared with control tights because oedema and swelling were reduced (Kraemer et al., 2000). Venous pooling was alleviated for low and high compression tights because popliteal and tibial vein diameter decreased when compared with the control tights ($P<0.05$; Kraemer et al., 2000). The CK levels were lowest when participants wore the high compression tights and perceptual comfort was higher for participants wearing the low and high compression tights compared with the control tights (Kraemer et al., 2000). The investigators concluded that normal sedentary

individuals benefitted from wearing graduated compression tights, and individuals with venous disorders required greater compression to receive similar physiological effects to the sedentary population (Kraemer et al., 2000). Regular exercise may provide similar benefits to sedentary individuals that are provided by GCS (Monahan et al., 2001).

Athletic Population

Endurance athletes who are required to stand for long periods between training sessions due to travel or work commitments may considerably reduce standing fatigue and consequently slow twitch muscle fibre fatigue by wearing GCS (Kraemer et al., 2000). Athletes who participate in sports where jumping is critical to performance may receive similar benefits from wearing GCS. Participants landing from a maximal vertical jump experienced less longitudinal and anterior muscle oscillation and improved their repeat vertical jump performance (Kraemer et al., 1998a). However, comparisons between changes in muscle movement between compression and control interventions were determined indirectly using video recordings of the landing with reflective markers placed on anatomical landmarks (Kraemer et al., 1998a). This method is not as accurate as EMG recordings which directly measure electrical activity in the contracting muscles. This means any inferences the investigators made about changes in muscle fatigue are speculative. Bringard et al. (2006) state that lower limb compression decreases muscle fatigue by applying pressure that supports dynamically moving muscle fibres in their contraction direction. The reduced muscle oscillation from GCS garments may additionally diminish electrical activity in the skeletal muscles (Nigg et al., 2001). In combination these mechanisms may facilitate lower energy expenditure at a given

submaximal running speed. These studies indicate that endurance runners undertaking training runs on non-absorbent surfaces (e.g. footpath and road) longer than 90 minutes may reduce the prevalence of overuse injuries to gastrocnemius, soleus, and tibialis anterior by wearing GCS during training.

Venous Return

Venous return is the flow of blood from the systemic circulation back to the heart via the venules, small veins, large veins, and eventually the superior or inferior vena cava. The effect of gravity causes blood pooling in the lower leg when standing. To counter this effect humans utilise the skeletal muscle pump to assist blood flow back to the heart. This is achieved by skeletal muscle contraction in the lower leg and one-way valves in the veins that prevent blood flowing backwards (Brooks et al., 2001). Other cardiac features that improve venous return include: heart suction, respiratory muscle pump, heart contraction and relaxation, and ventricle contractions that expand the size of the atria (Brooks et al., 2001). Improved venous return may also be observed as higher blood flow velocity in the femoral vein (Benko et al, 1999).

Competitive sports are considered detrimental to venous return because undetected thromboses and excessive effort during exercise may cause extreme strain on the valve system in veins (Reinhartz, 1980). Maximal running efforts over 200-2000 m may increase arterial flow up to 20 times more than basal levels (Sciacca et al., 1991). This could cause venous overload and increased superficial vein flow that contribute to venous reflux that was inferred from the results of Sciacca et al. (1991). Most athletes

have a well-developed skeletal muscle pump that is able to accommodate rapid increases in blood flow. The rapid increase in venous blood flow and mechanical action of the skeletal muscle pump ensures an adequate supply of blood is returned to the heart to maintain cardiac output during exercise (Mayberry et al., 1991; Brooks et al., 2001).

Wearing elastic compression has substantial positive effects on improving blood flow in the lower limb in medical patients with vascular and circulation issues. Elastic compression stockings worn during daily walking reduced venous diameter and prevented intimal tears in the endothelium (Buhs et al., 1999). Patients who wore GCS to treat deep vein thrombosis experienced superior stagnant blood clearance from behind venous valves (Lewis et al., 1976) and decreased venous stasis. Deep venous blood flow velocity was enhanced up to 80% for patients (Lawrence et al., 1980). Venous diameter was reduced and blood flow velocity was enhanced for athletes wearing GCS compared with a control group (Berry et al., 1987). However, Sciacca et al. (1991) found that venous return was not improved for sprint and endurance runners. No published studies have investigated whether athletes wearing GCS had diminished venous stasis or stagnant blood accumulation behind veins. A possible reason is that only athletes with venous disorders may experience the same symptoms as clinical patients. It may be likely that athletes have developed training adaptations that decrease the incidence of venous deficiencies. There is no known published study that has made a specific investigation into GCS use by athletes with venous deficiencies.

Venous Return in Athletes

The potential cardiovascular benefits an athlete may experience wearing GCS include enhanced skeletal muscle pump action, improved blood flow through the legs back to the heart (Mayberry et al 1991; Ali et al., 2007), greater blood lactate clearance (Berry et al., 1987; Kraemer et al., 1998a) and other metabolite removal. Sprinters and middle distance runners who trained at least 4 h·day⁻¹ showed increased arterial blood flow during exercise compared with pre-exercise levels measured at rest (Sciacca et al., 1991). However, some of the participants (n=6) wore GCS (25-32 mmHg, length not specified) during training without observed changes in venous flow immediately after exercise. Whether the stockings were removed from or remained on the GCS participants for measurement was not mentioned; if the stockings were removed any venous return augmentation may have been abolished. Another reason that no changes were observed may have been because the participants were highly trained. Highly trained athletes may have a greater capacity to cope with arterial overload to the venous system through progressive physiological adaptation achieved through years of training.

Blood Lactate Clearance

Enhanced venous return caused by improved venous flow in the lower leg may assist metabolite clearance from contracting skeletal muscle. Reduced lactate concentrations observed in exercising athletes (Berry et al., 1987; Berry et al., 1990; Chatard et al., 2004) have led a number of manufacturing companies to claim that their product 'decreases lactic acid build-up' (e.g. Skins, 2XU, Kompressorz). However,

investigators have proposed different mechanisms to explain why changes in blood [La] have been observed in participants wearing compression garments during and after exercise.

Blood lactate concentrations sampled from the antecubital vein after $\dot{V}O_2$ max treadmill runs were significantly lower 15-min post-exercise and tended to be lower during exercise in the group wearing knee-length compression stockings (18 mmHg at ankle, 8 mmHg at calf) compared with a control group (Berry et al., 1987). In the same study participants wearing knee-length GCS (18 mmHg ankle, 8 mmHg calf) during cycling for three minutes at 110% peak $\dot{V}O_2$ max followed by 30 min recovery produced significantly lower [La] compared with participants who wore non-compression cycling shorts (Berry et al., 1987). However, GCS worn during 110% $\dot{V}O_2$ max cycling then removed during 30-min recovery produced the highest and significantly different [La] (Berry et al., 1987). The investigators concluded the cause was decreased lactate perfusion from the muscle bed post-exercise caused by a tourniquet effect (a term coined by Lewis et al., 1976). The GCS did not enhance lactate or other metabolite clearance from the deep venous system proposed in other research papers (e.g. Husni et al., 1970; Lewis et al., 1976; Okoye et al., 1984) possibly due to elevated hydrostatic pressure in the muscles or because GCS created an inverse pressure gradient (Berry et al., 1987). Berry et al. (1987) proposed that lower [La] were due to constriction which restricted lactate within the muscle, though they were unable to prove this. Compression decreased the diameter of superficial veins that moved blood away from the muscle bed and

inhibited lactate, phosphate and CO₂ clearance (Berry et al., 1990). However, the only effective method to determine that wearing GCS causes lactate or other metabolites to be retained in muscles would be serial muscle biopsies immediately after exercise (Berry et al., 1987). Plasma volume remained unchanged for participants wearing compression garments indicating that fluid shifts did not influence metabolite concentrations or levels. For these reasons the investigators concluded that exercise performance would be detrimentally affected by wearing GCS.

Lower blood [La] was observed in a group of elderly cyclists wearing GCS during two 5-min maximal exercise bouts separated by an 80-min recovery period. Elastic compression garments (intervention) or cycling shorts (control) were worn during exercise and recovery (Chatard et al., 2004). The investigators proposed that lower circulating lactate was caused by an enhanced blood lactate clearance at the exercising muscle in the group wearing GCS during recovery. However, blood flow, oxygen consumption and muscle lactate concentration were not measured and a placebo effect from wearing the elastic compression cannot be excluded.

The purported benefits of GCS lowering [La] may not be relevant to recovery. This is because lower circulating [La] may not influence blood pH and therefore have no effect on exercise recovery (Robergs et al., 2004; Barnett, 2006). Higher muscle [La] would infer that GCS constricted lactate clearance from muscle whereas increased blood [La] would indicate that wearing GCS enhanced lactate clearance from contracting muscle.

Thermoregulation

Bringard et al. (2006) tested the thermal stress induced by wearing GCS in runners dressed in normal training attire (shorts, singlet, socks, and shoes). The test protocol was 30 min of treadmill running at 70% $\dot{V}O_2$ max in a room heated to approximately 30°C. They found that wearing GCS did not significantly effect thermoregulation, thermal comfort or sweating sensations (Bringard et al., 2006). The authors observed that there were no differences in thermal stress, body mass loss, clothing comfort, sweating sensations, or perceived exertion when participants wore GCS, elastic tights or running shorts (Bringard et al., 2006). Thermoregulation may not have been compromised for participants in the study by Bringard et al. (2006) because the knee-length GCS did not affect the body's ability to offload heat through convection and evaporation. Improved venous blood flow velocity may also have prevented blood pooling at the skin and ensured more blood was available to flow to contracting skeletal muscle. Doan et al. (2003) found that skin temperature was significantly increased for athletes wearing compression shorts. However, the shorts were 15% smaller than the athletes measurements and made of 75% neoprene and 25% butyl rubber that was not designed to 'breathe'.

$\dot{V}O_2$ Kinetics

Running economy has been identified as a critical performance determinant in endurance running (Conley et al., 1980; Noakes, 1988). It is defined as the volume of

oxygen an athlete requires to run at a given submaximal speed (Costill et al., 1970; Daniels, 1974), and is an integral determinant of running performance in athletes with similar $\dot{V}O_2$ max values. This is especially relevant for highly trained and elite distance runners where the best athletes are the most economical rather than those that possess the greatest running speed at $\dot{V}O_2$ max (Conley et al., 1980; Noakes, 1988).

Running economy may be measured by the oxygen cost or energy cost of exercise at any given intensity. Energy cost and $\dot{V}O_2$ during submaximal running was significantly lower at 12 km·h⁻¹ and tended to be lower at 10 km·h⁻¹ and 14 km·h⁻¹ in trained runners wearing knee-length GCS compared with running shorts and elastic tights (Bringard et al., 2006). However, at maximal intensity participants achieved the same economy running at $\dot{V}O_2$ max in the GCS (18 mmHg at ankle, 8 mmHg at calf) and control (no stocking) interventions (Berry et al., 1987). The results from both studies indicate that compression garments augment running economy at submaximal, but not maximal running intensity.

Greater proprioception, muscle coordination and propulsive force were purported to improve movement economy (Bringard et al., 2006). Movement economy is critical for ultra-endurance athletes (e.g. Ironman triathlon, adventure racing, ultra marathon), who would gain considerable benefit from wearing a garment that reduces energy cost. The mechanism may be superior motor unit recruitment patterns at steady submaximal

running pace causing improved movement economy, and reduced $\dot{V}O_2$ slow component (Casaburi et al., 1987; Gaesser & Poole, 1996; Borrani et al., 2001; Krstrup et al., 2004).

It has been shown that GCS worn for 15-min of sub-maximal running at 80% $\dot{V}O_2$ max improved $\dot{V}O_2$ slow component by 26% when compared with elastic tights, and 36% when compared with non-compression running shorts (Bringard et al., 2006). The $\dot{V}O_2$ slow component was defined as the difference in oxygen consumption at the end of the second minute of exercise (steady state reached by athlete) to the end of exercise (Bringard et al., 2006). Despite a steady rise in oxygen consumption blood lactate does not affect $\dot{V}O_2$ slow component (Poole et al., 1994). The proposed mechanisms that attenuated oxygen consumption were decreased muscle fatigue caused by greater support in muscle contraction direction and improved circulation from higher/greater venous return (Bringard et al., 2006). However, these mechanisms were not measured with EMG to detect muscle fatigue or colour Doppler ultrasound to assess venous return. Measuring the electrical activity in the contracting muscles using EMG would identify if muscle oscillation was decreased for participants wearing the GCS intervention. Decreased electrical activity would indicate less muscle oscillation and therefore that the GCS provided greater structural support to the contracting muscle. Further, colour Doppler ultrasound would accurately compare vein diameter and venous blood flow velocity between participants wearing a GCS or control intervention. Increased vein diameter or increased venous blood flow velocity would indicate that circulation and venous return were augmented.

Wearing GCS may effectively support muscle contractions and decrease muscle damage and exhaustion that is exacerbated at the end of prolonged continuous running. During running events that cause substantial leg fatigue such as the end of the marathon or the run leg of the triathlon fast-twitch fibres were gradually recruited to maintain running speed and oxygen consumption increased considerably (Xu et al., 1995; Hausswirth et al., 1996). This was confirmed by skeletal muscle EMG data collected concurrently with $\dot{V}O_2$ slow component data (Shinohara et al., 1992; Borrani et al., 2001). This may be because repeated eccentric muscle contractions during prolonged running cause muscle damage and exhaustion to slow twitch muscle fibres (Noakes, 2001). This was not alleviated by consuming water or carbohydrate supplements to attenuate glycogen depletion or dehydration (Sproule, 1998). Though muscle damage may be decreased, fast twitch muscle fibre recruitment may be delayed, and $\dot{V}O_2$ slow component decreased, there has been no published study that has shown that running performance was improved by wearing GCS during marathon or triathlon running.

Perception

Compression clothing enjoys extensive popularity among the athletic population as a training aid and recovery modality. Key factors that influence perception include comfort, aesthetic feeling and aesthetic appearance, which product marketers have used to promote their products to consumers. Participants involved in compression studies express heightened feelings of support when running wearing GCS (Ali et al., 2007).

Anecdotal evidence suggests athletes who wear compression clothing overnight considerably alleviate muscle soreness. Participants wearing GCS during running (Ali et al., 2007) and cycling (Chatard et al., 2004) have reported lower leg pain sensation after exercise compared with their responses after the control condition when no stocking was worn. The difference may be caused by a placebo effect because participants did not wear any stocking during the control intervention. At present no studies have assessed the perceptual differences between wearing a GCS garment and a placebo garment that provides no compression.

2.4 Types of Sport

Endurance Sports

The effects of GCS on cycling and running exercise have been discussed in detail (Berry et al., 1987; Berry et al., 1990; Sciacca et al., 1991; Chatard, 1998; Chatard et al., 2004; Bringard et al., 2006; Ali et al., 2007). Professional cycling teams racing in the major tours wear compression socks during stage races and pneumatically controlled pressure sleeves post-race to assist lactate clearance from their legs (Kimmage, 2008). These procedures have been used successfully for clinical patients however there is no published research that suggests highly trained cyclists experience benefits from using compression garments/devices during and following races.

Athletes may also choose to wear compression garments in other endurance sports including rowing, swimming, and kayaking. Compression clothing manufacturers make claims on their websites that athletes in these sports wear compression to improve their

training performance and recovery from training (www.Skins.net; www.2XU.com; www.kompressorz.com). One group of rowers planning a world record attempt at the trans-Atlantic crossing in December 2008 plan to wear compression garments as part of their recovery during the record attempt (www.tri247.com). However, there are no published studies that indicate that athletes in these sports experience any benefits during or following exercise.

Jumping and Sprinting Sports

Compression shorts have been shown to improve power maintenance over repeated jumps for college-level male and female volleyball players (Kraemer et al., 1996; Kraemer et al., 1998a) and maximal effort CMJ in nationally competitive track and field athletes (Doan et al., 2003). The improvement in maximal jump height observed by Doan et al. (2003) contrasted with the study by Kraemer et al. (1998a), who found that compression shorts did not improve maximal jump power. Doan et al. (2003) stated the reason for this difference was due to the participants' perception that wearing compression shorts would improve their CMJ performance. This highlights the importance of including a placebo control to determine if a compression garment has a real effect on performance.

Power lifters wear high-compression 'super suits' during competition to improve force development for a 1RM lift (Kraemer et al., 1996). The whole body high-compression can only be tolerated for a short period of time due to extreme discomfort and numbness. Further, participants wearing very tight compression shorts ('one size too

small') complained about discomfort (Doan et al., 2003) suggesting incorrectly fitted compression garments may actually have ergolytic effects.

Team Sports

Team sports that require high levels of cardiovascular fitness, long periods of standing, high impact forces from repeated landing, and tournament format competitions may benefit from wearing GCS as part of their sport equipment. Sports that fit these criteria include football, field hockey, netball, basketball, handball, baseball, softball, and touch rugby. American Football players have worn compression shorts during training and games to minimise impact injuries (Doan et al., 2003). This study found that the impact force from a helmet dropped onto the material decreased the impact force by more than 10% when compared with a pair of non-compression football pants (Doan et al., 2003). Wearing GCS for 12 hours recovery after rugby matches induced less muscle damage compared with passive recovery, but no significant difference was observed between active recovery or contrast water therapy (Gill et al., 2006). Athletes are encouraged to treat impact, muscle strain, and overuse injuries with ice and compression to improve recovery time (Bleakley et al., 2007). A GCS garment may be beneficial for arm and leg injuries where considerable swelling has occurred to remove lymph and improve circulation. An intervention that decreased the inflammatory phase time period would considerably shorten the time taken for an athlete to return to exercise (Bleakley et al., 2007). Muscle trauma from impact, sprain, or strain injuries may be alleviated by including compression as a supplement to other interventions such as protective clothing in contact sports, structural support in non-contact sports, and combined with rest, ice and

elevation for recovery. Wearing GCS exclusive to other interventions may not alleviate muscle soreness, damage, or pain. Athletes who have no muscle damage or injuries may not gain any substantial benefit from wearing GCS. However, athletes that do suffer from injuries may gain considerable benefits wearing GCS to reduce injury risk and improve recovery.

2.5 User Groups

Elderly

The venous system and musculoskeletal system are adversely affected by the aging process (Booth et al., 1994). Vein compliance decreases with age leading to a higher incidence of venous problems (Monahan et al., 2001). Venous problems are more common in a sedentary elderly population (Monahan et al., 2001). Though aging decreases venous compliance it is attenuated much more effectively in individuals who exercise regularly (Monahan et al., 2001). Aging also causes muscles and tendons to lose their elasticity, making them more prone to injury and increasing recovery time between exercise bouts (Noakes, 2001). This effect is exacerbated in elderly runners who have completed heavy training for many years (Noakes, 2001). Wearing a compression garment could provide support to leg muscles and decrease muscle oscillation during repeated ground impact (Kraemer et al., 1998a). However, this mechanism requires further investigation because changes in muscle oscillation were inferred from video recordings, not changes in EMG electrical activity. If the leg muscles received enhanced support from a compression garment then some of the muscle soreness experienced by elderly individuals during and/or after exercise may be alleviated.

Few studies have investigated GCS effects on exercise performance in an elderly population. Chatard et al. (2004) found that wearing GCS during a 5-min constant-load cycle test then elevating the legs for 80 min afterwards improved performance time by 6.3 s and lowered blood lactate concentration. This indicates that competitive elderly athletes may benefit more substantially than their younger counterparts from wearing GCS during hard exercise.

Untrained

Untrained individuals may gain the most benefits from wearing GCS (Kraemer et al., 1998a). Untrained participants performed eccentric bicep contractions prescribed to cause considerable muscle damage to investigate whether a compression garment would alleviate muscle soreness and damage (Kraemer et al., 2001). Participants wore either arm compression sleeves or no compression for five days after eccentric exercise. Participants in the compression group had lower plasma CK levels, lower perceived soreness, reduced swelling, greater elbow ROM, and greater force production recovery (Kraemer et al., 2001). These results indicate that wearing GCS may also alleviate post-exercise muscle soreness and DOMS suffered by sedentary individuals who want to undertake a regular exercise programme. The effect of wearing compression garments becomes less significant for trained individuals. Running performance was not significantly different (relative to control) when moderately trained athletes wore elastic tights during 5 km running (Chatard, 1998) or GCS during 10 km running (Ali et al., 2007). Well-trained sprint and endurance runners did not experience any enhancements in

running performance or venous return when wearing compression (Sciacca et al., 1991). This led the authors to state that well-trained athletes may have developed physiological adaptations to exercise that GCS garments cannot enhance further (Sciacca et al., 1991). Taken together these studies indicate GCS may be effective for untrained individuals, but individuals who exercise regularly may not gain the same beneficial effects.

2.6 Summary

Graduated compression garments have a number of different applications to sport performance. Initial studies that tested the beneficial effects for athletes wearing GCS for running and cycling (Berry et al., 1987; Berry et al., 1990; Sciacca et al., 1991) found no significant performance benefits. Further studies with athletes involved in running, cycling, and jumping sports (Kraemer et al., 1996; Kraemer et al., 1998a; Chatard et al., 2004; Bringard et al., 2006) found that wearing GCS significantly improved repeated effort jump height, running economy, and cycling for elderly individuals. However, no study has investigated how different grades of compression effect running performance or the physiological and perceptual mechanisms that underpin running performance. A large number of studies have been completed with a clinical population to determine the optimum compression grade for patients with venous deficiencies. Untrained and moderately trained athletes have shown promising improvements or trends for improvement in performance and physiological tests wearing GCS during jumping, running, and cycling exercise. However, no studies have been undertaken to determine

the optimum compression grade that could potentially assist running performance for a highly trained or elite group of endurance athletes.

3.0 GENERAL METHODS

Preliminary Procedures

All potential participants involved in both studies were fully informed about the study design and expectations in an initial meeting. If the participants decided to become involved in the study they returned to the laboratory at a later date. The testing procedures were repeated verbally and an information sheet was given to the participants a second time (Appendices 8-9). The participants then signed an informed consent form and completed a health screen questionnaire (Appendices 1-3). The participants' legs were measured to determine the correct GCS size (Appendix 9). Participants were given the control stocking in their size to confirm the fit was correct and comfortable. Participants were also encouraged to run on the treadmill to ensure stockings were correctly fitted and felt comfortable.

Graduated Compression Stockings

The compression garments (Julius Zorn GmbH, Postfach 1280, 86543 Aichach, Germany) used in these studies were knee high stockings that provide greatest compressive pressure at the ankle which gradually dissipate to the calf. Eighteen different sizes were available based on the length (three sizes: short, standard, and long) and circumference (six sizes: I-VI) of participants legs.

The participants' leg dimensions were measured according to the manufacturer's guidelines (Julius Zorn: www.elitemedical.com/juzosizechart.html). The correct fit for each participant was determined by measuring the distance from the ground to the

popliteal line behind the knee, the leg circumference immediately below the knee along the transverse plane, the leg circumference at the widest part of the calf along the transverse plane, and leg circumference at the narrowest part of the ankle along the transverse plane. Participants donned the GCS by turning the stocking inside out and rolling the sock over the toes, foot, and leg. The stocking was adjusted so the top was flush below the knee and above the calf muscles. Any bunching was smoothed over to prevent a tourniquet effect (Figure 3.1).

Compression for each individual participant was verified using a pressure bladder (Kikuhime BG3792, Advancis Medical; Nottingham, UK) placed between the stocking and the skin above the lateral malleolus (ankle) and lateral aspect of the shank below the knee (calf). The pressure bladder was calibrated before each measurement and checked between measuring the ankle and calf pressures to ensure that the device re-zeroed. Compression was measured immediately before warm-up to ensure that the stocking size was correct and to compare the measured compression with the manufacturer's guidelines (Figure 3.2).



Figure 3.1: GCS correctly fitted over legs flush under the knee and smoothed to avoid bunching.



Figure 3.2: Compression level measured at the ankle using a pressure bladder connected to a digital meter.

Four different types of stocking were used. The first stocking was designed to have no compression at the ankle or calf (0 mmHg). It was used as a control garment to minimise any placebo effect that participants may have perceived from wearing the stockings. The placebo effect was reduced further because experimenters told the participants that all stockings may improve running performance. Previous studies (Chatard, 1998; Ali et al., 2007) did not use a control garment. Instead they compared a GCS or compression garment with non-compression running shorts and/or socks. An experimental design without a control garment may not eliminate a placebo effect. A placebo effect may improve the likelihood that an intervention has a more positive effect on the outcome than a control treatment simply because the patient or participant believes the intervention will be more effective (Moerman et al., 2002).

The three types of GCS garments used in these studies were designated as low (Low), medium (Med), and high (Hi) compression (Table 3.1). The different compression grades at the ankle and calf were achieved by the length, width, and weave of the garment i.e. tighter weave produced greater compression around the leg tissues.

Table 3.1: Compression applied by GCS at the ankle and below the knee according to manufacturer's guidelines when fitted correctly from sizing chart (Appendix 10)

Compression Type	Compression at ankle (mmHg)	Compression at knee (mmHg)
Control	0	0
Low	15	12
Medium	21	18
High	32	23

Muscle Function

Counter Movement Jumps

Counter movement jumps were measured to estimate changes in leg power for comparison between the control and GCS interventions. Participants were instructed to step on to a jump mat (Just Jump, Just Run; Probotics inc. 8602 Esslinger CT Huntsville, AL), place their hands on their hips, and use a counter-movement to optimise jump height. Three maximal-effort jumps were completed and the highest jump recorded to infer changes in leg power. Leg power was inferred from jump height using the following formula for peak power (Johnson et al., 1996):

$$PP = 78.6 \times CMJ + 60.3 \times \text{mass} - 15.3 \times \text{height} - 1308$$

PP: peak power (W)

CMJ: counter-movement jump (cm)

Mass: body mass (kg)

Height: standing height (cm)

Pressure Sensitivity

Lower limb soreness was assessed before and after treadmill running using anatomical landmarks and a pressure algometer (Force Dial FDK 60, Wagner Instruments, Greenwich, CT) to quantify muscle soreness. An algometer is a rubber-tipped metal probe attached to a force meter. The algometer measures applied pressure in $\text{N}\cdot\text{cm}^{-2}$ or $\text{kg}\cdot\text{cm}^{-2}$ provided the rubber tip has a 1cm^2 surface area. Pressure was applied to the surface of the body and participants indicated when the pressure became painful. Fischer (1987) found that when pressure sensitivity was lower in muscle than bone it indicated hypersensitivity and tenderness in the muscle. Measurements were recorded as

the minimum pressure applied to a body surface that caused pain. This method produced repeatable and valid indicators of muscle pressure sensitivity (Fischer, 1987). Up to 11 kg·cm⁻² (110 N) of pressure was applied to each site. Participants were asked to verbally indicate when the force became ‘uncomfortable’; if no indication was given soreness was considered ‘not present’ (Bailey et al., 2001).

The 6 sites for pressure application were palpated using anatomical landmarks and marked with a pen as follows: vastus lateralis muscle 20 cm above distal end of the lateral aspect of the femur, vastus medialis muscle 10 cm above distal end of the medial aspect of the femur, biceps femoris muscle 20 cm above the popliteal line, centre of the medial gastrocnemius muscle belly, centre of lateral gastrocnemius muscle belly, tibialis anterior muscle 10 cm above proximal aspect of lateral malleolus. Each site was pressure tested for muscle soreness twice and the mean taken. If measurements were different by greater than 1 kg·cm⁻² a third measurement was completed and the median taken (Figure 3.3).

Pressure sensitivity was quantified by calculating individual and group pain threshold. This was determined by taking the mean for each set of measurements (sum of applied force divided by number of regions measured) to give a score out of 11. A higher score signified a higher pain threshold for an individual or group wearing a GCS intervention (Bailey et al., 2001). A limitation of this technique was how accurately participants reported pressure sensitivity.

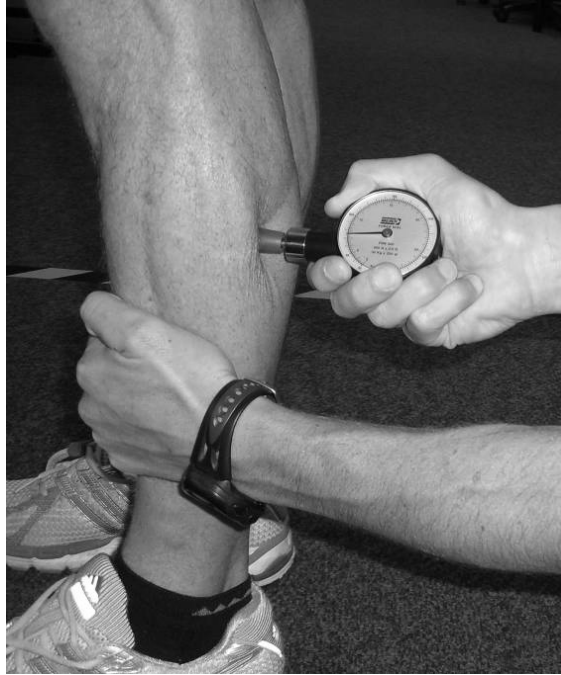


Figure 3.3: Pressure sensitivity measured at the lateral head of the left gastrocnemius muscle using a pressure algometer.

Muscle Soreness

Muscle soreness was assessed by participants drawing on an anatomical diagram differentiated into different major muscle group regions identified by a letter (Thompson et al., 1999; Ali et al., 2007, Appendix 11). Participants were asked to indicate muscle soreness by shading any regions that felt sore and assigning a level of muscle soreness to it. The amount of muscle soreness was described by a scale that ranged from no ache/soreness through to the highest possible pain/soreness (Appendix 11). The average muscle soreness for each GCS intervention was determined by the aggregate total from all participants that each region was shaded – a darker shade indicated a higher frequency of muscle soreness.

Blood Sampling

Venous blood samples were taken from participants to measure levels of creatine kinase (CK) in plasma and myoglobin in blood. A 10 ml venous blood sample was drawn by venepuncture from an antecubital vein at pre-exercise and then 0-, 24-, and 48-h post-run by a trained phlebotomist (Figure 3.4). Samples were centrifuged for 7 min at 3500 rpm at 4°C to separate red blood cells from plasma (Heraeus Labofuge 400R, DJB Healthcare Ltd, Buckinghamshire, England). Plasma was transferred in duplicate for each sample into two aliquots of 1 mL and labelled according to the participant ID, condition, time, and date of the sample. The samples were stored at -20°C for CK and myoglobin analysis. Samples were coded to ensure investigators were unaware of the results. Blood analyses were carried out using a Vitalab Flexor clinical chemistry analyser (Vital Scientific NV, The Netherlands), a Roche CK-NAC liquid assay kit (Roche Diagnostics GmbH, Mannheim, Germany) was used to analyse CK. The upper limit of the normal range for CK was accepted as 70 U·L⁻¹. The latex enhanced immunoturbidimetric assay using a Randox Kit (Vitalab Flexor E, AC Dieren, The Netherlands) was used to determine Mb. The upper limit for the normal range of Mb was accepted as 85 ng·ml⁻¹.

Creatine kinase is an enzyme associated with ATP resynthesis that provides energy to contracting muscle. It is an accurate marker of skeletal muscle damage (Byrnes et al., 1985) as repeated and intense muscle contractions (Schwane et al., 1983) cause CK to leak from skeletal muscle into plasma (Clarkson et al., 1992; Noakes, 1987), peaking at 24- to 72-h post-exercise (Lijnen et al., 1988). However, CK should be used tentatively to determine comparisons in muscle damage (Clarkson et al., 1986) and may be effective

when used in conjunction with other methods that measure muscle damage. Muscle damage from high intensity or unfamiliar exercise increases protein levels circulating in the cytosol because CK and other proteins and metabolites are unable to cross the plasma membrane (Pyne, 1994).



Figure 3.4: Venous blood sampled from the right antecubital vein for creatine kinase and myoglobin analysis.

Myoglobin is a muscle protein that binds and transports oxygen in cardiac myocytes and skeletal muscle fibres (Ordway et al., 2004). Muscle damage caused by physical exercise causes myoglobin to leak out of the sarcolemmal membrane into the bloodstream causing a rapid increase in myoglobin levels (Suzuki et al., 1999). Myoglobin has been used in conjunction with other blood markers from muscle damage including C-reactive protein and lactate dehydrogenase. Myoglobin is most effective as a muscle damage marker when it is measured concurrently with CK. This is because the

change in myoglobin levels are more pronounced in acute exercise bouts. However, myoglobin is also metabolised faster by the kidneys, so the measurement must be timed accurately to ensure reliable results (Suzuki et al., 1999). A spike in myoglobin levels may accurately indicate the period of time taken for the endocrine system to react to high-intensity exercise. Measuring both levels concurrently was important to determine the intensity and timing of the endocrine response to muscle damage.

Physiological Measures

Venous Return

Changes in venous return to the heart affect the baroreceptor control of heart rate (Baron et al., 1986). This infers that changes in heart rate can be used as a surrogate measure to estimate venous return changes. A lower heart rate achieved at the same exercise intensity may indicate that venous return was higher. Venous return can be measured directly using colour Doppler ultrasound imaging of the femoral vein, or indirectly by injecting a bolus of fluid into a limb, using strain gauge plethysmography that occludes venous blood flow, or using light reflection rheography that reflects red light directed to a vein.

Colour Doppler ultrasound is recognised as the most effective non-invasive method to detect and diagnose venous thromboses (blocked blood flow in veins) in clinical patients (Wiese et al., 2004). It is used extensively in hospitals to detect venous deficiencies. Blood flow in a vein can be monitored by placing an ultrasound transducer over the vein. The Doppler sounds that bounce back from the vein and blood flow through

it are converted on a computer into colours that indicate the speed and direction of blood flow in the vein (Nissl, 2007).

Venous return may be determined by injecting Technetium-99 into the participants' deep foot venous system then recording the duration for the injected bolus to reach a scintillation counter placed over the femoral vein (at the femoral triangle; Lawrence et al., 1980). Xenon-133 may be injected intramuscularly (Lassen et al., 1964), Sodium-24 injected into the blood flow (Ketty, 1949), or Evans Blue Dye may be injected into a limb (Stanton et al., 1949) and the time required for the bolus to dissipate from the local injection site recorded. The disadvantage of these methods is that they cannot be used repeatedly on consecutive days due to their radioactive (Technetium-99, Xenon-133, Sodium-24) or carcinogenic (Evans Blue Dye; Haller et al., 1992) properties, and that the procedure is highly invasive for the participant.

Venous occlusion plethysmography accurately measures arterial inflow and venous outflow by occluding venous blood flow with a pressure cuff inflated to 50 mmHg, which is sufficient to occlude venous, but not arterial flow. The cuff is wrapped around a limb and changes in limb volume are measured by non-invasive mercury strain gauges on both sides. The equipment is used regularly to identify blood flow changes caused by exercise (Fehling et al., 1999) and correlates closely to other methods except colour Doppler ultrasound techniques (Levy et al., 1979; Tschakovsky et al., 1995). Light Reflection Rheography uses infra-red light emitting diodes surrounding a photodetector

to measure the intensity of reflected light which is transferred into an electrical signal and recorded on a chart (Sciacca et al., 1991).

Due to time constraints and difficulties obtaining the correct equipment none of the above methods were used to measure venous return. Changes in venous return were inferred by changes in heart rate. Though this was not a direct measurement of venous return it indicated changes in the volume of blood returned to the heart.

Heart Rate

Heart rate was measured continuously every 5 s during running trials using either the Polar Team system chest straps (Polar Team; Kempele, Finland) or a downloadable heart rate monitor (S400, Polar; Kempele, Finland) to infer changes in venous return. For the 10-km time trials participants wore a coded Polar Team chest strap. The data were downloaded after the run and checked against the participants' run time. For the treadmill running trials participants wore a heart rate chest strap that was recorded by a downloadable heart rate watch.

Heart rate was measured during running to measure changes in physiological stress and venous return. Lower heart rate at any given running speed may indicate that cardiac adaptation from chronic endurance training has occurred. This would happen from improved contractility, larger total blood volume or improved venous tone causing an enhanced stroke volume (Brooks et al., 2005). Such adaptations are caused by chronic

endurance training over weeks to months. However, this was unlikely in trials separated by seven days in highly trained participants.

Oxygen Uptake

Oxygen uptake ($\dot{V}O_2$) was measured using breath-by-breath gas analysis (Cortex Metamax 2.3; Leipzig, Germany) to determine changes in running economy between the different compression conditions. The gas analyser was calibrated before each trial for barometric pressure in the laboratory using a portable barometer. Pressure calibration was successful if the offset was less than 65 mBar. The turbine that measured the volume of inspired and expired gases was calibrated by injecting and withdrawing air at different velocities using a 3-L syringe (Hans Rudolph Inc; Kansas City, MO). The volume calibration was successful if the injected and withdrawn gas volumes were within 150 mL of 3 L. The oxygen and carbon dioxide sensors were calibrated using two separate mixtures of medical grade gas of room air concentrations (Gas 1) and 15% O₂, 5% CO₂ (Gas 2). Participants wore a face mask (Hans Rudolph Inc; Kansas City, MO) fitted specifically to the contours of their face that covered the mouth and nose to ensure no air leaked from the mask. The face mask was held firmly in place during running by a head strap (Hans Rudolph Inc; Kansas City, MO) that clipped on to the face mask. The turbine was attached to the face mask and the gas sampling line connected to the turbine in the flow of the participants' inspired and expired breath. At least 90 s of resting gas analysis was collected and checked to ensure the ventilatory variables were normal before starting exercise. During the running trials the gas analyser measured breath-by-breath tidal

volume, breathing frequency, minute ventilation, $\dot{V}O_2$, $\dot{V}CO_2$, respiratory exchange ratio, ventilatory equivalent for O_2 , ventilatory equivalent for CO_2 , and heart rate (Figure 3.5).



Figure 3.5: Breath-by-breath gas analysis and heart rate recorded during 40-min treadmill running wearing GCS.

Blood Lactate Testing

Blood lactate was measured to make comparisons between control and GCS intervention garments during and after exercise. Participants received a fingertip prick from a lancet (BD Contact activated lancet; Franklin Lakes, NJ) and 1 drop of blood was collected on a Lactate Pro strip (Lactate Pro, Arkray Inc. Kyoto, Japan). Samples were recorded to $0.1 \text{ mmol}\cdot\text{L}^{-1}$. The Lactate Pro was calibrated prior to testing using the calibration strips for that specific batch. Samples were collected while the participants

were running (continuously) every 5 min. Previous research indicated that GCS lowered capillary blood lactate concentrations (Chatard et al., 2004; Berry et al., 1987; Berry et al., 1989) by restricting lactate within the muscle rather than allowing it into the systemic blood stream. Samples were taken to find if the control and GCS garments replicated the findings from previous research.

Perceptual Measures

The Feeling Scale (FS) was used to measure the perceived ratings of affective valence before and following exercise (Hardy & Rejeski, 1989; Appendix 4). The FS indicates the level of pleasure or displeasure felt about running using an 11-point scale ranging from -5 (very bad), 0 (neutral), to +5 (very good) with markers at each odd integer.

The Felt Arousal Scale (FAS; Svebak and Murgatroyd, 1985; Appendix 5) was used to measure the participants' levels of activation/arousal at a specific time during exercise. The scale ranges from 1, indicating low arousal characterised by feeling bored, apathetic or tired, to 6, indicating high arousal characterised by feeling excited, angry, or energetic.

The 15-point Ratings of Perceived Exertion (RPE) scale (Borg, 1973; Appendix 6) was used to measure how hard the participants perceived they were running immediately after or during the running trials. The scale ranged from 6 (very, very light) to 20 (very, very hard) to describe effort.

A number of other Likert scales were used to assess the comfort, tightness, and (where applicable) any induced pain from wearing GCS (Ali et al., 2007; Appendix 7). Responses for each factor ranged from 1 (very uncomfortable, slack/loose, no pain) through to 10 (very comfortable, very tight, very painful).

10-km Time Trial Running

The 10-km time trials were run on a dry outdoor 400-m track in overcast or sunny conditions. The outdoor tracks were synthetic Mondo at Mt Smart Stadium (Auckland) and Rekortan at Millennium Stadium (North Shore). Participants ran on the same track for every trial. Running was completed at the same time of day (18:00-20:00 h) in November and December. The environmental conditions were (mean \pm SD): $18 \pm 3^{\circ}\text{C}$, $71 \pm 13\%$ humidity, $2.1 \pm 0.6 \text{ m.s}^{-1}$ wind speed. The 10-km distance was selected to reproduce the performance test used by Ali et al. (2007) that found a trend ($P=0.15$) for lower heart rates in trained males wearing GCS during paced 10-km running compared with running shorts. Secondly, the positive GCS effects (particularly movement economy) may be too subtle to analyse accurately over shorter duration tests. Longer running distances may produce more accurate comparisons in mechanical efficiency (Bringard et al., 2006). Thirdly, a 10-km paced run increased immediate-onset muscle soreness in moderately trained participants in control and GCS intervention conditions, and more muscle soreness than after completing a multi-stage shuttle run (beep) test (Ali et al., 2007).

Treadmill Running

Running on a treadmill is a valid simulation of normal gait (Arsenault et al, 1986), though kinematic and muscle firing patterns change. Athletes running on a Woodway treadmill (Woodway, ELG70; Munich, Germany) at 14.4 km·h⁻¹ and 21.6 km·h⁻¹ decreased stride length, increased stride frequency, and reduced ground contact time significantly ($P<0.05$) compared with over-ground running at the same speed. However, electrical activity (EMG) in six lower limb muscles was similar between treadmill and over-ground running (Wank et al, 1998). Walking (Arsenault et al., 1986) and sprinting (Frishberg, 1983) on a treadmill had similar effects on kinematics and muscle firing patterns. The greatest source of variation between treadmill and over-ground running was caused by belt speed variation between strides. High-powered treadmills (such as the Woodway) minimise speed variation and eliminate the differences between treadmill and over ground running (Schache et al., 2001). Alterations in stride length and frequency may have an effect on running economy, as these factors have been identified as integral to running economy (Noakes, 2001). However, this would only be an issue if comparisons were made between running economy over-ground versus treadmill while manipulating other variables as well.

Concurrent $\dot{V}O_2$ max and Lactate Test

Participants completed a concurrent $\dot{V}O_2$ max and lactate test on a Woodway treadmill before both studies to determine their aerobic power, running economy, and lactate thresholds. A warm-up was completed at a self-selected speed for at least 5 min.

After the warm-up participants were fitted with a heart rate chest strap, a head strap, and a face mask connected to a turbine and sampling line (Figure 3.5). Readings from the turbine and sample line were transferred to a gas analyser that recorded volume and concentration of expired gases. The test was started at an appropriate speed decided by the experimenter after thorough consultation with the participant based on their recent training volume, personal best run times and most recent racing performances. The incline was set at 1.5% and remained at that gradient for the remainder of the test. Stages were 4 min long with a 1-min rest period between each stage to collect blood lactate samples. The increment between each stage was $1 \text{ km}\cdot\text{h}^{-1}$. The test concluded when the participant could no longer keep up with the treadmill speed (test terminated by experimenters) or when the participant reached volitional exhaustion (test terminated by participant).

Statistical Analysis

Data collected for all measured variables were compared using a two-factor (treatment x time) analysis of variance (ANOVA) with repeated measures (SPSS version 15.0). The change in values between groups comparing pre- and post-run measures were also assessed using one-way ANOVA. When significant differences between GCS interventions were identified post-hoc Student's t-test, using the Bonferroni adjustment, were performed. Mauchly's test for sphericity was applied to the data to confirm if sphericity was violated. When sphericity was violated the Huynh-Feldt estimate was used to correct the data. Correlations between variables were verified using simple linear regression equations and reported as Pearson's correlation co-efficient. The co-efficient

of variation (CV) was calculated to indicate within-participant variation between running trials. Data are presented as means \pm SD (unless otherwise indicated). Figures are presented as mean \pm 95% confidence interval. Participant characteristics are presented as mean (\pm SD). Statistical significance was set at $P < 0.05$.

4.0 THE EFFECTS OF GRADUATED COMPRESSION STOCKINGS ON RUNNING PERFORMANCE

4.1 Abstract

Purpose: The aim of this study was to quantify run time and physiological and perceptual variables for runners completing 10-km time trials whilst wearing different grades of graduated compression stockings (GCS). **Methods:** Following an initial familiarisation run, 9 male and 3 female competitive runners ($\dot{V}O_2$ max 68.7 ± 5.8 ml·kg⁻¹·min⁻¹) completed four 10-km time trials on an outdoor 400-m track wearing either control (0 mmHg; Con), low (12-15 mmHg; Low), medium (18-21 mmHg; Med), or high (23-32 mmHg; Hi) GCS in a randomised counterbalanced order in similar environmental conditions. Based on their performance in the familiarisation trial, athletes were set off at 1-min intervals and the same order was used for all subsequent trials. Leg power was assessed pre- and post-run via counter movement jump (CMJ) using a jump mat. Blood lactate concentration ([La]) was assessed pre and post-run while heart rate (HR) was monitored continuously during exercise. Perceptual scales were used to assess the comfort, tightness and any pain associated with wearing GCS. **Results:** There were no significant differences in performance time between trials ($P=0.99$). The change in pre- to post-exercise CMJ performance was significantly better in Low and Med than Con ($P<0.001$). Mean HR ($P=0.99$) and [La] ($P=1.00$) were not different between trials. Participants rated Con and Low as more comfortable than Med and Hi ($P<0.01$), Med and Hi were rated as tighter than Low ($P<0.01$), all GCS were rated as tighter than Con ($P<0.01$), and Hi was associated with the most pain ($P<0.01$). **Conclusions:** GCS worn by competitive runners during 10-km time trials did not affect performance time. Low and Med GCS resulted in greater maintenance of leg power following endurance exercise.

4.2 Introduction

Running performance is determined by a person's ability to complete a measured distance in the shortest possible time. Individuals have searched for ergogenic aids to achieve superior results during training and racing to gain an advantage over their opponents (Applegate et al., 1997). Competitive runners have worn graduated compression stockings (GCS) – a form of mechanical ergogenic aid - during races to enhance their potential to run faster, though minimal research exists to confirm performance enhancement and no research exists that compares different grades of compression tightness on performance. Despite the scarcity of research world records have been set wearing GCS for 20 km (Lornah Kiplagat, 1:02:57, 14th October 2007, Udine, Italy) and treadmill marathon (Michael Wardian, 2:23:58, 11th December 2004, Arlington, USA). Though these world record performances were undoubtedly the combination of exceptional athletic talent and comprehensive training the runners' choice to wear GCS indicates these athletes place considerable faith in their performance effects.

Previous research suggests that there may be some performance benefits from using GCS. Despite an attempt to pace moderately-trained athletes, participants tended to run faster ($P=0.15$) but with lower average heart rates ($P=0.15$) during a 10-km run when wearing GCS relative to control (Ali et al., 2007). Further, recreational athletes running 5-km races achieved faster run times when wearing elastic tights compared to when they wore no elastic tights (Chatard, 1998).

Other studies show that power may be enhanced when wearing GCS. Track athletes showed improved vertical jump height while wearing compression garments compared to non-compression gym shorts (Doan et al., 2003). Material testing showed that elasticity of the compression garments increased flexion and extension torque. Similarly, athletes and non-athletes wearing graduated compression shorts had improved vertical jump after endurance exercise (30 min running at 70% of maximum heart rate; Kraemer et al., 1998a). Diminished jump height may be used to infer changes in maximum or mean leg power (Johnson et al., 1996). Therefore, an improvement in CMJ immediately following endurance exercise may indicate a maintenance of leg power and muscle function. Other findings show that single sprint performance and repeated-sprint performance was not altered by wearing GCS (Doan et al., 2003; Duffield et al., 2007). However, none of the studies mentioned above used a placebo garment as a control, but rather compared the GCS/elastic tights (intervention) with running shorts (control). Therefore, participants and experimenters were not blinded to the intervention to remove bias and a possible placebo effect. Additionally, most previous studies have employed untrained and moderately trained participants and to date it is unclear whether some of the previous benefits of using GCS would occur when used by well-trained athletes.

In addition to the purported performance benefits, the popularity of GCS may be partially due to the fact that they look and feel good. Responses from participants wearing GCS (18-22 mmHg) and ankle-length socks (control) indicated that athletes felt GCS were tighter but more comfortable (Ali et al., 2007). This inferred that GCS made athletes feel more comfortable while running, however, no study has attempted to define

which level of GCS tightness is most comfortable for athletes while running. There may be an optimal compression level where athletes feel most comfortable and perform better, however, this remains to be identified.

Therefore, the main aim of this study was to examine the effects of wearing different grades of GCS on 10-km running performance in well-trained athletes. A secondary aim was to assess the effects of wearing GCS on various physiological and perceptual responses following exercise. The null hypothesis was that wearing Lo, Med and Hi grades of GCS during 10-km running would have no effect on running performance, physiological variables, or subjective perceptions when compared with a placebo control garment.

4.3 Methods

Participants

Twelve participants provided informed consent to take part in this study which complied with the Massey University Human Ethics Committee guidelines (05/077). The participants were well-trained, competitive, male and female runners who were (mean \pm SD) 33 ± 10 years old, 68.5 ± 6.2 kg body mass, and 1.74 ± 0.06 m in stature (Table 4.1). All participants completed and signed health screening questionnaires (Appendix 1) before beginning any exercise tests.

The participants competed regularly in 800 m to marathon distances during the previous 12 months. Run training time ranged from 7 to 16 hours per week, interspersed with competitive events. No participants reportedly suffered from deep vein thrombosis (DVT), varicose veins or other vascular illnesses. The personal best times for 10 km were (mean \pm SD; min:s) $37:30.4 \pm 2:00.4$ (males) and $40:52.2 \pm 3:23.4$ (females).

Table 4.1: Anthropometric measures and performance characteristics of participants determined by a concurrent $\dot{V}O_2$ max and lactate test.

ID	Height (m)	Mass (kg)	Age (years)	$\dot{V}O_2$ max (ml·kg ⁻¹ ·min ⁻¹)	v at 4 mmol (km·h ⁻¹)	Peak v (km·h ⁻¹)	Best 10km Time (% World Record)
1 ^F	1.63	54.6	20	60.6	14.5	16	41:50 (71%)
2	1.72	67.0	39	69.9	14.0	16	40:02 (66%)
3	1.76	73.9	47	67.1	15.0	17	37:09 (71%)
4	1.74	72.7	48	68.1	16.0	18	36:58 (71%)
5	1.75	63.8	43	75.4	17.0	19	34:24 (76%)
6	1.68	69.5	23	73.1	15.0	18	38:10 (69%)
7 ^F	1.74	71.6	27	64.3	15.0	17	37:06 (80%)
8	1.85	67.4	26	76.8	15.5	18	36:14 (73%)
9	1.83	70.5	44	78.0	16.0	18	34:50 (75%)
10 ^F	1.73	63.5	29	61.5	14.5	16	43:41 (68%)
11	1.72	76.2	37	63.7	14.0	16	40:12 (65%)
12	1.81	73.6	24	75.1	15.0	18	37:04 (71%)
Mean	1.75	68.7	34	69.5	15.1	17.3	
SD	0.06	6.0	10.2	6.2	0.9	1.1	

F: Female participants

*Men's world record 10 km: 26:17.53 set by Kenenisa Bekele (Ethiopia) in Belgium, 2005.

Women's world record 10 km: 29:31.78 set by Wang Junxia (China) in Beijing, 1993.

Preliminary Procedures

Participants completed a concurrent $\dot{V}O_2$ max and lactate test protocol within two weeks before beginning the first trial to assess their level of physical fitness. The time trial protocol was explained and leg measurements were taken to ensure participants received the correct stocking size for each time trial run. The GCS worn by each participant during the time trials were determined by a partially counter-balanced design that was double blinded to the experimenters and participants. Participants were also familiarised with the correct counter-movement jump (CMJ) technique. An experimenter

described and demonstrated the correct movements and stressed the importance that each attempt was a maximal effort. The perceptual scales used during the study were explained to participants so as to ensure they gave correct answers for subjective perception.

Counter Movement Jumps

CMJ performance was measured pre- and post-run to estimate changes in leg power. Participants were encouraged to practice the correct jumping technique after they had completed their warm-up (10-min self-selected running and stretching, consistent between trials). Participants were instructed to step on to a jump mat (Just Jump, Just Run, Probotics Inc.; 8602 Esslinger Court, Huntsville AL, USA), place their hands on their hips, and use a counter-movement to optimise jump height. Three maximal-effort jumps were performed by participants with the best jump used for comparison with post-run CMJ. All CMJ efforts were separated by at least 10 s rest. Leg power from the best jump was calculated using the formula developed by Johnson et al. (1996).

Perceptual Measures

The Feeling Scale (FS) was used to measure the level of pleasure or displeasure before and following exercise using an 11-point scale ranging from -5 (very bad), 0 (neutral), to +5 (very good) with markers at each odd integer (Hardy & Rejeski, 1989; Appendix 4). The Felt Arousal Scale (FAS) was used to measure participants' level of arousal/activation before and after exercise using a 6-point scale that ranged from 1 (bored, apathetic, tired) to 6 (excited, angry, energetic: Svebak and Murgatroyd, 1985; Appendix 5). The Ratings of Perceived Exertion (RPE) was used to measure how hard the

participants perceived they were running during the trials, ranging from 6 (very, very light) to 20 (very, very hard: Borg, 1973; Appendix 6). A number of other Likert scales were used to assess the comfort, tightness, and (where applicable) any induced pain from wearing GCS (Ali et al., 2007; Appendix 7). Responses for each factor ranged from 1 (very uncomfortable, slack/loose, no pain) through to 10 (very comfortable, very tight, very painful).

Experimental Procedures

Five 10-km time trials were run on an artificial surface outdoor 400-m track interspersed by at least 6 days of recovery. The track surfaces used for the time trial runs were synthetic rubber at Mt Smart Stadium (Mondo, Auckland) and Millennium Stadium (Rekortan, North Shore). All participants were advised to prepare for the trial with the same routines they followed prior to a running race and to maintain consistency with their preparation in the 48-h period leading up to each trial. An 8-week testing period at both tracks was booked to allow for wet weather, high wind speeds ($>5 \text{ m}\cdot\text{s}^{-1}$), or extenuating circumstances preventing participants from running the time trials. If track conditions or wind speeds were not conducive to running the participants were informed when they arrived and alternate testing dates were announced. Participants arrived at the same time and same day of the week for each time trial 20 min before they were due to start the run. During this period the participants were fitted with a pair of GCS, a downloadable heart rate monitor (Polar Team System, Polar; Kempele, Finland), and reported perceptual ratings. Participants were allowed a 10-min warm-up period before the assessment of leg power. Thereafter [La] was measured from finger prick samples (Lactate Pro, Arkray Inc.

Kyoto, Japan) immediately before beginning the time trial run (Figure 4.1). Environmental conditions including wind speed, wind direction, weather conditions, track conditions, ambient temperature, relative humidity, barometric pressure, and wet bulb globe temperature were recorded using a portable weather station (Kestrel 4500 Portable Weather Tracker, Neilsen-Kellerman, Boothwyn, PA).

Each participant was started for the 10-km run individually and separated from the next runner by a 60-s gap in order from slowest to fastest. The runners were separated to avoid pacing strategies affecting run performance time. Run performance was motivated by monetary rewards for a personal best time or gift rewards for finishing ahead of the runner who started in front of them. During the run heart rate was recorded every 5 s and lap counters recorded splits for every 400 m. Run time was measured with two stopwatches to ensure the correct finishing time and run speed were recorded. During the run participants received feedback about the number of laps they had completed but not heart rate or lap time information.

Immediately after completing the run participants' blood lactate was measured, leg power was assessed and the perceptual ratings were recorded. Following the post-run tests each runner was asked to perform a short warm-down and stretching as part of their normal routine after finishing a race. The starting times and participant running order was unchanged between trials. No performance feedback was given to participants until after the final trial.

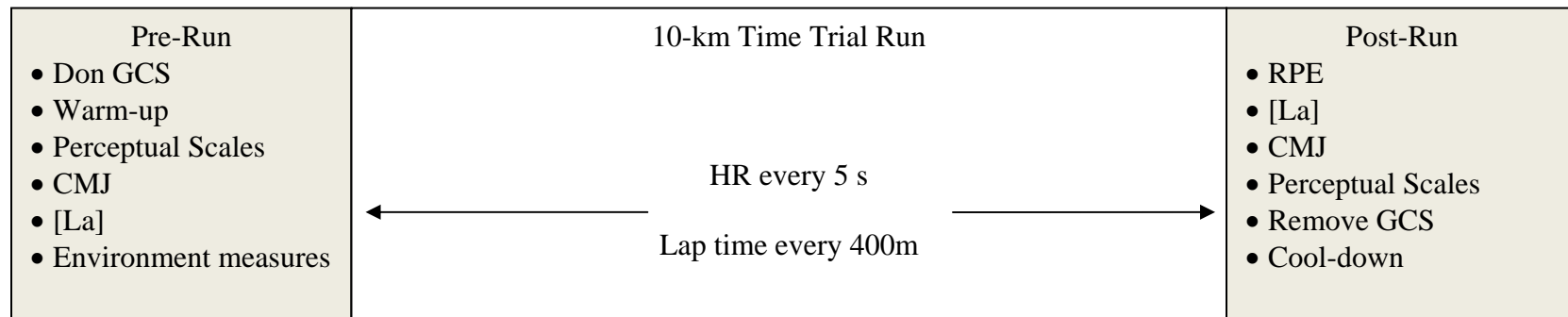


Figure 4.1: Experimental protocol for each 10-km time trial run.

Statistical Analyses

Data collected for all measured variables were compared between each GCS intervention worn using one-way or two-way repeated measures analysis of variance (ANOVA, SPSS version 15.0). Delta change values between groups comparing pre- and post-run measures were also assessed using one way ANOVA. Mauchly's test of sphericity was used to identify when sphericity was violated. When the assumption of sphericity was violated the Huynh-Feldt correction was used. When significant differences between GCS interventions were identified paired t-tests, using the Bonferroni adjustment, were applied. The co-efficient of variation (CV) was calculated to indicate within-participant variation between running trials. Correlations between variables were verified using simple linear regression equations and reported as Pearson's correlation co-efficient. Data are presented as means \pm SD (unless otherwise indicated) and statistical significance was set at $P < 0.05$.

4.4 Results

Time trials were run at an average temperature of 18°C (12-22°C), 71% humidity (53-94%), 2.1 m·s⁻¹ wind speed (0.5-5.0 m·s⁻¹), on a dry 400 m synthetic track under sunny or overcast conditions at the same time of day (18:00-20:00 h). The average group run time for the familiarisation trial (min:s, wearing control GCS) was 39:38 with a CV between participants running the familiarisation and control trial of 1.6%. Participants ran the familiarisation trial 12.2 s faster than the control trial. No order effect was observed between GCS conditions.

Performance Data

No significant differences were observed between interventions for 10 km performance time (min:s; Con 39:50 \pm 4:58, Low 39:26 \pm 3:57, Med 39:41 \pm 3:46, Hi 39:51 \pm 4:01, $P > 0.05$, Figure 4.2). The within participant average run time for all trials had a CV of 10.3%.

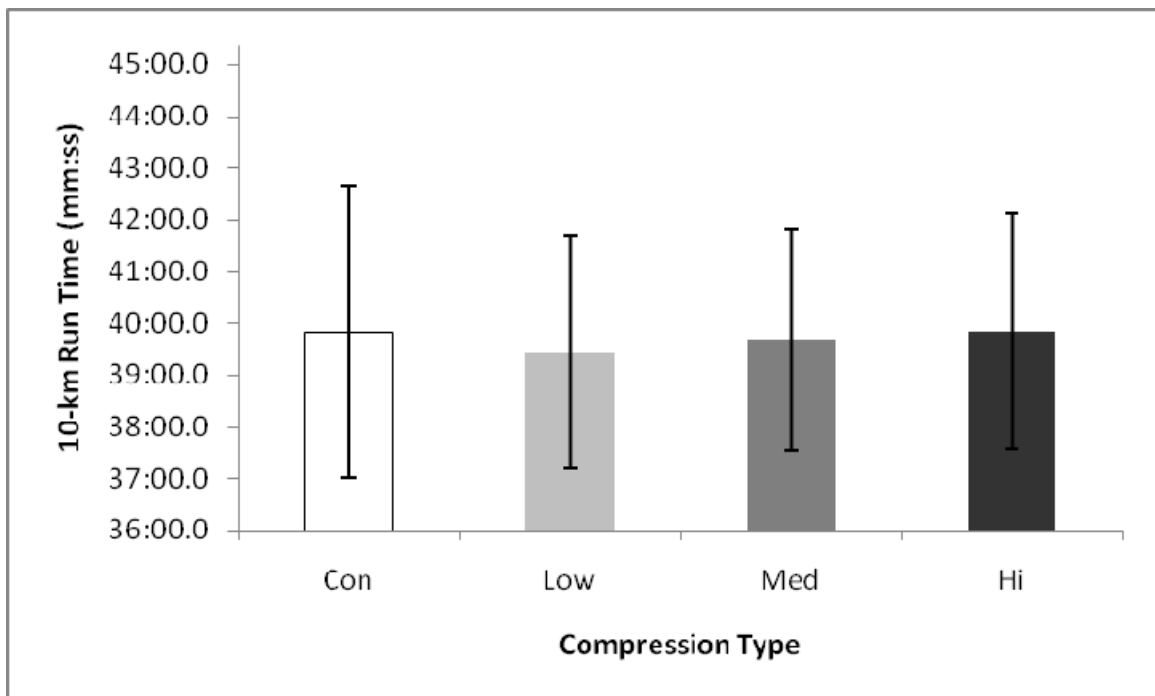


Figure 4.2 Performance time for participants completing 10-km time trials wearing different GCS (mean \pm 95% CI).

There were no main effects of treatment or time for CMJ (Table 4.2). However, one-way ANOVA performed on the change in CMJ from pre- to post-run showed a significant improvement for participants wearing Low (+1.2 \pm 6.0 cm, $P < 0.05$) and Med

($+1.7 \pm 4.8$ cm, $P < 0.05$) GCS compared with Con (-2.9 ± 3.9 cm). The change in CMJ for Hi GCS compared with Con was not significantly different (-0.6 ± 5.3 cm).

Table 4.2 Maximum counter-movement jump height (mean \pm SD) achieved over three attempts before and after 10-km time trial running wearing different GCS.

Trial	Pre-run (cm)	Post-run (cm)
Con	33.8 ± 9.2	30.9 ± 9.7
Lo	32.4 ± 8.5	33.6 ± 9.4
Med	34.9 ± 8.0	36.6 ± 5.5
Hi	33.6 ± 8.2	33.1 ± 8.4

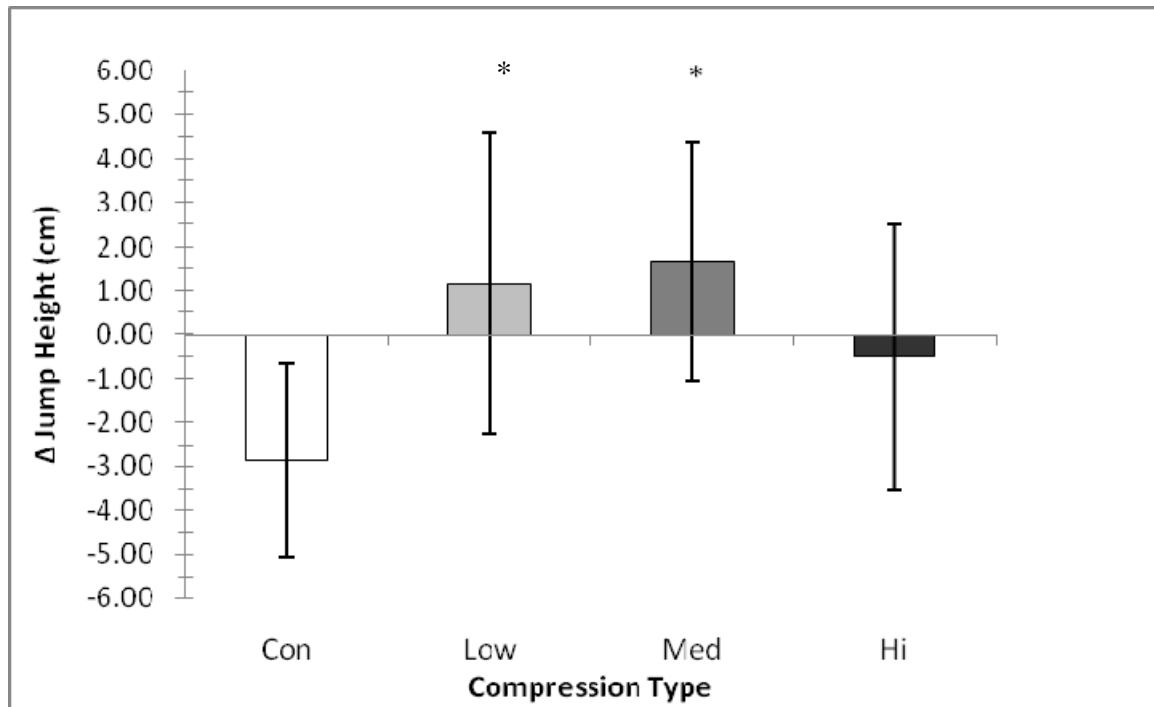


Figure 4.3 Change in counter-movement jump height (cm) from pre- to post-10-km time trial runs (mean \pm 95% CI, * $P < 0.05$ when compared with control).

Physiological Data

Mean heart rate was not significantly different between GCS interventions (168-169 beat·min⁻¹; Table 4.3). There was a main effect of time for [La], which changed significantly from pre-run to post-run measures in all GCS interventions (P<0.001); however, there were no treatment effects (Table 4.3).

Table 4.3 Changes in blood lactate concentration (mmol·L⁻¹) from pre- to post- 10-km run and heart rate at each 2-km mark of the time trial run (mean ± SD).

Trial	Pre-run Lactate (mmol·L ⁻¹)	Post-Run Lactate (mmol·L ⁻¹)	Exercising Heart Rate (beat·min ⁻¹)				
			2 km	4 km	6 km	8 km	10 km
Con	1.5 ± 0.8	6.5 ± 2.8	167 ± 9	169 ± 9	169 ± 9	170 ± 11	173 ± 10
Low	1.4 ± 0.6	6.9 ± 2.8	167 ± 8	169 ± 8	169 ± 8	169 ± 8	173 ± 9
Med	1.2 ± 0.5	7.0 ± 2.9	168 ± 9	170 ± 9	172 ± 10	173 ± 10	177 ± 11
Hi	1.5 ± 0.9	6.9 ± 2.8	170 ± 10	170 ± 10	171 ± 8	171 ± 8	175 ± 10

Perceptual Data

Ratings of perceived exertion were not significantly different between GCS interventions. Participants consistently reached 16-18 at the end of the run (17 = very hard, Table 4.4). There were no significant time or treatment effects for ratings of pleasure/displeasure (FS) or perceived activation (FAS). Feelings of pleasure/displeasure for running were rated as neutral (between 0 and 1) pre- and post-exercise in each trial. Participant ratings of arousal and motivation were similar between control and GCS interventions.

Table 4.4 Subjective perceptions of exertion (RPE), pleasure/displeasure (Feeling Scale), and perceived activation (Felt Arousal Scale) experienced by participants during each trial (mean \pm SD).

Trial	RPE	Feeling Scale		Felt Arousal Scale	
		Pre-run	Post-run	Pre-run	Post-run
Con	16.7 \pm 1.3	0.8 \pm 1.4	1.1 \pm 2.5	3.1 \pm 0.9	3.6 \pm 0.9
Low	16.7 \pm 1.5	1.0 \pm 1.5	1.2 \pm 2.0	3.1 \pm 0.8	3.5 \pm 0.8
Med	17.1 \pm 1.5	-0.2 \pm 1.8	0.5 \pm 2.5	3.0 \pm 1.2	3.4 \pm 0.9
Hi	16.5 \pm 2.0	0.8 \pm 1.7	0.6 \pm 1.3	3.2 \pm 0.9	3.8 \pm 1.1

There was a main effect of treatment for perceptions of GCS comfort ($P<0.05$). Specifically, Con were more comfortable than Med and Hi GCS ($P<0.05$) and Low were more comfortable than Med ($P<0.05$) and Hi GCS ($P<0.05$; Figure 4.4). There was no main effect of time indicating that GCS comfort did not change from pre- to post-run. There was a weak correlation between perceived comfort and run performance time ($r=0.15$, $P=0.31$).

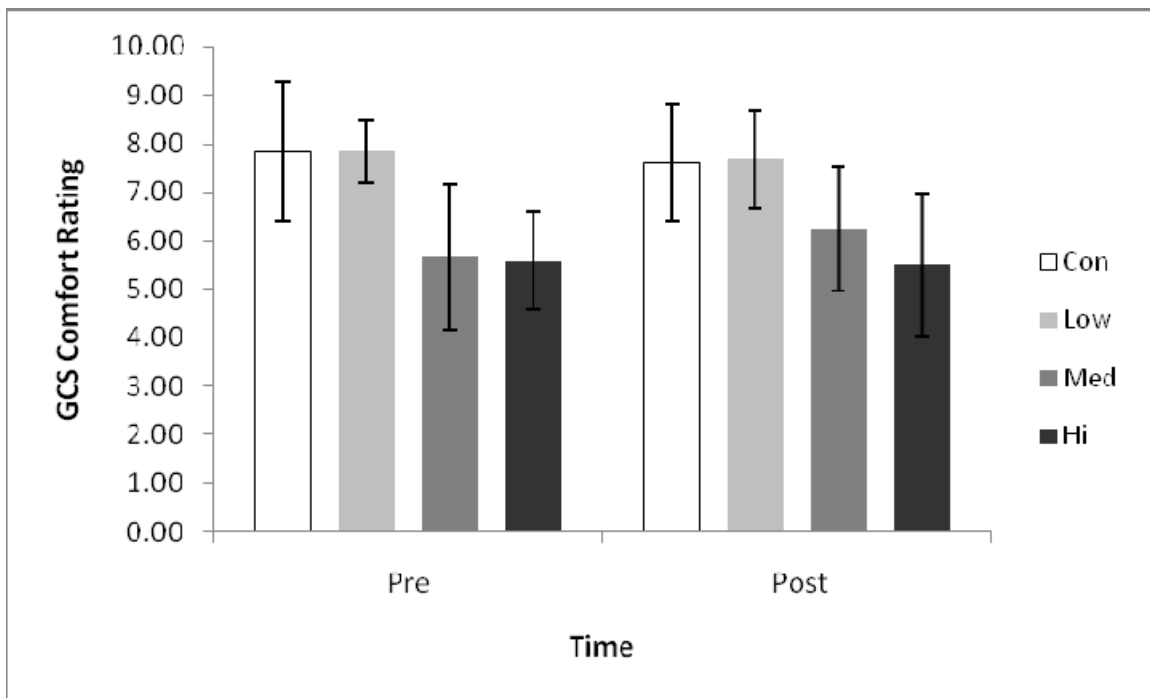


Figure 4.4 Perceived GCS comfort recorded pre- and post-10-km running time trials for participants wearing different GCS (mean \pm 95% CI).

There was a main effect of treatment for ratings of perceived tightness of GCS ($P<0.001$, Figure 4.5). Post-hoc analyses revealed Hi were perceived as tighter than all other groups ($P<0.05$) and Med were tighter than Low and Con ($P<0.05$). There was no statistically significant difference between Con and Low. There was no main effect of time indicating tightness ratings remained consistent throughout each trial.

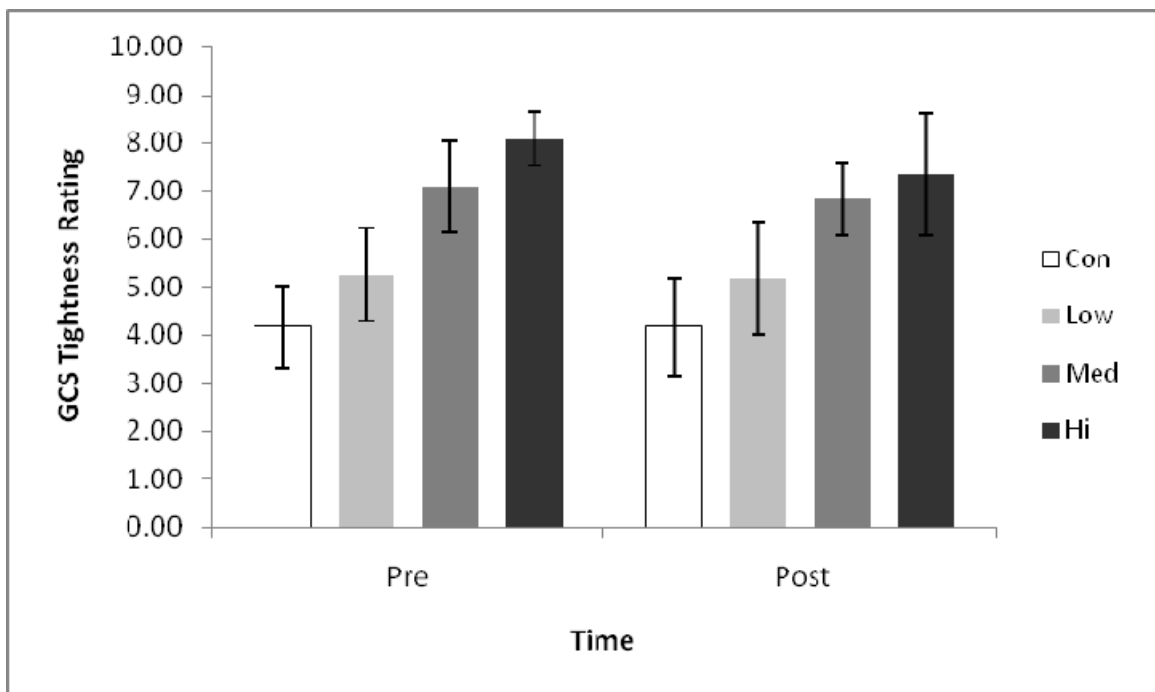


Figure 4.5 Perceived GCS tightness recorded pre- and post-10-km running time trials GCS (mean \pm 95% CI)

There were main effects of time ($P=0.045$) and treatment ($P=0.001$) for perceptions of pain wearing different GCS. Post-hoc tests showed that Hi GCS induced more pain than Con and Low GCS ($P<0.05$), and Med GCS induced more pain than Con and Low GCS ($P<0.05$, Figure 4.6).

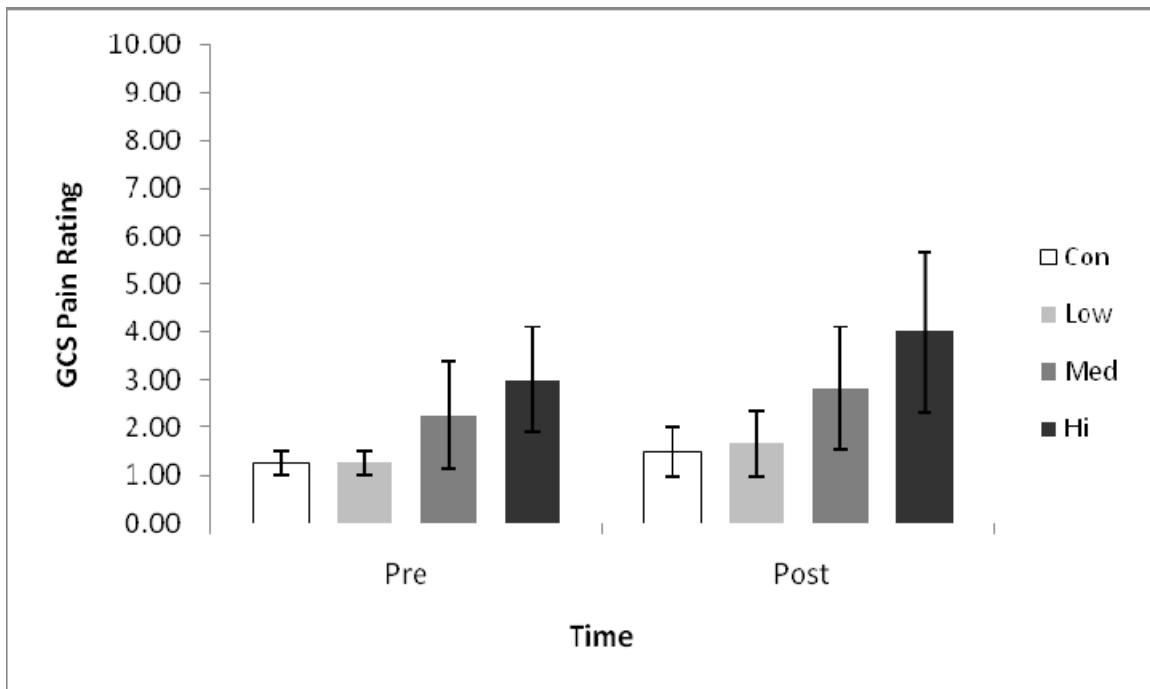


Figure 4.6 Perceived pain for participants wearing GCS pre- and post-10-km running time trials (mean \pm 95% CI).

4.5 Discussion

The aim of this study was to examine the efficacy of wearing different grades of compression stockings (GCS) on 10-km running performance in well-trained runners. There was no effect of wearing different GCS on performance time when compared to a non-GCS control. However, there was a small but significant increase in jump height post-exercise when wearing low (12-15 mmHg) and medium (18-21 mmHg) grade GCS relative to control. Furthermore, subjective perceptions of comfort, tightness, and pain were most favourable wearing the low grade GCS and non-GCS control.

No significant changes were found between performance time trials for participants wearing any type of compression stocking. All participants completed two trials wearing a control (0 mmHg) garment under the same experimental conditions (i.e. the control garment was worn during familiarisation and control trials). The within participant average run time for all trials had a CV of 10.3%. This high CV exceeded any measurable change in run performance the athletes may have achieved. Such high variability was not expected because participants were blinded to the type of stocking worn and were told to run as hard as possible in all trials. Further, participants were told the familiarisation trial was a genuine trial, and was conducted under the same conditions with the same extrinsic motivators. There was no order effect between the trials and participants did not run substantially faster from the familiarisation trial to the next trial they completed.

Though mean 10-km run time was 24 s faster for participants when wearing the Low GCS (compared to Con) the large CV for all trials (10.3%) and small sample size (n=12) indicate that any significant effects from wearing GCS compared with a control garment were very small. The experimental protocol was designed to decrease the CV by including a familiarisation trial and recruiting athletes who were competitive runners and experienced in track running. However, this was not sufficient to control within-participant variation in the five trials.

Significant performance changes by 1% or less were considered to indicate a practical performance enhancement for highly-trained athletes. Similar performance enhancements have been observed for recognised training aids including creatine supplementation in highly trained rowers (1% performance time improvement) (Rossiter et al., 1996), caffeine supplementation in highly trained rowers (1.2% performance time improvement) (Clinton et al., 2000), and live high, train low altitude exposure for highly trained runners (1.4% performance time improvement) (Chapman et al., 1998). Though run time was 24 s (1%) faster for participants wearing Low GCS the result did not have any practical significance for runners because individual variation was greater than the performance change and the result was not statistically significant.

Counter-movement jump height from pre- to post-run was significantly improved for participants when wearing Low (+3.6%) and Med (+4.9%) GCS compared with Con. Greater jump height post-run indicates improved muscle power maintenance (Kraemer et

al., 1998a). The result contrasts with Doan et al. (2003) and Duffield et al. (2007) who found no significant changes in jump height from wearing graduated compression garments. Further investigations may be required to determine why there was a significant improvement in leg power post-exercise for participants wearing Low and Med GCS compared with Con. Running speed was not measured for the finishing straight of the run, therefore any beneficial effects to leg power from wearing GCS remain unknown.

The reduced jump height post-run during Con could be due to fatigue affecting the contraction-coupling process within the muscle (Allen et al., 1992), skeletal muscle damage due to repeated contractions and impact causing shear forces (e.g. tearing; Armstrong et al., 1991) or altered neuromuscular activity. In contrast, CMJ was improved post-exercise during Low and Med thus suggesting muscle function was better maintained during these trials. The GCS may have reduced muscle oscillations that lead to muscle exhaustion or damage (Noakes, 2001). Previous research has postulated that greater compressive pressure around the exercising muscle decreases muscle damage by reducing muscle oscillations (Kraemer et al., 1998b). This is supported by some studies showing reduced post-exercise CK levels during trials when graduated compression garments are worn compared to control (Duffield et al., 2007). Alternatively, the elasticity of the Low and Med GCS may have improved flexion/extension torque around the ankle joint similarly to the elasticity observed by Doan et al. (2003) at the hip joint that allowed a greater jump performance. While the results of the present study do not provide mechanisms for the greater CMJ during the Low and Med trials, they do indicate

that leg muscle function is better maintained following intense endurance exercise using these GCS.

Another claim purported by many GCS manufacturers is improved removal of blood lactate. In the present study, [La] samples taken immediately post-run were not different between the trials. Some reports have shown that GCS result in reduced post-exercise blood [La] (Kaijser, 1970; Berry et al., 1987; Chatard et al., 2004), while others show no influence of GCS (Duffield et al., 2007). The time trials in the present study were all maximal effort, and this is likely to explain the similar post-run blood lactate values across trials. To determine if GCS have any affect on [La] further studies should control exercise intensity to determine if there are any differences in the [La] response during constant load exercise, as the [La] during the time trials may have been effected by the performance times and pacing strategies the runners used. However, the present study shows that GCS do not affect the [La] response during a 10-km time trial.

Exercising heart rate was not altered by wearing GCS. Ali et al. (2007) reported no difference in heart rate during a 10-km run, although there was a tendency ($P=0.15$) for heart rate to be lower during the GCS trial compared to control with moderately trained athletes. However, that study did not use an all-out protocol and attempted to pace the participants. Previous research has shown no difference in heart rate between graduated compression garments and control when exercise is performed at $\dot{V}O_2$ max (Duffield et al., 2007). This study required maximal efforts in each 10-km run, which elicited similar heart rates. This indicates that GCS may not alter venous return in well-

trained athletes. Further research using controlled constant pace exercise and more direct measurement techniques are required to further justify this conclusion

All participants believed they expended similar efforts for each trial as there were no significant changes in RPE, FS or FAS in each trial. The perceptual scales provide a reflection of subjective intensity and, coupled with the physiological measures, it indicates that all participants had performed at a similar intensity across all trials.

The Con and Low GCS garments were rated most comfortable by the runners, though anecdotal comments from two athletes suggested the highest compression stocking was most comfortable due to the support it offered. Participants could successfully perceive different GCS grades based on feelings of perceived tightness despite being blinded to the intervention they were assigned to. While runners were able to guess how tight the GCS were, they could not predict the true GCS intervention they were assigned to. This was achieved using a random and counter-balanced design that produced no order effect between trials. Participants were also told that all GCS garments could facilitate performance improvements and part of the research was to determine which garment was best. Hi GCS had no measured physiological effect when compared with the other interventions, but appeared to have a slightly poorer (though non significant) effect on CMJ and a significantly detrimental perceptual effect. The change in jump height from pre- to post-exercise was influenced by the grade of GCS, which highlights the importance of choosing the appropriate garment for well-trained athletes.

Conclusion

This is the first study that compares the performance effects of wearing different GCS grades with a placebo control garment. Wearing GCS had no performance benefits for well-trained runners. There were no differences in run time or heart rate when different GCS were compared. Superior post-run CMJ for participants wearing Low and Med GCS indicates that more investigation is required to determine why jump height is maintained after 10-km running. Well-trained runners rated Low GCS and control garments most comfortable, therefore runners considering wearing GCS for training and/or racing should select a relatively slack stocking.

5.0 THE PHYSIOLOGICAL AND PERCEPTUAL EFFECTS OF WEARING GRADUATED COMPRESSION STOCKINGS DURING RUNNING

5.1 Abstract

Purpose: The aim of this study was to examine the effect of wearing different grades of graduated compression stockings (GCS) on physiological and perceptual measures during and following exercise in well-trained runners. **Methods:** One female and nine male competitive runners ($\dot{V}O_2$ max: 70.4 ± 6.1 ml·kg⁻¹·min⁻¹) performed three 40-min continuous treadmill runs wearing either control (0 mmHg; Con), low (12-15 mmHg; Low), or high (23-32 mmHg; Hi) GCS in a randomised counterbalanced order. Participants ran at 90% of their personal best 10-km run pace ($80 \pm 5\%$ $\dot{V}O_2$ max). Changes in muscle function and damage were determined pre-, 0, 24, and 48 h post-run by measuring creatine kinase (CK) and myoglobin (Mb) concentrations, counter-movement jump (CMJ) height, muscle soreness, and pressure sensitivity. Heart rate (HR), oxygen uptake ($\dot{V}O_2$), blood lactate concentration [La], and ratings of perceived exertion (RPE) were measured during exercise. Perceptual scales were used pre- and post-run to assess the comfort, tightness and any pain associated with wearing GCS. **Results:** CK and MB levels ($P < 0.05$), CMJ ($P < 0.001$) and peak leg power were higher ($P < 0.001$) and pressure sensitivity was more pronounced ($P < 0.05$) 0 h post-run in each condition. Few participants (4/10) reported muscle soreness at any one location. There were no significant differences between treatments for HR, $\dot{V}O_2$, [La], and RPE. Con and Low were rated more comfortable than Hi ($P < 0.05$). Hi were perceived as tighter ($P < 0.05$) and more pain-inducing ($P < 0.05$) than the other interventions. **Conclusions:** Well-trained athletes wearing GCS during fast-paced running did not experience improved physiological responses or muscle function compared with a control garment. However, 40 min treadmill running at 80% $\dot{V}O_2$ max may not be strenuous enough to elicit a loss of muscle function in well-trained runners. Further, athletes felt more comfortable wearing GCS that had less compression whilst running.

5.2 Introduction

Graduated compression stockings (GCS) are garments that create compressive pressure around body tissues that is tightest at the most distal segment and gradually decays (with even pressure) up to the most proximal segment (Lawrence et al., 1980). The garments were originally developed to treat deep vein thrombosis (Byrne, 2001) and venous insufficiencies (Jonker et al., 2001; van Geest et al., 2003) for clinical patients. The types of GCS include a full length ankle-to-hip garment, a hip-to-knee-length short, an ankle-to-mid-thigh stocking, and an ankle-to-knee stocking. Knee-length GCS are favoured for clinical use over thigh- and hip-length garments because they are easier to use, cause fewer treatment complications (Lawrence et al., 1980), and enhance the skeletal muscle pump just as effectively as stockings reaching above the knee (Lawrence et al., 1980; Cooke et al., 1995; Byrne et al., 2001).

Patients are prescribed GCS to enhance blood and lymph flow from the lower extremities back to the heart. Clinical studies have shown that the optimum compression level for DVT patients is 20 mmHg at the ankle dissipating to 10 mmHg at the calf (Lawrence et al., 1980). However, increasing compression at the ankle to 30 mmHg created too much compression and decreased subcutaneous tissue flow and deep vein velocity, possibly via a tourniquet effect (Lawrence et al., 1980). Though clinical trials recommend compression at the ankle between 15 and 20 mmHg that dissipates to the knee this may not be appropriate for healthy athletes.

Athletes who suffer from DVT or similar venous disorders may have perceived training benefits while wearing GCS. The reasons why athletes initially selected GCS as a training aid may include an enhanced skeletal muscle pump (Kraemer et al., 2000), increased deep venous velocity, and decreased blood pooling in the calf veins (Sigel et al., 1975). Anecdotal evidence from elite level track-and-field athletes wearing GCS while competing in triple jump, long jump, and high jump indicates that performance was enhanced. Furthermore, repeat jump performances have been enhanced by wearing GCS despite muscular fatigue induced by endurance exercise (Kraemer et al., 1998a).

Research supporting enhanced endurance running performance has been more ambiguous than evidence for improved jump height. Running economy improved for participants wearing GCS by diminishing the $\dot{V}O_2$ slow component at 12 km·h⁻¹, but not at 14 or 16 km·h⁻¹ (Bringard et al., 2006). However, running at 12 km·h⁻¹ would be too slow to provide performance benefits to highly-trained athletes unless they were competing in ultra-marathon distances. GCS have been postulated to reduce cardiovascular load by enhancing the skeletal muscle pump. However, Ali et al. (2007) found no significant difference in heart rate for moderately-trained athletes wearing GCS (compared with a control condition) over paced 10-km runs. However, both studies were field trials with a lack of experimental control. Further, these studies used moderately-trained athletes; athletes specifically trained for endurance running may not gain the same physiological benefits.

Wearing compression garments during exercise has also been advocated to alleviate exercise-induced muscle damage (Noonan et al., 1999). GCS may alleviate inflammation (Armstrong et al., 1984) and reduce lower leg volume and gastrocnemius vein diameter after a half marathon run (Benigni et al., 2001). Leg pain and DOMS were also alleviated 24 h after 10-km running (Ali et al., 2007) and high-intensity cycling (Chatard et al., 2004). Wearing a compression garment during training or racing that causes considerable loss of muscle function or muscle damage may help an athlete return to training more rapidly. However, endurance athletes such as cyclists and runners are likely to train despite muscle soreness and pain. The decreased inflammation, swelling and pain may improve an athlete's subjective comfort but not necessarily muscle repair and recovery.

Claims made by manufacturers of compression garments include performance gains, enhanced subjective perception, and improvements in various physiological responses; however, there is a distinct lack of published research supporting these claims. Moreover, previous investigations have used medical-grade GCS (18-30 mmHg) designed to treat patients with venous deficiencies (e.g. Bringard et al 2006; Ali et al. 2007). No study has attempted to compare different levels of compression to determine which (if any) is most beneficial for running. Furthermore, as far as we are aware no study has used an adequate control GCS garment blinded to the participants to control for placebo effects.

Therefore, the aim of this study was to examine the physiological and perceptual responses of well-trained athletes to wearing different grades of GCS during fast-paced running in a controlled laboratory environment. A non-compression garment was used to control for possible placebo effects. The null hypothesis was that wearing Lo and Hi grades of GCS during 40-min treadmill running would have no effect on physiological variables, subjective perceptions, or DOMS at pre-, during, 0-h post-, 24-h post-, and 48-h post-exercise compared with a placebo control garment.

5.3 Methods

Participants

One female and nine male competitive runners and triathletes provided informed consent to take part in this study. The protocols were approved by the Massey University Human Ethics Committee (07/64). The participants were well-trained competitive athletes who competed regularly in 5-42 km running and sprint to Ironman triathlon distances and were (mean \pm SD) 36 ± 10 years old, 72.9 ± 13.2 kg body mass, and 1.80 ± 0.08 m in stature, with a mean $\dot{V}O_2$ max of 70.4 ± 6.1 ml \cdot kg $^{-1}\cdot$ min $^{-1}$ (Table 5.1). Run training time ranged from 6 to 16 hours per week, interspersed with competitive events. All participants completed and signed health screening questionnaires (Appendix 1) before beginning any exercise tests.

Table 5.1 Anthropometric measures and performance characteristics of participants determined by a concurrent $\dot{V}O_2$ max and lactate test.

ID	Height (m)	Mass (kg)	Age (years)	$\dot{V}O_2$ max (ml·kg ⁻¹ ·min ⁻¹)	v at 4 mmol (km·h ⁻¹)	Peak v (km·h ⁻¹)	Recent 10km Personal Best Time (% World Record*)
1	1.75	63.8	43	75.4	17	19	34:24 (76%)
2	1.82	74.8	27	72.9	16	19	34:49 (75%)
3	1.81	73.6	24	75.1	15	18	37:30 (70%)
4 ^F	1.63	50.1	37	69.4	16	18	37:30 (79%)
5	1.83	70.5	44	78.0	16	18	34:52 (75%)
6	1.78	65.2	57	72.5	15	16	40:15 (65%)
7	1.92	98.8	30	58.3	13	15	44:20 (59%)
8	1.76	67.9	42	72.1	14	17	44:18 (59%)
9	1.91	86.2	25	63.0	15	16	40:12 (65%)
10	1.77	78	35	66.8	13	16	44:10 (59%)
Mean	1.80	72.9	36	70.4	15.0	17.2	
SD	0.08	13.2	10.4	6.1	1.3	1.4	

^FFemale athlete

*Men's world record 10 km: 26:17.53 set by Kenenisa Bekele (Ethiopia) in Belgium, 2005.

Women's world record 10 km: 29:31.78 set by Wang Junxia (China) in Beijing, 1993.

Experimental Measurements

GCS used for this study were individually fitted for the correct levels of compression based on the manufacturer's recommendations (Julius Zorn GmbH, Aichach, Germany). Participants were required to perform each trial with one of three different grades of compression garments. The first stocking was a placebo control garment designed to have no compression at the ankle or calf (0 mmHg). The other two garments were low (Low) and high (Hi) GCS (Table 5.2). The different compression grades at the ankle and calf were achieved by the length, width, and weave of the garment: tighter weave produced greater compression around the leg tissues.

Table 5.2 Compression applied by GCS at the ankle and below the knee according to manufacturers guidelines when fitted correctly from sizing chart (Appendix 10)

Trial	Compression at ankle (mmHg)	Compression at knee (mmHg)
Con	0	0
Low	15	12
Hi	32	23

Counter movement jumps (CMJ) were measured pre- and post-run to estimate leg power. Participants were instructed to step on to a jump mat (Just Jump, Just Run; Probotics inc. 8602 Esslinger CT Huntsville, AL), place their hands on their hips, and use a counter-movement to optimise jump height. When participants were ready they performed a series of three maximal-effort jumps separated by at least 10 s of rest. Participants were instructed and allowed to practice the correct jumping technique to maintain consistency between efforts.

Muscle soreness was assessed by participants drawing on an anatomical diagram differentiated into major muscle group regions identified by a letter (Thompson et al 1999; Ali et al 2007, Appendix 11). Participants were asked to indicate muscle soreness by shading any regions that felt sore and assigning a level of muscle soreness to it. The average muscle soreness for each GCS intervention was determined by the aggregate total from all participants that each region was shaded (Thompson et al., 1999).

Lower limb soreness was assessed before and after treadmill running using a pressure algometer (Force Dial FDK 60, Wagner Instruments; Greenwich, CT) to apply

pressure and measure changes in pressure sensitivity. Six anatomical landmarks were selected to quantify muscle soreness (Appendix 12). Up to $11 \text{ kg}\cdot\text{cm}^{-2}$ (110 N) of pressure was applied to each site using the algometer with a metal probe covered by a rubber tip. Participants were asked to verbally indicate when the force became 'uncomfortable' and this value was recorded. If no indication of discomfort was given, soreness at that site was considered 'not present' (Bailey et al., 2001). Each site was pressure tested for muscle soreness twice and the mean taken. If measurements were different by greater than $1 \text{ kg}\cdot\text{cm}^{-2}$ a third measurement was completed and the median taken. Measurements were taken pre-exercise and then 0, 24, and 48 h post-test.

A number of scales were used to assess the psychological state of the athletes during treadmill running. The Ratings of Perceived Exertion scale (RPE; Borg, 1973, Appendix 6) was used to quantify subjective exercise effort. The Feeling Scale (FS; Hardy & Rejeski, 1989, Appendix 4) was used to measure affective response to exercise in participants. The FS indicates level of pleasure or displeasure using an 11-point scale ranging from -5 (very bad), 0 (neutral), to +5 (very good) with markers at each odd integer. The Felt Arousal Scale (FAS; Svebak and Murgatroyd, 1985, Appendix 5) was used to measure perceived activation or arousal. The scale ranges from 1 (low arousal) to 6 (high arousal). A number of Likert scales were used to assess the comfort, tightness, and any associated pain from wearing GCS during exercise (Ali et al., 2007). Responses for each variable range from 1 (very uncomfortable, slack/loose, no pain) through to 10 (very comfortable, very tight, very painful).

Preliminary Procedures

Participants completed a concurrent $\dot{V}O_2$ max and lactate test protocol within two weeks before beginning the first trial to assess their level of physical fitness. The experimental procedures were explained and leg measurements were taken to ensure participants received the correct stocking size for each time trial run. The GCS worn by each participant during the trials were determined by a counter-balanced design that was blinded to the participants.

Experimental Procedures

Participants consumed 250 ml of water when they arrived at the laboratory to ensure they received some hydration prior to exercise. This was followed by a venous blood sample and experimental measurements including muscle soreness diagrams, pressure sensitivity measures, CMJ height, perceptual scales, and Likert scales. Participants then donned a pair of GCS (Con, Low, or Hi) and also wore running socks over the GCS. Participants were instructed to slide the sock over their foot inside out, and then roll the stocking up their leg to fit the stocking flush at the bottom of their knee without any bunching at the ankle or calf. The stockings were secured using electrical tape to ensure they did not slide down during the running trial. Participants performed a standardised warm-up on the treadmill for 5-10 min starting at $8 \text{ km}\cdot\text{h}^{-1}$ and increasing to 90% of 10 km personal best speed at 1.5% incline ($80 \pm 5\% \dot{V}O_2 \text{ max}$; Jones et al., 1996). Following the warm-up participants were fitted with a downloadable heart rate chest strap (S400, Polar; Kempele, Finland), a head strap, and a face mask (Hans Rudolph Inc; Kansas City, MO). The face mask was connected to a turbine and gas sampling line

(Cortex Metamax, 2.3; Leipzig, Germany) to measure expired ventilatory volumes and gas concentrations continuously during exercise. Resting gas analysis was measured for approximately one min before commencing the test to ensure correct values were obtained. Heart rate and [La] were measured after the warm-up to indicate baseline data (Figure 5.1). Each treadmill running trial was separated by at least 7 days for each participant.

A pressure bladder was used prior to exercise to assess the actual pressure of the GCS for each subject for each trial. The bladder was attached by tubing to a digital pressure meter (Kikuhime BG3792, Advancis Medical; Nottingham, UK) and was placed between the skin and GCS above the lateral malleolus and on the lateral aspect of the widest circumference of the calf muscle. Participants were asked to stand and wait at least 5 s for the digital meter to settle before recording the measurement. The pressure bladder was calibrated before each measurement by adjusting a tension screw, and observed immediately after taking measurements to ensure pressure returned to 0 mmHg.

Heart rate and $\dot{V}O_2$ were monitored continuously during the run. Capillary blood lactate was sampled from the finger tip and a rating of perceived exertion (RPE) was selected every 5 min and immediately after the treadmill run. Perceptual scales, CMJ height, muscle soreness diagrams, pressure sensitivity measures and a venous blood sample were completed immediately following the run (Figure 5.3). Follow-up measurements including a venous blood sample for CK and myoglobin, perceived

soreness, pressure sensitivity, and CMJ from each participant were collected 24 and 48 h after the treadmill test (Figure 5.3).

Blood sampling and analyses

A 10-ml venous blood sample was drawn from an antecubital vein by a trained technician and stored in vacutainers containing EDTA (BD Diagnostic Systems; Sparks, MD) at 4°C or on ice for a maximum of 2 hours. Samples were centrifuged at 3500 rpm for 7 min at 4°C (Heraeus Labofuge 400R; DJB Healthcare Ltd, Buckinghamshire, England) to separate red blood cells from plasma. Duplicate aliquots of 500 µL plasma were transferred to plastic tubes and stored in a freezer at -20°C. The plasma samples were later analysed for creatine kinase (CK) and myoglobin levels. Blood analyses were carried out using a Vitalab Flexor clinical chemistry analyser (Vital Scientific NV, The Netherlands). CK analysis was conducted with a Roche CK-NAC liquid assay kit (Roche Diagnostics GmbH, Mannheim, Germany). The average intra-assay coefficients of variation was <5%. Myoglobin was analysed by the latex enhanced immunoturbidimetric assay using a Randox Kit (Vitalab Flexor E, AC Dieren, The Netherlands).

Statistical Analyses

Data collected for all measured variables were compared between each GCS intervention worn using one-way or two-way repeated measures analysis of variance (ANOVA, SPSS version 15.0). Delta change values between groups comparing pre- and post-run measures were also assessed using one way ANOVA. When significant differences between GCS interventions across time were identified post-hoc Student's t-test, using the Bonferroni adjustment, were performed. Correlations between variables

were verified using simple linear regression equations and reported as Pearson's correlation co-efficient. Data are presented as means \pm SD (unless otherwise indicated). Statistical significance was accepted at $P < 0.05$.

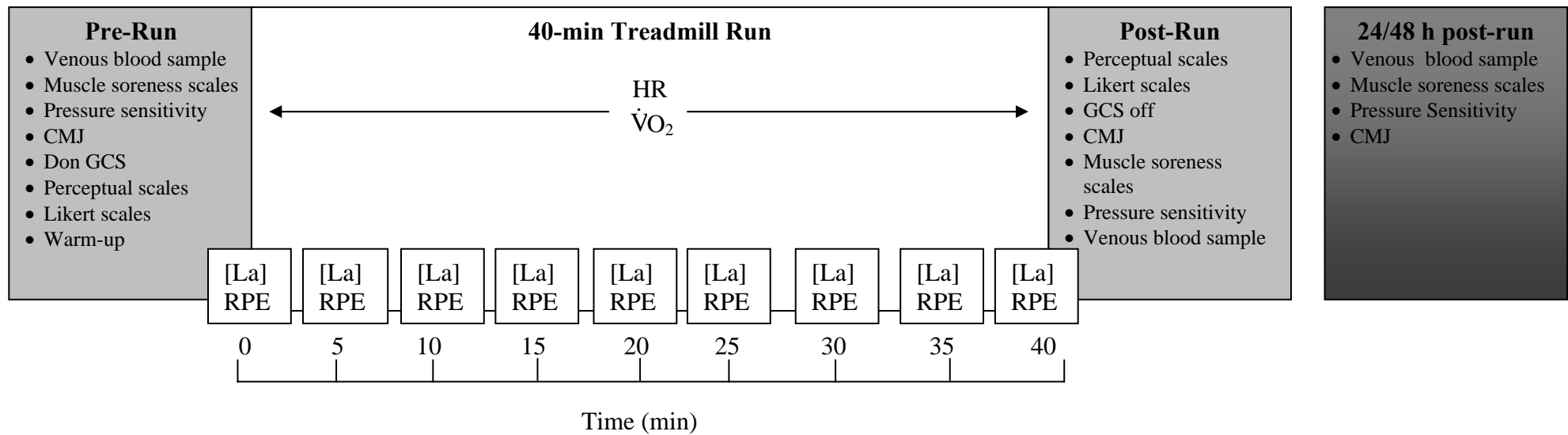


Figure 5.2: Experimental protocol for 40-min treadmill running wearing GCS.

5.4 Results

The level of compression measured for Low and Hi GCS were similar to the manufacturer's ratings. The mean compression for Low GCS was 11 ± 2 mmHg at the ankle and 8 ± 1 mmHg at the calf whereas the Hi GCS was 26 ± 3 mmHg at the ankle and 15 ± 2 mmHg at the calf. Although the Con garment applied more compression than the reported 0 mmHg there was a consistent level of compression throughout the lower leg (4 ± 1 mmHg at the ankle and calf).

Muscle Function

There was a main effect of time for CMJ height and leg power. Athletes jumped significantly higher and produced significantly more peak power at 0 h post-run compared to all other time points ($P < 0.001$; Figures 5.3 and 5.4). However, there were no significant effects of treatment for jump height or leg power.

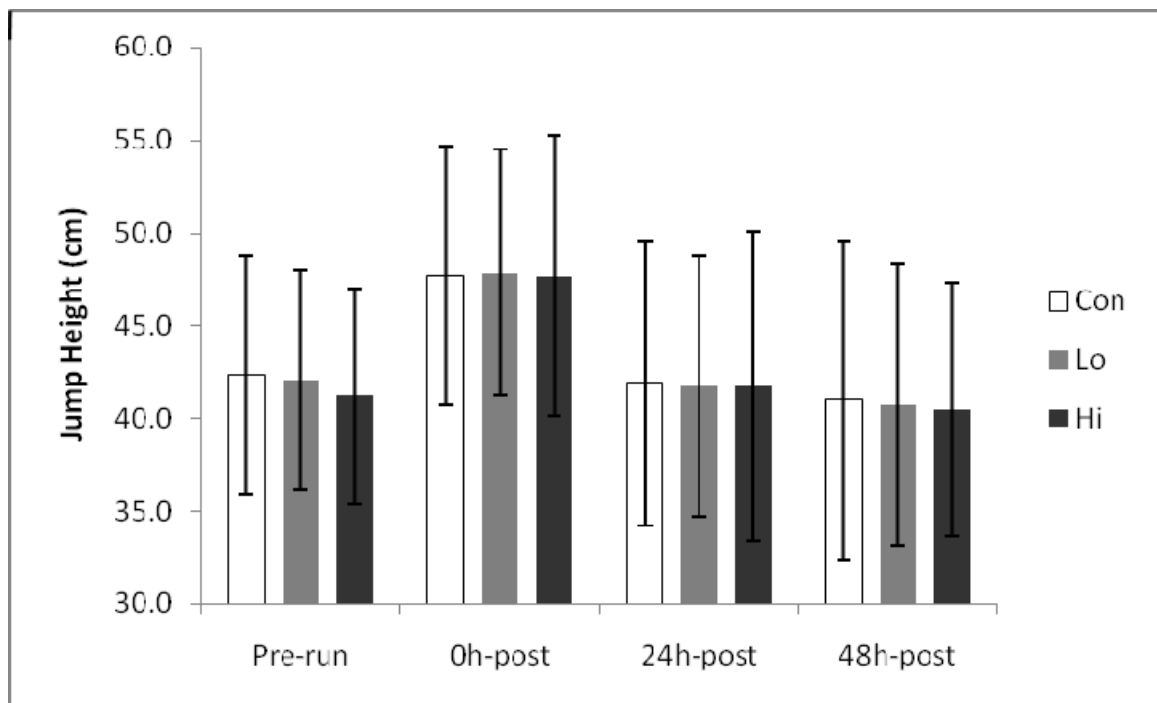


Figure 5.3 Counter-movement jump height measured at pre-exercise and 0, 24, and 48 h post-run for each GCS intervention (mean \pm 95% CI).

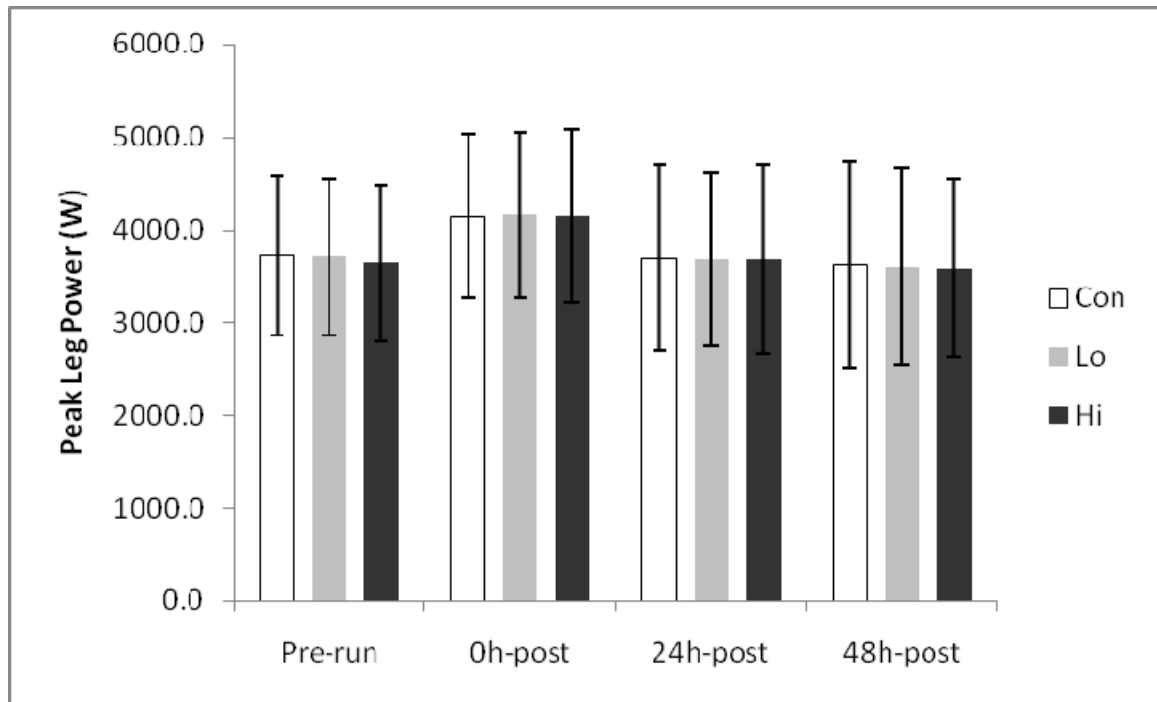


Figure 5.4 Peak leg power calculated from jump height at pre-exercise and 0, 24, and 48 h post-run for each GCS intervention (mean \pm 95% CI).

The most frequent regions where muscle soreness occurred were the left and right calf muscles. However, it must be noted that only 4 out of 10 subjects reported soreness at any one particular location. A small number of participants indicated muscle soreness with three participants feeling no muscle soreness for any trials. Upper body soreness was rare and unrelated to running (Figure 5.5a-c).

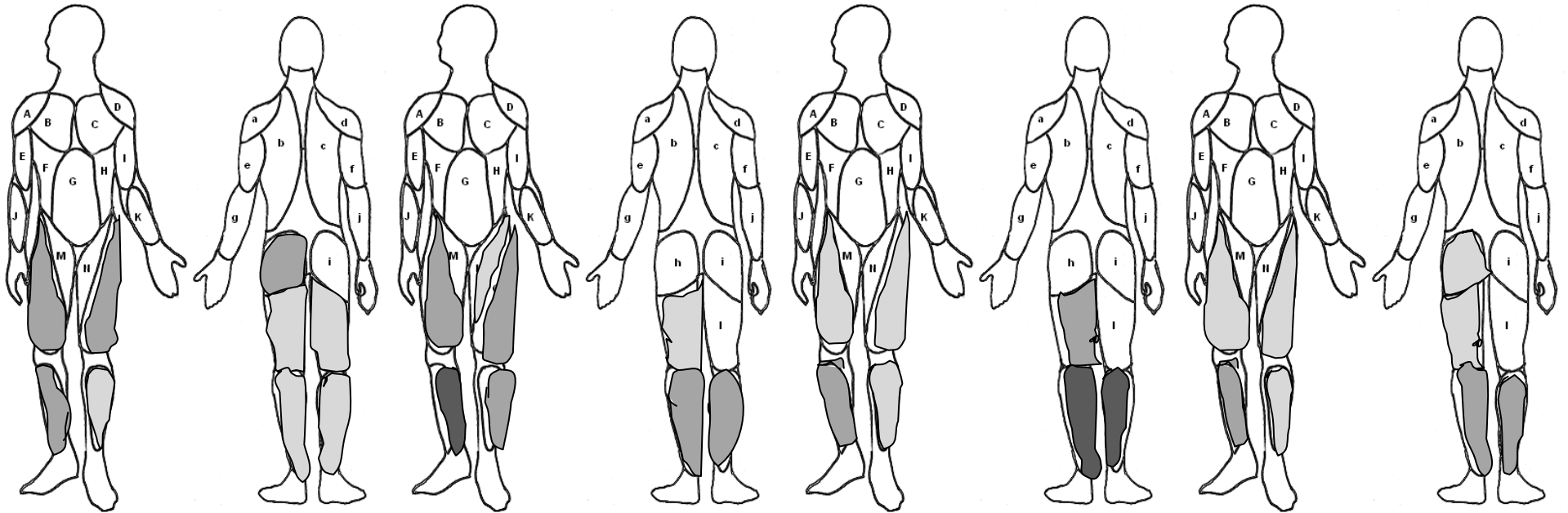
Condition: Con

Pre

Post

24h-Post

48h-Post



Legend

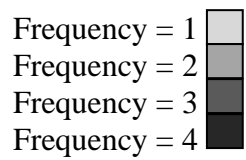


Figure 5.5a Location and frequency of muscle soreness during the Con trial only

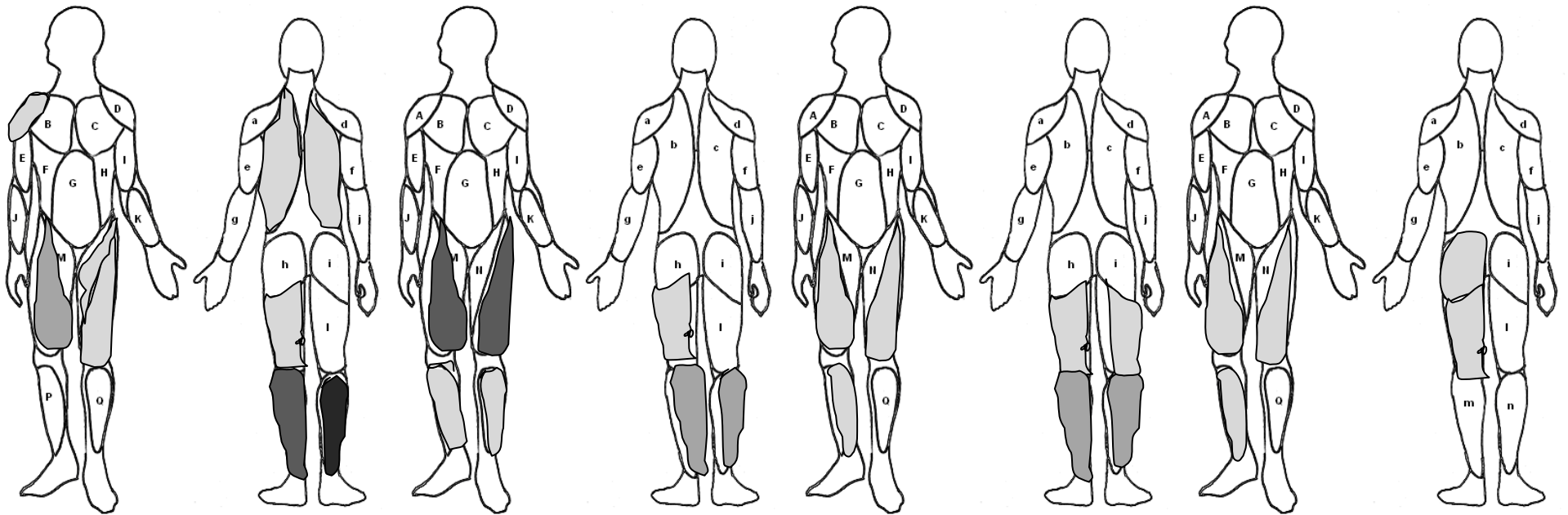
Condition: Low

Pre

Post

24h-Post

48h-Post



Legend

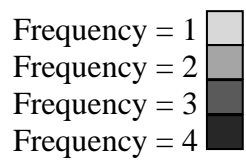


Figure 5.5b Location and frequency of muscle soreness during the Low GCS trial only

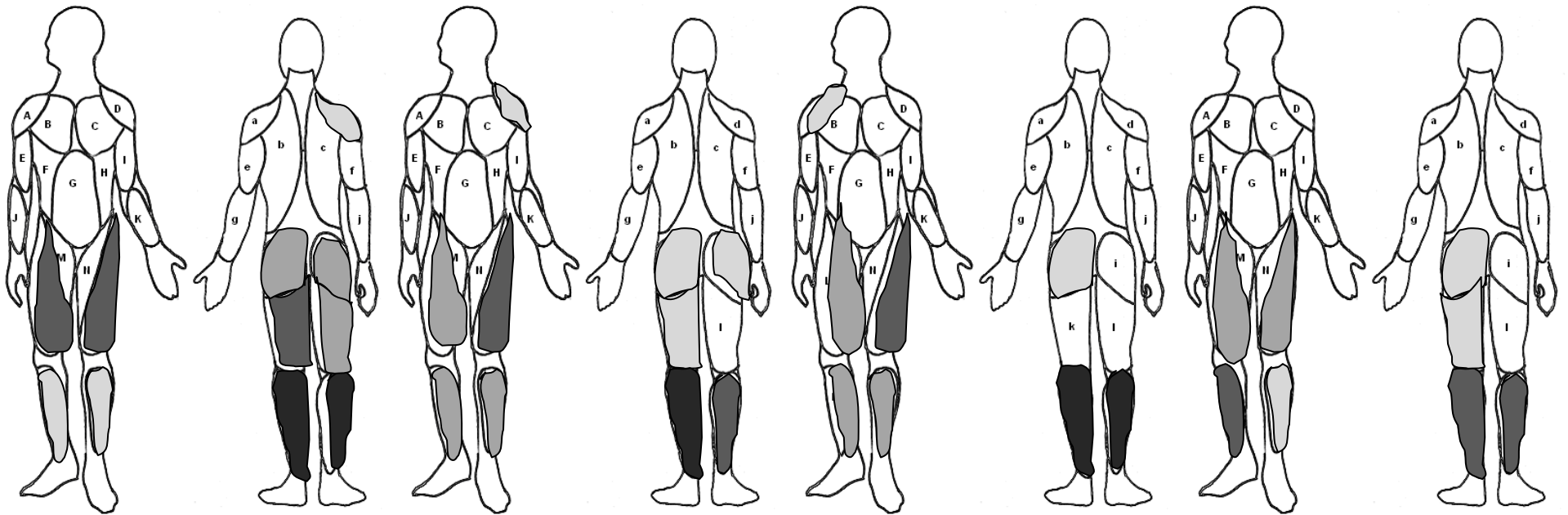
Condition: Hi

Pre

Post

24h-Post

48h-Post



Legend

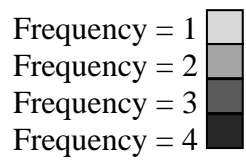


Figure 5.5c Location and frequency of muscle soreness during the Hi GCS trial only

There was a significant main effect of time for pressure sensitivity ($P<0.05$; Figure 5.6). Sensitivity was more pronounced at 0 h post-run compared with pre-run ($P<0.05$); it remained lower after 24 h post-run ($P<0.05$) but recovered after 48 h post-run ($P>0.05$). There was a trend for an interaction effect ($P=0.07$) with subjects tending to have a more pronounced pressure sensitivity wearing Hi GCS. There was no significant difference between pressure sensitivity measured at the left and right leg.

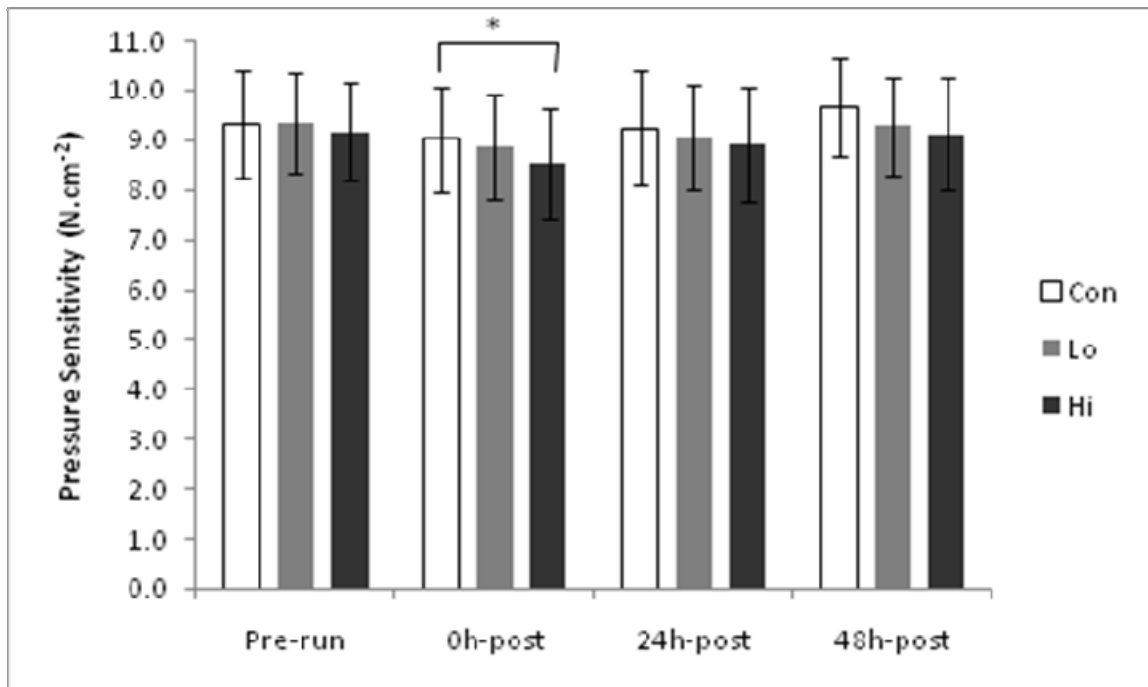


Figure 5.6 Mean (\pm 95% CI) pressure sensitivity as measured by pressure algometer during each trial (left and right legs combined for each trial; *main effect of time, significantly lower than pre-run and 24 h post, $P<0.05$).

Physiological Data

There was a significant time effect for oxygen uptake ($P < 0.05$) from 5 (3.8 ± 0.6 L·min⁻¹) to 40 min (4.1 ± 0.6 L·min⁻¹). However, there were no significant differences between each 5-minute block. There were no significant differences between Con (3.94 ± 0.10 L·min⁻¹), Low (3.92 ± 0.09 L·min⁻¹) and Hi (3.97 ± 0.10 L·min⁻¹) GCS interventions (Figure 5.7).

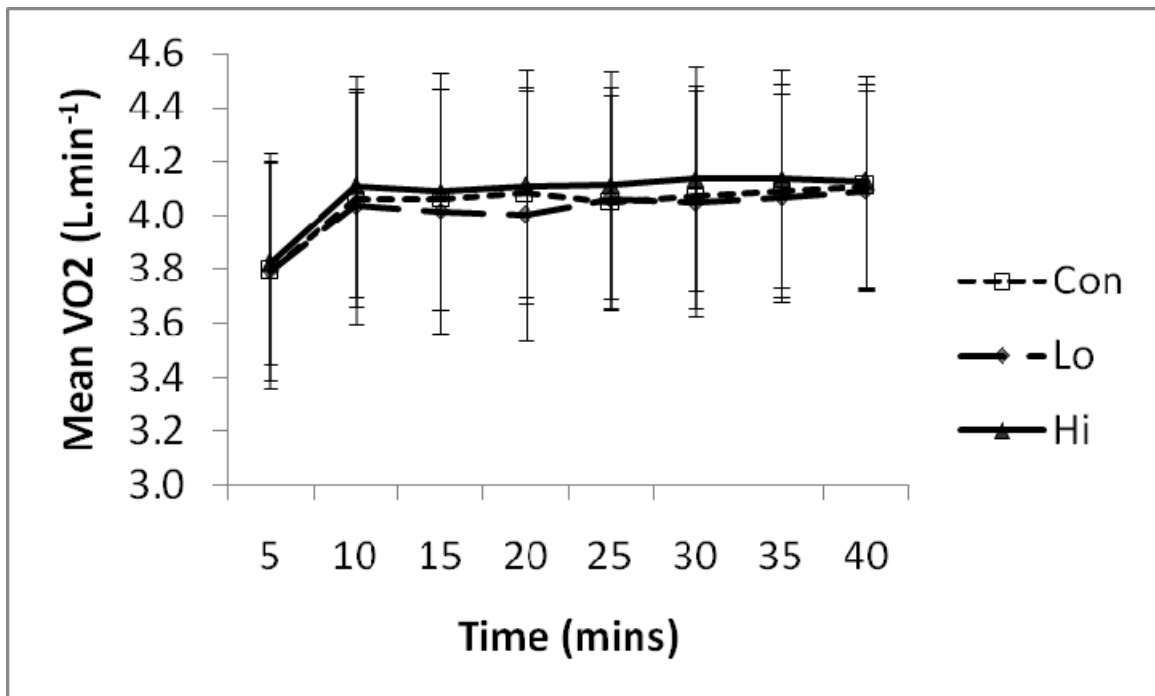


Figure 5.7 Oxygen uptake ($\dot{V}O_2$) for each 5-min block of treadmill running during each trial (mean \pm 95% CI).

Heart rate increased at each 5-min interval during exercise (main effect of time, $P < 0.05$; Figure 5.8). However, there were no significant differences between Con ($159 \pm 7 \text{ beat} \cdot \text{min}^{-1}$), Low ($160 \pm 7 \text{ beat} \cdot \text{min}^{-1}$) or Hi ($160 \pm 8 \text{ beat} \cdot \text{min}^{-1}$) GCS trials.

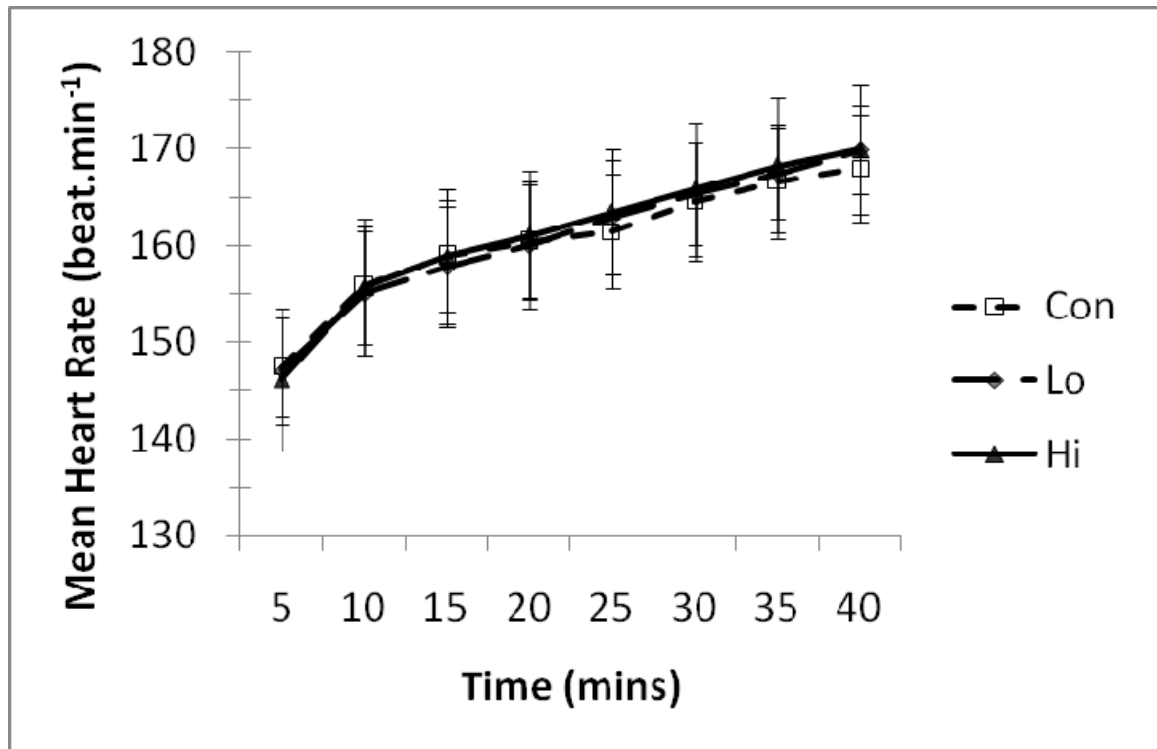


Figure 5.8 Heart rate for each 5-min block of treadmill running during each trial (mean \pm 95% CI; main effect of time; $P < 0.05$).

[La] increased steadily from 5 (2.4 ± 0.9 mmol·L⁻¹) to 40 min (3.6 ± 1.7 mmol·L⁻¹) (main effect of time, P<0.05; Figure 5.9). There were no significant differences between Con (2.6 ± 0.7 mmol·L⁻¹), Low (3.1 ± 0.8 mmol·L⁻¹), and Hi (3.3 ± 0.7 mmol·L⁻¹) GCS trials (Figure 5.9).

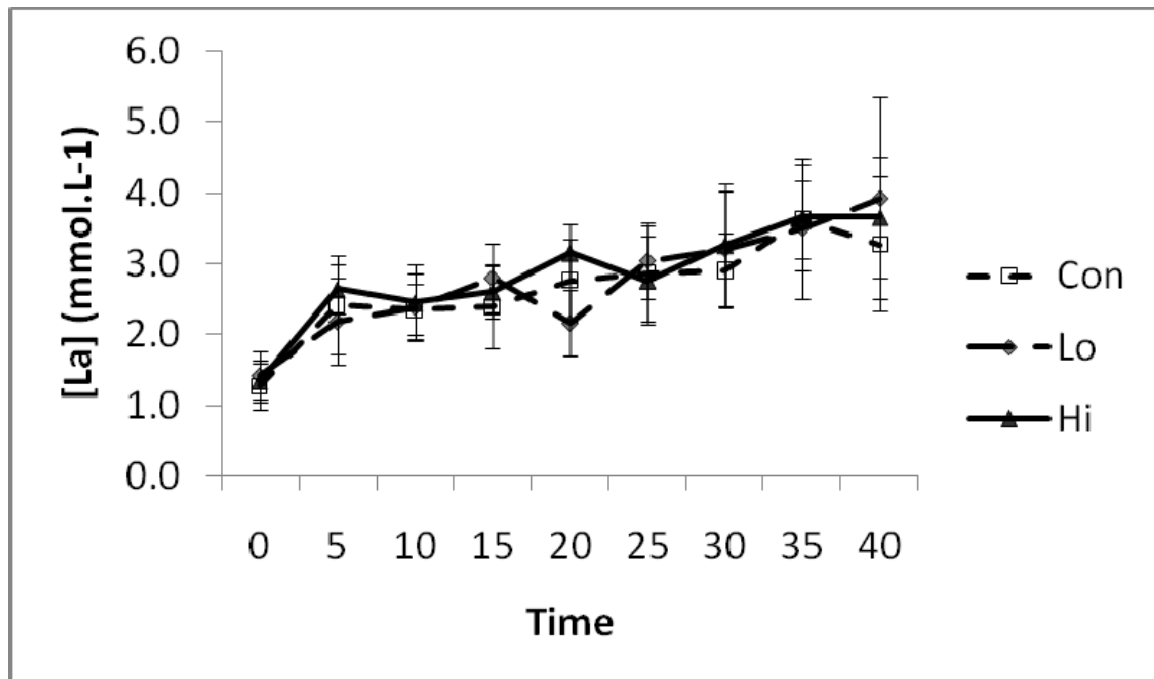
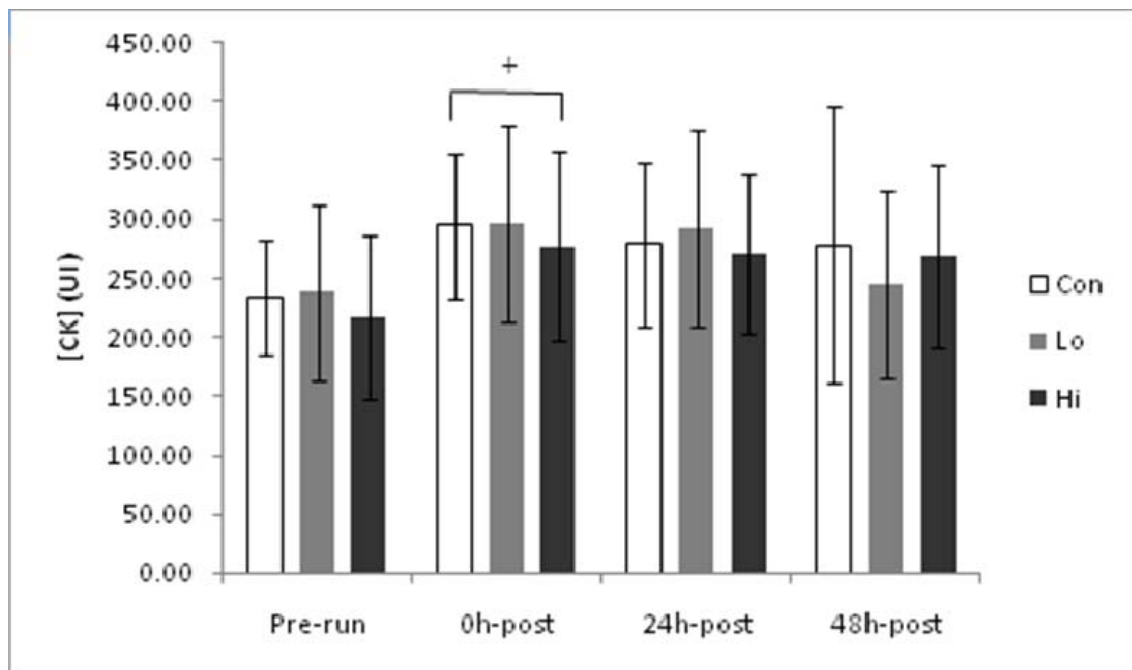


Figure 5.9 Blood lactate concentration (mmol·L⁻¹) at rest, during treadmill running at each 5-min block and immediately post-exercise (mean ± 95% CI; main effect of time; P<0.05).

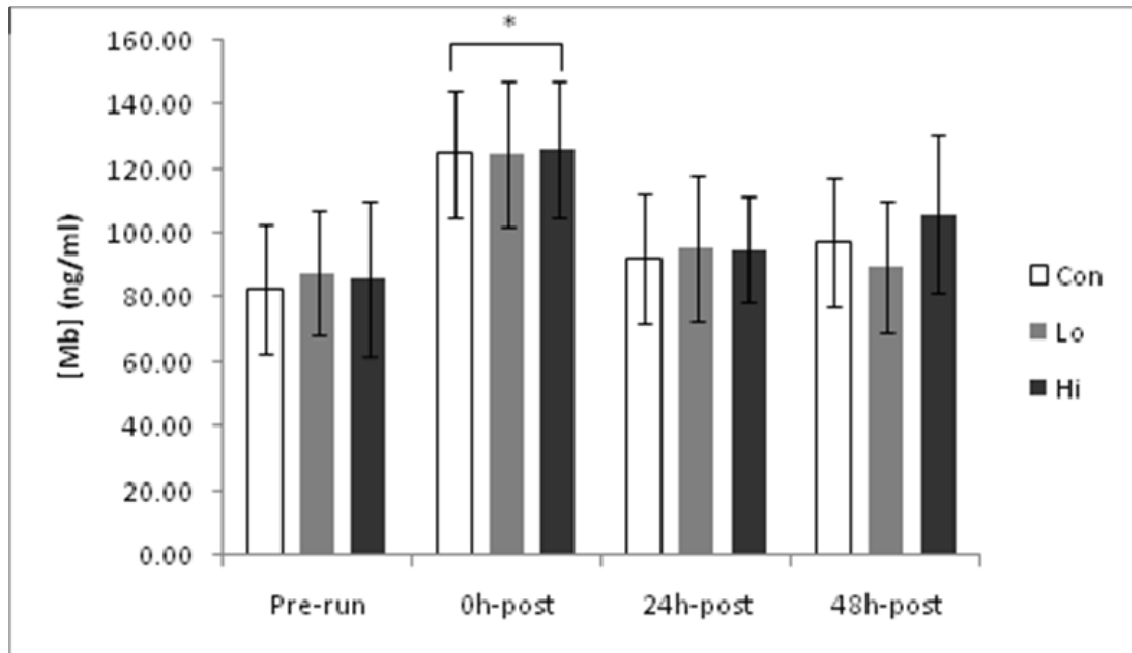
Blood Analyses

There was a significant main effect of time for CK levels ($P < 0.05$; Figure 5.10). CK levels were significantly higher at 0 h post-run compared with pre-run ($P < 0.001$). Levels remained elevated but were not significantly different compared with pre-run at 24 ($P = 0.11$) and 48 h ($P = 0.54$) post-run.



5.10 Mean (\pm 95% CI) Creatine Kinase levels during each trial; ⁺main effect of time, significantly higher than pre-run ($P < 0.001$).

There was a main effect of time for Myoglobin levels ($P<0.001$); at 0 h levels were significantly elevated compared with all other time points ($P<0.05$). Mb decreased at 24 h and remained lower at 48 h, similar to pre-run levels (Figure 5:11).



5.11 Mean (\pm 95% CI) Myoglobin levels during each trial; *main effect of time, significantly higher than all time points $P<0.05$).

Perceptual Data

Ratings of perceived exertion increased during exercise (main effect of time $P < 0.05$; Figure 5.12). However, there were no statistically significant differences between Con (13 ± 1), Low (14 ± 1), and Hi (14 ± 1) GCS interventions. There were no time or treatment effects for affective valence (FS) and felt activation (FAS; Table 5.3).

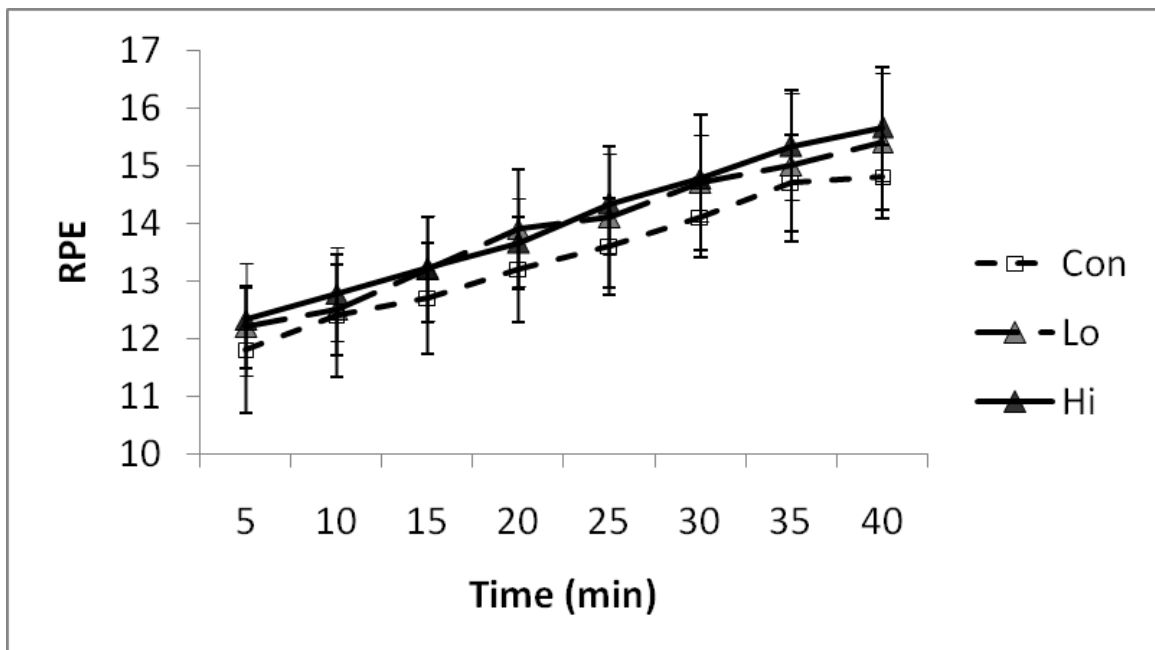


Figure 5.12 RPE at each 5-min block of treadmill running for participants wearing different GCS interventions (mean \pm 95% CI).

Table 5.3 Subjective perceptions of pleasure/displeasure (Feeling Scale), and perceived activation (Felt Arousal Scale) experienced by participants during each trial (mean \pm SD).

Trial	Feeling Scale		Felt Arousal Scale	
	Pre-run	Post-run	Pre-run	Post-run
Con	1.7 \pm 1.2	2.8 \pm 1.5	3.2 \pm 1.0	4.3 \pm 1.1
Low	2.5 \pm 1.6	1.2 \pm 2.0	3.1 \pm 1.0	3.9 \pm 1.0
Hi	1.7 \pm 2.3	2.1 \pm 1.4	3.1 \pm 0.7	3.8 \pm 0.8

There was a main effect of treatment for perceived GCS comfort ($P < 0.05$, Figure 5.13). Con were rated as more comfortable than Hi GCS ($P < 0.05$) but there were no significant differences between Con and Low or Low and Hi GCS. Ratings of comfort remained the same throughout each trial indicating there was no effect of time.

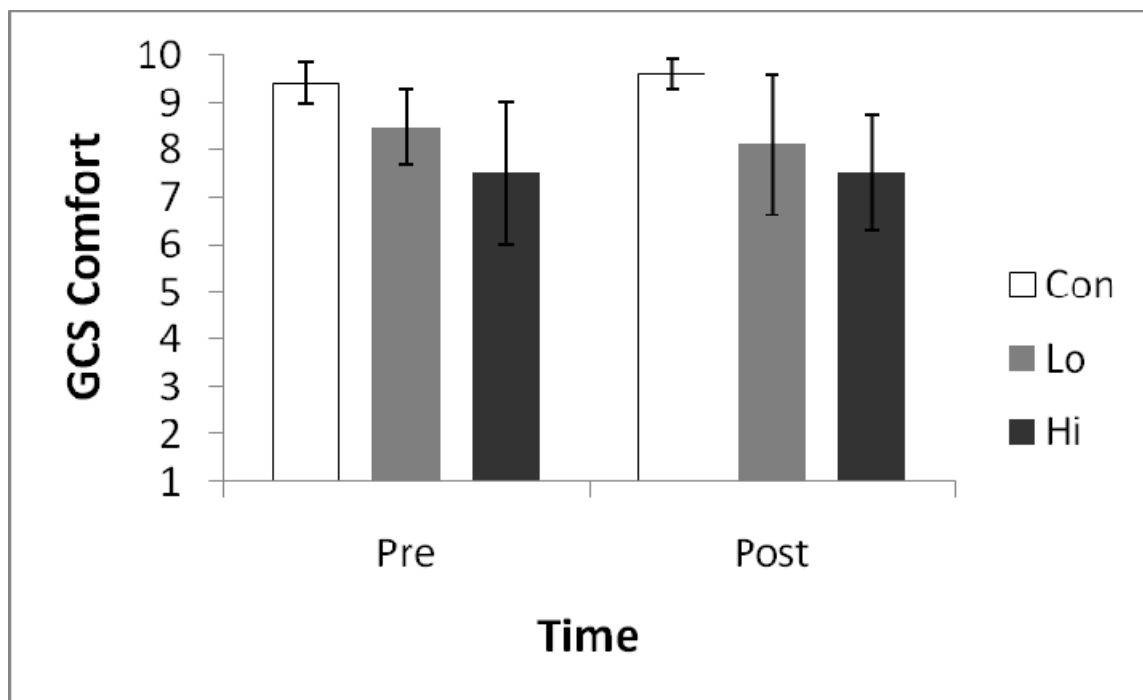


Figure 5.13 Ratings of perceived comfort at pre- and post-run for participants wearing different GCS (mean \pm 95% CI).

There was a main effect of treatment for perceived tightness of GCS ($P < 0.001$; Figure 5.14). Hi GCS were perceived as tighter than Con ($P < 0.001$) and Low GCS ($P < 0.05$). There was no main effect of time from pre- to post-run.

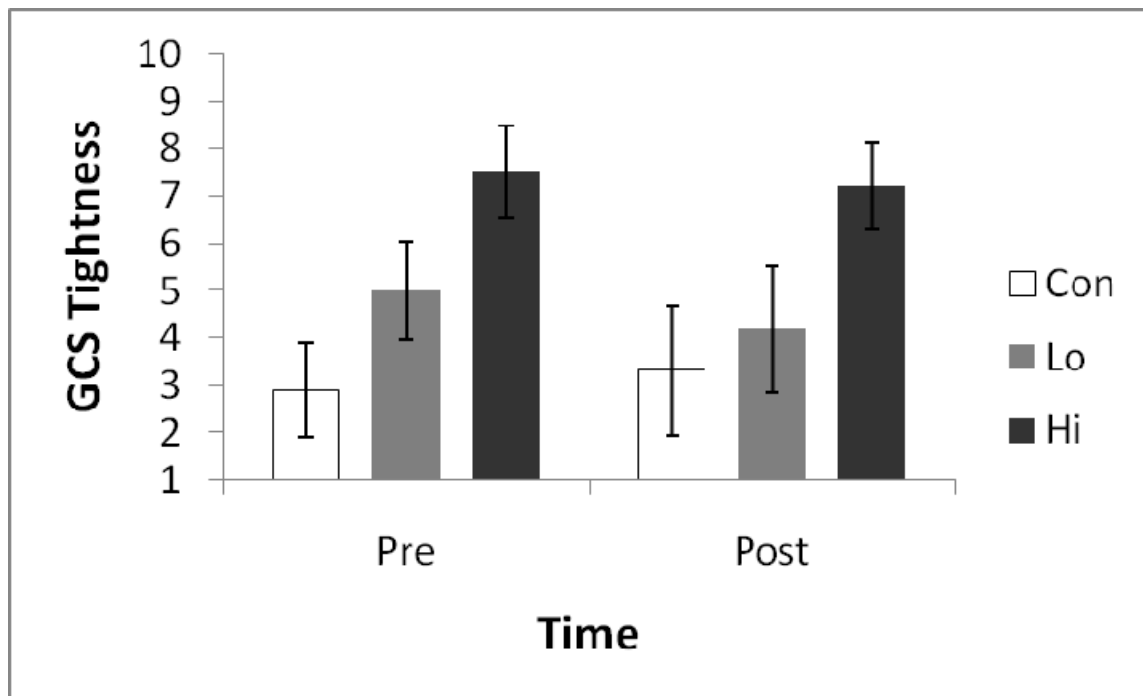


Figure 5.14 Ratings of perceived tightness at pre- and post-run for participants wearing different GCS (mean \pm 95% CI).

There was a main effect of treatment for perceived pain wearing GCS ($P<0.05$, Figure 5.15). Hi GCS were rated as inducing more pain than the other trials ($P<0.05$). As with the ratings of comfort and tightness, there was no main effect of time for ratings of perceived pain.

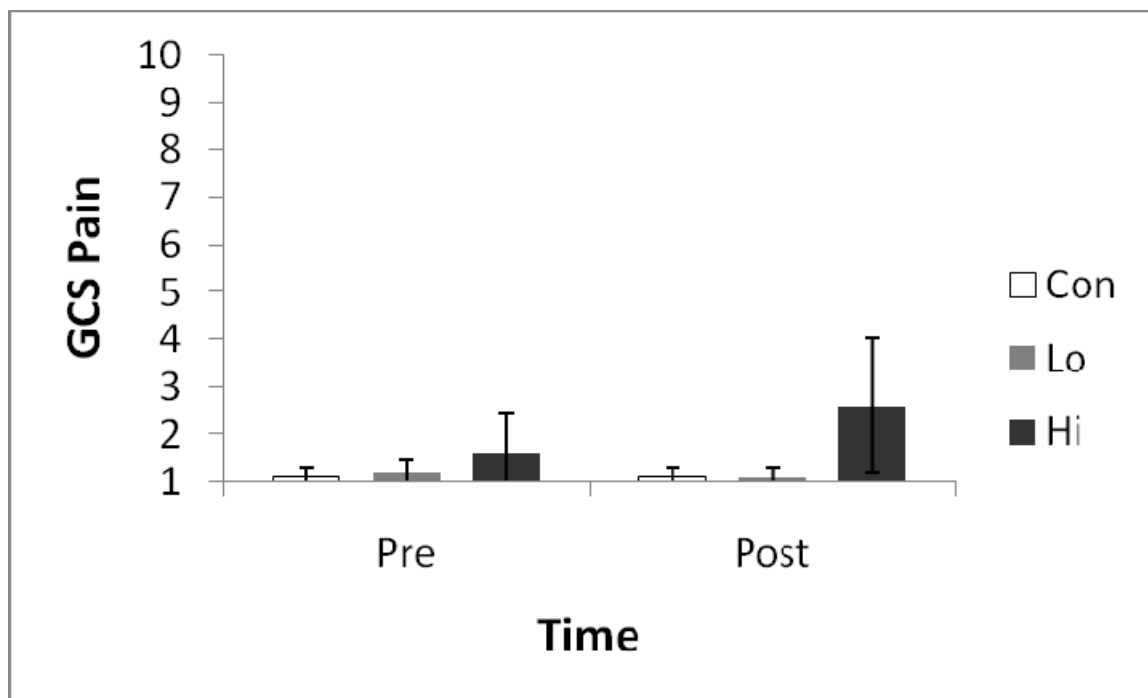


Figure 5.15 Ratings of perceived pain at pre- and post-run for participants wearing different GCS (mean \pm 95% CI).

5.5 Discussion

This study investigated the effects of wearing various grades of graduated compression stockings (GCS) on physiological and perceptual measures during and following high-intensity treadmill exercise in well-trained runners. There were no differences in oxygen uptake, heart rate or blood lactate concentrations during exercise between trials. In this cohort GCS did not have an impact on muscle function or muscle soreness in the days following exercise. Ratings of perceived comfort were higher for low level compression (4-12 mmHg) than higher grades of compression (23-32 mmHg). In addition, ratings of perceived pain were significantly elevated in the higher GCS trial.

Wearing GCS may have positive performance effects for sports where jump height is critical for success. Anecdotal evidence from athletes wearing compression garments during track-and-field jumping events (Y. Savigne, Cuba, Womens Triple Jump: osaka2007.iaaf.org) and maintenance of CMJ height in volleyball players (Kraemer et al., 1996) indicates that leg power may be maintained wearing graduated compression garments. However, this study showed there were no significant differences between a non-GCS placebo and GCS interventions at any time after treadmill running. Immediately after treadmill running there was a 13-16% improvement in CMJ performance for all interventions compared with pre-run performance ($P < 0.01$; Figure 5.3). This was not expected when compared with the results from Chapter 4, which found CMJ height was significantly better for participants wearing Low and Med GCS, but not Con. The reason for the difference between the results in Chapters 4 and 5 may be due to

the different running trials. Participants running 10-km time trials on an outdoor track at maximal effort achieved superior jump height immediately post-run when wearing Low and Med GCS compared with Con. The proposed mechanism was that runners who wore Low and Med GCS while running experienced reduced muscle oscillation according to the mechanical stress theory (Armstrong, 1984). This would reduce the shear forces during ground impact that may cause muscle tears to the lower leg. Participants in this study ran at 90% of personal best 10 km time rather than at maximal effort. This may have been a considerable factor because faster running speeds may cause more muscle damage (Ali et al., 2007). Running trials in this study were completed on a Woodway treadmill with a suspension system. It is highly likely that the treadmill reduced ground reaction forces compared with running on a rubberised outdoor track (though this was not measured). These two factors may have reduced ground reaction forces that participants experienced in the 10 km running trials. The treadmill running protocol used in this study may not have caused enough muscle damage to significantly inhibit muscle function.

Muscle function (inferred from CMJ) was expected to deteriorate considerably at 24 and 48 h post-run when compared with pre-run measures due to acute muscle damage leading to DOMS (Newham et al., 1983). However, muscle function was relatively well maintained post-exercise in this cohort of athletes. This was because the athletes were accustomed to the exercise from regular running. Significantly higher CMJ 0 h post-run may have been due to a warm-up effect that was not completed pre-, 24 and 48 h post-exercise. A higher body temperature achieved from a thorough warm-up enhances physiological mechanisms including increased muscle blood flow, increased nerve

receptor sensitivity, increased neuromuscular efficiency, greater development of chemical reactions, decreased muscle viscosity, and/or higher rate of metabolic reactions (Shellock et al., 1985). A combination of these factors may have significantly increased jump height 0 h post-run despite the muscle fatigue induced by hard and continuous treadmill running.

Muscle function, muscle soreness and ratings of pain were not different between trials. Relative to pre-exercise, pressure sensitivity was highest at 0 h post-run ($P < 0.05$), remained high at 24 h ($P < 0.05$) and returned to pre-run levels at 48 h post-exercise (Figure 5.6). Nevertheless, these values (ratings of 8.5-9.5) were close to the maximum possible value of 11 indicating that muscle soreness was very low. Participant responses to whole body soreness questionnaires indicated that soreness was “just noticeable” at 0, 24 and 48 h post-run. Moreover, Figures 5.5a-c show that few subjects indicated soreness at any specific body part and this was not different between trials.

It is likely that training status and volume were critical aspects differentiating the group of athletes in the present study (Table 5.1) with studies that have included athletes unaccustomed to high training volumes (Chatard 1998; Bringard et al., 2006; Ali et al., 2007; Duffield et al., 2007). For example, Ali et al (2007), using games players, found that 13 out of 14 subjects reported soreness in the calf area in the control condition 24 h following a 10-km run (compared with 4 out of 10 in the current study). The high volume of running that the current cohort of subjects regularly completed may have developed training adaptations that improved the muscles’ capacity to recover for the next training

session (Kuipers et al., 1989). This was observed in changes in pressure sensitivity, CK, and myoglobin levels across all time points. The treadmill protocol caused muscle soreness (Figure 5.6) and damage (Figures 5.10, 5.11) at 0 h post-run. However, pressure sensitivity, CK, and Mb levels recovered within 24 h, returning to similar levels at 24 and 48 h compared to pre-run. This indicates that the participants in this study were capable of recovering from significant muscle damage and soreness within 24 h of an exercise bout.

Participants complained about soreness or numbness in their feet immediately after completing the treadmill run when wearing Hi GCS. This may have been due to the excessive compression around the foot which created a tourniquet effect (Lewis et al., 1976) impeding blood flow and causing metabolite accumulation. Therefore, although there were no differences in muscle soreness ratings between GCS, lower grade garments should be recommended for competitive runners.

An interesting speculation regarding wearing GCS is that they can improve running economy during exercise. However, oxygen uptake was not significantly different between time points for each GCS intervention. This finding contrasts with Bringard et al. (2006) who reported considerable improvements in oxygen economy when running at $12 \text{ km}\cdot\text{h}^{-1}$. Nevertheless, they also found that oxygen economy was not significantly different at higher running speeds (14 and $16 \text{ km}\cdot\text{h}^{-1}$). The mechanisms proposed for improved oxygen economy were improved muscle fibre support in the same contraction direction and improved circulation by assisting the skeletal muscle pump.

Participants in this study ran at 80 ± 5 % of their $\dot{V}O_2$ max, the same relative intensity as the athletes in the study by Bringard et al. (2006), but at a higher running speed (14 ± 1.4 km·h⁻¹ compared with 12 km·h⁻¹). However, it cannot be discounted that wearing GCS may improve running economy in untrained or moderately trained individuals.

Heart rate increased steadily during the treadmill runs for all GCS conditions indicating the expected cardiovascular drift (Figure 5.8). GCS have been postulated to assist the skeletal muscle pump and possibly enhance venous return (Mayberry et al., 1991; Ali et al., 2007) which could lower heart rate during constant pace exercise. However, there were no differences in HR between trials, indicating venous return may not have been altered in these well-trained athletes. This is probably because these athletes have an adequate blood flow from the lower leg to the heart during intense exercise due to physiological training adaptations.

Another purported benefit of wearing GCS during exercise is its ability to remove lactate; however, this study shows that there was no difference in blood [La] between trials (Figure 5.9). Berry et al. (1987) and Berry et al. (1990) also found no evidence to support superior lactate clearance following GCS use. Lewis et al. (1976) suggested a possible mechanism for lower [La] (if at all) was due to lactate being held in the muscle by a tourniquet effect. This suggestion is not supported by the current study as there were no differences in [La] between a relatively slack (Con) garment and a very tight (Hi GCS) garment.

There were no differences in FS, FAS or RPE indicating that subjective perceptions of mood, motivation, and effort were the same for all trials. However, there were significant differences in terms of perceptual ratings related to the compression garments themselves. Con were rated as significantly more comfortable than Hi GCS ($P<0.05$; Figure 5.13) with a trend for Low to be more comfortable than Hi. There was no change in comfort ratings in any GCS intervention between pre- and post-run inferring that comfort perception was a reliable and robust measurement. Participants could successfully differentiate the tightness between different GCS interventions despite being blinded to the stocking they received. Wearing the Hi GCS caused minor but significantly more pain than Low and Con ($P<0.05$; Figure 5.15). This matches subjective comments from participants and the higher muscle soreness frequency reported 0 h post-run. Pain increased considerably for some participants in the second half of the run that began as a dull ache and progressed to numbness or 'pins and needles'. This highlights the importance of selecting the correct amount of compression, as a garment that is too tight may negatively affect an athlete's running capability. All participants reported high perceptual comfort ratings (Figure 5.13) pre-run for the Hi GCS; it was only during or following exercise that some mild pain was felt (Figure 5.15). Anecdotal comments from the athletes suggested they felt that the Hi GCS impeded their ability to maintain a steady pace, a critical factor in running performance. This contradicts Bringard et al. (2006) who stated that athletes ran most economically when compression was 23.5 mmHg compared with 5 mmHg. The findings from this study indicate that the opposite is true, with higher

perceived comfort ratings for Con and Low GCS. Even a small increase in pain from wearing a GCS garment may inhibit any beneficial effects it could provide to the wearer.

This is the first study that has compared the physiological and perceptual effects of wearing different levels of GCS. It shows that well-trained runners did not gain significant muscle function benefits from wearing GCS because CMJ height did not improve, pressure sensitivity increased, and CK and Mb levels decreased at 24 and 48 h post-run. Though the treadmill running trials were stressful enough to cause significant changes in muscle damage markers and pressure sensitivity the participants were able to recover within 24 h. Future studies should investigate groups of untrained or moderately trained individuals or develop a protocol for well-trained or elite individuals that causes prolonged muscle damage for 48 h. These runners experienced no physiological benefits while wearing GCS from enhanced lactate clearance, improved running economy, or reduced heart rate. The runners favoured the control stocking, indicating that GCS offer no perceptual benefits for well-trained and uninjured athletes. Future studies should investigate the potential positive effects GCS could provide to untrained and/or older individuals and athletes with venous disorders.

6.0 GENERAL DISCUSSION

The aims of these experiments were to examine the effects of wearing knee-length GCS garments on running performance and physiological and perceptual responses during and following exercise in well-trained endurance athletes. There was no effect of wearing different GCS on 10-km run time when compared to a non-GCS control (Chapter 4). Jump height increased by a small but significant amount when wearing Low and Med GCS relative to Con. For athletes completing a 40-min treadmill run there were no differences in oxygen uptake, heart rate or blood lactate concentrations between trials (Chapter 5). Wearing different GCS did not appear to have an impact on muscle function or muscle soreness in the days following exercise. In both studies subjective perceptions of comfort, tightness, and pain were most favourable wearing non-GCS Con and Low GCS. Therefore, well-trained athletes may not receive beneficial performance or physiological effects from wearing GCS.

The improvement in running performance time for participants wearing GCS was not statistically significant. However, participants wearing Low GCS ran 20 s faster on average over 10 km. Though this was not significant it may be practically important for competitive runners who measure performance improvements in seconds. Hopkins et al. (1999) have established that a performance improvement for the very best athletes may be as small as 0.3%. Participants, on average, ran 1% faster wearing Low, 0.5% faster wearing Med, and 0.5% slower wearing Hi GCS compared with a Con stocking. However, the CV for within participant variation for all running trials was 10.3%, which

indicates there was too much variation between running performances to determine if any GCS grades were superior to others.

The beneficial effects of wearing knee-length GCS on leg power remain inconclusive. Though participants wearing Low and Med GCS jumped higher after 10-km track running compared with Con (Chapter 4) there were no significant differences between Con, Low and Hi GCS interventions after 40 min of continuous treadmill running (Chapter 5). This may have been because the 40-min treadmill run was not strenuous enough to cause a loss of muscle function. Both studies do show that wearing GCS improves CMJ height from pre- to post-run. However, study 2 showed that the Con stocking improved CMJ as well. From these results it is unclear if CMJ improved independently of wearing GCS, and that increased leg power may be due to another factor.

Comfort was an important factor for the participants in these studies. Complaints about numbness in the feet and cramping in the calf muscles were made by participants wearing Hi GCS immediately after 10-km track and 40-min treadmill running. Looser or slacker GCS (Con and Low GCS) were rated most comfortable by participants in both studies. Although there was no correlation between perceived comfort and run performance time ($r=0.15$, $P=0.31$), comfort is presumably a key feature for runners. Therefore, GCS garments that promote discomfort should not be used as training or racing aids.

Untrained individuals wearing GCS have achieved significant improvements in jump height (Kraemer et al., 1998a) and decreased arm soreness from eccentric exercise (Kraemer et al., 2001). Moderately-trained athletes wearing GCS have indicated a trend to perform faster running times with lower heart rates over 10 km and significantly decreased muscle soreness 24 h post-exercise (Ali et al., 2007). However, well-trained athletes did not have significantly different performance, physiological, or muscle damage outcomes when a control stocking was compared with different GCS grades (Chapter 5). These results suggest that as training status increases from untrained to well-trained the beneficial effects from wearing GCS decrease. This may be because consistent and specific training develops adaptations that allow an athlete to perform and recover more effectively than less-trained individuals. Future investigations should attempt to determine the performance, physiological, muscle soreness, and perceptual benefits for a group of untrained participants wearing knee-length GCS.

The 10-km track and 40-min treadmill running tests may not have been physically demanding enough for this group of athletes. The distance was initially selected to mimic the study by Ali et al. (2007) who found trends for lower heart rates over paced 10-km running in moderately-trained individuals. A more appropriate running test may have been a marathon distance trial. However, a protocol that required athletes to run a marathon distance wearing different stockings under the same environmental conditions separated by a one-week, or even a one-month recovery period were beyond the expectations of this thesis. The most elite marathon runners experience considerable physiological stress and muscle damage from running 42.2 km due to the duration,

intensity and impact forces specific to the race. The marathon distance has been described as the limit of human running endurance due to the metabolic reliance on limited carbohydrate stores (Noakes, 2001). Marathon running may be the only test suitable to determine the beneficial effects of wearing GCS during running for highly trained and elite athletes. Extremely careful planning and experimental design would be required to discover if highly trained and elite runners experience benefit from wearing GCS during a marathon. Though a cross-over study design would effectively compare interventions it would not be feasible for a study with marathon runners. Athletes could be matched for age, gender, aerobic fitness, and projected marathon time (controlled design) wearing different interventions. However, this would require a substantial sample size to find a performance improvement meaningful for athletic performance (Hopkins, 2006) and this may be too difficult for many sport science investigations (Hopkins et al., 1999).

A highly trained athletic group that may gain considerable advantages from wearing GCS may be athletes who suffer from venous deficiencies. Though these athletes may not experience significant performance gains the venous system in their legs would receive considerable support during sports that require high cardiac output rates and/or repetitive impact forces from landing. A large number of individual, team, and endurance sports athletes could potentially benefit from wearing GCS in sports that require long periods of standing (Kraemer et al., 2000), heavy impact forces from repeated jumping and landing (Kraemer et al., 1998a), and competitions where multiple games and races are held on the same or consecutive days. However, the benefits from exercise itself may

be much more beneficial than wearing a compression garment (Monahan et al., 2001; Hernandez and Franke, 2005).

There were a number of limitations which affected these studies. The sample size and within-participant CV for Chapter 4 decreased the statistical power of the study, making any inferences about the performance effects of wearing GCS non significant. This may have been avoided by selecting more participants or a more highly trained group of participants who were thoroughly familiarised with the testing protocol. Inferring leg power and muscle function from CMJ height may have been more accurate if jumps were conducted on a force plate. However, the study in Chapter 4 was a field trial at a location where a force plate was not accessible and the laboratory facilities used in the study in Chapter 5 did not include a force plate. The study in Chapter 5 required participants to run on the treadmill at 90% of their recent personal best 10 km time. The intensity that participants ran at was $80\% \pm 5\%$ of their $\dot{V}O_2$ max, however, the running speed was different for participants and two participants were forced to pull out of the study because they could not complete the 40-min run, decreasing the participant numbers from 12 to 10. Though the run speeds on the treadmill were selected individually based on personal best times the difference in running speeds on the treadmill between individuals may have been a factor that influenced the results. Both studies did not consider the performance, physiological or perceptual effects on individuals with different training status. Only highly and specifically trained runners were included in the studies in Chapter 4 and 5. The same tests with a matched group of

moderately trained and untrained participants may have provided more significant results and comparisons could have been made between groups based on training status. Pressure sensitivity was restricted by an upper limit of $11 \text{ kg}\cdot\text{cm}^{-2}$ with two participants regularly reaching this upper limit. If there had been no upper limit the pressure sensitivity may have shown differences between interventions.

Future research should investigate how GCS affect running performance, leg power, muscle soreness, cardiovascular function, and subjective perception for untrained and elderly individuals. Untrained individuals who complete weight training may gain considerable benefits from wearing GCS during and after exercise, particularly from decreased DOMS experienced in the 48 h following exercise (Kraemer et al., 2001). Whether this effect extends to untrained individuals participating in running deserves further investigation. Elderly individuals have an increased incidence of venous deficiencies (Silverstein et al., 1998) which may be alleviated by wearing GCS (Clagett et al., 1995). Elderly cyclists who wore GCS during and after exercise achieved significantly better performances in a subsequent cycling test compared with a control intervention who wore non-compression cycling shorts (Chatard et al., 2004). However, the results may be different for a group of elderly runners.

In summary, well-trained athletes did not improve their running performance or experience lower heart rates, improved muscle function, enhanced running economy, or lower blood lactate concentrations wearing different GCS interventions when compared with a control garment. The most likely cause was the high training status of the groups

of athletes in both studies. Adaptations gained through consistent and specific daily training possibly superseded any beneficial effects that wearing GCS may have provided the participants.

7.0 REFERENCES

- Ali, A., Caine, M.P., Snow, B.G. (2007). "Graduated compression stockings: physiological and perceptual responses during and after exercise." Journal of Sport Science **25**(4): 413-419.
- Allen, D. G., Westerblad, H., Lee, J. A., Lannergren, J. (1992). "Role of excitation-contraction coupling in muscle fatigue." Sports Medicine **13**(2): 116-126.
- Applegate, E. A., Grivetti, L. E. (1997). "Search for the competitive edge: A history of dietary fads and supplements." The Journal of Nutrition **127**(5): 869S-873S.
- Armstrong, R. B. (1990). "Initial events in exercise-induced muscular injury." Medicine and Science in Sports and Exercise **22**(4): 429-435.
- Armstrong, R. B., Warren, G.L., Warren, J.A. (1991). "Mechanisms of exercise-induced muscle fibre injury." Sports Medicine **12**: 184-207.
- Arsenault, A. B., Winter, D. A., Marteniuk, R. G. (1986). "Treadmill versus walkway locomotion in humans: an EMG study." Ergonomics **29**(5): 665-676.
- Bailey, D. M., Davies, B., Young, I.S., Hullin, D.A., Seddon, P.S. (2001). "A potential role for free radical-mediated skeletal muscle soreness in the pathophysiology of acute mountain sickness." Aviation, Space, and Environmental Medicine **72**: 513-521.

- Balsom, P. D., Ekblom, B., Soerlund, K., Sjodln, B., Hultman, E. (1993). "Creatine supplementation and dynamic high-intensity intermittent exercise." Scandinavian Journal of Medicine & Science in Sports **3**(3): 143-149.
- Barnett, A. (2006). "Using recovery modalities between training sessions in elite athletes." Sports Medicine **36**(9): 781-796.
- Batterham, A. M., Hopkins, W.G. (2006). "Making meaningful inferences about magnitudes." International Journal of Sports Physiology and Performance **1**: 50-57.
- Benigni, J. P., Sadoun, S., Schadeck, M., Rastel, D. (2001). "Marathon runners, veins, and compression stockings." Phlebology **54**(2): 171-217.
- Benko, T., Kalik, I., Chetty, M.N. (1999). "The physiological effect of graded compression stockings on blood flow in the lower limb: An assessment with colour Doppler ultrasound." Phlebology **14**: 17-20.
- Berry, M. J., McMurray, R.G. (1987). "Effects of graduated compression stockings on blood lactate following an exhaustive bout of exercise." American Journal of Physical Medicine **61**(3): 121-132.
- Berry, M. J., Bailey, S. P., Simpkins, L. S., TeWinkle, J.A. (1990). "The effects of elastic tights on the post-exercise response." Canadian Journal of Sport Science **15**(4): 244-248.

- Bleakley, C. M., O'Connor, S., Tully, M. A., Rocke, L. G., MacAuley, D. C., McDonough, S. M. (2007) "The PRICE study (Protection Rest Ice Compression Elevation): design of a randomised controlled trial comparing standard versus cryokinetic ice applications in the management of acute ankle sprain." BMC Musculoskeletal Disorders **Volume**, DOI: 10.1186/1471-2474-8-125
- Booth, F. W., Weeden, S. H., Tseng, B. S. (1994). "Effect of aging on skeletal muscle and motor function." Medicine and Science in Sports and Exercise **26**: 556-560.
- Borrani, F., Candau, R., Millet, G.Y., Perrey, S., Fuchslocher, J., Rouillon, J.D. (2001). "Is the VO2 slow component dependent on progressive recruitment of fast-twitch fibres in trained runners?" Journal of Applied Physiology **90**: 2212-2220.
- Bringard, A., Perrey, S., Belluye, N. (2006). "Aerobic energy cost and sensation response during submaximal running exercise - positive effects of wearing compression tights." International Journal of Sports Medicine **27**: 373-378.
- Brooks, G. A., Fahey, T. D., White, T. D., Baldwin, K. M. (2001). Exercise physiology: Human Bioenergetics and Its Applications. Mayfield Publishing.
- Byrne, B. (2001). "Deep vein thrombosis prophylaxis: the effectiveness and implications of using below-knee or thigh-length graduated compression stockings." Heart and Lung **30**: 277-284.

- Byrne, C., Eston, R.G., Edwards, R.H.T. (2001). "Characteristics of isometric and dynamic strength loss following eccentric exercise-induced muscle damage. ." Scandinavian Journal of Medicine & Science in Sports **11**(3): 134-140.
- Byrnes, W. C., Clarkson, P.M., White, J.S., Hsieh, S.S., Frykman, P.N., Maughan, R.J. (1985). "Delayed onset muscle soreness following repeated bouts of downhill running." Journal of Applied Physiology **59**: 710-715.
- Caine, M. P., Ali, A., Snow, B. G. (2003). The influence of graduated compression stockings on heart rate, muscle soreness and other indicators of performance during and following exercise. L. U. S. T. R. Group. Loughborough.
- Cannon, J. G., Fielding, R.A., Fiatarone, M.A., Orencole, S.F., Dinarello, C.A., Evans, W.J. (1989). "Increased interleukin-beta in human skeletal muscle after exercise." American Journal of Physiology **257**: R451-R455.
- Casaburi, R., Storer, T. W., Ben-Dov, I., Wasserman, K. (1987). "Effect of endurance training on possible determinants of VO₂ during heavy exercise." Journal of Applied Physiology **62**(1): 199-207.
- Chapman, R. F., Stray-Gundersen, J., Levine, B.D. (1998). "Individual variation in response to altitude training." Journal of Applied Physiology **85**(4): 1448-1456.

Chatard, J.-C., Atlaoui, D., Farjanel, J., Louisy, F., Rastel, D., Guezennec, C.-Y. (2004). "Elastic stockings, performance and leg pain recovery in 63-year-old sportsmen." European Journal of Applied Physiology **93**: 347-352.

Chatard, J. C. (1998). Elastic bandages, recovery and sport performance. Proceedings of the techtextil symposium, Lyon, France, Health and protective textiles.

Chester, N., Reilly, T., Mottram, D.R. (2003). "Physiological, subjective and performance effects of Pseudoephedrine and Phenylpropanolamine during endurance running exercise." International Journal of Sports Medicine **24**: 3-8.

Clagett, G. P., Anderson, F. A., Heit, J., Levine, M. N., Wheeler, H. B. (1995). "Prevention of Venous Thromboembolism." Chest **108**: 312-334.

Clark, J. F. (1997). "Creatine and phosphocreatine: A review of their use in exercise and sport." Journal of Athletic Training **32**(1): 45-51.

Clarkson, P. M., Kroll, W., Graves, J., Record, W.A. (1982). "The relationship of serum creatine kinase, fibre type, and isometric exercise " International Journal of Sports Medicine **3**: 145-148.

Clarkson, P. M., Byrnes, W.C., McCormick, K.M., Turcotte, L.P., White, J.S. (1986). "Muscle soreness and serum creatine kinase activity following isometric, eccentric, and concentric exercise." International Journal of Sports Medicine **7**: 152-155.

Clarkson, P. M., Tremblay, I. (1988). "Exercise-induced muscle damage, repair and adaptation in humans." Journal of Applied Physiology **65**: 1-6.

Clinton, B. R., Anderson, M.E., Fraser, S.F., Stepto, N.K., Klein, R., Hopkins, W.G., Hawley, J.A. (2000). "Enhancement of 2000-m rowing performance after caffeine ingestion." Medicine and Science in Sports and Exercise **32**(11): 1958-1963.

Cohen, J. (1988). Statistical power analysis for the behavioural sciences. New York, Academy Press.

Cohen, J. (1992). "A power primer." Psychological Bulletin **112**(1): 155-159.

Conley, D. L., Krahenbuhl, G. S. (1980). "Running economy and distance running performance of highly trained athletes." Medicine and Science in Sports and Exercise **12**: 357-360.

Cooke, E. A., Benko, T., O'Connell, B.M., McNally, M.A., Mollan, R.A.B. (1996). "The effect of graduated compression stockings on lower limb venous haemodynamics." Phlebology **11**: 141-146.

Costill, D. L., Winrow, E. (1970). "A comparison of two middle-aged ultramarathon runners." Research Quarterly **41**: 135-139.

Costill, D. L., Dalsky, G. P., Fink, W.J. (1978). "Effects of caffeine ingestion on metabolism and exercise performance." Medicine and Science in Sports **10**(3): 155-158.

Dalen, J. E. (2002). "Pulmonary embolism: What have we learned since Virchow?*" Chest **122**: 1801-1817.

Daniels, J. (1974). "Physiological characteristics of champion male athletes." Research Quarterly **45**: 342-438.

Dirix, A. (1972). "Analyses of doping products used by cyclists in Belgium in 1970." Journal of Sports Medicine and Physical Fitness **12**: 261-263.

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

Duffield, R., Portus, M. (2007). "Comparison of three types of full-body compression garments on throwing and repeat-sprint performance in cricket players." British Journal of Sports Medicine **41**: 409-414.

- Duncan, C. J., Jackson, M. J. (1987). "Different mechanisms mediate structural changes and intracellular enzyme efflux following damage to skeletal muscle." Journal of Cell Science **87**(1): 183-188.
- Ebbeling, C. B., Clarkson, P.M. (1989). "Exercise-induced muscle damage and adaptation." Sports Medicine **7**: 207-234.
- Faulkner, J. A., Brooks, S. V., Opitck, J. A. (1993). "Injury to skeletal muscle fibres during contractions: conditions of occurrence and prevention." Physical Therapy **73**(12): 911-921.
- Fehling, P. C., Arciero, P.J., MacPherson, C.J., Smith, D.L. (1999). "Reproducibility of resting peripheral blood flow using strain gauge plethysmography." International Journal of Sports Medicine **20**: 555-559.
- Fischer, A. (1987). "Pressure algometry over normal muscles. Standard values, validity and reproducibility of pressure threshold." Pain **30**: 115-126.
- Flomenbaum, N. E., Goldfrank, L. R., Hoffman, R. S. (2006). Goldfrank's Toxicologic Emergencies. New York, McGraw-Hill Medical Publishing.
- Frishberg, B. A. (1983). "An analysis of overground and treadmill sprinting." Medicine and Science in Sports and Exercise **15**(6): 478-485.

Gaesser, G. A., Poole, D. C. (1996). "The slow component of oxygen uptake kinetics in humans." Exercise and Sport Science Reviews **24**(1): 35-70.

Gill, N. D., Beaven, C.M., Cook, C. (2006). "Effectiveness of post-match recovery strategies in rugby players." British Journal of Sports Medicine **40**: 260-263.

Gomez, A. L., Radzwich, R.J., Denegar, C.R., Volek, J.S., Rubin, M.R., Bush, J.A., Doan, B.K., Wickham, R.B., Mazzetti, S.A., Newton, R.U., French, D.N., Hakkinen, K., Ratamess, N.A., Kraemer, W.J. (2002). "The effects of a 10-kilometer run on muscle strength and power." Journal of Strength and Conditioning Research **16**(2): 184-191.

Graham, T. E. (2001). "Caffeine and exercise: Metabolism, endurance and performance." Sports Medicine **31**(11): 785-807.

Haller, M., Brechtelsbauer, H., Finsterer, U., Bein, T., Briegel, J., Peter, K. (1992). "Determination of plasma volume with indocyanine green in humans." Anaesthetist **41**(3): 115-120.

Hauswirth, C., Bigard, A. X., Berthelot, M., Thomaidis, M., Guezennec, C. Y. (1996). "Variability in energy cost of running at the end of a triathlon and a marathon." International Journal of Sports Medicine **17**: 572-579.

Hernandez, J. P., Franke, W. D. (2005). "Effects of a 6-mo endurance-training program on venous compliance and maximal lower body negative pressure in men and women." Journal of Applied Physiology **99**(3): 1070-1077.

Hopkins, W. G., Hawley, J.A., Burke, L.M. (1999). "Design and analysis of research on sport performance enhancement." Medicine and Science in Sports and Exercise **31**(3): 472-485.

Hopkins, W. G. (2000). "A new view of statistics." Internet Society for Sport Science.

Hopkins, W. G. (2006) "Estimating sample size for magnitude-based inferences." Sportscience **Volume**, 63-70 DOI:

Husni, E. A., Ximenes, J.O.C., Goyette, E.M. (1970). "Elastic support of the lower limbs in hospital patients: A critical study." Journal of the American Medical Association **214**(1465-1462).

Imura, H., Fukata, J., Mori, T. (1991). "Cytokines and endocrine function: an interaction between the immune and neuroendocrine systems." Clinical Endocrinology **35**: 107-115.

Jenkins, R. R. (1988). "Free radical chemistry: relationship to exercise." Sports Medicine **5**: 156-170.

- Jensen, K., Andersen, H. O., Olesen, J., Lindblom, U. (1986). "Pressure-pain threshold in human temporal region. Evaluation of a new pressure algometer." Pain **25**(3): 313-323.
- Johnson, D. L., Bahamonde, R. (1996). "Power output estimate in university athletes." Journal of Strength and Conditioning Research **10**(3): 161-166.
- Jones, A. M., Doust, J. H. (1996). "A 1% treadmill grade most accurately reflects the energetic cost of outdoor running." Journal of Sport Sciences **14**(4): 321-327.
- Jones, A. M. (1998). "A five year physiological case study of an Olympic runner." British Journal of Sports Medicine **32**: 39-43.
- Jones, D. A., Newham, D. J., Torgan, C. (1989). "Mechanical influences on long-lasting human muscle fatigue and delayed-onset pain." Journal of Physiology **412**: 415-427.
- Jonker, M. J., de Boer, E. M., Adèr, H. J., Bezemer, P.D. (2001). "The Oedema-Protective Effect of Lycra® Support Stockings." Dermatology **203**: 294-298.
- Kajiser, L. (1970). "Limiting factors for aerobic muscle performance." Acta Physiologica Scandinavica **346**(Supplement): 5-89.
- Ketty, S. S. (1949). "Measurement of regional circulation by the local clearance of radioactive sodium." American Heart Journal **38**: 321-328.

Kimmage, P. (2008). Riding The Slipstream. The Sunday Times. London: 16.

Kraemer, W. J., Bush, J.A., Bauer, J.A., Triplett-McBride, N.D., Paxton, N.J., Clemson, A., Koziris, L.P., Mangino, L.C., Fry, A.C., Newton, R.U. (1996). "Influence of compression garments on vertical jump performance in NCAA Division I volleyball players." Journal of Strength and Conditioning Research **10**(3): 180-183.

Kraemer, W. J., Bush, J.A., Newton, R.U., Duncan, N.B., Volek, J.S., Denegar, C.R., Canavan, P., Johnston, J., Putukian, M., Sebastianelli, W.J. (1998a). "Influence of a compressive garment on repetitive power output production before and after different types of muscle fatigue." Sports Medicine Training and Rehabilitation **8**: 163-184.

Kraemer, W. J., Bush, J.A., Triplett-McBride, N.T., Koziris, L.P., Mangino, L.C., Fry, A.C., McBride, J.M., Johnston, J., Volek, J.S., Young, C.A., Gomez, A.L., Newton, R.U. (1998b). "Compression garments: Influence on muscle fatigue." Journal of Strength and Conditioning Research **12**(4): 211-215.

Kraemer, W. J., Volek, J.S., Bush, J.A., Gotshalk, L.A., Wagner, P.R., Gomez, A.L., Zatsiorsky, V.M., Duzrte, M., Ratamess, N.A., Mazzetti, S.A., Selle, B.J. (2000). "Influence of compression hosiery on physiological responses to standing fatigue in women." Medicine and Science in Sports and Exercise **32**(11): 1849-1858.

- Kraemer, W. J., Bush, J.A., Wickham, R.B., Denegar, C.R., Gomez, A.L., Gotshalk, L.A., Duncan, N.B., Volek, J.S., Newton, R.U., Putukian, M., Sebastianelli, W.J. (2001). "Continuous compression as an effective therapeutic intervention in treating eccentric-exercise-induced muscle soreness." Journal of Sports Rehabilitation **10**: 11-23.
- Krustrup, P., Soderlund, K., Mohr, M., Bangsbo, J. (2004). "The slow component of oxygen uptake during intense, sub-maximal exercise in man is associated with additional fibre recruitment." Pflugers Archiv European Journal of Physiology **447**(6): 855-866.
- Kuipers, H., Janssen, G. M. E., Bosman, F., Frederik, P. M., Guerten, P. (1989). "Structural and ultrastructural changes in skeletal muscle associated with long-distance training and running." International Journal of Sports Medicine **10**: S156-159.
- Kumagai, S., Tanaka, K., Matsuura, Y., Matsuzaka, A., Hirakoba, K., Asano, K. (1982). "Relationships of the anaerobic threshold with the 5 km, 10 km, and 10 mile races." European Journal of Applied Physiology **49**: 13-23.
- LaFontaine, T. P., Londree, B. R., Spath, W. K. (1981). "The maximal steady state versus selected running events." Medicine and Science in Sports and Exercise **13**: 190-192.
- Lassen, N. A., Lindberg, I.F., Munck, O. (1964). "Measurements of blood flow through skeletal muscle by intramuscular injections of xenon-133." Lancet **1**: 686-689.

- Lawrence, D., Kakkar, V.V. (1980). "Graduated, static, external compression of the lower limb: a physiological assessment." British Journal of Surgery **67**: 119-121.
- Levine, B. D., Stray-Gundersen, J. (1997). ""Living high-training low": effect of moderate-altitude acclimatization with low-altitude training on performance." Journal of Applied Physiology **83**(1): 102-112.
- Lewis, C. E., Antoine, J., Mueller, C., Talbot, W.A., Swaroop, R., Edwards, W.S. (1976). "Elastic compression in the prevention of venous stasis." American Journal of Surgery **132**: 739-743.
- Lijnen, P., Hespel, P., Fagard, R., Lysens, R., Vanden Eynde, E., Goris, M., Goossens, W., Lissens, W., Amery, A. (1988). "Indicators of cell breakdown in plasma of men during and after a marathon race." International Journal of Sports Medicine **9**: 108-113.
- Litter, J. (1952). "Thromboembolism: its prophylaxis and medical treatment." Med. Clin. North Am. **36**: 1309-1321.
- MacIntyre, D. L., Reid, W.D., McKenzie, D.C. (1995). "Delayed muscle soreness. The inflammatory response to muscle injury and its clinical implications." Sports Medicine **20**(1): 24-40.

- Matson, L. G., Tran, Z. V. (1993). "Effects of sodium bicarbonate ingestion on anaerobic performance: a meta-analytic review." International Journal of Sport Nutrition **3**(1): 2-28.
- Matsui, H., Kitamura, K., Miyamura, M. (1978). "Oxygen uptake and blood flow of the lower limb in maximal treadmill and bicycle exercise." European Journal of Applied Physiology **40**: 57-62.
- Mayberry, J. C., Moneta, G. L., DeFrang, R. D., Porter, J. M. (1991). "The influence of elastic compression on deep venous hemodynamics." Journal of Vascular Surgery **13**(1): 91-99.
- McComas, A. J. (1996). Skeletal Muscle; Form and Function. Champaign, IL, Human Kinetics.
- McHugh, M. P. (2003). "Recent advances in the understanding of the repeated bout effect: the protective effect against muscle damage from a single bout of eccentric exercise." Scandinavian Journal of Medicine and Science in Sports **13**: 88-97.
- Messonier, L., Freund, H., Denis, C., Dormois, D., Dufour, A., Lacour, J.R. (2002). "Time to exhaustion at VO₂ max is related to the lactate exchange and removal abilities." International Journal of Sports Medicine **23**: 433-438.
- Moerman, D. E., Jonas, W. B. (2002). "Deconstructing the placebo effect and finding the meaning response." Annals of Internal Medicine **136**(6): 471-476.

- Monahan, K. D., Dinunno, F. A., Seals, D. R., Halliwill, J. R. (2001). "Smaller age-associated reductions in leg venous compliance in endurance exercise trained men." American Journal of Physiology Heart and Circulation Physiology **281**(3): H1267-H1273.
- Newham, D. J., Mills, K. R., Quigley, B. M. (1983). "Pain and fatigue after concentric and eccentric contractions." Clinical Science **64**: 55-62.
- Newham, D. J., Jones, D. A., Clarkson, P. M., (1987). "Repeated high force eccentric exercise: effects on muscle pain and damage." Journal of Applied Physiology **63**: 1381-1386.
- Nigg, B. M., Wakeling, J. M. (2001). "Impact forces and muscle tuning: A new paradigm." Exercise And Sport Science Reviews **29** (1): 37-41.
- Nikolaidis, M. G., Protosyggellou, M.D., Petridou, A., et al. (2003). "Hematologic and biochemical profile of juvenile and adult athletes of both sexes: implications for clinical evaluation." International Journal of Sports Medicine **24**: 506-511.
- Nissl, J. (2007). "Doppler Ultrasound." Diagnostic Radiology Retrieved Sunday 29 June 2008.
- Noakes, T. D. (1988). "Implications of exercise testing for prediction of athletic performance: A contemporary perspective." Medicine and Science in Sports and Exercise **20**: 319-330.
- Noakes, T. D. (2001). Lore of Running. Champaign, IL, Oxford University Press.

Noonan, T. J., Garrett, W.E. (1999). "Muscle strain injury: diagnosis and treatment." Journal of the American Academy of Orthopaedic Surgeons **7**: 262-269.

Nosaka, K., Sakamoto, K., Newton, M., et al. (2001). "How long does the protective effect on eccentric exercise-induced muscle damage last?" Medicine and Science in Sports and Exercise **33**: 1490-1495.

Okoye, G. C., Evans, J.H., Beattie, J., Lowe, G.D.O., Lorimer, A.R., Forbes, C.D. (1984). "Response of femoral oxygen tension to graduated pressure stockings - possible relation to deep vein thrombosis." Thrombosis and Haemostasis **51**: 103-104.

Ordway, G. A., Garry, D. J. (2004). "Myoglobin: an essential hemoprotein in striated muscle." Journal of Experimental Biology **207**: 3441-3446.

Poole, D. C., Gladden, L. B., Kurdak, S., Hogan, M. C. (1994). "L-(+)-lactate infusion into working dog gastrocnemius: no evidence lactate per se mediates VO_2 slow component." Journal of Applied Physiology **76**: 787-792.

Proske, U., Morgan, D.L. (2001). "Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptations and clinical applications." Journal of Physiology **537**: 333-345.

Pyne, D. B. (1994). "Exercise-induced muscle damage and inflammation: A review." The Australian Journal of Science and Medicine in Sport **26**(3/4): 49-58.

Reinhartz, D., (1980). "Fitness and competitive sports in venous pathology." Phlebology **33** (3): 513-521.

Robergs, R. A., Ghiasvand, F., Parker, D. (2004). "Biochemistry of exercise-induced metabolic acidosis." American Journal of Physiology: Regulatory Integrative and Comparative Physiology **287**: R502-516.

Roecker, K., Schotte, O., Niess, A. M., Horstmann, T., Dickhuth, H. H. (1998). "Predicting competition performance in long-distance running by means of a treadmill test." Medicine and Science in Sports and Exercise **30**: 1552-1557.

Rossiter, H. B., Cannell, E.R., Jakeman, P.M. (1996). "The effect of oral creatine supplementation on the 1000-m performance of competitive rowers." Journal of Sport Sciences **14**: 175-179.

Russell, R. D., Redmann, S.M., Ravussin, E., Hunter, G.R., Larson-Meyer, D.E (2004). "Reproducibility of endurance performance on a treadmill using a preloaded time trial." Medicine and Science in Sports and Exercise **36**(4): 717-724.

Sahlin, K. (1992). "Metabolic factors in fatigue." Sports Medicine **13**: 99-107.

- Schache, A. G., Blanch, P. D., Rath, D. A., Wrigley, T. V., Starr, R., Bennell, K. L. (2001). "A comparison of overground and treadmill running for measuring the three-dimensional kinematics of the lumbo-pelvic-hip complex." Clinical Biomechanics **18**(8): 667-680.
- Schwane, J. A., Johnson, S.R., Vandenakker, C.B., Armstrong, R.B. (1983). "Delayed-onset muscular soreness and plasma CPK and LDH activities after downhill running." Medicine and Science in Sports and Exercise **15**: 51-56.
- Sciaccia, V., Buonopera, P., Mingoli, A., Di Marzo, L., Matteucci, E. (1991). "Evaluation of venous flow by light reflection rheography (LRR) in athletes performing track race." Journal of Sports Medicine and Physical Fitness **31**: 265-271.
- Scurr, J. H., Ibrahim, S. Z., Faber, R. G. et al (1977). "The efficacy of graduated compression stockings in the prevention of deep vein thrombosis." British Journal of Surgery **64**: 371-373.
- Shellock, F. G., Prentice, W. E. (1985). "Warming up and stretching for improved physical performance and prevention of sports-related injuries." Sports Medicine **2**(4): 267-278.
- Shinohara, M., Moritani, T. (1992). "Increase in neuromuscular activity and oxygen uptake during heavy exercise." Annals of Physiology and Anthropometry **11**: 257-262.

Sigel, B., Edelstein, A.L., Savitch, L. (1975). "Type of compression for reducing venous stasis."

Arch Surg **110**: 171-175.

Silverstein, M. D., Heit, J. A., Mohr, D. N., Petterson, T. M., O'Fallon, W. M., Melton, L. J.

(1998). "Trends in the incidence of deep vein thrombosis and pulmonary embolism."

Archives of Internal Medicine **158**(6): 585-593.

Smith, L. (1991). "Acute inflammation: the underlying mechanism in delayed onset muscle

soreness?" Medicine and Science in Sports and Exercise **23**: 542-551.

Spriet, L. L., MacLean, D. A., Dyck, D. J., Hultman, E., Cederblad, G., Graham, T. E. (1992).

"Caffeine ingestion and muscle metabolism during prolonged exercise in humans."

American Journal of Physiology **262**: E891-898.

Sproule, J. (1998). "The influence of either no fluid or carbohydrate-electrolyte fluid ingestion

and the environment (thermoneutral versus hot and humid) on running economy after

prolonged high-intensity exercise." European Journal of Applied Physiology **77**: 536-542.

Stanton, J. R., Fies, E.D., Wilkins, R.W. (1949). "Acceleration of linear flow in the deep veins of

the lower extremity of man by local compression." Journal of Clinical Investigation **28**:

553-558.

Stauber, W. T., Fritz, V.K., Vogelbach, D.W. (1988). "Characterization of muscles injured by forced lengthening." Medicine and Science in Sports and Exercise **20**(4): 345-353.

Stray-Gundersen, J., Levine, B.D. (1999). "'Living high and training low' can improve sea level performance in endurance athletes." British Journal of Sports Medicine **33**: 150-151.

Stray-Gundersen, J., Chapman, R.F., Levine, B.D. (2001). "'Living high-training low' altitude training improves sea level performance in male and female elite runners." Journal of Applied Physiology **91**: 1113-1120.

Suzuki, K., Totsuka, M., Nakaji, S., Yamada, M., Kudoh, S., Liu, Q., Sugawara, K., Yamaya, K., Sato, K. (1999). "Endurance exercise causes interaction among stress hormones, cytokines, neutrophil dynamics, and muscle damage." Journal of Applied Physiology **87**(4): 1360-1367.

Tee, J. C., Bosch, A.N., Lambert, M.I. (2007). "Metabolic consequences of exercise-induced muscle damage." Sports Medicine **37**(10): 827-836.

Trenell, M. I., Rooney, K.B., Sue, C.M., Thompson, C.H. (2006). "Compression garments and recovery from eccentric exercise: A ³¹P-MRS Study." Journal of Sport Science and Medicine **5**: 106-114.

- van Geest, A. J., Franken, C. P. M., Neumann, H. A. M. (2003). "Medical elastic compression stockings in the treatment of venous insufficiency." Current Problems in Dermatology **31**: 98-107.
- Vanhees, L., Defoor, J., Schepers, D., Brusselle, S., Reybrouk, T., Fagard, R. (2000). "Comparison of cardiac output measured by two automated methods of CO₂ rebreathing." Medicine and Science in Sports and Exercise **32**(5): 1028-1034.
- Vuori, J., Syrjala, H., Vaananen, H.K. (1996). "Myoglobin/Carbonic anhydrase III ratio: Highly spoeific and sensitive early indicator for myocardial damage in acute myocardial infarction." Clinical Chemistry **42**(1): 107-109.
- Wank, V., Frick, U., Schmidbleicher, D. (1998). "Kinematics and electromyography of lower limb muscles in overground and treadmill running." International Journal of Sports Medicine **19**: 455-461.
- Warren, G. L., Lowe, D.A., Armstong, R.B. (1999). "Measurement tools used in the study of eccentric contraction-induced injury." Sports Medicine **27**(1): 43-59.
- Wells, P. S., Lensing, A. W. A., Hirsh, J. (1994). "Graduated compression stockings in the prevention of postoperative venous thromboembolism." Archives of Internal Medicine **154**: 67-72.

Westerblad, H., Lee, J.A., Lannergren, J., Allen, D.G. (1991). "Cellular mechanisms of fatigue in skeletal muscle." American Journal of Physiology **30**: C195-C209.

Wiese, P., Nonnast-Daniel, B. (2004). "Colour Doppler ultrasound in dialysis access." Nephrology Dialysis Transplantation **19**(8): 1956-1963.

Wilkins, R. W., Mixter, G., Stanton, J. R., et al (1952). "Elastic stockings in the prevention of pulmonary embolism: a preliminary report." New England Journal of Medicine **246**: 360-364.

Xu, F., Montgomery, D. L. (1995). "Effect of prolonged exercise at 65 and 80% of VO₂ max on running economy." International Journal of Sports Medicine **16**: 309-315.

8.0 APPENDICES

Appendix 1: Pre-exercise health screening questionnaire

Appendix 2: Informed consent: The effect of wearing graduated compression stockings on running performance

Appendix 3: Informed consent: Physiological and perceptual benefits of wearing graduated compression stockings during high intensity running.

Appendix 4: Feeling State

Appendix 5: Felt Arousal Scale

Appendix 6: Rating of Perceived Exertion

Appendix 7: Comfort, tightness, and pain scales

Appendix 8: Information sheet: The effect of wearing graduated compression stockings on running performance

Appendix 9: Information sheet: Physiological and perceptual benefits of wearing graduated compression stockings during high intensity running.

Appendix 10: Juzo sizing chart

Appendix 11: Muscle soreness diagram

Appendix 12: Pressure algometer measurement charts

Appendix 13: Training logbook

Appendix 14: Nutrition diary

Appendix 15: Abstract accepted for the 13th annual Congress of the European College of Sport Science ECSS – ESTORIL, PORTUGAL 9-12 July 2008.

Appendix 1

Pre-Exercise Health Screening Questionnaire

Name: _____

Address: _____

Phone: _____

Age: _____

Please read the following questions carefully. If you have any difficulty, please advise the medical practitioner, nurse or exercise specialist who is conducting the exercise test.

Please answer all of the following questions by ticking only one box for each question:

This questionnaire has been designed to identify the small number of persons (15-69 years of age) for whom physical activity might be inappropriate. The questions are based upon the Physical Activity Readiness Questionnaire (PAR-Q), originally devised by the British Columbia Dept of Health (Canada), as revised by ¹Thomas *et al.* (1992) and ²Cardinal *et al.* (1996), and with added requirements of the Massey University Human Ethics Committee. The information provided by you on this form will be treated with the strictest confidentiality.

Qu 1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?

Yes ☐ No ☐

Qu 2. Do you feel a pain in your chest when you do physical activity?

Yes ☐ No ☐

Qu 3. In the past month have you had chest pain when you were not doing physical activity?

Yes ☐ No ☐

Qu 4. Do you lose your balance because of dizziness or do you ever lose consciousness?

Yes ☐ No ☐

Qu 5. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?

Yes ☐ No ☐

Qu 6. Do you have a bone or joint problem that could be made worse by vigorous exercise?

Yes ☐ No ☐

Qu 7. Do you know of any other reason why you should not do physical activity?

Yes ☐ No ☐

Qu 8. Have any immediate family had heart problems prior to the age of 60?

Yes ☐ No ☐

Qu 9. Have you been hospitalised recently?

Yes ☐ No ☐

Qu 10. Do you have any infectious disease that may be transmitted in blood?

Yes ☐ No ☐

Qu 11. This test may include the taking of blood via venepuncture. Do you have any objection to this?

Yes ☐ No ☐

Qu 12. Have you ever suffered from any sleep disorders?

Yes

☐

No

☐

You should be aware that even amongst healthy persons who undertake regular physical activity there is a risk of sudden death during exercise. Though extremely rare, such cases can occur in people with an undiagnosed heart condition. If you have any reason to suspect that you may have a heart condition that will put you at risk during exercise, you should seek advice from a medical practitioner before undertaking an exercise test.

I have read, understood and completed this questionnaire.

Signature: _____ Date: _____

References

1. Thomas S, Reading J and Shephard RJ. Revision of the Physical Activity Readiness Questionnaire (PAR-Q). *Can J Sport Sci* 17(4): 338-345.
2. Cardinal BJ, Esters J and Cardinal MK. Evaluation of the revised physical activity readiness questionnaire in older adults. *Med Sci Sports Exerc* 28(4): 468-472

Appendix 2

THE EFFECT OF WEARING GRADUATED COMPRESSION STOCKINGS ON
RUNNING PERFORMANCE

PARTICIPANT CONSENT FORM

This consent form will be held for a minimum period of five (5) years

I have read the Information Sheet and have had the details of the study explained to me. My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I understand that I have the right to withdraw from the study at any time and to decline to answer any particular questions.

I agree to provide information to the researcher on the understanding that my name will not be used without my permission. (The information will be used only for this research and publications arising from this research project).

I agree to participate in this study under the conditions set out in the Information Sheet.

Signature: _____

Date _____

Full Name (printed)

Appendix 3

THE PHYSIOLOGICAL AND PERCEPTUAL EFFECTS OF WEARING GRADUATED
COMPRESSION STOCKINGS DURING RUNNING

This consent form will be held for a minimum period of five (5) years

I have read the Information Sheet and have had the details of the study explained to me. My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I understand that I have the right to withdraw from the study at any time and to decline to answer any particular questions.

I agree to provide information to the researcher on the understanding that my name will not be used without my permission. (The information will be used only for this research and publications arising from this research project).

I agree to participate in this study under the conditions set out in the Information Sheet.

Signature: _____

Date _____

Full Name (printed)

Appendix 4

Feeling Scale (FS)**+5 Very Good****+4****+3 Good****+2****+1 Fairly Good****0 Neutral****-1 Fairly Bad****-2****-3 Bad****-4****-5 Very Bad**

Appendix 5

Felt Arousal Scale (FAS)

1 Low Arousal

2

3

4

5

6 High Arousal

Appendix 6

RPE Scale (Borg)

6	
7	Very Very Light
8	
9	Very Light
10	
11	Fairly Light
12	
13	Fairly Hard
14	
15	Hard
16	
17	Very Hard
18	
19	Very Very Hard
20	

Appendix 7

GCS Comfort, Tightness & Pain Scales

For each of the statements below please point to the number that best describes how you feel.

1. Rate 1-10, the comfort of the sock.

1	2	3	4	5	6	7	8	9	10
Very Uncomfortable					Very Comfortable				

2. Rate 1-10, the tightness of the sock.

1	2	3	4	5	6	7	8	9	10
Very Slack					Very Tight				

3. Rate 1-10, the pain induced by the sock.

1	2	3	4	5	6	7	8	9	10
No Pain					Very Painful				

Appendix 8

THE EFFECT OF WEARING GRADUATED COMPRESSION STOCKINGS ON RUNNING PERFORMANCE

PARTICIPANT INFORMATION SHEET

Invitation to Participate in Research Study

My name is Rob Creasy and I am a student studying for an MSc degree at the Institute of Food, Nutrition and Human Health, Massey University (Albany). With the help of my supervisor Dr Ajmol Ali and colleagues, Dr Andrew Fosskett and MS Helen Ryan we will be completing a research study to investigate the effects of wearing graduated compression stockings (GCS) on running performance.

Graduated compression stockings have been shown to improve blood flow to the heart and help 'flush' away bi-products that can cause fatigue when standing for long periods of time. Therefore, they have been promoted as a method of reducing the effects of deep vein thrombosis (DVT) and varicose veins. Moreover, the improved clearance of metabolites such as lactic acid from the calf muscle could promote reduced levels of soreness and fatigue. Thus, some athletes have worn (GCS) during training and also during competitive races. However, there is little scientific evidence on the exact effects of these garments on levels of muscular soreness and performance. Therefore, the primary aim of this study is to examine the influence of wearing GCS during 10-km running time trials on an outdoor track. Many studies recommend that a compression level of 18–22 mmHg is optimal but this is due to results based on clinical trials. Therefore, a further aim of this study is to investigate the optimal level of compression for sports performance.

Participant Recruitment

All participants will be recruited from the Auckland area. I am looking to recruit 16 healthy male and female competitive runners and multisport athletes, aged 18-40 years.

Project Procedures and Participant Involvement

During the preliminary session, you will be informed of the study (verbally and in written form), sign the consent form, complete the Health Screen questionnaire, and have lower leg measurements taken (for correct fitting of GCS). You will also be shown how to correctly put on the GCS. You will then perform a concurrent maximal oxygen uptake (VO_2 max) and lactate test.

During the main trials (5 occasions) you will be asked to arrive at the Mt Smart or Millennium track at least 30 minutes before the run starts. Following completion of a

daily health questionnaire, you will either wear GCS or just ankle length (non-compression) sports sock and then perform a standardised 5-min warm up. You will be asked a series of questions about how you feel followed by completing 3 counter-movement jumps and providing a capillary blood lactate sample. You will then perform a 10-km time-trial on track. where heart rate and time will be monitored, You will receive feedback about how many laps you have completed, but you will receive no feedback about time throughout the trial. Following the run you will complete the same pre-run measures followed by a warm-down..

Participant's Rights

You are under no obligation to accept this invitation. Should you choose to participate, you have the right to:

- decline to answer any particular question
- withdraw at any time up to one week after the data collection is complete
- ask any questions about the study at any time during participation
- provide information on the understanding that your name will not be used unless you give permission to the researcher
- be given access to a summary of the project findings when it is concluded

Confidentiality

All data collected will be used solely for research purposes and has the possibility of being presented in a professional journal. All personal information will be kept confidential by assigning numbers to each participant. No names will be visible on any papers on which you provide information. All data/information will be dealt with in confidentiality and will be stored in a secure location for five years on the Massey University Albany campus. After this time it will be disposed of by an appropriate staff member from the Sport and Exercise Science department.

Project Contacts

If you have any questions regarding this study, please do not hesitate to contact any of the following people for assistance:

- Rob Creasy (Primary Investigator, Sport and Exercise Science, IFNHH, Massey University): (09)414-0800 ext.41179; rhcreasy@gmail.com
- Dr. Ajmol Ali (Project Supervisor, Sport and Exercise Science, IFNHH, Massey University): (09)414-0800 ext.41184; a.ali@massey.ac.nz
- Dr Andrew Foskett (Lecturer, Sport and Exercise Science, IFNHH, Massey University): (09)414-0800 ext.41104; a.foskett@massey.ac.nz

Appendix 9

PHYSIOLOGICAL AND PERCEPTUAL BENEFITS OF WEARING GRADUATED
COMPRESSION STOCKINGS DURING HIGH INTENSITY RUNNING

PARTICIPANT INFORMATION SHEET

Invitation to Participate in Research Study

My name is Rob Creasy and I am a student studying for an MSc degree at the Institute of Food, Nutrition and Human Health, Massey University (Albany). With the help of my supervisor Dr Ajmol Ali and colleagues, Dr Andrew Foskett and Mr Phil Collins, we will be completing a research study to investigate the physiological effects of wearing graduated compression stockings (GCS) during running.

Graduated compression stockings have been shown to improve blood flow to the heart and help 'flush' away by-products that can cause fatigue when standing for long periods of time. Therefore, they have been promoted as a method of reducing the effects of deep vein thrombosis (DVT) and varicose veins. Moreover, the improved clearance of metabolites such as lactic acid from the calf muscle could promote reduced levels of soreness and fatigue. Thus, some athletes have worn (GCS) during training and also during competitive races. However, there is little scientific evidence on the exact effects of these garments on levels of muscular soreness and performance. Therefore, the primary aim of this study is to examine the influence of wearing GCS during exercise for a 40-minute treadmill time trial. Many studies recommend that a compression level of 18–22 mmHg is optimal but this is due to results based on clinical trials. Therefore, a further aim of this study is to investigate the optimal level of compression for sports performance.

Participant Recruitment

All participants will be recruited from Auckland. I am looking to recruit 14 healthy men, aged 18-45 years, who are competitive runners or competitive sportsmen whose primary sport is based upon running (triathlon, duathlon, multisport, orienteering).

Project Procedures and Participant Involvement

If you are satisfied with the study information and wish to be involved in the study you will be required to attend a preliminary session. During this session the study information will be presented to you a second time verbally and in written form. You will sign the consent form, complete the Health Screen questionnaire, and have lower leg measurements taken (for correct fitting of GCS). **You will be given a daily diet recording sheet and asked to fill it out for the 24-hour period prior to completing**

each 40-minute treadmill run to ensure your dietary intake is standardised between tests. You will also be shown how to correctly put on the GCS. You will then perform a concurrent maximal oxygen uptake (VO_2 max) and blood lactate test.

During the main trials (3 occasions) you will be asked to report to the laboratory after observing at least a 3-h fast (to avoid effects of prior food intake on performance). You will also be asked to submit a 24-hour dietary intake record and training log from the previous three days to ensure exercise and nutrition are standardised between tests. Following completion of a daily health questionnaire you will sit quietly for 20 minutes and, after this period, a venous blood sample will be taken; perceptual variables (FAS, FS, GCS comfort, and perceived soreness), lower-limb pressure sensitivity, and counter-movement vertical jumps will be measured. You will be given a pair of GCS to wear, a chest belt for monitoring heart rate, and a mouthpiece with nose clip for VO_2 measurement. When you are ready you will perform a standardised 5-min warm up followed by measurements of venous blood flow velocity. The test itself requires you to complete a 40-minute treadmill run at 90% of personal best 10km run time. Heart rate and VO_2 will be monitored continuously; blood lactate and RPE will be sampled at 5-minute intervals. You will receive information about how long you have run for every five minutes. When you have completed the 40-minute run your venous blood flow, RPE, counter-movement vertical jump, lower-limb pressure sensitivity, Feeling Scale, Felt Arousal Scale, GCS comfort, perceived soreness, and a venous blood sample will be measured. Following these measurements you will complete a self-paced warm-down. After 24 and 48 hours from completing the treadmill run you will be required to return to the lab to complete a perceived soreness scale, a venous blood sample, a lower-limb pressure sensitivity assessment, and perform a counter-movement jump.

Some discomfort is possible from venous blood sampling and you may experience minor bruising to your arm. However, the experience of the staff involved will help minimise these effects. Hard treadmill running during the 40-minute run and the VO_2 max and lactate test may cause substantial fatigue, but you will recover from this quickly. **Completing maximal effort or high intensity exercise of any type has potential risks including sudden collapse or death. Staff trained in the most up to date first aid procedures will be in the room during all testing sessions to ensure that any health issues encountered will be dealt with competently.**

A full explanation of your own results and the group results will be provided at the conclusion of all data collection during a debrief function held for all the participants in the study. During this debrief any questions you have about the results of the research and its implications will be answered.

Participant's Rights

You are under no obligation to accept this invitation. Should you choose to participate, you have the right to:

- decline to answer any particular question
- withdraw at any time up to one week after the data collection is complete
- ask any questions about the study at any time during participation
- provide information on the understanding that your name will not be used unless you give permission to the researcher
- be given access to a summary of the project findings when it is concluded

Confidentiality

All data collected will be used solely for research purposes and has the possibility of being presented in a professional journal. All personal information will be kept confidential by assigning numbers to each participant. No names will be visible on any papers on which you provide information. All data/information will be dealt with in confidentiality and will be stored in a secure location for five years on the Massey University Albany campus. After this time it will be disposed of by an appropriate staff member from the Sport and Exercise Science department.

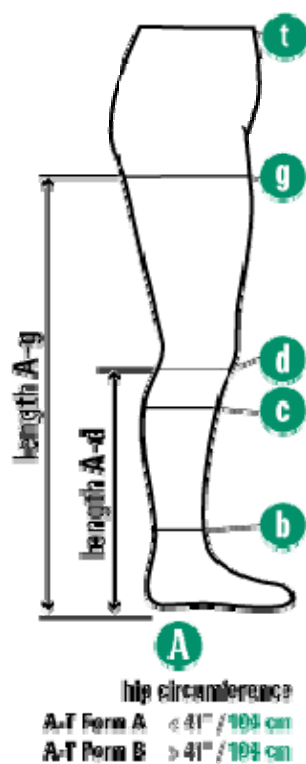
Project Contacts

If you have any questions regarding this study, please do not hesitate to contact any of the following people for assistance:

- Rob Creasy (Primary Investigator, Sport and Exercise Science, IFNHH, Massey University): (09)414-0800 ext.41179; rhcreasy@gmail.com
- Dr. Ajmol Ali (Project Supervisor, Sport and Exercise Science, IFNHH, Massey University): (09)414-0800 ext.41184; a.ali@massey.ac.nz
- Dr Andrew Foskett (Lecturer, Sport and Exercise Science, IFNHH, Massey University): (09)414-0800 ext.41104; a.foskett@massey.ac.nz

Appendix 10

Juzo Sizing Chart

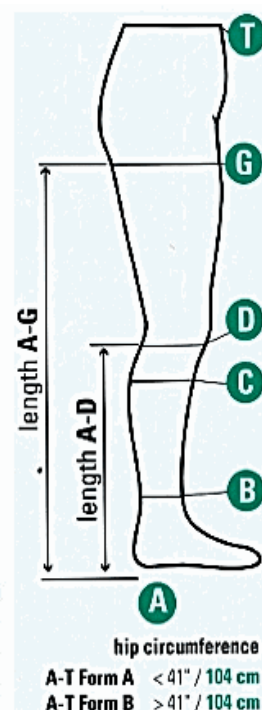


	I	II	III	IV	V
g	41-60 cm 16.25-23.5 in	50-68 cm 19.5-26.75 in	54-75 cm 21.25-29.5 in	57-79 cm 22.5-31 in	62-85 cm 24.5-33.5 in
g*	45-55 cm 17.75-22 in	50-61 cm 19.5-24 in	54-68 cm 21.25-26.75 in	57-73 cm 22.5-28.75 in	62-78 cm 24.5-30.75 in
*with silicone border					
c	29-38 cm 11.5-15 in	34-43 cm 13.25-17 in	37-49 cm 14.5-19.25 in	41-53 cm 16.25-21 in	46-58 cm 18-23 in
b	18-21 cm 7-8.25 in	21-24 cm 8.25-9.5 in	24-27 cm 9.5-10.75 in	27-31 cm 10.75-12.25 in	31-35 cm 12.25-13.75 in



	I	II	III	IV	V	VI
G	43-56 cm 17"-22"	47-62 cm 18 1/2"-24 1/2"	49-66 cm 19 1/4"-26"	55-73 cm 21 3/4"-28 3/4"	59-77 cm 23 1/4"-30 1/4"	64-82 cm 25 1/4"-32 1/4"
G with silicone	46-53 cm 18"-21"	51-58 cm 20"-23"	53-62 cm 21"-24 1/2"	60-69 cm 23 1/2"-27 1/4"	64-73 cm 25 1/4"-28 3/4"	69-78 cm 27 1/4"-30 3/4"
C	27-34 cm 10 1/2"-13 1/2"	29-37 cm 11 1/2"-14 1/2"	33-41 cm 13"-16 1/4"	36-45 cm 14 1/4"-17 3/4"	39-47 cm 15 1/2"-18 1/2"	42-50 cm 16 1/2"-19 3/4"
B	18-20 cm 7"-7 3/4"	20-22 cm 7 3/4"-8 1/2"	22-24.5 cm 8 1/2"-9 1/2"	24.5-27 cm 9 1/2"-10 1/2"	27-30 cm 10 1/2"-11 3/4"	30-33 cm 11 3/4"-13"

	length A-D	length A-G
A-D Regular	15 3/4-18 1/4" / 40-46 cm	A-G Regular and A-T Regular - 28 1/4-32 3/4" / 72-83 cm
A-D Short	13-15 3/4" / 34-40 cm	A-G Short and A-T Short - 24 3/4-28 1/4" / 63-72 cm
A-D Petite	< 13" / 33 cm	A-G Petite and A-T Petite - 21 3/4-24 3/4" / 55-63 cm



Knee High Length A-d		Thigh and Pantyhose Length A-g	
A-d Regular	40-46cm 15 3/4-18 1/4 in	A-g Regular and A-t Regular	72-83 cm 28 1/4-32 3/4 in
A-d Short	34-40cm 13-15 3/4 in	A-g Short and A-t Short	63-72 cm 24 3/4-28 1/4 in
A-d Petite	<33cm <13 in	A-g Petite and A-t Petite	55-63 cm 21 3/4-24 3/4 in

Appendix 11

**PHYSIOLOGICAL AND PERCEPTUAL BENEFITS OF WEARING GRADUATED
COMPRESSION STOCKINGS DURING HIGH INTENSITY RUNNING**

PRE-TEST MUSCLE SORENESS

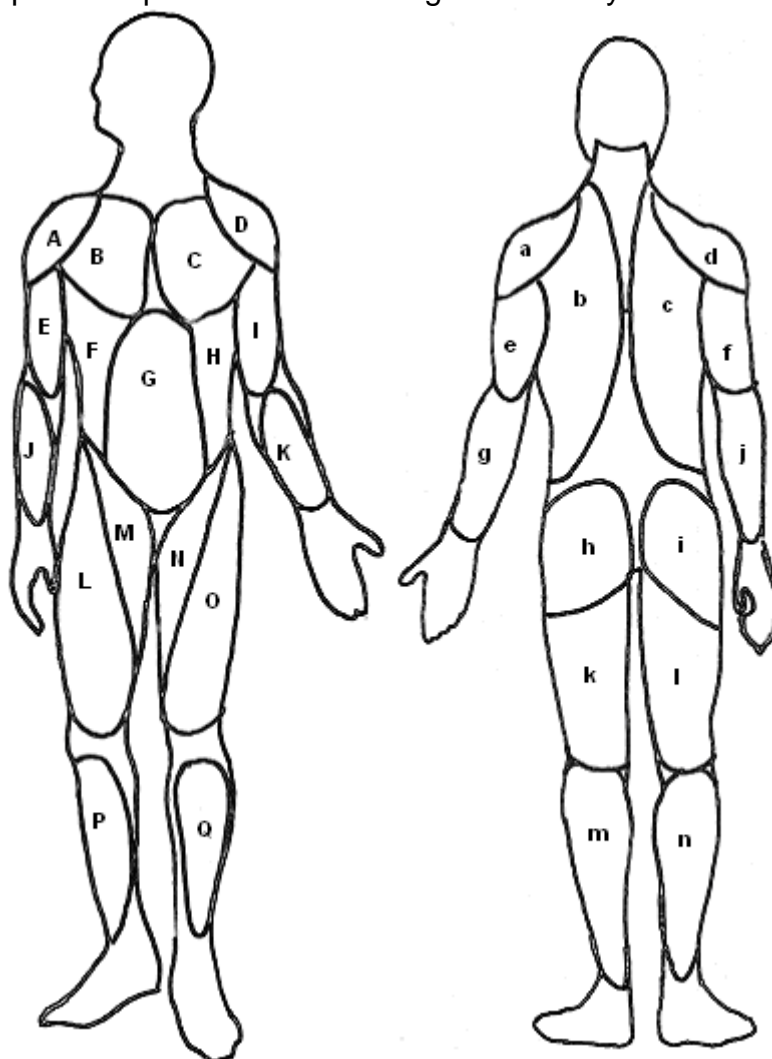
Name:

Time:

Date:

LOCATION OF SORENESS

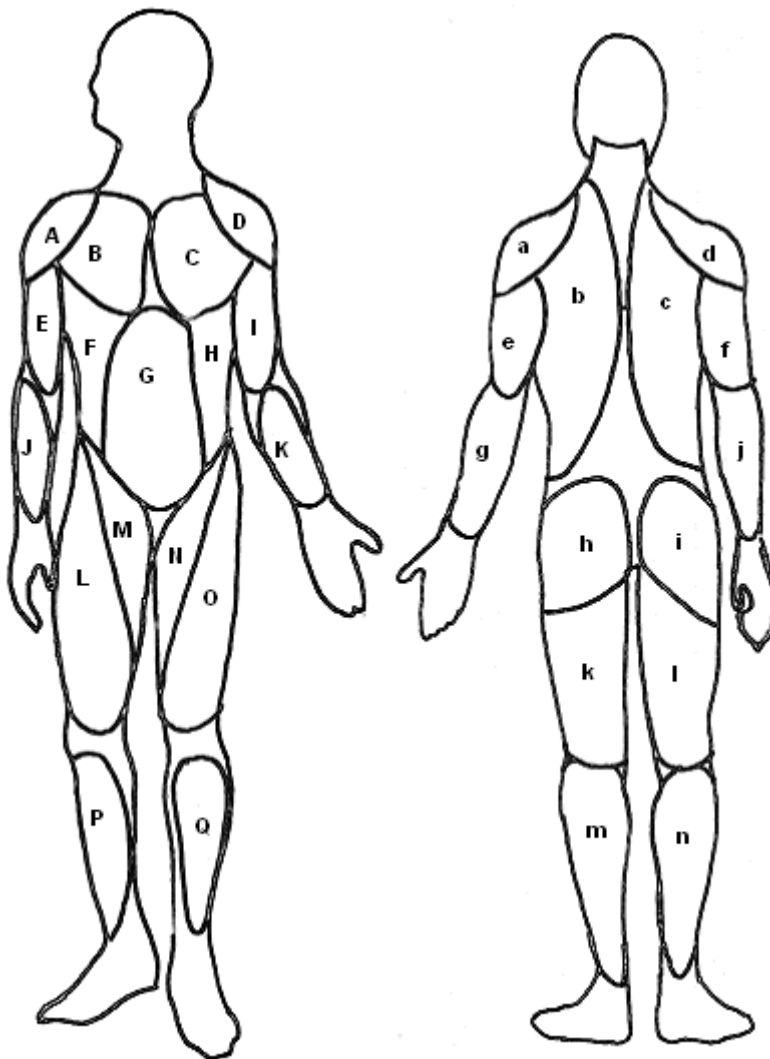
Using the pencil provided please shade the regions where you feel muscle soreness.



POST-TEST MUSCLE SORENESS

LOCATION OF SORENESS

Using the pencil provided please shade the regions where you feel muscle soreness.

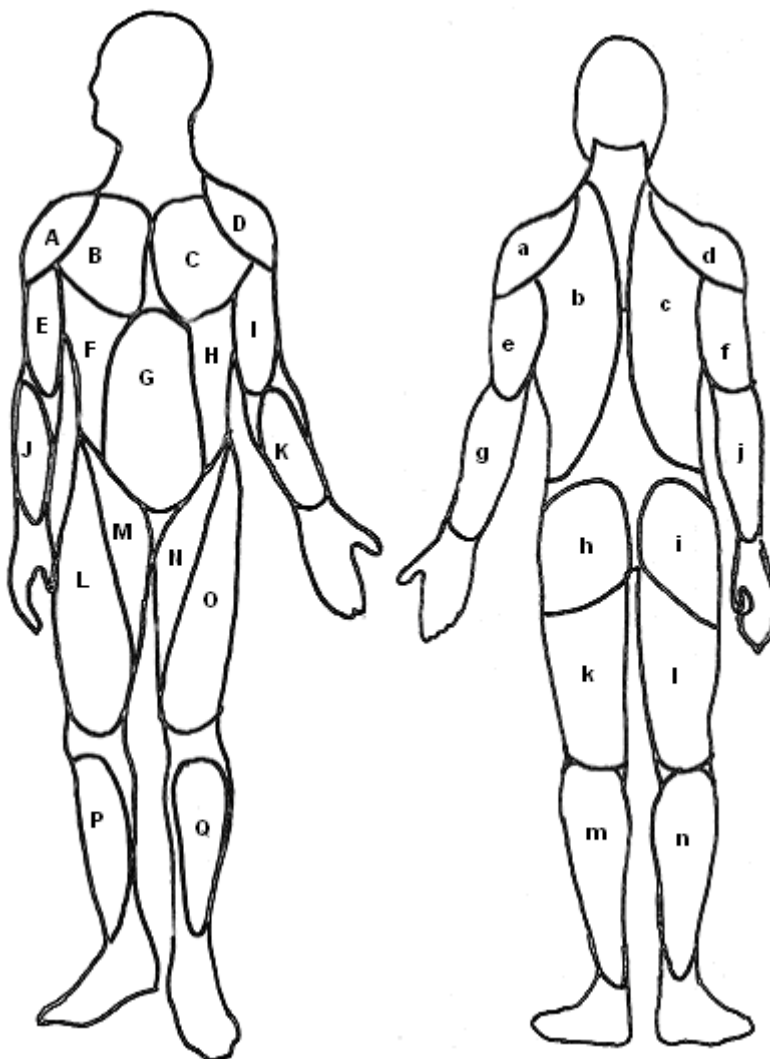


Notes

24 HOURS POST-TEST MUSCLE SORENESS

LOCATION OF SORENESS

Using the pencil provided please shade the regions where you feel muscle soreness.

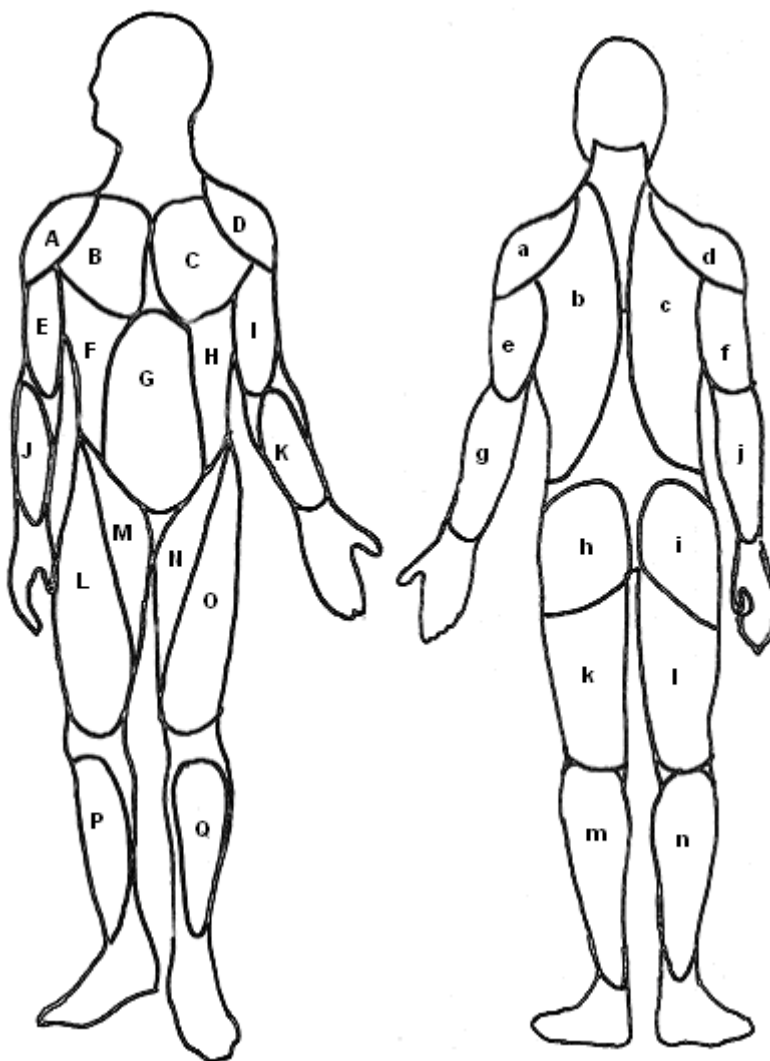


Notes

48 HOURS POST-TEST MUSCLE SORENESS

LOCATION OF SORENESS

Using the pencil provided please shade the regions where you feel muscle soreness.



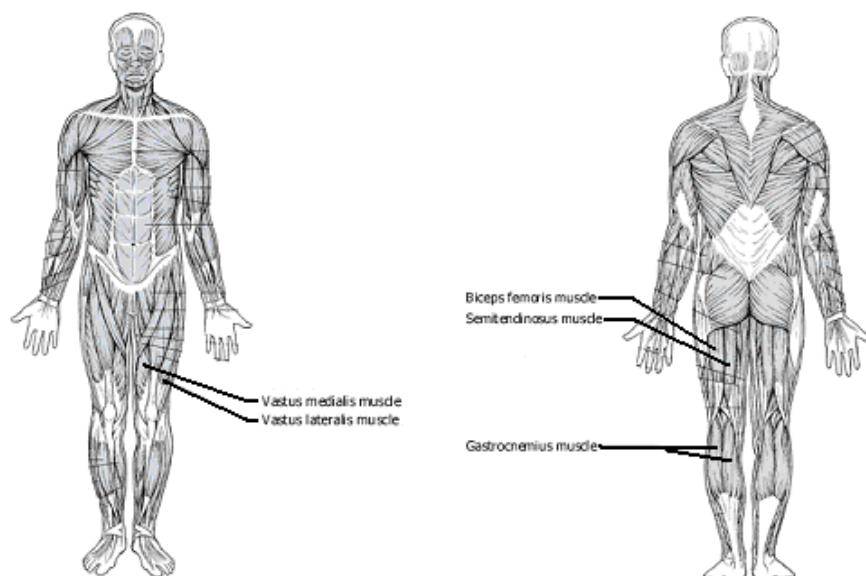
Notes

Please rate the intensity of muscle ache or soreness by marking any where on the line (at or between the descriptors) on the scale below.

	No Ache/Soreness
	Just Noticeable
	Very Weak
	Weak Ache/Soreness
	Moderate
	Strong Ache/Soreness
	Very Strong
	Extremely Strong
★	Highest Possible Ache/Soreness

MUSCLE SITE	FORCE (kg)							
	Right Side			Av	Left side			Av
Vastus lateralis (20 cm proximal the knee joint)								
Vastus Medialis (medial aspect)								
Biceps Femoris (middle of hamstrings)								
Gastronemius medial head								
Gastromemius lateral head								
Tibialis Anterior								
Sum of Forces								
Pain Threshold								

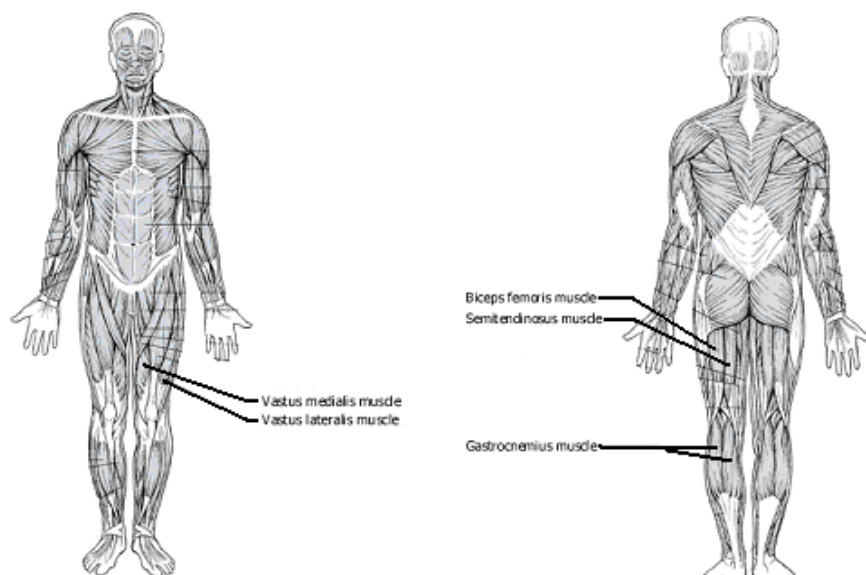
POST-TEST



MUSCLE SITE	FORCE (kg)							
	Right Side			Av	Left side			Av
Vastus lateralis (20 cm proximal the knee joint)								
Vastus Medialis (medial aspect)								
Biceps Femoris (middle of hamstrings)								
Gastronemius medial head								
Gastromemius lateral head								
Tibialis Anterior								
Sum of Forces								
Pain Threshold								

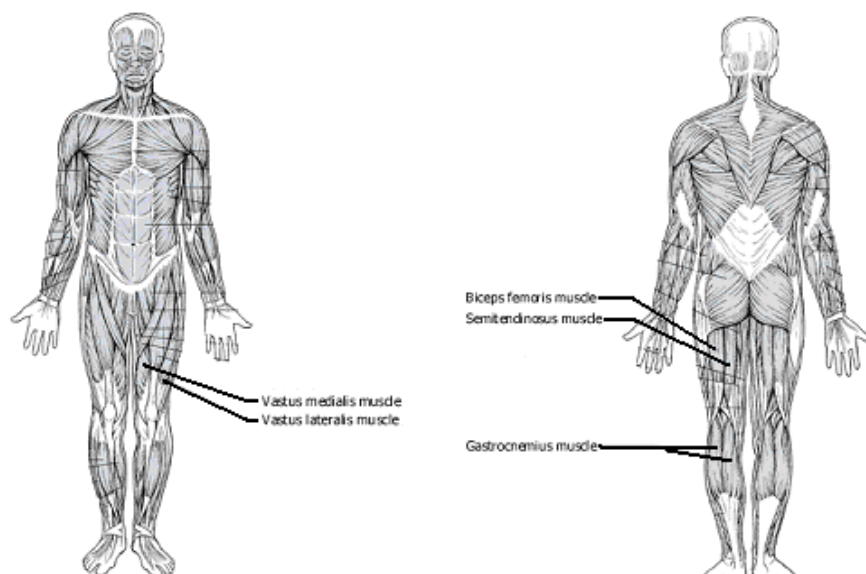
Reference: Nussbaum, E. T., & DownesL. (1998). Reliability of clinical pressure-pain algometric measurements obtained on consecutive days. *Physical therapy* 78: 160-169.
 Fischer, A. A. (1987). Pressure algometry over normal muscles. Standard values, validity and reproducibility of pressure threshold. *Pain* 30, 115-126.

24 HOURS POST-TEST



MUSCLE SITE	FORCE (kg)							
	Right Side			Av	Left side			Av
Vastus lateralis (20 cm proximal the knee joint)								
Vastus Medialis (medial aspect)								
Biceps Femoris (middle of hamstrings)								
Gastronemius medial head								
Gastromemius lateral head								
Tibialis Anterior								
Sum of Forces								
Pain Threshold								

Reference: Nussbaum, E. T., & DownesL. (1998). Reliability of clinical pressure-pain algometric measurements obtained on consecutive days. *Physical therapy* 78: 160-169.
 Fischer, A. A. (1987). Pressure algometry over normal muscles. Standard values, validity and reproducibility of pressure threshold. *Pain* 30, 115-126.

48 HOURS POST-TEST

MUSCLE SITE	FORCE (kg)							
	Right Side			Av	Left side			Av
Vastus lateralis (20 cm proximal the knee joint)								
Vastus Medialis (medial aspect)								
Biceps Femoris (middle of hamstrings)								
Gastronemius medial head								
Gastromemius lateral head								
Tibialis Anterior								
Sum of Forces								
Pain Threshold								

Reference: Nussbaum, E. T., & DownesL. (1998). Reliability of clinical pressure-pain algometric measurements obtained on consecutive days. *Physical therapy* 78: 160-169.

Fischer, A. A. (1987). Pressure algometry over normal muscles. Standard values, validity and reproducibility of pressure threshold. *Pain* 30, 115-126.

Appendix 13

PHYSIOLOGICAL AND PERCEPTUAL BENEFITS OF WEARING GRADUATED COMPRESSION STOCKINGS DURING HIGH INTENSITY RUNNING

TRAINING LOG

Please record your training in the three days leading up to the test, the day of the test and day after the test. Include enough detail so that you can perform similar training sessions leading up to each testing session. The activity refers to the type of exercise, *for example weight training, running, cycling, etc.* Distance in km. There is room to record two exercise sessions per day, if needed. If you have races or competitions you must record them also. **You will be asked to repeat similar training patterns before each testing session at the lab!**

Name _____

Date	Time	Duration (min)	Activity Type	Distance	Focus	Intensity
					Endurance <input type="checkbox"/> Intervals <input type="checkbox"/> Strength <input type="checkbox"/> Skill <input type="checkbox"/>	Light-Easy <input type="checkbox"/> Light-Medium <input type="checkbox"/> Medium-Moderate <input type="checkbox"/> Medium-Heavy <input type="checkbox"/> High-Heavy <input type="checkbox"/>
					Endurance <input type="checkbox"/> Intervals <input type="checkbox"/> Strength <input type="checkbox"/> Skill <input type="checkbox"/>	Light-Easy <input type="checkbox"/> Light-Medium <input type="checkbox"/> Medium-Moderate <input type="checkbox"/> Medium-Heavy <input type="checkbox"/> High-Heavy <input type="checkbox"/>
					Endurance <input type="checkbox"/> Intervals <input type="checkbox"/> Strength <input type="checkbox"/> Skill <input type="checkbox"/>	Light-Easy <input type="checkbox"/> Light-Medium <input type="checkbox"/> Medium-Moderate <input type="checkbox"/> Medium-Heavy <input type="checkbox"/> High-Heavy <input type="checkbox"/>

					Endurance <input type="checkbox"/> Intervals <input type="checkbox"/> Strength <input type="checkbox"/> Skill <input type="checkbox"/>	Light-Easy <input type="checkbox"/> Light-Medium <input type="checkbox"/> Medium-Moderate <input type="checkbox"/> Medium-Heavy <input type="checkbox"/> High-Heavy <input type="checkbox"/>
Date	Time	Duration (min)	Activity Type	Route	Discipline	Intensity
					Endurance <input type="checkbox"/> Intervals <input type="checkbox"/> Strength <input type="checkbox"/> Skill <input type="checkbox"/>	Light-Easy <input type="checkbox"/> Light-Medium <input type="checkbox"/> Medium-Moderate <input type="checkbox"/> Medium-Heavy <input type="checkbox"/> High-Heavy <input type="checkbox"/>
					Endurance <input type="checkbox"/> Intervals <input type="checkbox"/> Strength <input type="checkbox"/> Skill <input type="checkbox"/>	Light-Easy <input type="checkbox"/> Light-Medium <input type="checkbox"/> Medium-Moderate <input type="checkbox"/> Medium-Heavy <input type="checkbox"/> High-Heavy <input type="checkbox"/>

[illegible]

[illegible]

Appendix 15

Abstract accepted for 13th annual Congress of the European College of Sport Science (ECSS) - ESTORIL, PORTUGAL 9-12 July 2008

THE EFFECT OF WEARING GRADUATED COMPRESSION STOCKINGS ON RUNNING PERFORMANCE

Robert CREASY¹, Ajmol ALI¹ and Johann EDGE²

¹*Sport and Exercise Science, IFNHH, Massey University, Auckland, NZ*

²*Sport and Exercise Science, IFNHH, Massey University, Palmerston North, NZ*

Background: Graduated compression stockings (GCS) have been worn by world champion endurance runners to enhance performance; however, minimal published research has stipulated the optimal compression required to enhance performance. Athletes wearing knee-length GCS during 10,000-m running tests achieved lower average heart rate (HR) at the same performance time¹, indicating a possible performance enhancement.

Purpose: To quantify run time and physiological and perceptual variables for runners completing 10,000-m time trials whilst wearing different compression grades of GCS.

Methods: Following an initial familiarisation run, 9 male and 3 female competitive athletes (mean \pm SD; $\dot{V}O_2$ max 68.7 ± 5.8 ml·kg⁻¹·min⁻¹, age 33 ± 10.3 years, mass 68.5 ± 6.2 kg) completed four 10,000-m time trial runs on an outdoor 400-m track wearing either control (0 mmHg; Con), low (12-15 mmHg; Lo), medium (18-21 mmHg; Med), or high (23-32 mmHg; Hi) GCS in a randomised counterbalanced order. All trials were conducted between 18:00-20:00 h and average temperature and humidity were 18°C (12-22°C) and 71% (53-94%), respectively. Based on their performance in the familiarisation trial, athletes were set off at 1-min intervals and the same order was used for all subsequent trials. Leg power was assessed pre- and post-run via counter movement jump (CMJ) using a jump mat. Blood lactate concentration ([La]) was assessed pre and post-run while HR was monitored continuously during exercise. Perceptual scales were used to assess the comfort, tightness and any pain associated with wearing GCS.

Results: There were no statistically significant differences in performance time between trials (min:s; Con 39:50 \pm 4:58, Lo 39:26 \pm 3:57, Med 39:41 \pm 3:46, Hi 39:51 \pm 4:01, $P=0.99$). The delta change in pre- to post-exercise CMJ performance was significantly better in Lo (1.2 ± 6.0 cm) and Med (1.7 ± 4.8 cm) than Con (-2.9 ± 3.9 cm; $P<0.001$). Mean HR was not different between trials (168-169 beat·min⁻¹; $P=0.99$) but [La] was significantly higher in GCS trials relative to Con ($P<0.001$). Participants rated Con and Lo as more comfortable than Med and Hi ($P<0.01$), Med and Hi were rated as tighter than Lo ($P<0.01$) and all GCS were rated as tighter than Con ($P<0.01$), and Hi was associated with the most pain ($P<0.01$).

Conclusions: In competitive runners wearing GCS does not appear to affect 10,000 m performance time. However, low and medium grade GCS help retain leg power following exercise thus possibly having implications for sprint performance at the end of a race. Furthermore, low grade GCS appear to be the most comfortable type of garment for runners.

References: ¹Ali, A., Caine, M.P., Snow, B.G. (2007). "Graduated compression stockings: physiological and perceptual responses during and after exercise." *Journal of Sport Sciences* **25** (4): 413-419.

Appendix 16

**Abstract accepted for annual Sport and Exercise Science New Zealand (SESNZ) ·
DUNEDIN, NEW ZEALAND 13-16 November 2008**

**The physiological and perceptual effects of wearing graduated compression
stockings during running**

R. Creasy¹, A. Ali¹, J. Edge²

¹Massey University, Auckland, New Zealand

²Massey University, Palmerston North, New Zealand

Purpose: The aim of this study was to examine the effect of wearing different grades of graduated compression stockings (GCS) on physiological and perceptual measures during and following exercise for well-trained runners.

Methods: One female and nine male competitive runners ($\dot{V}O_2$ max: 70.4 ± 6.1 ml·kg⁻¹·min⁻¹) performed three 40-min continuous treadmill runs wearing either control (0 mmHg; Con), low (12-15 mmHg; Low), or high (23-32 mmHg; Hi) GCS in a randomised counterbalanced order. Participants ran at 90% of their personal best 10-km run pace ($80 \pm 5\%$ $\dot{V}O_2$ max). Changes in muscle function and damage were determined pre-, 0, 24, and 48 h post- treadmill running by creatine kinase and myoglobin concentrations, counter-movement jump (CMJ) height, muscle soreness, and pressure sensitivity. Heart rate (HR), oxygen cost ($\dot{V}O_2$), blood lactate concentration [La], and ratings of perceived exertion (RPE) were measured during treadmill running. Perceptual scales were used pre- and post-run to assess the comfort, tightness and any pain associated with wearing GCS.

Results: CMJ was higher ($P < 0.001$) and pressure sensitivity was more pronounced ($P < 0.05$) 0-h post-run in each condition. Few participants (4/10) reported muscle soreness at any one location. There were no significant differences between treatments for HR, $\dot{V}O_2$, [La], and RPE. Con were rated more comfortable than Hi ($P < 0.05$). Hi were perceived as tighter ($P < 0.05$) and induced more pain ($P < 0.05$) than other interventions.

Conclusions: Highly-trained runners wearing GCS did not experience changes in HR, $\dot{V}O_2$, [La], or muscle function compared with a control garment. A 40-min treadmill run at 80% $\dot{V}O_2$ max may not be strenuous enough to elicit a loss of muscle function in highly-trained runners. Further, runners felt more comfortable wearing loose GCS during running.

