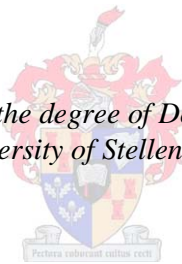


# **The value of graduated compression socks as a post-exercise recovery modality in long distance runners.**

by  
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*Dissertation presented for the degree of Doctor of Sport Science at the  
University of Stellenbosch*



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## DECLARATION

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## ABSTRACT

The purpose of this two part investigation was to examine the efficacy of graduated compressive knee-high socks (CS) to modulate the recovery of muscle damage and athletic performance in well-trained distance runners after an actual 56 km ultra-marathon. In the first part of the research (part I) the objective was to compare the use of graduated compression socks and a placebo sock during a 56 km ultra-distance event. The next part of the investigation (part II) endeavoured to establish the optimal time to wear graduated compression socks i.e. during or after exercise.

In part I, 40 competitive male distance runners (age:  $42 \pm 8$  years;  $VO_{2max}$ :  $50 \pm 8$  mL.kg<sup>-1</sup>.min<sup>-1</sup>; height:  $180 \pm 7$  cm and body mass:  $80 \pm 10$  kg) were randomly divided into an experimental (EXP) and control (C) group. The EXP group wore compression socks (~20 – 30 mmHg) during the 56 km race as well as for the subsequent 72 hours, while the C group wore a placebo sock (~0 mmHg). In part II, 43 competitive male distance runners (age:  $41 \pm 8$  years;  $VO_{2max}$ :  $49 \pm 6$  mL.kg<sup>-1</sup>.min<sup>-1</sup>; height:  $178 \pm 6$  cm and body mass:  $76 \pm 11$  kg) were randomly divided into three treatment groups  $CS_{Run}$ ,  $CS_{Rec}$  and  $CS_{Run\&Rec}$ . In both parts recovery was assessed by measuring serum creatine kinase (CK), skeletal myoglobin (s-Mgb), C-reactive protein (hsCRP), lower limb circumferences (cmf), blood lactate (LT), Visual analogue scales (VAS), running economy (RE) and a peak power (PP) for muscle function.

All variables in both parts changed significantly over time, indicating that the 56 km did induce muscle damage ( $P < 0.05$ ). The EXP group in part I demonstrated lower s-Mgb levels directly after the 56 km race ( $P < 0.05$ ), reduced swelling in calf and ankle ( $P < 0.05$ ) compared to the C group. CK, hsCRP and RE did not differ between the groups ( $P > 0.05$ ). Runners perceived less pain in the calf and *Quadriceps* muscles until 48 hours subsequent to the race ( $P < 0.05$ ). At 24 hours PP improved by 6.5% more in CS than C group. [La] was lower in those running with CS in both parts within 30 minutes after the race ( $P < 0.05$ ). Part II corresponded to the results in part I with  $CS_{Run}$  and  $CS_{Run\&Rec}$  demonstrating less s-Mgb directly and at CK 24 and 48hrs compared to  $CS_{Rec}$  ( $P < 0.05$ ). VAS, PP, RE and hsCRP did not differ between the three groups ( $P > 0.05$ ).



The results of part I suggest that wearing CS during a race and during a 72 hour recovery period has a beneficial effect on recovery time over the first 48 hours compared to those runners not wearing CS. Part II in this investigation suggest that wearing CS during exercise will reduce muscle damage more so than wearing the CS only subsequent to exercise.



## OPSOMMING

Die doel van hierdie tweedelige ondersoek was om die effektiwiteit te bepaal waarmee gegraduateerde kompressie knie-hoë kouse (CS) die herstel van spierskade en atletiese prestasie in goed gekondisioneerde langafstand atlete, na 'n 56 km ultra-marathon, kan moduleer. In die eerste deel (deel I) van die navorsing was die doel om die gebruik van CS en kontrole sokkies tydens 'n 56 km ultra-marathon te vergelyk. In die tweede deel (deel II) het gepoog om die optimale tyd vir die dra van kompressie sokkies te ondersoek o.a. tydens en/of na oefeninge..

In deel I was 40 kompeterende manlike langafstand atlete (ouderdom:  $42 \pm 8$  jaar;  $VO_{2max}$ :  $50 \pm 8$  mL.kg<sup>-1</sup>.min<sup>-1</sup>; lengte:  $180 \pm 7$  cm en gewig:  $80 \pm 10$  kg) ewekansig verdeel in 'n eksperimentele (EXP) en kontrol (C) groep. Die EXP groep was geklee in kompressie sokkies (~ 20-30 mmHg) gedurende die 56 km wedloop asook vir die daaropvolgende 72 uur, terwyl die C groep geklee was in 'n kontrole sokkie (~ 0 mmHg). In deel II was 43 kompeterende manlike langafstand atlete (ouderdom:  $41 \pm 8$  jaar;  $VO_{2max}$ :  $49 \pm 6$  mL.kg<sup>-1</sup>.min<sup>-1</sup>; lengte:  $178 \pm 6$  cm en gewig:  $76 \pm 11$  kg) ewekansig verdeel in drie behandelingsgroepe  $CS_{Run}$ ,  $CS_{Rec}$  en  $CS_{Run\&Rec}$ . In albei dele was herstel bepaal deur die meting van serum kreatien kinase (CK), skeletale mioglobien (s-Mgb), C-reaktiewe proteïen (hsCRP), onderste ledemaat omtrekke (cmf), die bloed laktaat (LT), Visuele analogiese skale (VAS), hardloop ekonomie (RE) en 'n piek plofkrag (PP) toets vir spierfunksie.

Alle veranderlikes in die twee dele het betekenisvol verander oor tyd, wat aandui dat die 56 km spierskade veroorsaak het ( $P < 0.05$ ). Die EXP groep in deel I het laer s-Mgb vlakke direk na die 56 km wedloop gehad ( $P < 0.05$ ) en verminderde swelling in die kuit en enkel in vergelyking met die C groep ( $P < 0.05$ ). CK, hsCRP en RE het nie verskil tussen die twee groepe nie ( $P > 0.05$ ). Die EXP het minder pyn in die kuite en bobeenspiere ervaar tot 48 uur na die wedloop ( $P < 0.05$ ). By 24 uur het PP met 6.5% meer verbeter in CS as C groep. [La] was laer binne 30 minute na die wedloop in die atlete wat gehardloop het met CS in albei dele. Deel II stem ooreen met die resultate in deel I, met  $CS_{Run}$  en  $CS_{Run\&Rec}$  wat minder s-Mgb toon direk na die wedloop en 24 tot 48 uur laer CK vlakke het in vergelyking met  $CS_{Rec}$  ( $P < 0.05$ ). VAS, PP, RE en hsCRP het nie verskil tussen die drie groepe ( $P > 0.05$ ).



Die resultate van 'n deel I stel voor dat die dra van CS tydens 'n wedloop en gedurende 'n 72 uur herstel periode voordelig is vir die eerste 48 uur herstelperiode, in vergelyking met dié hardlopers wat nie die CS gedra het nie. Deel II dui daarop dat die dra van CS tydens oefening 'n groter effek op spiërskade het as die dra van die CS na oefening.



## DEDICATION

*In loving memory of my brother, Heinrich, who showed me how to dream and that limitations are only determined by our own lack of imagination.*

*I am a witness to your life.*



## ACKNOWLEDGEMENTS

*“I have that happy and content feeling. “*

*R.J. Welman, 2005*

The last few years have taught me that it is the combination of perseverance and laughter that helps you to overcome obstacles. I am indebted to every single person that selflessly helped me. From the smallest gestures such as a cup of coffee to the many long hours and sacrifices, nothing has gone unnoticed. I once again realized that we are nothing without the support of others and I am very grateful to everyone that assisted me.

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










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


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


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


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


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## ABBREVIATIONS

ACSM	:	American College of Sport Medicine
ADP	:	Adenosine Diphosphate
ANOVA	:	Analysis of Variance
AS	:	Anterior Pressure Group
ASL	:	Above Sea Level
AT	:	Anaerobic Threshold
ATC	:	Anterior Tibial Compartment
ATP	:	Adenosine Triphosphate
AUC	:	Area Under the Curve
BF	:	<i>Biceps Femoris</i>
BIA	:	Bioelectrical Impedance Analysis
bpm	:	Beats per Minute
C	:	Control Groups
<i>c</i>	:	Filtration Coefficient
Ca <sup>2+</sup>	:	Calcium
CCL	:	Continental European Compression Classification System
CG	:	Compression Garment
CK	:	Creatine Kinase
Units.L <sup>-1</sup>	:	Unit per Litres
cm	:	Centimeter(s)
cm.s <sup>-1</sup>	:	Centimeter per Seconds
cm <sup>2</sup>	:	Centimetre Squared
CMJ	:	Countermovement Jump



CNS	:	Central Nervous System
CO <sub>2</sub>	:	Carbon Dioxide
CS	:	Compression Sock Group
CS <sub>Rec</sub>	:	Compression Sock Recovery Group
CS <sub>Run</sub>	:	Compression Sock Exercise Group
CS <sub>Run&amp;Rec</sub>	:	Compression Sock Exercise and Recovery Group
CWT	:	Contrast Water Therapy
DOMS	:	Delayed Onset of Muscle Soreness
EIMD	:	Exercise Induced Muscle Damage
EMG	:	Electromyography
SEM	:	Standard Error of Measurement
<i>ES &amp; d</i>	:	Cohen's Effect Sizes ( <i>d</i> )
ET	:	Elastic Tights
EXP	:	Experimental Group
F	:	Filtration Force; Origin of Lymph
F <sub>bmax</sub>	:	Maximum Breathing Frequency (Breaths.Min <sup>-1</sup> )
g	:	gram
g.kg <sup>-1</sup>	:	gram per kilogram
g.m <sup>-2</sup>	:	Gram Per Square Meter
GA	:	<i>Gastrocnemius</i>
GCP	:	Good Clinical Practice
GLUT 4	:	Glucose Transporter Protein (4)
H <sup>+</sup>	:	Hydrogen Ion
HbO <sub>2</sub>	:	Oxyhaemoglobin
hh:mm:ss	:	Hour(s): Minute(s): Second(s)
HR	:	Heart Rate (bpm)



$Hr_{max}$	:	Maximum Heart Rate (Bpm)
Hrs	:	Hour(s)
Hscrp	:	Ultrasensitive C- reactive Protein
Hz	:	Hertz
IAAF	:	International Association of Athletic Federation
ICC	:	Intraclass Correlation Coefficient
Inc.	:	Incorporated
IPC	:	Intermittent Pneumatic Compression
ISAK	:	International Standards for Anthropometric Kinanthropometry
$IU.l^{-1}$ or $u.l^{-1}$	:	Units per Litres
kg	:	Kilogram(S)
$kg.m^{-2}$	:	Kilogram Per Square Meter
$kg.min^{-1}$	:	Kilogram Per Minute
KJ	:	Kilojoules
km	:	Kilometer (S )
$km.h^{-1}$	:	Kilometres Per Hour
$km.w^{-1}$	:	Kilometers Per Week
L	:	Litre (S)
$L.min^{-1}$	:	Litres per Minute
LDH	:	Lactate Dehydrogenase
LT	:	Lactate Threshold
[La]	:	Lactate
Ltd.	:	Limited
M	:	Meter(S)
$m.ml^{-1}.kg^{-1}$	:	Meter per Volume of Oxygen Consumed in Millilitres



		per Kilogram
MAST	:	Military Anti Shock Trousers
Max	:	Maximum
mg.l <sup>-1</sup>	:	Milligrams Per Litre(S)
Min	:	Minimum
Min	:	Minute(S)
min <sup>-1</sup> .kg	:	Millilitre Per Kilogram
ml	:	Millilitre(S)
ml.kg <sup>-1</sup>	:	Millilitre per Kilogram
ml.kg <sup>-1</sup> . m <sup>-1</sup>	:	Millilitre per Kilogram Per Meter
ml.kg <sup>-1</sup> . min <sup>-1</sup>	:	Millilitre per Kilogram Per Minute
ml.min <sup>-1</sup>	:	Millilitre per Minute
mmol.l <sup>-1</sup>	:	Millimole per Litre
mm	:	Millimetre(S)
mmHg	:	Millimetres of Mercury
mmol.Kg <sup>-1</sup>	:	Millimoles per Kilogram
μMol.L <sup>-1</sup>	:	Micromoles per Litre
MPF	:	Mean Power Frequency
MRC	:	Medical Research Council
MVF	:	Maximum Voluntary Farce
<i>n</i>	:	Number of Subjects
n.a.	:	None Available
n.d.	:	No Date
N <sub>2</sub>	:	Nitrogen
ng.ml <sup>-1</sup>	:	Nanograms Per Millilitre
Nm	:	Nanometre(S)



NO	:	Nitric Oxide
NSAID	:	Non-Steroidal Anti-Inflammatory Drugs
O <sub>2</sub>	:	Oxygen
OBLA	:	Onset Of Blood Lactate Accumulation
°C	:	Degrees Celsius
°s <sup>-1</sup>	:	Degree Per Second
<i>p</i>	:	Hydrostatic Pressure
<i>P</i>	:	Probability Value
PAO <sub>2</sub>	:	Partial Pressure Of Oxygen In Arterial
P <sub>c</sub>	:	Capillary Blood Pressure
P <sub>c</sub>	:	Capillary Pressure
P <sub>cr</sub>	:	Phosphorcreatine
PDE	:	Phosphodiester
Ph	:	Hydrogen Ion Concentration
P <sub>i</sub>	:	Inorganic Phosphate
PME	:	Phosphormonoester
PO <sub>2</sub>	:	Partial Pressure of Oxygen
PPO	:	Peak Power Output (W)
PS	:	Posterior Pressure
P <sub>t</sub>	:	Tissue Pressure
P <sub>t</sub>	:	Tissue Pressure
PTY	:	Proprietary
Q	:	Cardiac Output
Q <sub>max</sub>	:	Maximal Cardiac Output
<i>R</i>	:	Correlation Coefficient
<i>Rad</i>	:	Radius



RE	:	Running Economy
RER	:	Respiratory Exchange Ratio
RF	:	<i>Rectus Femoris</i>
RM	:	Repetition Maximum
ROM	:	Range of Motion
RPE	:	Ratings of Perceived Exertion
s	:	Second(S)
s-Mgb	:	Skeletal Myoglobin
SPS	:	Superficial Posterior Compartment
SV	:	Stroke Volume
T	:	Tensile Force
TA	:	<i>Tibialis Anterior</i>
TM	:	Trademark
TP	:	Total Power
UK	:	United Kingdom
USA	:	United State Of America
UCT	:	University Of Cape Town
VAS	:	Visual Analogue Scales (Mm)
VE	:	Minute Ventilation (L.min <sup>-1</sup> )
V <sub>max</sub>	:	Peak Treadmill Velocity (Km.H <sup>-1</sup> )
VO <sub>2</sub>	:	Oxygen Consumption (mL. min <sup>-1</sup> .kg <sup>-1</sup> )
VO <sub>2max</sub>	:	Maximum Oxygen Consumption
vs.	:	Versus
W	:	Watts
%	:	Percentage
~	:	About





$\pi_C$	:	Capillary Oncotic Pressure
$\pi_T$	:	Tissue Oncotic Pressure
$\bar{x}$	:	Arithmetic mean
®	:	Registered Trademark

## CHAPTER ONE

### INTRODUCTION

#### I. BACKGROUND

Distance running is a very popular recreational and competitive activity, especially for the associated health benefits. The 7324 runners who completed the 56 km ultra-marathon in 2010 represent a 26% increase in finishers compared to 2009 (Jones, 2010). The physiological and psychological effects associated with distance running follow a J-curve shape. In other words, when training volume and/or intensity are plotted on a graph against the risk of injury, it often results in a J-shaped curve. This curve shows that those with higher training loads, closer to the top of the curve, are more likely to be prone to injuries from the high or accumulative training loads. In addition the curve shows that those at the lowest end of the curve, with very low training load, also have a higher injury rate. Hence the high training volumes and intensities accompanying distance running could override the health benefits and result in injury if training and competition is excessive and without adequate recuperation.

Prolonged hard training, especially for those competing at a high level, brings about severe strain and fatigue which may result in overtraining and chronic injuries. Overtraining due to increased training volume and too little recovery will negatively influence endurance and maximum performances due to accumulated fatigue (Lehmann *et al.*, 1992). Consequently recovery is necessary, not only for optimal athletic performance, but also to minimize possible future injuries related to long term overreaching. Post-exercise recovery interventions are therefore included in well-prepared training programs to induce restoration and adaptation (Barnett, 2006). The recovery modalities aim to restore the disrupted homeostasis and can be used on its own or in combination with other therapies to help athletes achieve this balance. Examples of recovery modalities include passive and active recovery, massage, contrast water immersion therapy, hyperbaric oxygen therapy, nonsteroidal anti-inflammatory drugs (NSAID), cryotherapy, stretching, electromyostimulation and compression garments (Barnett, 2006; Cortis *et al.*, 2010). Most research on these modalities reported conflicting results and to date there is no one modality that stands out as more effective than the others (Gill *et al.*, 2006).



Recent recovery research focused more on water immersion and compression therapy (French *et al.*, 2008; Montgomery *et al.*, 2008). Both of these recovery modalities aim to create a favourable pressure gradient to improve blood flow through the working muscles, similar to what is achieved with active recovery, but without the extra metabolic cost. Compression garments have been advocated as a recovery modality that may reduce the strain of physical activity, as well as the time needed to recover (Kraemer *et al.*, 2001<sup>a</sup>; Perrey *et al.*, 2008; Kraemer *et al.*, 2010). It is also one of the most popular recovery modalities used by endurance athletes (Nusser and Senner, 2010), though it is backed by limited scientific research.

The rationale behind compression garments as a recovery aid comes from clinical research that demonstrated external compression therapy's ability to increase venous blood flow velocity, reduces venous stasis, eliminate oedema and increase scar healing (Ogata and Whiteside, 1982; Gniadecka *et al.*, 1998; Benkö *et al.*, 2001). Additionally, researchers found that compression garments provide mechanical support to the active muscles which would assist recovery after strenuous exercise (Kraemer *et al.*, 1998<sup>a</sup>; Kraemer *et al.*, 2001<sup>a</sup>; Silver *et al.*, 2009).

Whether these clinical benefits would translate into benefits for athletic populations remain uncertain (Barnett, 2006). It is only in the past four years that recovery research has gradually shifted its focus to athletic populations and sport specific protocols. To date, research have shown that compression garments increase tissue oxygenation, reduce perceived muscle soreness, eliminate oedema and improve range of motion, improve fatigue and assist regeneration after eccentric muscle action exercises (Kraemer *et al.*, 2001<sup>a</sup>; Bringard *et al.*, 2006<sup>a</sup>; Maton *et al.*, 2006<sup>a</sup>; Trenell *et al.*, 2006; Thedon *et al.*, 2008).

Most research is still laboratory based, focusing on younger populations and sprint-type activities of short duration. In addition, no practical guidelines such as when to apply compression are specified. Up to now, no research has been done on the recovery of experienced distance runners after an actual distance event. Therefore, this research endeavoured to determine the efficacy of knee-high compression socks as a post-exercise recovery intervention after prolonged exercise in trained distance runners.



## *Overview*

This dissertation is separated into eight chapters which includes investigations on the influence of graduated compression garments on the recovery of exercise induced muscle damage (EIMD) and functional capacity in experienced distance runners. Chapter two reviews the literature on the possible physiological mechanisms involved in compression therapy, as well as the application of sports compressive clothing. Chapter three states the problem which has been investigated and underlines the need for the investigation. Chapter four summarizes the methodology of this study. Chapter five considers the physiological, perceptual and functional results after wearing class II knee-high graduated compression socks during an actual 56 km road race and up to 72 hours thereafter. Chapter six describes the various approaches in wearing class II knee-high graduated compression socks for optimal physiological, perceptual and functional effects after an actual 56 km road race. Chapter seven provides a systematic discussion of the results of both studies in relation to the current literature. Finally chapter eight concludes with an overview of the findings.



## CHAPTER TWO

### LITERATURE REVIEW

#### I. INTRODUCTION

Various forms of external compression therapy are used to reduce venous stasis and to increase venous blood flow, not only in individuals with peripheral vascular disease but also in those with healthy vascular systems (Lawrence and Kakkar, 1980). According to Buhs *et al.* (1999), graduated compression stockings are the *gold standard* in treating venous insufficiencies.

The literature shows that compression garments assist peripheral circulation and venous return in patients with vascular disorders (Ibegbuna *et al.*, 2003; Felty and Rooke, 2005), limits swelling (Kraemer *et al.*, 2001<sup>a</sup>; Kraemer *et al.*, 2001<sup>b</sup>; Felty and Rooke, 2005), reduce blood lactate accumulation after exercise (Berry and McMurray, 1987; Chatard *et al.*, 2004), prevent muscle oscillation and vibration during activity (Kraemer *et al.*, 1998<sup>b</sup>; Doan *et al.*, 2003; Bringard *et al.*, 2006<sup>a</sup>), maintain repeated vertical jump power (Kraemer *et al.*, 1996; Kraemer *et al.*, 1998<sup>b</sup>; Doan *et al.*, 2003), reduce the cost of submaximal running (Bringard *et al.*, 2006<sup>a</sup>), improve tissue oxygenation (Bringard *et al.*, 2006<sup>b</sup>; Thedon *et al.*, 2008) and improve the clearance of muscle damage markers after exhausting exercise (Kraemer *et al.*, 2001<sup>a</sup>; Kraemer *et al.*, 2001<sup>b</sup>; Gill *et al.*, 2006).

#### II. COMPRESSION THERAPY

##### *a. Compression Garment Technology*

Research and the development of material technology and sporting equipment have led to the availability of a wide range of compression garments. They not only come in different materials and designs, but also in various compressive strengths (Choucair and Phillips, 1998; Laing and Sleivert, 2002; Felty and Rooke, 2005).



In the clinical setting compression, garments refer to multi- or single layer wraps, elastic or inelastic bandages, dynamic compression pumps such as intermittent pneumatic compression, orthotic devices and graduated compression garments, i.e. stockings and sleeves (Choucair and Phillips, 1998; Felty and Rooke, 2005). Examples of sporting compression garments include full body suits, tights, tops, sleeves, leggings and stockings. These compression garments can be made of silk, cotton, polyester, nylon, lycra® or combinations of various materials such as Coolmax® and Heatgear® (Kraemer *et al.*, 1996; Laing and Sleivert; 2002; Felty and Rooke, 2005). Keeping in mind that several inter-relating and complex factors contribute to human performance, it follows that the different types of compression garments are specific to each individual's diverse physiological needs, sport and environment. The choice of the correct garment is therefore important if one wants to achieve a beneficial effect under specific circumstances.

The shape of the human limb prevents pressure to be equally distributed. This is explained by the law of Laplace which states that the hydrostatic pressure ( $p$ ) in a vessel is directly proportional to the tensile force ( $T$ ) and inversely proportional to the radius ( $rad$ ). In other words, the highest pressure will be exerted at the smallest circumference of the extremity (Thomas, 2003). In view of this given fact, the earliest compression garments exerted a uniform pressure across the limb. However, regardless of the slight pressure gradient, which the human body's geometry creates, the garments were not entirely effective as anticipated. In fact, some uniform compression garments created a reverse gradient pressure and/or a tourniquet effect, which reduced venous return (Angle and Bergan, 1997).

In contrast, compression garments that exert a positive graduated pressure are considered better than uniform pressure (Sigel *et al.*, 1975; Angle and Bergan, 1997). These garments provide a controlled external pressure that is circumferentially graduated (Liu *et al.*, 2005). In other words, the highest pressure is exerted at the distal (or narrowest) part of the limb and decreases proximally in the direction of the heart (Choucair and Phillips, 1998; Laing and Sleivert, 2002; Felty and Rooke, 2005; Liu *et al.*, 2005). This means that the graduated pressure gradient not only adds additional pressure to the limb, but also amplifies the gradient created by the extremities' irregular geometrical shape. Consequently, this amplifies the natural flow of blood towards the heart.



Liu *et al.* (2005) also observed that the pressure of the compression garment was more on the anterior side of the limb, than the medial or lateral side. This was later confirmed by Maton *et al.* (2006<sup>b</sup>) who reported that there was a statistically significant difference between the posterior (PS) and anterior (AS) pressures of the lower limb ( $P < 0.001$ ) with more pressure from the compression garments on the anterior side (AS:  $14.5 \pm 6.2$  mmHg vs. PS:  $12.8 \pm 4.3$  mmHg). The reason for this is that the curvature of the leg is greater at the tibial process than at calf level (Laplace's law). Therefore, the influence of the compression garments is greater on the anterior side, with respect to muscle venous dynamics, recovery of force and muscle fatigue. Furthermore, variation of pressures between subjects indicates that limb morphology greatly affects the pressure exerted, even though the garment is usually specifically fitted for the individual. Sigel *et al.* (1975) found in their pioneer study on 7 healthy inactive participants that there was large variability in compression not only between subjects, but also between one's own extremities, when garments with different pressures were applied. Therefore, for compression garments to be effective, it should be specifically fitted to each individual. Maton *et al.* (2006<sup>b</sup>) also explained that the average pressures of the garments are not enough to cause fatigue, since the pressures exerted by the muscles are still more pronounced.

The scientific basis on which graduated compression was developed, originated from work done by Sigel *et al.* (1975) along with Lawrence and Kakkar (1980). According to Sigel *et al.* (1975) venous blood flow increases optimally with a pressure gradient of 18 mmHg to 8 mmHg (ankle to mid-thigh) in recumbent sedentary healthy individuals. Optimal pressure was defined as externally applied pressure producing the greatest increase in femoral vein blood flow velocity that is safe and practical. Sigel *et al.* (1975) reported a ~138% increase in femoral blood flow in individuals wearing a graduated compression garment (18 mmHg to 8 mmHg), which was a significantly greater haemodynamic response than the uniformly distributed compression (~ 11 mmHg) in the lower body.

In the clinical field individuals with varicose veins, leg fatigue and light oedema typically require a graduated pressure of 20 to 30 mmHg (Brown and Brown, 1995), and occasionally 30 to 40 mmHg depending on the severity. Patients who have ulcers and moderate venous insufficiencies usually tolerate a compression stocking of 30 to 40 mmHg. More severe chronic venous insufficiency, oedema and lymphoedema may require 40 to 50 mmHg or even 60 mmHg and



more (Choucair and Phillips, 1998; Felty and Rooke, 2005). However, the higher the compression, the more uncomfortable the garments will be. In patients, this discomfort may cause non-compliance and exercise cessation (Millet *et al.*, 2006; Ali *et al.*, 2010).

External pressure may be transmitted to deeper tissues to at least 3 cm below the skin (Thorsson *et al.*, 1987). This could be detrimental to tissue perfusion if the pressure is excessive. Early research assessed the intramuscular blood flow in eight middle distance runners (men;  $\bar{x}$  age: 17 – 26 years) during rest and immediately after a treadmill run (Thorsson *et al.*, 1987). The results indicated that an external pressure that is more than local diastolic blood pressure, which is usually 80 mmHg, impede intramuscular blood pressure, while moderate compression ( $\sim 40 \pm 5$  mmHg) reduces blood flow by half. This is consistent with the hypothesis that diastolic blood pressure relate to the muscle tissue perfusion pressure (Thorsson *et al.*, 1987). Too high pressure ( $> 125$  mmHg) may also exacerbate neuromuscular function and cause a functional muscular deficit because of a tourniquet effect.

Reduction in functional force production is the greatest directly below and distal to the compressed muscles (Mohler *et al.*, 1999). Furthermore, the added mechanical force from disproportionate pressure to the skin is associated with ischemia and tissue damage like skin disruption or muscle fibre break down (Sangeorzan *et al.*, 1989). It may also increase the interstitial fluid pressure around the capillaries, which would disrupt nutrient transport and exchange. In athletes these considerations are especially important since the pressures exerted by compression garments can further be altered during muscle contractions and joint flexion (Perrey, 2008).





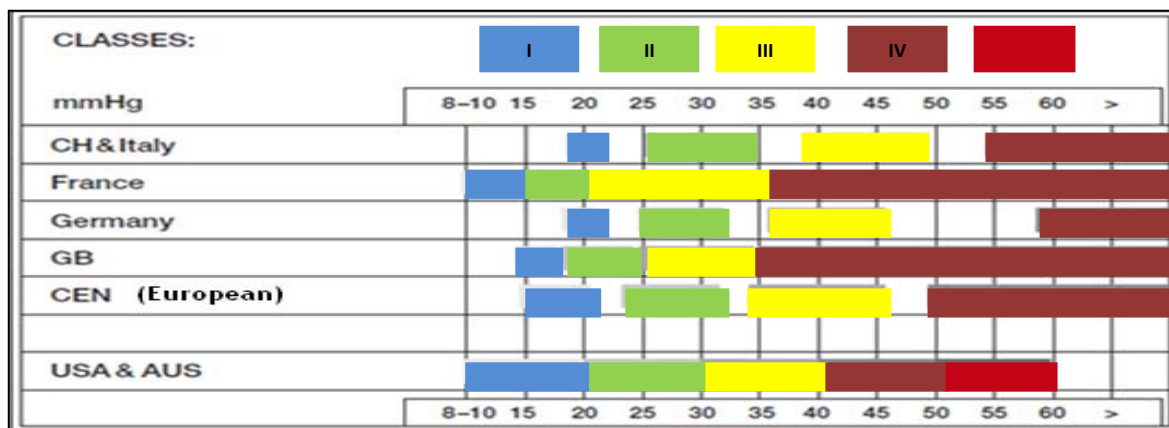


Figure 2.1 The various compression classes in different countries. (Adapted from Partsch, 2003<sup>b</sup>).

Pressure garments are mainly divided into four classes based on their pressure gradient, namely light, moderate, high and extra high (Choucair and Phillips, 1998; Lord and Hamilton, 2004; Partsch, 2003<sup>b</sup>; Felty and Rooke, 2005). These classes differ between countries as shown in Figure 2.1 and Table 2.1 (Partsch, 2003<sup>b</sup>).

Table 2.1 The Continental European Classification for knee-high graduated compression socks, adapted from Partsch (2003<sup>b</sup>).

Knee - high compression sock class	Compression at the ankle (mmHg)
CCL A light	10 - 14
CCL I mild	15 - 21
CCL II moderate	23 - 32
CCL III strong	34 - 46
CCL IV very strong	≥ 49

Optimal pressure ranges have not been established for sporting compression garments. Kügler *et al.* (2001) suggested that a pressure of 30 mmHg or more at the calf may reduce subcutaneous blood flow in healthy individuals, which may contribute to fatigue and delayed recovery. However, lower body sporting compression garments typically apply a low to moderate pressure gradient. Some investigators found that mild compression (CCL I; 15 - 21 mmHg) increases

intramuscular pressure during dynamic ankle movements and during rest (Maton *et al.*, 2006<sup>a</sup>), while Ali *et al.* (2010) reported that some runners experienced pins and needles sensations with a moderate compression garment (CCL II; 23 – 32 mmHg), which may indicate that blood flow was impeded.

Various factors influence the pressure exerted by the garments. The correct fit that takes into account the geometrical shape of the limb will allow the athlete to perform usual tasks without garment interference. The fact that the human limb needs a static as well as dynamic fit, makes it difficult to have a standardized sizing chart, while domestic and international sizes also differ. Laing and Sleivert (2002) asserted that the precise fit of sporting garments – not only compression garments – is essential for proper function and that inadequate fit could result in performance impairment or increased risk for injury. Other potential negative effects include adversely affected manual dexterity, restricted movement or range of motion and discomfort. In running and other endurance events, discomfort can be caused by tight fitting clothes that result in chaffing or friction injuries. Moreover, sporting garments should be designed for the biomechanical position in which the specific activity takes place (Laing and Sleivert, 2002). For instance, cyclists and rowers are mostly seated and the compression fit should therefore be designed for their specific body position.

It has been shown that multiple layer garments increase energy cost by about 1.2% for every kilogram of additional weight (Laing and Sleivert, 2002). Also, in weight-bearing activities like running, gravity is a major force to overcome and added weight would negatively influence running economy. It is, however, unlikely that the insubstantial weight of compression garments would affect the economy of movement, similar to light weight athletic clothing which has been shown to have no effect on performance.

It is also reported that many of the graduated compression stockings fail to produce the pressure recommended by the manufacturers (Liu *et al.*, 2005). Interestingly, pressures in the calf were in some of the moderate to high-pressure classes (~22.6 – 31.1 mmHg and 33.2 – 43.3 mmHg, respectively) only 12 to 7% lower than the ankle pressures, which meant the gradient did not differ as it is supposed to. Best *et al.* (2000) also found that only 2% of the compression stockings used in their research complied with the pressure recommendations and more than half caused a



tourniquet effect. Similarly, Morris and Woodcoco (2004) noted that most compression stockings exerted pressures lower than suggested and some of the garments even resulted in a reverse gradient. These findings may be one of the reasons why results vary so much between the reported studies.

A reverse gradient means that the calf muscle exerts a higher pressure than the ankle. This was especially true at the medial side of the limb, with the prominent calf muscle showing a 35% higher pressure in some of the garments. Liu *et al.* (2005) warns that reverse pressure gradients could have a negative effect or a tourniquet effect. The long superficial saphenous vein is located on the medial side of the lower limb and with a reverse pressure gradient the circulation will be impeded.

The more practical issues of compression garments should also be considered. Thigh-length garments have been perceived as too difficult to put on, slips down and do not compress the thigh well enough (Choucair and Phillips, 1998; Morris and Woodcoco, 2004; Felty and Rooke, 2005). Some garments are too difficult to put on or take off due to their high elasticity levels. Devices have been developed to help with the application of compression garments including rubber gloves, powders, creams, silk sleeves and frames that guides the garments over the limb (Choucair and Phillips, 1998). Compression socks will also eventually lose its elasticity. Therefore, clinical recommendations suggest that compression stockings be replaced at least every six months, depending on how often the sock is being used (Choucair and Phillips, 1998; Felty and Rooke, 2005). Felty and Rooke (2005) recommended that if the application of the sock/garment is too easy, it shows that it has lost its functionality and would be ineffective. Drastic changes in body mass will also influence the fit of one's compression garment (Felty and Rooke, 2005).

Depending on the type, pressure and fit each compression garment will have different physiological and psychological effects. Furthermore, the user's shape, training level and type of sport would determine the type of compression garment required. This means that the proper fit of compression garments is vital to take advantage of its benefits and to minimize possible risks.



### ***b. Venous Physiology and Pressure during Dynamic Contractions***

The muscle-pump mechanism account for the manner in which kinetic energy, developed through dynamic muscle contractions, is transformed into improved blood flow, both centrally and locally (Sherrif *et al.*, 2005; Bringard *et al.*, 2007).

As the runner takes his/her heel off the ground, the *Gastrocnemius* and *Soleus* muscles contract and temporarily reduces intramuscular and intermuscular blood flow by physically compressing the muscle fibres as well as, veins such as the popliteal vein. The physical compression of the veins increases venous pressure by about 10 mmHg in the ankle. The blood is drawn from the superficial veins via the perforating veins into the deep veins and blood is squeezed into the deep circulation. It is this shunting of the blood into the deeper veins that increases the deep venous velocity towards the heart. Simultaneously, the muscle contraction empties the venous compartment and venous pressure drops to about 52 mmHg in the ankle. The reduced venous pressure causes blood to move from the arteries into the venous compartments, with one-way venous valves preventing blood from flowing back and pooling in the lower extremities. During the swing phase the heel lifts and the calf muscle relaxes. Subsequently the thigh muscles contracts, shunting the blood further towards the heart. When the calf muscle relaxes the inter- and intramuscular veins dilate, which is associated with a brief reflux forcing the proximal venous valves to close and thereby preventing the blood from flowing back. This negative pressure in the veins increases the pressure gradient and therefore blood flow. Throughout dynamic contractions there are these cyclic changes in pressure, since as soon as the foot touches the ground again the calf muscle contracts and venous pressure is increased again (Pollack and Wood, 1949; Folkow *et al.*, 1970; Bringard *et al.*, 2007).

Pollack and Wood (1949) determined that venous pressure in the upright position is about 87 mmHg in the ankle, while Liu *et al.* (2005) reported standing venous pressures between 80 – 87 mmHg. Murthy *et al.* (1994) reported intramuscular pressures in the *Soleus* and *Anterior Tibialis* muscles of 37 mmHg and 35 mmHg, respectively, during standing, with lower values (8 and 11 mmHg) when lying down. The higher pressure during standing is due to the forces of gravity acting on the venous system. During walking and running the intramuscular pressure in the *Soleus* muscle increases by 311% and 511% during walking and running (152 and 226 mmHg,



respectively), and 140% - 314% (84 and 145 mmHg, respectively) in the *Anterior Tibialis* muscle (Murthy *et al.*, 1994).

Styf (1995) also reported similar intramuscular pressures during supine exercises. During muscle contractions the pressure was between 100 and 250 mmHg (depending on the force produced by the muscle), and between 10 to 25 mmHg in-between contractions as well as immediately after exercise. The intramuscular pressure in the lower extremities returned to pre exercise values of 5 and 15 mmHg within 5 to 10 minutes after exercise. Due to the calf muscle-pump function, the pressure in-between contractions would be lower than after exercise in the standing position (Styf, 1995). When a healthy individual moves from a recumbent position to upright, the gravitational forces causes 500 to 800 ml of blood to pool below the heart and this reduces cardiac output secondary to the reduced venous return (Madalosso *et al.*, 2005). At the same time an average person experiences a pressure change of 75 to 100 mmHg at the ankle and 60 to 80 mmHg at the knee when changing from recumbent to standing (Lord and Hamilton, 2004).

When the person is in a stationary position such as during travelling, the calf muscle-pump is ineffective to overcome these pressure changes and deep vein thrombosis (DVT) may result. The long term effect of dilated veins is an increased compliance resulting in chronic venous insufficiencies (Bringard *et al.*, 2007). Applying additional external pressure would therefore increase the normal pressure within the venous system (Partsch, 2003<sup>b</sup>) and thus compression garments have been recommended as a non-surgical conservative treatment for peripheral venous insufficiencies (Agu *et al.*, 2004). The application of compression garments reduce the diameter of the distended superficial veins as well as alleviate associated pain, fatigue and discomfort. Moreover, compression garments may improve venous valve functioning and thus reduce venous pooling and oedema formation and also prevent re-accumulation (Wertheim *et al.*, 1999; Partsch, 2003<sup>b</sup>; Perrey *et al.*, 2008).

### **III. PROPOSED PHYSIOLOGICAL MECHANISMS OF COMPRESSION GARMENTS**

The precise mechanisms of action brought about by external compression therapy are not completely understood (Agu *et al.*, 2004; Liu *et al.*, 2005). Nevertheless, researchers have gained



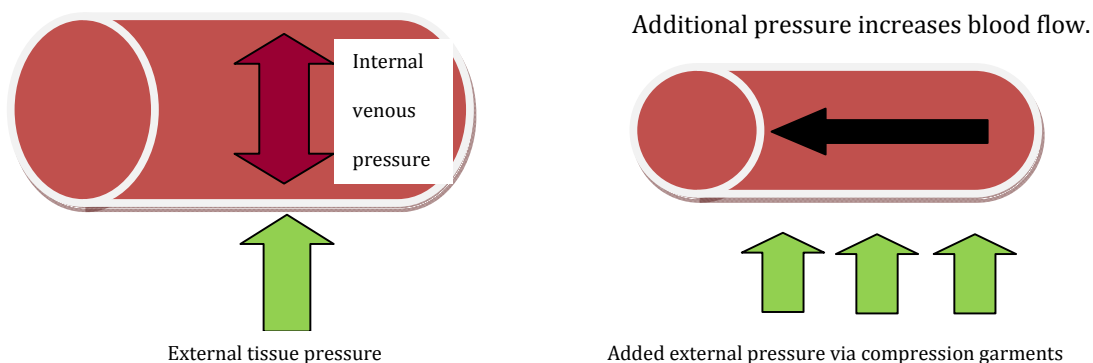
a lot of invaluable knowledge on possible mechanisms, relevant to exercise, through clinical studies. Thus by understanding the physiology behind vascular insufficiencies, researchers were able to draw inferences on how compression therapy could assist healthy athletes. Ultimately, compression garments function by a) augmenting the muscle-pump actions by creating ideal pressure gradients and mechanically shunting blood back to the heart, and/or b) by physically supporting the limb involved.

#### ***a. Augmenting the Muscle Pump Function***

When muscle contracts, it compresses the veins, pushes the blood forward and empties the venous compartment. Upon relaxation, the vessels open and the transmural venous pressure in the deep and superficial veins drops. The reduced venous pressure increases the arterio-venous pressure gradient in the central and local muscle vascular beds. This enhances the venous blood flow as well as the muscle perfusion. In other words, the increased venous return indirectly improves muscle perfusion by supplying more blood to the active muscles as well as directly by increasing muscle perfusion through the negative pressure. As long as venous pressure is reduced, the muscle-pump will enhance the blood flow. Hereafter, the arterial inflow replaces the blood expelled and venous pressure is restored. Dynamic muscle contractions thus cause alternating lower and higher venous pressures, which increase the perfusion pressure in the muscle vascular bed (Wood, 1959; Folkow *et al.*, 1970; Sheriff *et al.*, 2005).

Venous flow velocity depends on the width of the cross sectional area of the veins, while the cross sectional area of the veins rely on effective transmural venous pressure. Transmural pressure is the difference between the internal lateral venous pressure, which tries to keep the veins distended, and the external tissue pressure (~ 3 mmHg in the leg) (Figure 2.2). Consequently, by reducing the diameter of the venous lumen with external pressure, both the external tissue pressure and the internal venous pressure are increased thus causing a reduction in transmural pressure. This reduction in transmural pressure not only increases the venous blood flow (Litter, 1952), but also prevents oedema formation (Wood, 1959).





**Figure 2.2** External pressure increases venous blood flow velocity, adapted from Litter, 1952.

Compression garments augment cardiovascular function by mimicking or augmenting the muscle-pump actions (O'Donnell *et al.*, 1979; Choucair and Phillips, 1998; Bergan and Sparks, 2000; Morris and Woodcoco, 2004). Research has shown that applying low external compression of 10 to 15 mmHg in patients increases the blood flow about five fold ( $0.5 \text{ cm.s}^{-1}$  to  $2.5 \text{ cm.s}^{-1}$ ) by reducing the superficial and deep venous system from  $2.63 \text{ cm}^2$  to  $0.53 \text{ cm}^2$  (Litter, 1952). In healthy non-athletic individuals, Sigel *et al.* (1975) found that a pressure gradient of 18 mmHg - 14 mmHg - 8 mmHg - 10 mmHg - 8 mmHg from ankle to calf to knee to lower-thigh to upper-thigh increases blood flow velocity by 138% of the femoral vein. A few years later Lawrence and Kakkar (1980) confirmed these findings and reported a 53% increase in the average deep venous blood flow from resting with below the knee compression and 84% increase in blood flow with whole limb compression.. The compression below the knee shows the largest variation in pressure and contributes most to femoral blood flow velocity (Perrey *et al.*, 2008).

The first research to investigate the influence of compression garments on resting IMP and dynamic contraction IMP in healthy individuals was done by Maton *et al.* (2006<sup>a</sup>). Nine participants wore a compression stocking (15 - 20 mmHg; Varisma® Innothera, Nomexy, France) on the right leg (EXP) while the left leg was the control (C). Prior to the experiment the researchers provided evidence for the use of EMG as an indicator of IMP changes during dynamic contractions. While lying supine, the participant's resting IMP and EMG was recorded for 60 s with the subject's foot in full plantar flexion. Then the participant performed 10 to 15 dorsal flexion movements as fast and with the largest amplitude possible and after each the subject

returned to the baseline position. Hereafter subjects performed 1 to 2 gradual isometric contractions of the ankle dorsal flexors. During the dynamic and static contractions IMP in the anterior tibial (ATC), superficial (SPC) and deep posterior compartments (DPC) and EMG of *Tibialis Anterior* (TA), *Soleus* (SO) and *Gastrocnemius* (GA) were recorded.

The results showed that resting IMP ranged between 12.3 to 26.6 mmHg in the lower leg. When external compression was applied the IMP increased significantly by 52%, 46% and 79% in the *Anterior Tibial*, superficial and deep posterior compartments, respectively ( $P < 0.001$ ). This increase in IMP was accompanied by a reduction in corresponding EMG amplitude of 44%, 18% and 47% in the TA, SO and GA, respectively ( $P < 0.001$ ). In addition, during ankle dorsal flexion movements the EMG amplitudes showed a linear relationship with the IMP values. This was true for all the muscles and compartments but it was the most pronounced in the TA and *Anterior Tibial* compartment. When compression was applied this linear relationship between IMP and EMG amplitudes shifted towards more pronounced IMP values. Another finding showed that TA activation initiated voluntary ankle dorsal flexion and with the compression garment *Tibialis Anterior* activation increased the IMP 12 milliseconds faster than the control leg.

What these results suggest is that external compression applied to muscles increase resting IMP in all muscular compartments and does not influence muscle relaxation during rest. Also, during voluntary ankle dorsal flexion there is a sudden increase in IMP of the *Tibialis Anterior*, which would cause shunting of blood out of the superficial and deep vessels back to the heart during dynamic contractions. In other words the compression garment amplifies the natural muscle-pump function of active muscles.

It is unclear if the muscle-pump action influences arterial flow. The arteries adjust to pressure and flow variations through dilation and constriction (Ku, 1997). Findings by Bochmann *et al.* (2005) showed increased arterial inflow in the forearm during handgrip exercises with compression sleeves ( $3.7 \pm 0.9$  to  $8.8 \pm 2.0$  mL.min<sup>-1</sup>.100 ml tissue<sup>-1</sup>). They suggested that the external compression increases the tissue pressure which causes a drop in transmural pressure. The blood flow in the arteries and arterioles then increase secondary to the reduction in transmural pressure which would trigger a myogenic response causing the arteries to relax and dilate and subsequently arterial flow increases. Bochmann *et al.* (2005) also established while





experimenting with pressures between 13 and 23 mmHg, that 20 mmHg is the optimal pressure to increase blood flow maximally (two fold) in the forearm during exercise and at rest.

### ***b. Physical Support of the Muscle***

The physical pressure exerted by compression garments not only affects central haemodynamics, but also provides structural support to the involved muscle and joints. This results in the preservation of muscle structure and function (Kraemer *et al.*, 2001<sup>a</sup>), reduced muscle oscillations (Kraemer *et al.*, 1998<sup>b</sup>; Doan *et al.*, 2003), limited oedema formation (French *et al.*, 2008) and enhanced muscle regeneration (Kraemer *et al.*, 2001<sup>a</sup>). Thus it has been suggested that this mechanical support of the involved muscle(s) is either responsible for, or contributes to enhanced performance and recovery.

The physical properties of the compression garment could aid recovery after exercise by forcibly restricting the space available for fluid accumulation. This reduction in swelling supposedly would diminish secondary muscle damage, associated with inflammation, and aid recovery (Fridèn *et al.*, 1986; Jakeman *et al.*, 2010). Sarcomere disruption as a result of exercise, contribute to contractile dysfunction and disruptions in the integrity of the excitation-contraction coupling (Proske and Morgen, 2001). External support stabilizes the alignment of the muscle fibres and facilitates the clearing of the inflammatory response (Kraemer *et al.*, 2001; Kraemer *et al.*, 2010). Subsequently, the physical support would reduce the magnitude of muscle damage, accelerate functional recovery and minimize recovery time after injury (Jakeman *et al.*, 2010; Kraemer *et al.*, 2010). Kraemer *et al.* (2001<sup>a</sup>) thus referred to the compression garments as a “dynamic cast”.

Other investigations suggested that the physical support provided by the compression garments could reduce muscle oscillations, as well as enhance proprioception (Kraemer *et al.*, 1996; Kraemer *et al.*, 1998<sup>a</sup>; Kraemer *et al.*, 1998<sup>b</sup>; Doan *et al.*, 2003). Proprioception is an intricate physiological system that involves a variety of neural pathways from the various receptors in the skin, joints, muscle and ligaments to the brain. Improved proprioception would enhance an athlete’s performance and recovery by allowing the athlete to better perceive joint or limb movement and position in space, despite muscle fatigue and muscle damage (Kraemer *et al.*, 1996, Kraemer *et al.*, 1998<sup>a, b</sup>; Doan *et al.*, 2003).



Kraemer *et al.* (1996) and Kraemer *et al.* (1998<sup>a</sup>) found that compression garments maintained repeated jump power in trained athletes. Even though the exact mechanism is not clear, the authors suggested that compression garments interact with, or enhances movement proprioceptive signalling-systems from the skin and joint receptors particularly when athletes are fatigued. Kraemer *et al.* (1998<sup>a</sup>) also suggested that the cutaneous receptors interact with the compression garment fabric and that this interaction enhances proprioception signals and improve position sense.

Muscle damage is associated with loss of muscle function, which may be related to a disruption in neural function (Michaut *et al.*, 2002). In addition, compression garments may thus influence the level of muscular excitation through the pressure applied to the skin. It is known that information from skin receptors can alter motor control and change the recruitment order of muscle motor units (Kraemer *et al.*, 1996). Thus, the compression garment would be beneficial especially during fatigue when proprioception is affected.

Research has also found that compression garments reduces vertical muscle movement velocity during the impact after a jump (Kraemer *et al.*, 1998<sup>a</sup>) and attenuates impact forces (Doan *et al.*, 2003). Muscle oscillations during landing from a jump were reduced by 0.32 cm (longitudinal axis) and 0.40 cm (anterior-posterior axis). This reduction in muscle movement may enhance neurotransmission, allowing for optimal mechanics and possibly contribute to a reduction in fatigue. In addition, the mechanical support may lessen structural damage to the muscle upon impact, which could further prevent injuries (Kraemer *et al.*, 1996; Kraemer *et al.*, 2010).

#### **IV. ERGOGENIC EFFECTS OF SPORTS COMPRESSION GARMENTS**

The rationale for using external compression in sport comes from the benefits observed in clinical settings. Until now research on the possible performance benefits of compression garments have been mostly inconsistent, especially for short duration, high intensity activities and team sports (Doan *et al.*, 2003; Duffield and Portus, 2007; Duffield *et al.*, 2010). Furthermore, in the past 10 years the focus has shifted more to the potential recovery benefits of compression garments (Kraemer *et al.*, 2001<sup>a</sup>; Kraemer *et al.*, 2001<sup>b</sup>; Gill *et al.*, 2006; Kraemer *et al.*, 2010).



### **a. The Influence of Compression Garments on Endurance Performance**

One would expect that compression garments would benefit endurance activities more than sprinting activities (Kraemer *et al.*, 1996; Higgins *et al.*, 2007), mainly because of the positive effect of compression garments on circulatory function. Surprisingly, however, no study has in fact shown an improvement in aerobic capacity with compression garments. Nevertheless, other performance benefits for endurance athletes have been reported (Bringard *et al.*, 2006<sup>b</sup>; Kemmler *et al.*, 2009).

#### **i. Aerobic Capacity**

The rationale for using compression garments during endurance activities comes from early research on the effect of positive pressure on the upper body, since upper body exercises are typically associated with increased heart rate but reduced stroke volume due to venous pooling in the inactive lower extremities. Therefore, when a positive pressure is applied to the lower body, it would augment cardiac output during exercise, since the compression will reduce vein diameters and transmural pressure in the leg (Ng *et al.*, 1987). This in response shunts blood from the periphery, thereby augmenting left ventricular end-diastolic (volume) filling. According to Frank-Starling, stroke volume will then be increased (Kaprielian *et al.*, 1998; Goodman *et al.*, 1994) and consequently maximum oxygen consumption during aerobic exercise would be increased.

Ng *et al.* (1987) investigated the use of military anti-shock trousers (MAST; 50 mmHg) in 12 healthy men ( $\bar{x}$  age: 28  $\pm$  3 years) during incremental upper body arm-crank exercises. The participants completed each 6 minute steady-state workload with the anti-shock trousers inflated or deflated in random order while physiological measurements were taken during the last 2 minutes of each workload increment. The researchers found an increase in cardiac output (5%;  $P = 0.0006$ ), stroke volume (9%;  $P = 0.0000$ ) and mean arterial blood pressure (3%;  $P = 0.0000$ ) and a decrease in heart rate (5%;  $P = 0.002$ ) when the trousers were inflated. However, there was no effect on the oxygen consumption (< 1% difference) or total peripheral resistance (< 2% difference) with the application of positive pressure.



The increase in cardiac output and mean arterial blood pressure can be explained by the elevated lower limb pressure which would enhance venous return, while an arterial baroreflex would explain the lower heart rate (Kaprielian *et al.*, 1998; Lanfranchi and Somers, 2002). The latter is often used as indirect evidence of reduced venous pooling and increased stroke volume (Kaprielian *et al.*, 1998; Ali *et al.*, 2007). Despite these cardiovascular changes, no change was observed in aerobic capacity. This finding has been confirmed in several subsequent studies (Kaprielian *et al.*, 1998; Bernhardt and Anderson, 2005; Kaprielian *et al.*, 1998; Bringard *et al.*, 2006<sup>a</sup>; Bringard *et al.*, 2006<sup>b</sup>; Kemmler *et al.*, 2009; Ali *et al.*, 2010). For instance, Bringard *et al.* (2006<sup>a,b</sup>) found no improvement in aerobic capacity in recreational runners wearing compression garments and Bernhardt and Anderson (2005) reported no effect on oxygen uptake during 20-meter shuttle runs in 13 active participants ( $\bar{x}$  age: ~ 26 years) wearing prophylactic compression shorts (Coreshorts®; pressure not specified) compared to normal shorts (C) (EXP:  $49.6 \pm 8.3 \text{ mL.kg}^{-1}.\text{min}^{-1}$  vs. C:  $49.9 \pm 8.7 \text{ mL.kg}^{-1}.\text{min}^{-1}$ ;  $P = 0.72$ ).

Chatard *et al.* (2004), on the other hand, found that the aerobic capacity of senior cyclists ( $\bar{x}$  age:  $63 \pm 3$  years) improved after an initial exercise bout followed by a recovery period during which the cyclists wore elastic lower body compression garments and sat with elevated legs for 80 minutes. In this study, however, both compression garments and elevation would have enhanced venous return and the combination effect could have been sufficient to also improve endurance capacity. Barnett (2006) also suggested that the application of combination recovery modalities would bring about better results.

Recent findings by Sperlich *et al.* (2010) did not support the results of Chatard and co-authors (2004). Although they did not include leg elevation in their intervention, the researchers not only investigated compression stockings (94% polyamide and 6% Lycra), but also compression tights (81% polyester and 19% Lycra) and whole body suits (81% polyester and 19% Lycra) (Craft®, Scandinavia) and the pressure for all the garments was ~20 mmHg. It was the first study to investigate various types of compression garments and its effect on endurance performance in experienced distance athletes. Maximal oxygen consumption was measured after a 15 minute submaximal treadmill run at 70%  $\text{VO}_{2\text{max}}$ , followed by a run to exhaustion at peak velocity. There was no significant change in endurance capacity with any of the garments and it was concluded



that regardless where the pressure was applied, it does not affect endurance performance in trained athletes.

One of the few studies that demonstrated improved running performances with compression garments was by Kemmler and colleagues (2009). Twenty-one experienced distance runners completed two incremental treadmill tests, with and without knee-high stockings, in random order. Not only did their research show an improvement in time-under-work (EXP:  $36.4 \pm 3.5$  min vs. C:  $35.0 \pm 3.6$  min;  $ES = 0.40$ ), peak treadmill velocity (EXP:  $\sim 17.0 \pm 1.2$  km.h<sup>-1</sup> vs. C:  $16.6 \pm 1.1$  km.h<sup>-1</sup>;  $ES = 0.32$  and  $P = 0.002$ ) and total work (EXP:  $422 \pm 78$  kJ vs. C:  $399 \pm 77$  min;  $ES = 0.30$ ), but the athletes also ran 1.5 – 2% faster at their aerobic (EXP:  $13.0 \pm 1.1$  km.h<sup>-1</sup> vs. C:  $12.7$  km.h<sup>-1</sup>  $\pm 1.0$ ;  $ES = 0.28$ ) and anaerobic (EXP:  $14.1 \pm 1.1$  km.h<sup>-1</sup> vs. C:  $13.9$  km.h<sup>-1</sup>  $\pm 1.1$ ;  $ES = 0.22$ ) thresholds ( $P < 0.05$ ) while wearing the compression stocking. Maximum performances improved from 2% to 6% with compression garments. Similarly to previous studies, physiological parameters such as maximum heart rate, maximum minute ventilation,  $VO_{2max}$  and maximum blood lactate concentration did not differ significantly between the experimental and control trials. A possible contributing factor for the improved performances could be the special gradient compression stocking they used. The knee-high stocking exerted a pressure of 24 mmHg at the ankle, with a slightly lower pressure at the calf (18 - 20 mmHg). However, in agreement with previous studies, Kemmler *et al.* (2009) also found no effect of compression garments on aerobic capacity. They speculated that either their repeated  $VO_{2max}$  tests lacked reliability, or there may be another physiological mechanism, perhaps improved running economy, that explains the runners' enhanced performances. The theory is that the mechanical support provided by the compression garment to the involved muscles (tissue and tendons) makes the athlete biomechanically more efficient, resulting in a lower metabolic cost during exercise. Kemmler *et al.* (2009) refers to this as “ergonomic interplay”.

From the above studies it can be concluded that there is not sufficient evidence to show that compression garments improve oxygen delivery to the muscles to such an extent that it manifests in an improved maximal exercise capacity ( $VO_{2max}$ ). Nevertheless, there are some indications that endurance performance may indeed be enhanced by external compression and perhaps this is the consequence of improved oxygen uptake by the muscles. A number of studies have therefore



focussed on the peripheral changes, i.e. oxygen extraction and peripheral blood flow, which are brought about by compression garments (Kaprielian *et al.*, 1998; Wagner, 1996).

Some studies have shown that compression garments may accelerate blood flow in the microcirculation and improve deep tissue oxygenation (Agu *et al.*, 2004; Bringard *et al.*, 2006<sup>a</sup>). To assess changes in intramuscular oxygenation and oxygen extraction, researchers measure deoxyhaemoglobin levels. Given that deoxyhaemoglobin is considered blood-volume insensitive during exercise (Bringard *et al.*, 2006<sup>a</sup>; Thedon *et al.*, 2008), a significant reduction in deoxyhaemoglobin with an associated increase in tissue haemoglobin oxygen saturation indicates an increase in muscle oxygenation (Bringard *et al.*, 2006<sup>a</sup>). Research measuring calf muscle tissue oxygenation is regarded as valuable, since the calf muscle plays such an important role during the eccentric muscle actions of running activities (Novacheck, 1997; Ali *et al.*, 2007).

Agu and co-researchers (2004) assessed three different grades of medical graduated compression stockings (I: 15 – 21 mmHg; II: 23 – 32 mmHg; III: 34 – 46 mmHg) in ten individuals with venous insufficiencies (3 men and 7 women;  $\bar{x}$  age:  $56 \pm 5$  years). Muscle deoxyhaemoglobin, mitochondrial oxygenation (via cytochrome oxidase) and oxyhaemoglobin content were assessed with near-infrared spectroscopy. The researchers reported significantly lower deoxyhaemoglobin concentrations in the participants with compression garments compared to no garments during standing ( $P = 0.005$ ), tip toe exercises ( $P = 0.04$ ) and slowly walking at  $1.6 \text{ km}\cdot\text{h}^{-1}$  ( $P < 0.001$ ). Tissue oxygenation was significantly improved during walking while wearing compression garments (EXP:  $5.8 \pm 4.4 \mu\text{mol}\cdot\text{l}^{-1}$  vs. C:  $2.9 \pm 2.4 \mu\text{mol}\cdot\text{l}^{-1}$ ;  $P = 0.03$ ). The researchers concluded that medical compression stockings increase calf tissue oxygenation, with more pronounced effects observed with class III stockings.

Bringard and co-authors (2006<sup>a</sup>) investigated the effects of various clothing with different pressures on calf muscle oxygenation and venous pooling in resting conditions. The investigators speculated that the pressure exerted in normal tights may be enough to induce similar responses as compression garments. The twelve endurance trained men ( $\bar{x}$  age:  $26.5 \pm 2.6$  years) were randomly separated into three groups, i.e. compression garments (EXP 1;  $\bar{x}$  pressure over calf: 23.2 mmHg supine vs. 24.1 mmHg standing), compared to Lycra@elastic tights (EXP 2;  $\bar{x}$  pressure over calf: 5.6 mmHg supine vs. 5 mmHg standing) and no compression shorts (C; 0



mmHg). The pressure of the compression garments was 4.5 times higher than the elastic tights. The participants' tissue oxygenation index, deoxyhemoglobin and right *Gastrocnemius Medialis*' blood pooling were monitored continuously by near-infrared spectroscopy (NIRS; 2 hertz) in a supine and a standing position. The subjects had to lay supine and then stand for five minutes in each position while alternating the different garments. The results showed that when the athletes wore compression tights they had significantly higher tissue oxygenation, whereas deoxyhemoglobin (~100% and ~90% lower than C and EXP 2, respectively) and *Gastrocnemius Medialis*' blood pooling were significantly lower ( $P < 0.001$ ) in EXP 1 compared to EXP 2 in supine and standing positions. Thus, the compression garments had a more positive effect on the athletes' calf muscle oxygenation and venous stasis during rest in supine and standing positions, compared to the elastic tights. Similarly to Agu and co-authors (2004), the higher compression exerted a more pronounced response. The authors reasoned that the smaller drop in total haemoglobin concentration with compression garments (~ 48% compared to C and EXP 2, respectively) might be as a result of a reduction in venous compliance by the compression tights. This would increase venous return and lead to an enhanced cardiac output. The authors recommended that compression garments be used post-exercise to oxygenate the muscles which would reduce regeneration time of fatigued muscles as well as enhance blood lactate clearance.

Scanlan *et al.* (2008) compared the effects of full length lower body compression garments (Skins®, Sydney, Australia, ~9.1 – 14.9 – 17.3 – 19.5 mmHg) to normal underwear (briefs, Jockey International, Australia, cotton) in 12 well-trained cyclists. There was no treatment effect in 60 minute time trial performance. However, there was a practical significant improvement in i) the power output at anaerobic threshold (C:  $246 \pm 56$  W vs. EXP:  $260 \pm 45$  W;  $ES = 0.6$ ) and ii) tissue oxygenation with the compression garment compared to the control (C:  $52 \pm 12\%$  vs. EXP:  $57 \pm 8\%$ ;  $ES = 0.6$ ). The researchers attributed this improvement in tissue oxygenation to enhanced circulation within the compressed muscle tissue, while the increased power output at anaerobic threshold (AT) may be due to altered lactate production-to-clearance ratio. Indirectly these alterations would delay fatigue and improve performance, while tissue oxygenation may also assist recovery.

Recent research (Sear *et al.*, 2010) showed that whole body compression garments improved the distance ran during a high intensity intermittent exercise protocol in trained team sport athletes





by improving muscle tissue oxygenation and associated metabolic benefits. Eight young men ( $\bar{x}$  age  $20.6 \pm 1.2$  years;  $VO_{2max}$ :  $57.5 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) wore a full body compression garment and control garment (pressures not specified) in random order during a prolonged high-intensity intermittent exercise protocol. The participants ran for a total of 45 minutes on a treadmill, at predetermined speeds alternated with self-paced sprints as fast as possible. Compared to the control trials, whole body compression garments moderately improved total distance (C:  $5.42 \pm 0.63$  km vs. EXP:  $5.88 \pm 0.64$  km;  $ES = 0.6$ ) and low intensity distance (C:  $4.21 \pm 0.51$  km vs. EXP:  $5.88 \pm 0.57$  km;  $ES = 0.6$ ) performances. Muscle tissue oxygenation was augmented by 2% (C:  $54 \pm 8\%$  vs. EXP:  $56 \pm 7\%$ ).

It can thus be concluded that compression garments significantly improves tissue oxygenation and that external compression have a greater effect on the peripheral factors that determine oxygen consumption by muscles than the central factors. The enhanced muscle oxygenation can be attributed to either (i) increased blood flow in the capillary bed which would supply more oxygen, (ii) better perfusion of the muscle and increased oxygen extraction, (iii) changes in skin blood flow and redistribution of blood to the deep active muscle, leading to an enhanced oxygenation in the muscle, or (iv) to a lesser extent, an increase in venous return and cardiac output delivering more oxygen to the muscles involved (Bringard *et al.*, 2006<sup>a</sup>).

## ii. Energy Cost with Associated Fatigue

Performances during sub-maximal long distance events are influenced by the athlete's ability to minimize energy expenditure at a specific intensity (Hauswirth and Lehénaff, 2001). This is referred to as running economy and can be used as an index of the athlete's efficiency. Hauswirth and Lehénaff (2001) defined the energy cost of movement as the oxygen consumption at a steady state, usually between 60 to 90% of maximum aerobic capacity. Improved efficiency would translate into lower metabolic fatigue or perhaps decreased perception of fatigue for the same velocity or power (Millet *et al.*, 2006). The change in energy cost over time, biomechanics, fatigue, inter-individual differences, environmental conditions, training status and the clothing that a runner wears may influence running economy (Hauswirth and Lehénaff, 2001; Millet *et al.*, 2006).





Distance running involves high volumes of work and the associated fatigue is influenced by the nature, duration and intensity of the particular activity, as well as the athlete's conditioning (Millet *et al.*, 2006). Furthermore, fatigue is also characterized by the loss of strength and an increase in the cost of movement. Millet *et al.* (2006) suggested that compression of the active muscles can minimize fatigue during endurance activities by either altering the impact forces, or limiting the energy cost of running.

Bringard *et al.* (2006<sup>b</sup>) assessed the influence of compression tights (Decathlon; ~23.5 mmHg), elastic tights (~5 mmHg; 20% elasthan and 80% polyester) and normal shorts (0 mmHg; control) on indicators of muscle efficiency in a two part study. In the first part of the experiment the energy cost was assessed at set speeds (10, 12, 14 and 16 km. h<sup>-1</sup>). The investigators found a significant reduction in energy cost in trained middle distance runners ( $n = 6$ ;  $\bar{x}$  age:  $31.2 \pm 5.4$  years) running with compression garments and elastic tights, compared to normal shorts at 12 km.h<sup>-1</sup>, and a similar trend at 10 and 14 km. h<sup>-1</sup>. The second part of the study reported a 26% and 36% lower VO<sub>2</sub> slow component when six endurance trained participants ( $\bar{x}$  age:  $26.7 \pm 2.9$  years) ran at 80% of their VO<sub>2max</sub> for 15 minutes with compression garments compared to elastic tights ( $P = 0.04$ ) and normal running attire ( $P = 0.01$ ). No significant differences were observed between the three groups for thermal stress, loss of body mass, subjective ratings of perceived clothing comfort, exertion, as well as sweating, heart rate, minute ventilation or VO<sub>2max</sub> values in both studies. The investigators concluded that compression garments resulted in improved running economy at submaximal running speeds of 12 km.h<sup>-1</sup>, but not at faster speeds, compared to normal running shorts. They attributed the improved running economy to various factors, such as the improved haemodynamic response, reduced muscle oscillations and improved proprioception, muscle coordination, and propulsive force (Bringard *et al.*, 2006<sup>b</sup>). A reduction in the energy cost over time has significant implications for exercise tolerance in active populations. For the competitive athlete, the ability to run at a faster running speed for a given VO<sub>2</sub> would give the runner a performance advantage by reducing the metabolic strain and resultant muscle fatigue (Carter *et al.*, 2000; Bringard *et al.*, 2006<sup>b</sup>).

The question arises whether compression garments would add significant weight to an athlete which could be detrimental to performance. Addition of one kilogram through equipment or clothing equals one kilogram of body mass and this added weight could increase the energy cost



of movement at a specific workload. Compression garments usually cover either upper or lower body extremities or sometimes both. It has been suggested that adding weight particularly to the extremities would have a more pronounced impact on metabolic fatigue (Laing and Sleivert, 2002). Cavanagh and Kram (1989), however, found that adding weight of up to 1.1 kg to each ankle has had no effect on the frequency or length of strides in runners. On the other hand, Millet *et al.* (2006) reported that research by Martin (1985) found an increase in stride length with an added 0.5 kg at the ankles which would have a positive effect on efficiency. Therefore, this increase in efficiency may result in reduced fatigue (Millet *et al.*, 2006) and enhanced performance. Whether compression garments, which are composed of lightweight materials, would add sufficient weight to impact running economy is doubtful.

Limited research has been done on the effect of compression garments on running economy. Millet *et al.* (2006) reckoned that compression garments only improved fatigue resistance in recreational athletes. However, no research has been done on higher level endurance athletes.

### *iii. Power Production and Neuromuscular Response*

When a runner can maintain high levels of power production it would translate into performance benefits for the athlete (Kemmler *et al.*, 2009). On the other hand, repeated muscle action may lead to impaired ability of the musculature to produce power. The inability to generate power is referred to as fatigue and in the absence of dehydration and with sufficient muscle glycogen concentrations, the fatigue observed is mainly due to neuromuscular and mechanical factors (Enoka and Duchateau, 2008; Lepers *et al.*, 2008; Montgomery *et al.*, 2008). Fatigue is also defined as the functional decline of one or more physical or physiological systems that leads to reduced performance and the inability to maintain the demands of the sport (Montgomery *et al.*, 2008).

Reduced proprioception may contribute to fatigue and indirectly result in injuries. Previous studies have found an improved proprioception by wrapping the knees with elastic bandages (Hassan *et al.*, 2002) while weightlifters commonly use knee bandaging to improve force production. This is likely due to potentiated sensory feedback from the skin or joint receptors as the wrap supports the joint. Indirectly this results in improved power performance (Harman *et*



*al.*, 1990). On the other hand, Bernhardt and Anderson (2005) found no effect of compression garments on healthy individuals' proprioception. They speculated that this might be because these subjects did not have any injuries and that different results may be seen with injured athletes. They reasoned that individuals with the worst inherent proprioception usually gain the most benefit from additional support.

Kraemer and co-authors (1996) were the first to investigate the effects of compression shorts (88% 70-denier Antron® nylon and 12% 40-denier Lycra® spandex) on power production during repeated vertical jump tests. Thirty six young highly skilled volleyball players (18 men and 18 women;  $\bar{x}$  age:  $20.5 \pm 3.1$  years) completed three sets of ten standardised countermovement jumps with their hands on their hips, with a ten minute rest period between each set. Subjects acted as their own control and each set was performed with a different garment condition, i.e. normal fitted compression short (EXP 1), undersized compression short (EXP 2) and regular gym shorts (C). With the fitted compression shorts athletes were able to maintain the average jump power over the 10 repetitions, but they did not improve maximal jump power output. In addition, the mean power and force production in the EXP 2 trial was significantly higher compared to the control, but only in the men ( $P \leq 0.05$ ). This research was the first study of its kind and showed that compression garments had the potential to enhance power output over repeated jumps, by possibly assisting the proprioceptive signals in the hip joint while being fatigued.

This study by Kraemer *et al.* (1996) on repetitive jump performance alluded to the fact that the benefits of compression garments are possibly more related to fatigue resistance than maximum power outputs. If one considers that running and jumping biomechanics are similar in that both rely on the stretch-shortening cycle, one could hypothesize that this research done on repeated jump ability is also relevant to running mechanics.

In the next study by Kraemer *et al.* (1998<sup>a</sup>) they determined if compression shorts and tights (waist to knee; 3 types of elastomeric mix synthetics  $\sim 210.2 - 281.4$  g.m<sup>-2</sup>) would maintain or enhance jump performances under different fatiguing conditions. The fatigue protocols varied in terms of the recruitment of force producing motor units, movement velocity and metabolic demand. The researchers measured vertical jump performance after endurance, strength and



power activities (part I), hip proprioception (joint position sense) (part II) and muscle oscillation, specifically movement velocity on landing impact (part III).

For part I, forty subjects (20 athletes and 20 non-athletes) completed 10 repeated countermovement jumps with their hands on their hips, before and after three sport-specific fatigue protocols. The subjects completed (i) a 30-minute submaximal treadmill run at 2% elevation and 70% of their maximum heart rate, (ii) a strength protocol of 4 sets of supine leg press exercises (10 RM) until muscular fatigue and (iii) 10 x 10 maximum countermovement jumps for the power protocol. The participants wore the compression shorts during the fatigue protocols and had to complete psychometric scales on how they perceived the compression garments. The results revealed that the compression garments had no effect on maximum power performance (the highest jump), but did enhance mean power output before and after the various fatigue tasks in both athletes and non-athletes.

In the second part of the research, the influence of compression garments on hip joint proprioception was assessed. Twelve participants ( $n = 6$ ;  $\bar{x}$  age:  $21.3 \pm 2.9$  years, men and women) were requested to perform 4 sets of 4 different hip flexion angles, i.e.  $30^\circ$ ,  $45^\circ$ ,  $60^\circ$  and  $90^\circ$  with and without compression garments. The four angles simulated the four possible hip joint positions. To reduce possible proprioceptive signals subjects were blindfolded and asked to keep their eyes closed, as well as lie supine to reduce surface contact. This open chain movement would therefore only allow proprioceptive stimulus from the skin and the involved joint. Furthermore, muscle oscillation was excluded because the participants did not perform any jump movements. After the participants were placed in the correct anatomical position, they were instructed to repeat the actions with and without the compression garment in random order. The difference between the correct and actual hip position was noted. It was found that hip joint proprioception at  $45^\circ$  and  $60^\circ$  flexion were significantly enhanced, especially when the limb was moved away from the end point of the range of motion.

Neuromuscular control is the unconscious motor efferent response to afferent sensory proprioceptive information from the sensation of movement in the involved joint (kinesthesia) and joint position (Myers *et al.*, 1999). It has been suggested that proprioception aids the athlete's performance by contributing to body awareness in relation to space, direction, and



speed. A number of complex factors stimulate an individual's proprioception, such as mechanoreceptors found in the skin and in articular, ligamentous, muscular, and tendinous tissue about a joint (Myers *et al.*, 1999). Tactile mechanoreceptors increase the sensitivity of an individual's proprioception and it is speculated that compression garments enforce this tactile stimulation, which increases proprioceptive sensitivity (Kraemer *et al.*, 1998<sup>a</sup>; Kraemer *et al.*, 1998<sup>b</sup>; Doan *et al.*, 2003). Mechanoreceptors convert functional and mechanical change into neural signals back to the central nervous system (CNS). As a muscle fatigues, proprioceptive feedback by mechanoreceptors is affected, and therefore neuromuscular control and joint function are affected (Myers *et al.*, 1999).

Most sporting modalities involve impact, which causes the muscles to vibrate, commonly referred to as muscle oscillation. In part III of the study by Kraemer *et al.* (1998<sup>b</sup>), the influence of compression garments on muscle oscillation were assessed. The theory is that the physical support provided by the compression garment will limit muscle vibration. Ten subjects completed 3 sets of 6 maximal countermovement vertical jumps with compression garments or normal gym shorts. Reflective markers placed on the bony protrusions of the subjects allowed the investigators to record their movements with a high-speed camera. Maximum and minimum mid-thigh displacement and velocity were recorded during each vertical jump. It was found that vertical, but not horizontal muscle movement on impact during the landing was significantly less while wearing the compression garment. The compression garment diminished the muscle velocity to almost nothing during the impact.

This elaborate study by Kraemer *et al.* (1998<sup>b</sup>) showed that compression shorts maintains or enhances average power during jumping activities and that compression garments interact with proprioceptive cues, thus improving proprioception. Furthermore, compression garments significantly limits muscle oscillations during jumping, which may not only contribute to fatigue resistance, but also limit muscle fiber damage.

Kraemer *et al.* (1998<sup>b</sup>) also established that compression shorts do not contribute to additional fatigue during repetitive force production. They first calculated the potential amount of force that the compression garments would contribute to the total work completed during resistance exercise. To this end, they created a mathematical model which assumed that the muscle



involved is a conservative cylinder and showed that compression garments added an inconsequential 0.004% to 0.02% force. To assess total work capacity and force production the protocol consisted of open- and close kinetic chain tests. The close kinetic chain protocol consisted of 3 sets of 50 maximal isokinetic knee extension/flexion movements at 180° per second, whereas the open kinetic chain protocol was a novel squat test to exhaustion at 70% of 1 repetition max (RM). The results showed no significant differences in peak torque or total work performed between compression shorts and the control condition. They concluded that compression garments do not contribute to additional fatigue in the thigh muscles during repetitive high-intensity exercise. This meant that the opposing forces of the compression garments were not enough to cause additional fatigue in the muscle (Kraemer *et al.*, 1998<sup>b</sup>).

Doan *et al.* (2003) investigated the effect of custom-fit compression tights on the athletic performance of 20 competitive track athletes, specializing in jump and sprint events. The athletes (men;  $\bar{x}$  age: 20.0 ± 0.9 years and women;  $\bar{x}$  age: 19.2 ± 1.3 years) wore compression shorts (EXP; 4.76 mm thick knee to the waist; 75% neoprene and 25% butyl rubber shorts; Model 950 GH, Antibody Inc., Cheltenham, Maryland district, USA) and standardized gym shorts (C; loose fitting) in random order and performed various performance tests.

There was no change in 60-meter sprint speed with the compression tights, despite the fact that skin temperature was significantly higher during the warm-ups with the compression shorts (EXP:1.09°C vs. C: 0.07°C;  $P = 0.003$ ). During the sprinting activities hip flexion was 6° more reduced in the treatment group compared to the control ( $P = 0.04$ ). Furthermore, vertical jump height was statistically significantly higher in the compression group (5%;  $P = 0.015$ ), while the total squat depth was statistically significantly less (~1.8 cm;  $P = 0.02$ ). Impact forces with compression tights was ~27% less at a drop height of 38.1 cm ( $P < 0.001$ ) and ~12% less at a drop height of 76.2 cm ( $P = 0.066$ ). The anterior-posterior and longitudinal oscillation in the thigh muscle upon impact from a jump was significantly lower with the compression garment compared to the control (0.40 cm and 0.32 cm, respectively;  $P = 0.01$ ). This research thus supports and confirms the data reported by Kraemer *et al.* (1998<sup>a</sup>). Athletes wearing compression garments will experience less muscle damage as well as improved repetitive jump performance due to the improvement in muscle proprioception and by limiting muscle vibration



upon impact. The results suggest that compression tights might aid athletic performances and reduce the risk of injuries.

Doan and co-investigators (2003) also studied the mechanized characteristics of the compression tights. They found that the hip joint torque (N.m) increased by 191 - 285% during extension at 200° and 195°, and 53 - 91% at 127° and 158° flexion ( $P \leq 0.05$ ). The elasticity of the garment thus allowed more flexion and extension torque in the hip joint at the end of the flexion and extension movement. Bernhardt and Anderson (2005) also found reduced hip flexion active range of motion (EXP:  $88.5 \pm 8.8^\circ$  vs. C:  $98.25 \pm 8.9^\circ$ ;  $P = 0.02$ ) in physically active men and women, using elastic rehabilitative compression tights (Coreshorts™; Vancouver, Canada; no pressure specified). Hyperextension of the hip was 3% and hip abduction was 7% degrees more in the treatment group. No differences were observed in flexion, hyperextension and abduction between the experimental and control trials. This means that athletes wearing compression shorts might be less injury prone, especially in the hamstrings, due to the considerable torque that is generated during hip flexion and extension (Doan *et al.*, 2003). The reduced hip flexion indicates a possible increase in average stride frequency and the elasticity might even aid the acceleration of the leg after the swing phase. Importantly, the garment did not interfere with the athlete's sprinting biomechanics, except for a small obstruction near full hip extension ( $> 180^\circ$  extension).

Maton *et al.* (2006<sup>b</sup>) investigated the effects of elastic compression garments (European class I, Varisma comfort II, France;  $\sim 6.8 - 23.6$  mmHg) on muscular fatigue and recovery after a fatiguing protocol in fifteen healthy subjects. The researchers wanted to establish whether i) the added external pressure would result in ischemia due to the increase in intramuscular pressure, and as a result contribute to peripheral fatigue or ii) would the compression stocking improve blood flow by augmenting the calf muscle pump and manipulate recovery time by restoring the initial muscle metabolism. They recorded surface electromyograms (EMGs) to examine muscle fatigue in the TA, GA, *Rectus Femoris* (RF), and *Biceps Femoris* (BF). For the fatiguing protocol, subjects were requested to sit with their right knee flexed at a 70-degree angle and the ankle in dorsiflexion at a 70° angle (with respect to the tibial line). Subjects had to complete two trials, one with a compression garment (EXP) and then, after 30 minutes of rest, another trial without a compression garment (C). During each trial the subjects had to sustain 50% of their ankle dorsal





flexion maximum voluntary force (MVF) for as long as possible. The time to exhaustion was recorded. At the end of the two trials the subjects rested for another 30 minutes before the pressure exerted on the skin by the compression garment was assessed (Salzmann apparatus). In the first 10 minutes of both 30 minute rest periods, the subjects had to perform static fatiguing contractions i.e. maximum ankle dorsiflexion, every 30 seconds until the initial MVF was restored or up to the end of the 10 minutes.

There are three markers of fatigue during sustained submaximal contractions, i.e. the increase in surface electromyography (EMG) amplitude, decrease in EMG frequency and finally the gradual increase in voluntary effort to maintain the force production (Thedon *et al.*, 2008). Furthermore, the velocity at which the muscle fiber's action potential is conducted affects the mean power frequency (MPF) in the muscle, while peripheral (i.e. metabolic changes) or central fatigue (i.e. motor unit recruitment) may delay this conduction. Maton and co-authors (2006<sup>b</sup>) reported that the endurance time, recovery times or EMG's recorded with the compression garments and without (C) did not differ significantly ( $P > 0.05$ ). In particular, no differences were noted between the compression garments and the control trials with respect to MPF or total power (TP). In other words, the results of Maton *et al.*'s (2006<sup>b</sup>) investigation showed that compression stockings did not contribute to fatigue, nor did it improve force recovery.

To regenerate 95% muscle force took on average 60 seconds faster in the experimental trial compared to the control. Although the experimental group recovered 29% faster than the control group, the difference in recovery times was not significantly different. Maton *et al.* (2006<sup>a</sup>) also pointed out that these recovery values correspond roughly to the time required for removing lactic acid. This study therefore shows that compression garments do not enhance recovery of force production, but also do not contribute to lower limb muscle fatigue.

However, the results of Thedon and co-investigators (2008) are in disagreement with the study by Maton *et al.* (2006<sup>b</sup>). These researchers reported that compression garments can alter neuromuscular (force and EMG), as well as haemodynamic function (blood volume and oxygenation) during strenuous exercise. It was determined that neuromuscular efficiency, i.e. the ability to maintain force and delay fatigue, was significantly improved (~22%) in subjects wearing a compression sleeve. All haemodynamic variables (total blood haemoglobin and tissue





oxyhaemoglobin) were more pronounced with the compression garment, but due to the small sample size ( $n=4$ ), differences between the compression and control trials were not statistically significant. They concluded that compression may counteract muscle fatigue by increasing muscle tissue oxygenation secondary to increased muscle perfusion via a myogenic response.

In summary, Kraemer *et al.* (1996 and 1998<sup>a</sup>) have shown that low pressure compression shorts improve repetitive jump power. They suggested that compression may assist performance through several mechanisms, i.e. improved proprioception, limiting muscle oscillation, enhanced blood lactate clearance, or perhaps psychologically (Kraemer *et al.*, 1998<sup>b</sup>). Thedon *et al.* (2008) found that compression garments limits fatigue by increasing tissue oxygenation. However, Millet *et al.* (2006) warns that excessive pressure could increase intramuscular pressure too much and impede blood flow to the muscles at rest and during exercise, which would result in fatigue. This means that the correct pressure is essential to draw any advantage from compression. Furthermore, Bernhardt and Anderson (2005) noted that the effectiveness of the compression garment will depend on the pressure exerted and the type of compression garment, as well as the athlete's inherent proprioception ability and previous injuries.

### ***b. The Influence of Compression Garments on Recovery***

Endurance activities such as running are typically associated with various indications of muscle fatigue such as metabolic acidosis, delayed onset of muscle soreness (DOMS), leg cramps and weakness (Bringard *et al.*, 2006<sup>a</sup>). The recovery process is characterised by the return to pre-exercise levels of metabolic factors, hydration levels, muscle damage, inflammation and functional performance. Nusser and Senner (2010) found that half the athletic and sport science population ( $n = 60$ ) they questioned on the use of compression garments believed that compression garments had an injury-protective effect. In addition, their results showed that 50% of coaches and 47% of medical staff recommend that athletes wear compression garments for recovery.



### *i. Exercise Induced Muscle Damage*

The eccentric phase of the stretch-shortening cycle together with the impact upon landing contributes greatly to muscle damage during weight-bearing activities, such as running (Millet *et al.*, 2006). The exact mechanisms involved with EIMD are not clear, but it is suspected that particularly excessive eccentric type exercises may disrupt striated skeletal muscle architecture, resulting in a failure of excitation-contraction coupling or direct alteration of contractile and elastic elements (Cheung *et al.*, 2003; Millet *et al.*, 2006). This leads to a temporary loss of functional activity, reduced range of motion and self-paced exercise capacity, increased perceived exertion during exercise and DOMS (Hauswirth and Lehénaff, 2001; Cheung *et al.*, 2003; Millet *et al.*, 2006; French *et al.*, 2008; Jakeman *et al.*, 2010). Delayed-onset of muscle soreness is a sensation of pain and discomfort that develop within ten hours after unaccustomed or strenuous exercise, then generally peaks between 24 – 72 hours and may persist up to seven to ten days (Craig *et al.*, 1996; Ball and Herrington, 1998; Miller *et al.*, 2004; Cochrane, 2004; Zainuddin *et al.*, 2005; Cleather and Guthrie, 2006; Takahashi *et al.*, 2006). Hence, one of the recognized methods to investigate skeletal muscle recovery is to induce DOMS through eccentric muscle action protocols (Cleather and Guthrie, 2006).

Exercise induced muscle soreness is coupled with the appearance of extracellular muscle myocellular proteins such as myoglobin (s-Mgb) and serum creatine kinase (CK) which appears within 1 hour and within up to 8 hours, respectively, in the circulation (Sayers *et al.*, 2000; Brancaccio *et al.*, 2007). These muscle damage markers usually leak from the damaged skeletal muscle fibres and is closely related to the foregoing neutrophil response (Hauswirth and Lehénaff, 2001; Suzuki *et al.*, 1999). S-Mgb is often used in conjunction with CK to quantify muscle damage, since it precedes any increase in total serum CK and thus appears faster in the circulation (Stone *et al.*, 1977; Sayers and Clarkson., 2003).

Previous research has shown that muscle damage, induced by eccentric muscle actions, can be alleviated by compression (Kraemer *et al.*, 2001<sup>a</sup>; Kraemer *et al.*, 2001<sup>b</sup>; Trenell *et al.*, 2006; Ali *et al.*, 2007), although there are also research that reported no benefits (French *et al.*, 2008).



Kraemer and co-authors (2001<sup>a</sup>) demonstrated that compression sleeves assist the recovery of soft tissue damage. Twenty non-strength trained healthy women were randomly divided into an experimental (EXP; *Raschell* fabric and 25% Lycra sleeves; ~10 mmHg;  $n = 10$ ;  $\bar{x}$  age:  $21.3 \pm 2.9$  years) and control group (C, normal attire;  $n = 10$ ;  $\bar{x}$  age:  $21.1 \pm 3.3$  years). The two groups were matched according to age, anthropometric data and one repetition maximum (1 RM) concentric arm strength. To induce muscle damage each participant performed two sets of 50 passive elbow flexor isokinetic exercises on a dynamometer and every fourth repetition was a strenuous eccentric muscle action. Women in the experimental group wore the compression sleeve only after the eccentric protocol on the exercised arm for the following 120-hours.

Plasma CK activity was significantly lower from day one to five after exercise in the experimental group compared to the subjects not wearing any compression garments (EXP: ~20% vs. C: ~117% increase;  $P \leq 0.05$ ). Cortisol and lactate dehydrogenase concentrations did not differ between the groups over the study period ( $P > 0.05$ ). The experimental group showed a significant improvement in force production (power and strength) from day three to five, compared to the control group ( $P \leq 0.05$ ). Elbow flexibility was also maintained in the experimental group and this was associated with significantly smaller circumference measurements and lower perceived muscle soreness ( $P \leq 0.05$ ). The relaxed elbow angle in those subjects wearing compression sleeves was unchanged, while the control group demonstrated significantly more flexion in the elbow ( $P \leq 0.05$ ).

In a following study, Kraemer *et al.* (2001<sup>b</sup>) demonstrated that non-strength trained men (EXP;  $\bar{x}$  age:  $22.3 \pm 2.9$  years vs. C;  $\bar{x}$  age:  $22.1 \pm 3.3$  years) who completed heavy eccentric exercise and then wore a compression sleeve for three days had an attenuation of the CK response, (EXP: ~490 vs. C: ~1390 u.L<sup>-1</sup>;  $P \leq 0.05$ ), reduced swelling and lower perceived muscle soreness with a greater force recovery. The experimental group had significantly less elbow extension stiffness at 48-hours (EXP: ~ 158° vs. C: ~ 153°) and 72-hours (EXP: ~ 158.5° vs. C: ~ 154.5°) after the eccentric protocol. During active range of motion, there was a significant increase in pain in both groups from pre-exercise levels, but significantly less perceived soreness in the experimental group, between 60 and 72-hours post-exercise (60 hrs.: EXP: ~22 vs. C: ~30 ratings; 72 hrs.: EXP: ~21 vs. C: ~30 ratings;  $P \leq 0.05$ ). At 72-hours all ratings of perceived muscle soreness were less in those wearing the compression sleeve group compared to the control group ( $P \leq 0.05$ ).



Furthermore, peak-force and power production were not significantly altered in the compression garment group after the protocol.

Gill *et al.* (2006) were the first investigators to study the effect of compression garments on post-exercise recovery in trained athletes after a real game situation. Twenty-three elite male rugby players ( $\bar{x}$  age:  $25 \pm 3$  years) were randomly assigned to one of four recovery groups: lower body compression garments (EXP 1; Skins®, Sydney, Australia, pressure not specified), active recovery (7 min cycling) (EXP 2), contrast water therapy (EXP 3) and passive recovery (C) (9 min seated). Testing took place during the competition season and participants had to be injury free and play for at least 20-minutes in a game to be included in the study. After the match, the compression garment group (EXP 1) went about their normal post-match routines before applying the compression garment and wearing it for ~ twelve hours.

Interstitial CK activity was more pronounced after the match (PRE:  $1023.0 \pm 308.3$  u.L<sup>-1</sup> vs. POST:  $2194 \pm 833.7$  u.L<sup>-1</sup>;  $P < 0.01$ ), indicating that muscle damage did occur. There was a significant difference ( $P < 0.05$ ) between passive recovery and the three recovery modalities at 36 and 84-hours after the matches. The subjects with the compression garments showed an 84% improvement in muscle damage, while with passive recovery there was only a 39% improvement at 84-hours post-match. Even though not statistically significant, compression garments had a greater recovery response at 36-hours post-match compared to all the other strategies (CG: ~ 67%; ACT: ~ 59 %; CWT: ~ 55% and PAS: ~ 28%). However, when compression garments were compared to the contrast bath and active recovery modalities at 84-hours, compression garments yielded a slower recovery response (CG: 84%; CWT: 85%; ACT: 88%). However, these differences were not statistically significant (Gill *et al.*, 2006). The study thus revealed that wearing lower body compression garments for 12 hours after a rugby union match aided recovery from muscle damage compared to passive recovery, but did not differ significantly from active or contrast bath water immersion recovery.

The CK activity levels were far greater in this study than usually observed after team sport matches. Gill *et al.* (2006) suggested that possible reasons for this may be that interstitial CK concentration may yield higher measured values than plasma CK, or perhaps the players were not completely recovered after matches or training. Also, rugby matches involve a great deal of



running, as well as contact trauma and this could also account for the high CK concentrations. The higher values in this study may limit the application of the findings to other non-contact sports.

Trenell and co-researchers (2006) explored muscle injury in humans with  $^{31}\text{P}$  magnetic resonance spectroscopy ( $^{31}\text{P}$ -MRS). This is a method by which researchers can detect changes in inorganic phosphate. Muscle damage is accompanied by various biochemical changes of which elevated inorganic phosphate is an example (Aldridge *et al.*, 1986). Inorganic phosphate may accumulate due to i) defective oxidative metabolism, ii) tissue necrosis and ii) cell membrane damage.

Eleven recreational athletes (men;  $\bar{x}$  age:  $21.2 \pm 3.1$  years), acting as their own controls, walked on a treadmill for 30 minute at  $6 \text{ km}\cdot\text{h}^{-1}$  and a 25% descent. The athletes wore the calf to thigh compression garment on one leg after the exercise for 48 hours (Skins®, Sydney, Australia; 76% Nylon and *Meryl Microfibre*, 24% *Roica* Spandex; no pressure specified). There was a significant increase in the perception of muscle soreness after the exercise in the experimental and control leg. However the athletes perceived similar pain in both legs at 48 hours ( $\sim 300\%$  and  $\sim 218\%$  increase from baseline in the treatment and control leg, respectively;  $P > 0.05$ ). There were no changes in PME, PCr/Pi and  $\text{Mg}^{2+}$  concentrations after exercise and also no differences between the two legs ( $P > 0.05$ ). The PCr/Pi relationship reflected non-specific muscle damage. One hour after exercise there was a significant but unusual increase in thigh PDE levels from baseline (EXP:  $\sim 0.653$  vs. C:  $0.550$ ;  $P < 0.05$ ), while both legs demonstrated a similar drop in pH ( $\sim 0.6\%$ ;  $P < 0.05$ ). By 48 hours, pH and PDE returned to pre-exercise levels.

The elevated phosphodiester may represent an increase in skeletal muscle membrane turnover or tissue regeneration, since PDE metabolites are the product of phospholipid breakdown. Consequently, Trenell and co-authors (2006) suggested that the increased [PDE] in healthy individuals indicated an accelerated inflammatory and repair process. Another possibility is that a change in [PDE] is due to under perfusion of the muscle or an altered nucleotide pool. If the compression garment caused vasoconstriction, less oxygen would be supplied to the muscle and together with an increase in ADP, protons will not be cleared. This may result in an increased [PDE] due to the stress response, which contribute to muscle tissue breakdown. Most likely, this



is not the explanation, since PCr/Pi was unchanged during the study; hence there was no accompanied increase in ADP. Additionally, even though elevated pH is associated with proton retention and vasoconstriction, the elevated pH after the exercise was visible in both legs and not only in the compression garment leg. They concluded that the 30-minute downhill walk did not significantly influence the CK equilibrium and it appears that compression garments improve the inflammatory responses to muscle damage and aid intramuscular repair. However, this is the only study to date which investigated the ratio of metabolites as markers of muscle damage. Consequently more research is needed to confirm these assumptions.

Duffield and Portus (2007) investigated the effects of three different makes of full body compression suits (Skins®, Adidas® and UnderArmour®) on the performance of well-trained cricket players (men;  $\bar{x}$  age: 22.1 ± 1.1 years;  $n = 10$ ). Subjects completed a maximal- and accuracy-throwing test as well as a 30-minute repeated-sprint test. The three different garments were worn during all the tests, as well as 24-hours post-exercise and compared to a control garment. No significant differences in 10m and 20m repeated sprint performance, throwing performance, heart rate and body mass were observed between the four conditions. Skin temperature was increased in all three cases. The 24-hour post-exercise CK levels and perceived muscle soreness were significantly lower in two of the garments (Skins® and UnderArmour®) compared to the control ( $P < 0.05$ ). The Adidas full body suit revealed large effect sizes for lower CK compared to the control ( $P > 0.05$ ). Similar to the CK concentrations, all three garments resulted in a lower perception of muscle soreness compared to the control ( $P < 0.05$ ) at 24 hours.

Perry *et al.* (2008) induced plantar flexor muscle fatigue and DOMS with a 30 minute backwards treadmill walk at a speed of 3.6 km.h<sup>-1</sup> and a descent of 25% with a vest loaded with additional weights equal to 12% of the participant's body mass. Eight physically active men ( $\bar{x}$  age: 26 ± 4.0 years) performed the DOMS protocol and then wore a compression garment on the one leg only. The men wore the graduated compression stocking (~17-24 mmHg; Supportive™, France) for 5 hours per day during the 3 consecutive days after the exercise protocol. There was a 28% reduction in DOMS after the exercise in the treatment leg ( $P < 0.05$ ). The protocol induced a similar reduction (15%) in maximum voluntary torque (MVT), as well as a ~ 5% reduction in voluntary activation of the plantar flexors in both legs ( $P < 0.02$ ). A reduction of voluntary activation usually indicates a reduction of voluntary recruitment of motor units during MVT and



is an indicator of central fatigue (Theurel and Lepers, 2008). The 22% reduction in contractile function, indicated by reduced peak twitch, contributed in part to this reduction in torque (peripheral fatigue). The reduction in power production (torque) would typically indicate muscle fatigue, which can originate from proximal sites (central fatigue) or distal to the neuromuscular junction (peripheral fatigue) (Theurel and Lepers, 2008). However, the researchers pointed out that the eccentric protocol was of a low intensity, thus it is more likely that muscle damage produced a drop in torque, and not necessarily muscle fatigue (Perry *et al.*, 2008).

Unlike the control leg, the contractile properties (i.e. peak twitch/peripheral fatigue) in the compression garment leg recovered within 24 hours ( $P < 0.01$ ), while maximum voluntary torque improved by 6%, although this change was not statistically significant. Perceived muscle soreness and discomfort (DOMS) increased in both legs over the study period, but only from 2 hours post-exercise ( $P < 0.001$ ). This also indicates that muscle soreness did not cause loss in power production, since MVT was reduced immediately after the exercise protocol. The participants reported significantly less DOMS in the experimental leg compared to the control leg ( $P < 0.05$ ), and was diminished by 72 hours. The researchers suggested that the compression garment physically supported the leg, and thus limited structural tissue damage.

In contrast to previous research, French *et al.* (2008) reported no recovery or performance benefits with compression garments in 26 resistance-trained athletes ( $\bar{x}$  age:  $24.1 \pm 3.2$  years). The subjects completed a high intensity resistance protocol which was designed to induce micro trauma to the skeletal muscle tissue. Various muscle damage markers, flexibility measures and physical performance tests were assessed prior to and two days after the exercise protocol. Subjects were randomly allocated to one of three recovery groups, namely contrast bath (EXP 1), compression garment (EXP 2) and control (C). Subjects of EXP 2 wore a full length compression garment (Skins®, Campbelltown, Australia; 12 mmHg to 10 mmHg, calf to thigh; Lycra® and Meryl) for 12 hours overnight.

CK was significantly elevated in all three groups at 24 hours (EXP1: 161%; EXP 2: 140% and C: 270%), but the differences were not statistically significant. Similar findings were observed for myoglobin concentrations 1 hour after exercise (EXP 1: 458%; EXP 2: 523% and C: 682%). No increase in post-exercise mid-thigh circumferences were observed for the compression garment





group, compared to the control group who had a 2% increase, and the contrast bath group who had a 1% increase.

Both knee flexion and hip flexion were significantly reduced in both the compression and control groups. Furthermore, 30m sprint time was 2% slower in the compression group, while the detriment in countermovement jumps was significantly less in the compression and contrast bath group (EXP 1: 4%; EXP 2: 5%; C: 9%). The authors concluded that compression garments did not protect the muscles against exercise induced damage, and it limited the athletes' range of motion in the lower extremities which could have contributed to weaker performances in the sprints.

The latest research by Kraemer *et al.* (2010) investigated resistance trained men and women after a heavy resistance workout routine. Weight lifters are accustomed to eccentric muscle actions which are associated with resistance workouts. Yet the results from this study show that whole body compression garments seemed to have beneficial effects on muscle damage in resistance trained athletes. Subjects completed 2 sessions of eight resistance exercises separated by 3 days. The athletes randomly wore a full body compression garments (EXP; Under Armour® Recharge™, Baltimore, Maryland district, USA; 75% Nylon and 25% spandex; no pressure specified) or normal non-compressive clothing (C) only after the resistance exercise protocol during the 24 hour recovery period.

Subjects experienced significantly better quality of sleep, vitality, resting fatigue, less muscle soreness, swelling and lower levels of lactate dehydrogenase and serum CK concentrations following the compression garment trial. However, there were no differences in circumferences and reaction times, squat jumps and countermovement jumps, between the two trials. The reduction in muscle swelling and muscle damage could be due to the haemodynamic benefits of compression garments and/or the immobilization provided by the garment. Bench throw power was significantly greater with the full body compression garment, which suggests that compression garments aided neuromuscular recovery in the upper body of experienced weightlifters. These results support the earlier findings of Thedon *et al.* (2008). Furthermore Jakeman *et al.* (2010), who studied the effects of compression garments on muscle damage, muscle soreness and various performance parameters in physically active women also found





comparable results. Following a plyometric exercise protocol, those who wore the compression garments during exercise had significantly less muscle soreness and muscle damage and performed better in most of the performance tests.

The investigators speculated that not all the parameters were influenced by the full body compression garment because of the very specific stresses of the exercises interacting with the extent of damage, damage geometry on specific surface areas (specific to each other) and the differences in the recovery kinetics of the variables. The fact that subjects were accustomed to resistance training could also explain some of the findings (Kraemer *et al.*, 2010).

## *ii. Swelling and External Compression*

O'Donnell and co-workers (1979) were some of the first researchers to suggest that compression garments may reduce swelling, haemorrhage or hematoma formation. External compression therapies, including compression garments (~20 to 60 mmHg), have been shown as an effective treatment for individuals with lymphoedema (Choucair and Phillips, 1998; Felty and Rooke, 2005).

In athletes, micro trauma to muscles, especially after exhaustive prolonged exercise, such as distance running, may result in oedema (Eston and Peters, 1999). Peripheral oedema (swelling) is the result of an imbalance between the plasma volume (intravascular) and interstitial compartment (extra vascular) (Cho and Atwood, 2002). This imbalance leads to an uncharacteristic accumulation of fluid in the interstitial space (Cho and Atwood, 2002; Partsch, 2003<sup>a</sup>). The role of the lymphatic system is to collect and remove fluid and proteins from this interstitial tissue, then return the fluid to the vascular compartment of the veins (Cho and Atwood, 2002; Partsch, 2003<sup>a</sup>).

Oedema occurs due to interactions between the permeability of the capillary walls and the pressure gradient between blood vessels and the surrounding tissue's hydrostatic and oncotic pressure (the osmotic pressure created by the protein colloids in plasma). Hydrostatic pressure differences result in filtration and oncotic pressure differences cause reabsorption (Partsch, 2003<sup>a</sup>). The relationship between these factors is described by Starling's equation:



$$F = c (P_c - P_t) - (\pi_c - \pi_t) \dots\dots\dots (Eq. 1)$$

where:

F = filtration force; origin of lymph

c = filtration coefficient

P<sub>c</sub> = capillary blood pressure

P<sub>t</sub> = tissue pressure

π<sub>c</sub> = capillary oncotic pressure

π<sub>t</sub> = tissue oncotic pressure

Thus external compression will oppose the loss of capillary fluid by increasing local tissue pressure and reinforcing reabsorption by pushing fluid into the veins and lymph vessels (Partsch, 2003<sup>a</sup>).

The most likely reason why oedema would occur in athletes is because of inflammation that increases capillary permeability. When the athlete's muscle is damaged, chemical mediators, e.g. CK and myoglobin are released into the circulation (Kraemer *et al.*, 2004) and an inflammatory response is produced. The capillary walls become more permeable and proteins are released into the intercellular fluid (Kraemer *et al.*, 2001<sup>b</sup>; Kraemer *et al.*, 2004). This alters the gradient between the two compartments by increasing the tissue oncotic pressure and elevating the hydrostatic pressure in the veins (Kraemer *et al.*, 2001<sup>b</sup>; Cho and Atwood, 2002; Kraemer *et al.*, 2004). In an attempt to equalize the osmotic gradient across the capillary membrane, fluid is drawn out of the veins into the interstitial compartment (Kraemer *et al.*, 2001<sup>b</sup>; Cho and Atwood, 2002). This in return disturbs homeostasis and oedema will form (Kraemer *et al.*, 2001<sup>b</sup>; Cho and Atwood, 2002; Kraemer *et al.*, 2004; Miller *et al.*, 2004).

Approximately one-hour after exercise, the mechanical alteration brings about a transfer of plasma volume and the extracellular compartment becomes noticeable (Maton *et al.*, 2006<sup>b</sup>). Swelling is generally intramuscular during the first 24 to 48 hours, and then becomes subcutaneous in the following hours (Kraemer *et al.*, 2004). Oedema in the muscular compartment increases intra-compartmental pressure, which in return inhibits lymphatic and

venous drainage of the area and promotes further swelling. As the muscle compartment becomes more turgid, range of motion is reduced (Cho and Atwood, 2002). This has been demonstrated by Kraemer *et al.* (2001<sup>b</sup>) where compression sleeves resulted in less upper arm swelling after exercise, which was significantly less than the control condition at 48-hours (~0.4 cm vs. ~1.0 cm increase;  $P \leq 0.05$ ). Furthermore, the active range of motion was restricted due to the swelling and there was a significant increase in pain in both groups from pre-exercise levels, but significantly less perceived soreness in the compression garment group.

Severe swelling frequently persists long after muscle soreness has subsided. This is either because the pain receptors adapted to the swelling response, or the swelling might be a secondary response to the primary cytokine and histamine mediators (Kraemer *et al.*, 2004). Inflammatory mediators such as bradykinin, serotonin, and histamine augment the responsiveness of the pain afferents in the injured areas and may contribute to the pain stimulus to some degree (Kraemer *et al.*, 2004). Swelling may also increase intramuscular pressure and stimulate the pain receptors, i.e. the type IV sensory neurons (Ball and Herrington, 1998; Miller *et al.*, 2004; Kraemer *et al.*, 2004). As a result swelling reduces range of motion, hampers muscle function and cause pain (Miller *et al.*, 2004). For this reason, diminished swelling and subsiding perception of pain are used by sport scientists as recovery indicators (Miller *et al.*, 2004). Assessing the circumferences of the involved extremities is typically used to measure swelling and a number of studies have shown reduced circumferences when wearing compression garments after eccentric exercise (Kraemer *et al.*, 2001<sup>a</sup>; Kraemer *et al.*, 2001<sup>b</sup>).

Externally applied compression not only prevents the occurrence of swelling, but also reduces the formation of oedema by removing excess lymph fluid accumulating within the limb (Brennan and Miller, 1998; Harris *et al.*, 2001). Compression therapy, unlike cryotherapy, will also remove swelling from a limb, by changing the tissue pressure gradient. This in return would prevent the formation of oedema and increase reabsorption.

Studies have shown that when fluid accumulates in pilots' arms during long flights, the oedema results in pain and discomfort. As a result, pressure sleeves are used to eliminate oedema and reduce the pain (Laing and Sleivert, 2002). Even patients with venous insufficiencies are advised to wear graduated compression socks when exercising to avoid oedema (Felty and Rooke, 2005).



The use of compression garments to manage oedema may also have subsequent effects on secondary muscle damage resulting from the inflammatory response (Hellsten *et al.*, 1997; Jakeman *et al.*, 2010). Felty and Rooke (2005) suggested that graduated compression stockings are more helpful to maintain limb circumferences than other compressive therapies. In other words, traditional compression therapies remove oedema by physically reducing the space available for fluid accumulation, but graduated compression stockings also preserve the swelling free limb and prevent further swelling by altering the haemodynamics (i.e. increase blood flow). It follows then that functional recovery should be enhanced by compression garments, as it would reduce or limit swelling and allow the restoration of range of motion at a faster rate.

Furthermore, prolonged aerobic training can predispose athletes to varicose veins, venous insufficiencies and orthostatic intolerance because of an elevated venous compliance (Bringard *et al.*, 2006<sup>a</sup>; Perrey *et al.*, 2008). This, together with EIMD would lead to excessive swelling in the lower limbs and associated pain and fatigue. Bringard *et al.* (2006<sup>a</sup>) suggested that wearing compression garments during rest after exercise will aid regeneration and delay the occurrence of varicose veins by increasing tissue oxygenation. Furthermore the external pressure will counteract the orthostatic strain and limit swelling.

During running (or any upright exercise) the calf muscles reduce the hydrostatic shifts (filtration) of the venous blood in the lower extremities, thus preventing or at least limiting oedema. However, after exercise athletes typically rest by sitting or lying down and this may result in swelling. The oedema will not only affect venous function, but also exacerbate muscle fatigue and discomfort in the lower extremities. These problems are mainly due to orthostatic stress, such as an increase in capillary hydrostatic pressure and gravity (Hirai *et al.*, 2002; Bringard *et al.*, 2006<sup>a</sup>) and can be limited through active recovery or external compression.

Studies focusing more on recovery after eccentric exercises also reported significantly lower circumferences with compression garments compared to control conditions after muscle damage has been induced (Kraemer *et al.*, 2001<sup>a</sup>; Kraemer *et al.*, 2001<sup>b</sup>). The reduction in muscle swelling and muscle damage could be due to the haemodynamic benefits of compression garments and/or the immobilization provided by the garment.



Less oedema is generally accompanied by a reduced inflammatory response and a lower perception of pain. Compression garments usually attenuate plasma CK concentration, either because of an increased CK clearance, or because less CK is released by the muscle fiber (Kraemer *et al.*, 2004; Trenell *et al.*, 2006). Whatever the mechanism, muscle function is better maintained when circulating CK is reduced.

Thus the compression garment counteracts swelling associated with muscle damage by mimicking or amplifying the muscle-pump action. In other words, the increased hydrostatic pressure leads to increased filtration of fluid across the capillary wall into the interstitial space of the tissues in the extremities. Swelling is reduced by (i) reducing the venous pressure, which sequentially reduces the effective filtration pressure, (ii) increasing lymph flow, which removes fluid and colloid proteins, which contribute to osmosis, from the interstitial space, (iii) increasing the muscle tissue pressure, which counteracts the intravascular pressure during muscle contraction, thus preventing swelling, and/or (iv) minimizing the available space for fluid accumulation (Brennan and Miller, 1998; Kraemer *et al.*, 2001<sup>a</sup>; Kraemer *et al.*, 2001<sup>b</sup>; Kraemer *et al.*, 2004).

### *iii. Perceptual Responses*

One should never underestimate the perceptual and psychological advantages provided by sporting equipment, including compression garments. Efficiency and psychological cost are some of the determining factors of endurance performance (Millet *et al.*, 2006) and are often the only discriminating factors between highly competitive athletes.

Although many investigators have not observed psychological benefits associated with compression garments (Bringard *et al.*, 2006<sup>b</sup>; Trenell *et al.*, 2006; French *et al.*, 2008; Rimaud *et al.*, 2010), others have reported positive effects (Kraemer *et al.*, 1998<sup>b</sup>; Kraemer *et al.*, 2000; Kraemer *et al.*, 2001<sup>a</sup>; Kraemer *et al.*, 2001<sup>b</sup>; Ali *et al.*, 2007; Duffield and Portus, 2007; Duffield *et al.*, 2008; Perrey *et al.*, 2008; Rimaud *et al.*, 2010; Jakeman *et al.*, 2010; Sperlich *et al.*, 2010). Most research indicate reduced perceived muscle soreness with compression garments, while some research reported that individuals perceived compression garments as being helpful. However, perceptions of exertion have rarely been worse with compression garments compared to control



conditions (Berry and McMurray, 1987; Berry *et al.*, 1990; Kraemer *et al.*, 1996; Kraemer *et al.*, 1998<sup>b</sup>).

The eccentric muscle action protocol of Kraemer *et al.* (2001<sup>b</sup>) significantly increased pain in the compression garment and control groups from pre-exercise levels, however, the compression group had significantly less perceived soreness between 60 and 72-hours post-exercise. Duffield and Portus (2007) found lower perceived muscle soreness in the arms and legs of cricket players with compression garments at 24-hour post exercise compared to the control ( $P < 0.05$ ). Perrey *et al.* (2008) also reported significantly less muscle soreness in the compression leg after a DOMS protocol ( $P < 0.05$ ). In more recent research on resistance trained athletes, Kraemer *et al.* (2010) reported that both men and women experienced significantly less muscle soreness and fatigue and more vitality in the whole body compression trial. Physically active women indicated that with compression garments their muscle soreness was 50% less after exercise compared to the control group (Jakeman *et al.*, 2010).

The lower levels of perceived fatigue with compression garments could be explained by altered peripheral processes distal to the neuromuscular junction, which accompany muscle contraction (Montgomery *et al.*, 2008). Peripheral sites and processes of fatigue usually include the motor neuron, neuromuscular junction, sarcolemma, excitation-contraction coupling, accumulation of metabolites, and depletion of fuels. Kraemer *et al.* (1998<sup>b</sup>) also suggested that the positive feeling experienced when wearing compression garments is not just a psychological effect, but that proprioceptive signals could also be responsible. Another likely possibility is that the compression garments reduce localised swelling, which may be one of the causes of soreness associated with exercise induced muscle damage (Kraemer *et al.*, 2000).

There are studies that did not find improvements in perceived muscle soreness with compression garments. For example, Trenell *et al.* (2006) found no differences between control and compression garment groups after a 30 minute downhill walking protocol and Sperlich *et al.* (2010) found no reduction in perceived exertion in trained distance runners with or without compression garments. Rimaud *et al.* (2010) also found no significant differences in ratings of perceived exertion of endurance athletes with and without compression garments during a maximal intensity cycle ergometer test. The different muscle actions, i.e. during heavy eccentric



exercise versus dynamic exercise could explain the different outcomes. Also individuals more familiar with heavy training loads (intensity or volume) could be more accustomed to the perception of fatigue (Sperlich *et al.*, 2010).

It must also be considered that the positive effects reported in some studies may only be a placebo effect. Only two previous studies compared the effects of compression garments with a placebo garment. The runners in the study of Ali *et al.* (2010) perceived no differences between the compression garments and the placebo. Similarly, Duffield and co-authors (2008 and 2010) did not find any significant improvement in recovery markers, although with the compression garments subjects reported less perceived muscle soreness post exercise ( $P < 0.05$ ).

Wearing compression garments after exercise could also have serious disadvantages if it indeed lowers the perception of muscle soreness. Westing *et al.* (1991) suggested that perceived muscle soreness after muscle damage could act as a protective mechanism, which will prevent the involved muscle to fully activate. This may prevent further muscular damage, even if it does mean a temporary loss of muscle functionality. Therefore, one must interpret the positive findings of studies such as Jakeman *et al.* (2010) with caution. The fact that individuals experienced less muscle soreness, but produced more muscle power and force 12 hours after a strenuous plyometric protocol, may not be in the best interest of the athlete in the long term.

#### iv. Recovery of Metabolic Intermediates

An athlete's physical exercise capacity is impeded when the muscles' ability to generate force is limited (Juel, 2008). Exhaustive endurance exercises, such as distance running, induce muscle deoxygenation which is linked with elevated blood lactate concentrations. Some researchers also believe that peripheral muscle fatigue may be the result of the accumulation of metabolic intermediates such as  $H^+$  and a resultant drop in pH. The acidosis and excess  $H^+$  interferes with neuromuscular propagation and excitation-contraction coupling in the peripheries (Bringard *et al.*, 2006<sup>a</sup>; Rimaud *et al.*, 2007; Rimaud *et al.*, 2010). Skeletal muscle lactate transport depends on two proteins, namely MCT1 and MCT 4. These two proteins are coupled with  $H^+$  transport. In addition, associated lactic acid can also go through the semi-permeable muscle membrane. Therefore, all movements of lactate ions in the body take place together with  $H^+$  ions at a 1:1



ratio and as a result, all movements of lactate ions influence pH through the co-transport of H<sup>+</sup> ions (Juel, 2008). In other words, circulatory lactate levels reflect H<sup>+</sup> movements and for this reason muscle and blood pH is closely associated with blood lactate concentrations during exercise and recovery (Juel, 2008). Consequently, even though lactate may not be the cause of muscular fatigue, there is a relationship between lactate or H<sup>+</sup> proton accumulation and the reduction in maximum voluntary contraction (Westerblad *et al.*, 2002; Cairns, 2006; Theurel and Lepers, 2008; Rimaud *et al.*, 2010).

There are researchers that disagree with this traditional 'lactic acid hypothesis', which has led to controversy over the validity of lactate concentration assessment as an indicator of recovery (Cairns, 2006; Barnett, 2006). Cairns (2006) reasoned that lactate production may not be the cause of metabolic acidosis and that acidosis has little detrimental effects on muscle contraction. He suggested that acidosis may even have protective effects. Studies which have induced acidosis have reported reduced performance, however it has been suggested that these effects are due to the activity of the central nervous system (Cairns, 2006). Barnett (2006) added that the half-life of muscle lactate is 9.5 minutes and 15 minutes in the circulation, meaning that lactate concentrations will return to pre-exercise levels by 90 minutes after exercise, even with passive recovery.

It is not the purpose of this dissertation to argue for or against the use of blood lactate kinetics as an indicator of recovery. The fact is that most studies report the changes in blood lactate and pH and studies on recovery modalities also use these parameters to gauge the rate of recovery.

Currently active recovery is considered the gold standard of post-exercise recovery methods to clear metabolic waste products from the body (Monedero and Donne, 2000; Rimaud *et al.*, 2010). Through active recovery blood flow and working muscle metabolism via the muscle-pump actions are improved (Monedero and Donne, 2000; Barnett, 2006). As a result, researchers speculated that compression garments would mimic those actions of the muscles during active recovery and produce similar recovery benefits.

The influence of compression on metabolic recovery is unclear. Research findings on the effects of compression garments on the lactate and pH profiles of a physically active individual have





been conflicting. Newer studies reported no significant differences or low effect sizes (0.23 – 0.33) in the blood lactate concentrations and pH between compression garments and control groups (Trenell *et al.*, 2006; Higgins *et al.*, 2007; Duffield and Portus, 2007; Scanlan *et al.*, 2008; Houghton *et al.*, 2009; Ali *et al.*, 2010; Duffield *et al.*, 2010; Sperlich *et al.*, 2010; Sear *et al.*, 2010). However, this is contradicted by a small number of studies that reported significantly less anaerobic metabolites after exercise with graduated compression garments (Berry and McMurray, 1987; Berry *et al.*, 1990; Chatard *et al.*, 2004; Rimaud *et al.*, 2007) and significantly higher maximum lactate levels with compression garments (Rimaud *et al.*, 2010).

It was the improved circulation observed during clinical compression studies that led to the first sports related research by Berry and McMurray (1987) twenty-three years ago. They hypothesised that compression garments would reduce circulatory lactate in physically active individuals. Three possible mechanisms have been suggested, namely that the external pressure would (i) result in less lactate production or (ii) shunt the blood away from the muscle so that the diffusion medium is removed and lactate will be preserved intramuscularly or (iii) the improved circulation, secondary to increased venous return, would clear and oxidize blood lactate more effectively from exercising muscles (Berry and McMurray, 1987).

In the first study, Berry and McMurray (1987) investigated whether graduated compression stockings (ankle to below knee; 18 to 8 mmHg) have an effect on maximum oxygen consumption ( $VO_{2max}$ ), time to exhaustion (TTE) and lactate recovery. Six trained subjects ( $\bar{x}$  age:  $22.5 \pm 5.4$  years;  $VO_{2max}$ :  $52.8 \pm 8.0$  mL.kg<sup>-1</sup>.min<sup>-1</sup>) completed two incremental maximal treadmill protocols, once with the compression garment (EXP) and once without (C). During recovery, the men walked for five minutes at a speed of ~5.63 kilometers per hour and thereafter they rested for 55 minutes in a seated position without the compression stockings. They reported no significant differences in  $VO_{2max}$  or TTE between the EXP and C trials. Lactate concentrations were lower during the experimental trial throughout the entire 60-minute recovery period, but were only significantly lower at 15-minutes post exercise (~31%  $P < 0.05$ ). However, oxygen consumption during the recovery period did not differ between the experimental and control trials. Thus if the compression garments improved blood flow to the active muscles secondary to increased venous return velocity, then lactate concentrations should be significantly lower in association with increased post-exercise oxygen consumption. Therefore, in conjunction with no changes in



plasma volume the findings suggest that the lactate was retained with the muscle. These results prompted the second study by Berry and McMurray (1987).

Six physically active men cycled at 110% of  $VO_{2max}$  for 3 minutes and then rested supine for 30 minutes. The participants wore the graduated compression stockings (a) during the exercise only (EXP 1) or (b) during the exercise and recovery period (EXP 2) or (iii) not at all (C), in random order. Similarly to the first study, there were no significant differences in post-exercise oxygen consumption or plasma volume between the three trials. However, those who cycled with the compression stocking and wore it during the recovery period (EXP 2) had significantly lower blood lactate concentrations compared to the trial in which the runners took the garments off during recovery (EXP 1) or the control trail (C) (EXP 2:  $47.0 \pm 13.79$  mmol vs. EXP 1:  $57.6 \pm 20.17$  mmol and C:  $53.5 \pm 18.54$  mmol;  $P < 0.05$ ). During recovery without compression garments (EXP 1) the blood lactate concentrations were 51% higher compared to EXP 2 when subjects wore the compression garments during recovery. It seems then that the compression stockings acted as a tourniquet which created an inverse pressure gradient, or augmented intramuscular hydrostatic pressure, to retain lactate within the muscular bed. If blood flow through the previously active muscle increased when the compression garments were removed after exercise (EXP 1), then post exercise oxygen uptake would also have increased.

In the next study by Berry and co-authors (1990), they compared the effects of elastic sport tights (Lycra®) and medically graduated compression stockings on the blood lactate concentrations and post-exercise physiological responses. Eight male runners ( $\bar{x}$  age:  $27.0 \pm 1.8$  years;  $VO_{2max}$ :  $56.5 \pm 1.5$  mL.kg<sup>-1</sup>.min<sup>-1</sup>) completed the supra-maximal running protocol on a treadmill under the same experimental conditions as before, namely elastic tights during exercise (EXP 1), during exercise and recovery (EXP 2) and with running shorts (C). No differences were found in heart rate,  $VO_2$ , lactate or haematocrit concentrations after exercise in any of the three conditions. Thus, elastic tights did not lower blood lactate concentrations post-exercise, but was neither beneficial nor harmful to high intensity exercise performance. They suggested that the pressure exerted by the elastic tights might not have been enough to induce a cardiovascular and/or metabolic response.



Bird and Bingham (1995) assessed the impact of tight fitting shorts (nylon and elastomeric Lycra®) and loose fitting shorts (nylon) on selected physiological parameters ( $VO_2$ ,  $VCO_2$ , RER, heart rate, blood lactate) during treadmill running at three different intensities and a time to exhaustion test. No significant differences were reported for the physiological variables. This suggests that the differences in physiological responses between compression stockings and normal tights are likely due to differences in the compressive properties between the products. This also means that normal sports clothing could function as control garments, since there were no significant differences between tights and loose fitting shorts.

In a study by Chatard *et al.* (2004) twelve trained cyclists ( $\bar{x}$  age:  $63 \pm 3$  years) performed two 5 minute maximal bouts on a cycle ergometer separated by an 80 minute recovery period, with or without compression stockings. While lower blood lactate concentrations ( $\sim 20\%$ ) were observed during the recovery period with the compression stockings, there was also a higher maximum power output during the second maximum exercise bout, compared to the control trial. Furthermore, the blood lactate difference, before and after the second maximal bout, in subjects with the compression garment was higher than those without the compression garment ( $8.8 \pm 2.0$  vs.  $8.0 \pm 2.0$  mmol.L<sup>-1</sup>;  $P < 0.03$ ). Chatard *et al.* (2004) concluded that compression garments aid the removal of lactate during recovery and the relationship between blood lactate clearance and an individual's  $VO_{2max}$  ( $r = 0.37$ ;  $P < 0.01$ ) indicate that compression garments work in a similar manner than active recovery. In other words, the compression mechanically increases the blood flow in the veins, which clears lactate from the active muscles, and increases lactate oxidation in the inactive muscles. Subjectively, the experimental group perceived less leg pain compared to the control and 83% of the cyclists thought that the compression garments contributed to their performance. This was the first study where athletes wore compression garments only during the recovery period, and also the first study on older subjects.

In one of the few studies where a placebo garment was used, Higgins *et al.* (2007) simulated a netball game with a sport specific circuit and assessed specific physiological and performance variables. They found improved distances and faster pace with compression garments, but no significant differences in heart rate or blood lactate concentrations ( $ES = 0.63$ ) between the compression and placebo garments. Scanlan *et al.* (2008) and Kemmler *et al.* (2009) found 6% and 1% improved workload ability at the anaerobic threshold, respectively, of trained endurance



athletes while exercising with compression garments. The researchers suggested that the likely mechanism by which AT is improved is through an increased venous return that would transport deoxygenated blood and lactate towards non-working muscle to be oxidized and hence cleared from the circulation and active muscle.

Wheelchair athletes often strap their lower extremities to prevent venous pooling and enhance cardiac output (Rimaud *et al.*, 2007). This led Rimaud *et al.* (2007) to investigate whether compression garments would affect physiological variables in well-trained individuals with spinal cord injuries (SCI). The athletes were divided into two groups, namely low SCI ( $n = 9$ ;  $\bar{x}$  age:  $36.9 \pm 11.79$  years) and high SCI ( $n = 5$ ;  $\bar{x}$  age:  $36.6 \pm 11.3$  years) and completed two progressive incremental exercise tests to exhaustion on a wheelchair ergometer. The athletes completed the exercise protocol with graduated compression stockings (EXP; Microfibers-2 tights; Olimpique, Tournier-Bottu, Gibaud Products, Saint-Etienne, France;  $\sim 21$  mmHg) or without (C) in random order, and they also wore the garments for 15 minutes post-exercise during a passive recovery period. There were no improvements in performance or cardiovascular responses with compression garments, but lactate recovery was accelerated in the low level SCI group by 12% (EXP:  $10.9 \pm 3.9$  mmol.L<sup>-1</sup> vs. C:  $12.5 \pm 4.6$  mmol.L<sup>-1</sup>;  $P < 0.05$ ). The researchers speculated that the low pressure exerted by the garments might be responsible for the lack of performance improvements.

Rimaud *et al.* (2010) also studied the effect of graduated compression stockings in eight endurance athletes ( $\bar{x}$  age:  $27 \pm 0.9$  years). They completed two maximal incremental cycle tests, with a 60 minute seated recovery period, one week apart. The men wore the positive graduated compression stockings (Gibaud®, Saint-Etienne, France; calf to ankle: 22 to 12 mmHg) either during the exercise and recovery phase of the protocol (EXP) or not at all (C), in random order. Another important difference was that the investigators did not use a negative graduated compression garment tapering from ankle to calf, as those used by Berry and McMurray (1987), Chatard *et al.* (2004) and Rimaud *et al.* (2007). This garment had a reverse graduated effect and as a result applied the highest pressure around the calf that tapered down to the ankle. The researchers explained that this focused-pressure would aid the calf muscle-pump function and they claim that this is the type of garment commonly used in the sporting environment. However,



this may be conflicting with one's natural geometrical graduated limb and most compression garments use graded pressures from ankle to calf.

Rimaud *et al.* (2010) used a mathematical model, formulated by Freund and Gentry in 1978, to determine the rate of lactate clearance and exchange between previously active muscle and the circulation. In other words, the investigators were able to determine how compression stockings influence lactate recovery indirectly, but non-invasively. This two compartmental model of lactate distribution allows researchers to calculate intramuscular lactate as well as the transfer of lactate into and out of the muscle. Thus researchers can determine the parameters which influence lactate exchange, namely production and clearance in the active muscles and in the circulation. Measuring muscular concentrations rather than blood concentrations is also more appropriate, since the site of lactate production during exercise is in the involved muscle. This model would allow the researcher to establish whether compression garments retain lactate within the muscle or improve lactate clearance and oxidation by improved circulation.

Rimaud *et al.* (2010) reported no significant differences in submaximal and maximal heart rate, oxygen consumption, power output or blood pressure. Higher blood lactate concentrations were observed at the termination of the maximal exercise in the EXP trial compared to the control (EXP:  $12.1 \pm 0.5$  vs. C:  $10.8 \pm 0.5$  mmol.l<sup>-1</sup>;  $P < 0.05$ ), but this was not accompanied by higher power outputs or perceived exertion.

The release of lactate from the active muscle depends on i) muscle-to-blood gradient (mmol.L<sup>-1</sup>) and ii) lactate clearance (l. min<sup>-1</sup>). The recovery kinetics of this experiment reported a 29% impairment in blood lactate exchange ability between the muscle and blood with the compression garment (EXP:  $0.32 \pm 0.02$  vs. C:  $0.23 \pm 0.04$   $\gamma_1$  velocity in min<sup>-1</sup>;  $P < 0.05$ ), as well as a 22% increase in lactate removal ability (EXP:  $0.05 \pm 0.01$  vs. C:  $0.06 \pm 0.01$   $\gamma_2$  velocity in min<sup>-1</sup>;  $P < 0.03$ ). The decreased lactate exchange during recovery supports the theory of Berry and McMurray (1987) that compression garments retain lactate within the muscle. Moreover, even with a 27% increase in the net amount of lactate released from the previously active muscles within the first 15 minutes of the experimental trial ( $P > 0.05$ ), only minutes two to four showed significantly more lactate released by the compression garment in the recovery period.



Rimaud *et al.* (2010) explained that a lower lactate exchange ratio observed between the muscle and blood and higher lactate clearance in the compression trial could be attributed to the higher net lactate values, which lead to increased lactate accumulation during exercise. They suggested that the compression garment impedes the release of lactate during muscle contractions, since the added pressure would alter blood flow within the muscle. This would also reduce tissue oxygenation leading to more lactate being produced because of enhanced anaerobic glycolysis.

Further support for their findings was illustrated during the recovery period, with the reduced exchange ability of lactate. Recovery lactate, nonetheless, was cleared or removed more efficiently during recovery in the EXP trial by the improved venous return. Consequently the researchers suggested that further research is needed on the use of compression garments only during recovery and concurred with Chatard *et al.* (2004) that perhaps the compression garment would be more applicable to older athletes' recovery than to young elite athletes. These result support previous findings which showed that the application of lower body positive external pressure during exercise caused greater lactate release from the exercising muscles and accumulation in blood (Sundberg and Kaijser, 1992).

There are thus two possible mechanisms to explain the improved lactate kinetics during recovery with compression garments. Firstly, the added pressure improves blood flow in the muscle which would positively influence lactate release from the active muscles and lactate uptake in inactive muscle, where the lactate would be oxidized. Secondly, added external compression to active muscle, which are already exerting higher pressure during muscle contractions, or with excessive external pressures, local muscle blood flow is reduced and lactate kinetics is impaired. It has been shown that when an external positive pressure of more than 40 mmHg is applied to the limb during exercise local blood flow in the working muscles is reduced by 50% (Thorsson *et al.*, 1987).

#### v. *Functional Recovery After Strenuous Exercise*

Severe training or competitions would lead to reduced subsequent training or sport performance. This means that recovery methods play a crucial role in the training and competitive regime of athletes of all levels. Most research on functional recovery involves



sprinting activities, typically found in track and field and team sports. The reason for this is that team sports typically have successive games or training sessions, while track and field events typically have more than one heat in a competition. Thus, complete functional recovery within a short period of time is essential and any intervention that can enhance recovery would be beneficial for the athlete. Endurance athletes, on the other hand, will use recovery interventions to optimize their training, as well as to prevent chronic muscle injuries.

Ali *et al.* (2007) assessed the physiological and perceptual effects of knee-length graduated compression stockings in recreational runners. Participants completed two multi-stage shuttle runs separated by a one-hour recovery period, while either wearing a compression garment (EXP: Venosan, 4001, St. Galen, Switzerland; 18 to 22 mmHg) or a normal athletic sock (C: no compression; ankle-height). There was no difference in total distance completed between the experimental and control trials (EXP:  $2213 \pm 77$  m vs. C:  $2272 \pm 75$  m (first bout) and EXP:  $2247 \pm 84$  m vs. C:  $2225 \pm 67$  m (second bout)). In addition, the average heart rate (EXP:  $\sim 168 \pm 5$  bpm vs.  $\sim$ C:  $167 \pm 3$  bpm), maximum heart rate ( $197 \pm 2$  bpm) perceived soreness (score:  $\sim 2$ ), and exhaustion (score:  $\sim 17$ ) were also similar for the two bouts, as well as between the two trials. Ali *et al.* (2007) suggested that the protocol was perhaps not long enough to induce muscle damage in the recreational athletes.

In the second part of the study fourteen participants completed a fast paced continuous ten-kilometer (km) run on a tarmac track with and without a graduated compression garments in random order. The times during a prior baseline 10-km run was used to determine the runners' pace, which was regulated by frequent time checks and an investigator cycling next to the athlete. No differences were found between the two groups and the two experiments for RPE ratings (EXP:  $17 \pm 0.5$  vs. C:  $17 \pm 0.5$ ) and the comfort-and-feel ratings of the compression garments (score:  $\sim 6$  to 8). Perceived muscle soreness was significantly lower (EXP:  $3 \pm 0.6$  vs. C:  $5 \pm 0.4$ ;  $P < 0.05$ ) 24-hours after the run in the experimental trial. Faster running pace (EXP: 44.7 min vs. C: 45.0 min) and lower heart rates (EXP:  $\sim 176$  bpm vs. C:  $\sim 180$  bpm) were reported for the experimental trial, but these differences were not statistically significant ( $P > 0.05$ ). The researchers concluded that wearing compression stockings during fast-paced activities attenuated muscle soreness in recreational runners, while the runners perceived the mild graduated compression garments as comfortable. However, no performance improvements were





observed and it is impossible to conclude from the results if venous return was improved by the compression garments.

In 2010 Ali and co-authors compared two types of graduated compression stockings, namely low pressure (EXP 1: 12 – 15 mmHg) and high pressure (EXP 2: 23 – 32 mmHg) with a placebo stocking (C: 0 mmHg). Ten distance runners completed three 40 minute treadmill runs at 80%  $VO_{2max}$  ( $\bar{x}$  speed:  $14 \pm 1.4 \text{ km}\cdot\text{h}^{-1}$ ) on separate occasions, under each experimental condition. There were no significant differences in the physiological variables or muscle damage markers between the three trials. However, the participants experienced more discomfort and pain with the higher pressure compression garment compared to the lower pressure and control garments ( $P < 0.05$ ). Even though all the variables, except blood lactate, showed a significant change over time, the muscle damage markers and pressure sensitivity were most pronounced immediately after the treadmill run and almost recovered by 24 hours. Hence the CK and pressure sensitivity did not follow the typical DOMS response with peak values between 24 and 72 hours after exercise (Suzuki *et al.*, 1999). This could indicate that the protocol was not effective in causing muscle damage in the well-trained athletes. The compression garments also did not aid lactate clearance, since lactate concentrations did not change during the 40 minute run, nor differed between any of the groups (C:  $2.6 \pm 0.7 \text{ mmol}\cdot\text{L}^{-1}$  vs. EXP 1:  $3.1 \pm 3.1 \text{ mmol}\cdot\text{L}^{-1}$  vs. EXP 2:  $3.3 \pm 0.7 \text{ mmol}\cdot\text{L}^{-1}$ ;  $P > 0.05$ ).

This research also does not support the findings of Bringard *et al.* (2006<sup>b</sup>), since no improvement in running economy was found with any of the compression garments. This may possibly be explained by the faster running pace of the runners, i.e. the runners ran almost  $2 \text{ km}\cdot\text{h}^{-1}$  faster during this treadmill run compared to those in Bringard's *et al.* (2006<sup>b</sup>) study, despite the fact that the pace was set at 80%  $VO_{2max}$  in both studies. This suggests another possible reason for the lack in results, namely higher fitness levels and experience of the runners. The runners competed regularly in 5 to 42.2 km races and trained between 6 and 16 hours per week. This research (Ali *et al.*, 2010) challenge the idea that compression garments have the same haemodynamic and supportive benefits in well-trained athletes compared to untrained healthy and unhealthy individuals.





Montgomery *et al.* (2008) investigated the effect of various recovery strategies on basketball performance and fatigue-related changes during a 3-day actual tournament. Twenty-nine national level basketball players, training 8 to 10 hours per week ( $\bar{x}$  age:  $19.1 \pm 2.1$  years) were randomly divided into three groups. The groups included the control group i.e. carbohydrate uptake with stretching (C:  $7.7 \pm 1.7$  g.kg<sup>-1</sup>.day<sup>-1</sup>;  $n = 9$ ), and two treatment groups i.e. cold water immersion (EXP 1: at 11°C, 5 x 1 minute;  $n = 10$ ) and compression garments (EXP 2: for about 18 hrs.;  $n = 10$ ). The basketball players played a 48-minute game per day and were assessed pre and post-games. All the players completed functional assessments such as a 20-meter acceleration, line-drill, Yo-Yo level 1 intermittent recovery, vertical jump, agility and flexibility tests. In addition, mid-and calf circumferences were assessed with visual analogue soreness- and fatigue scales. The compression group wore a full-length lower body compression garment (18 mmHg, LineBreak™, Australia).

Compression garments and cold water immersion maintained line-drill performance equally (CG:  $-2 \pm 2\%$  vs. CWT:  $-1 \pm 2\%$  increase in time, respectively) and better than the control ( $0.4 \pm 2\%$  increase in time). The investigators suggested that athletes could expect a 0.15 to 0.5 s improvement in performance. Compression garments had a detrimental effect on 20-meter acceleration compared to the other two groups, with a very large 3% reduction in time (0.11 seconds). None of the groups had a positive effect on agility time; both treatment groups had a large to very large reduction in agility ( $ES = 1.2$  to  $> 2.0$ ). Hamstring range of motion did not improve in any of the groups. The thigh circumferences in the control and compression groups increased (C: 1.2% vs. CG: 0.9%, respectively), but recovered by the morning after the game, whereas the cold water immersion was more effective than the compression garments (only a 0.5% increase).

Both fatigability and muscle soreness were minimized in the cold water immersion and compression groups. The conclusion was that cold water immersion was most beneficial in terms of recovery compared to compression garments. Whether a combination of cold water immersion and compression garments would yield better results, remains to be seen.

Davies *et al.* (2009) investigated the effects of lower body graduated compression tights (15 mmHg at the ankle; 20% Lycra and 80% nylon; LineBreak™) on recovery after plyometric



exercises. The athletes were asked to complete two sessions of 5 sets of 20 drop jumps from a 60 cm platform followed by a maximal upward jump and 2 minutes rest in between sets. The week prior to the first session baseline measurements for agility, countermovement jumps and 5, 10 and 20 meter sprint time were assessed. Blood markers for muscle damage (CK and LDH) and mid-thigh circumferences for swelling, together with perceived muscle damage scores were used to measure muscle damage. After the testing sessions athletes either wore the graduated lower body compression garments (EXP) or no garment (C) for up to 48 hours. Similarly to Jakeman *et al.* (2010) and Kraemer *et al.* (2010), the athletes also slept with the compression garment.

No significant differences were observed in any of the muscle damage variables (CK, LDH and mid-thigh swelling) between the two groups, although both groups reported a significant increase in perceived muscle soreness over 48 hours post-exercise ( $ES = 0.6$ ,  $P = 0.0002$ ). Both the experimental and control groups showed an increase in 10 and 20 meter sprint time from baseline to 48 hours ( $P < 0.01$ ). In addition, the EXP group showed a significant increase in 5 meter sprint time from baseline to 48 hours after the exercise protocol ( $P = 0.01$ ). Even though not statistically significant, on average the sprint speed over all the trials increased slightly more in the EXP trial than the control trial (EXP: ~6% vs. C: 4%;  $P > 0.05$ ). The researchers suggested that the trained athletes were accustomed to the eccentric type exercises and that the compression garment might not have exerted sufficient pressure to induce any performance recovery benefits.

Delayed onset of muscle soreness (DOMS) disrupts proprioception, which in turn negatively impacts performance. Pearce *et al.* (2009) explored the possible influence of compression garments (LineBreak™, Australia, ~ 12 mmHg) on motor control during a visuomotor tracking task. Time wise this was the longest duration study involving sports compression garments, lasting up to 14 days after an eccentric exercise protocol involving elbow exercises. The researchers assessed time course changes in strength and visuotracking ability as well as the influence that compression garments would have on disrupted proprioception. The participants also completed an elbow flexion and extension tracking task.

Twenty-four hours after the eccentric protocol all subjects' strength in their biceps were reduced by ~ 38% ( $P < 0.001$ ) and visuomotor tracking ability was impaired. This indicates that the



eccentric protocol was successful in inducing DOMS. Force production was reduced by about 31% from baseline until 120 hours after exercise and returned to baseline values by days seven and 14. Although there was no significant treatment effect, the experimental group made significantly less errors in the tracking task until 72 hours after the exercise, compared to the control trial ( $P < 0.05$ ). In fact, the experimental group's error scores improved by ~15% above baseline over the 72 hour period, which meant they actually became more accurate. Interestingly the compression garments were not worn continuously, but only during the various tests.

This study thus showed that compression sleeves improve motor performance despite muscle damage. The authors suggested that the compression sleeves provided mechanical guidance and stability, but not physiological recovery such as reduced DOMS. The compression garment thus increases sensory awareness and proprioception by means of a neurophysiologic mechanism. For instance, the pressure exerted by the compression garment could interact with the cutaneous skin afferents and soft tissue which then increases proprioceptive feedback to the brain. As a result the individual is more aware of limb position, has increased muscle activation and better functional motor control (Pearce *et al.*, 2009).

Lepers *et al.* (2010) recently reported that wearing long compression tights during eccentric muscle action circuit activities had neither added benefits, nor detrimental effects on muscular performance. The stretch-shortening activities included 20 meter sprints, 15 x 40 cm hurdle jumps, 8 x 40 cm countermovement jumps and a 90 second downhill run (-5% slope) at 75% of the participant's maximum treadmill speed. There was a similar and significant reduction in 20meter sprint and vertical jump performance for both the experimental and control trials after the circuit training protocol ( $P < 0.05$ ). No significant differences were observed between 20meter sprint velocity (EXP:  $4 \pm 5\%$  vs. C:  $6 \pm 5\%$  reduction), or countermovement jump height. At 6 hours post-exercise the sprint and jump performances returned to baseline values, which could suggest that the protocol was not sufficient in inducing fatigue. However, the findings of this study do not support previous studies that compression garments reduce muscle oscillation upon landing.

Duffield *et al.* (2010) investigated the effects of lower body compression garments (no pressure specified; Bioslyx®, Slazenger, Australia) on the recovery of muscle performance after two



fatiguing sprint and plyometric exercise sessions separated by seven days. High intensity and stretch-shortening cycle (SSC) activities such as those observed in team sport events lead to muscle damage. It is believed that damage to the involved muscle may interrupt contractile function and/ or cellular disturbances in metabolic function (Duffield *et al.*, 2010). The researchers therefore hypothesized that compression garments would either alter contractile function, or limit muscle damage, which would assist performance recovery.

Subjects completed the exercise protocol with and without the compression garments in random order. During the experimental trial, the compression garment was also worn for 24 hours post-exercise. There were no significant differences between the two trials in lactate concentration, pH, CK, C-reactive protein or heart rate. There were also no differences in peak concentric knee extension and flexion force. However, athletes perceived 23% less muscle soreness when recovering with the compression garment ( $P = 0.01$ ;  $ES = 1.1$ ), than without. Thus it seems that compression garments do not aid performance recovery.

### **c. Thermal Response**

Increased core body temperature, usually with a reduction in sweat rate, is associated with an increase in fatigue and reduced performance (McGregor *et al.*, 1999; Millet *et al.*, 2006). Small temperature variations of 1 – 2% can either be beneficial or detrimental to performance (Laing and Sleivert, 2002). Clothing in general can increase physiological as well as cognitive strain if it causes, or contributes to an imbalance in thermal regulation.

Various sporting gear have been developed to aid performances by creating micro climates and maintaining thermal balance. For example, in sprinting activities the athletes would typically benefit from warmer muscles, whereas endurance athletes would benefit from cooling the body (Laing and Sleivert, 2002). The fabric forms a perimeter between the covered body part and the external environment, which alters human thermoregulatory responses. Human thermal steady state is influenced by various factors, i.e. external work done, accumulated heat, metabolic heat production, evaporation, conduction, convection and radiation, of which clothing influences the latter five factors (Laing and Sleivert, 2002). Exercising in hot or humid environments may cause an increase in body temperature. This in return could negatively affect physical performance,



perception and cognitive behaviour. Evaporation is the fundamental method to dissipate heat and is regulated by thermo receptors. The circulation transport heat from the body core to the skin and then disperses heat via sweat (Laing and Sleivert, 2002).

The area of contact between fabric and the cutaneous surface is a complex microclimate. Characteristics of the skin's surface, like the texture and rigidity and ability to deform under pressure influence this parameter. Therefore, heat dissipation relies on the temperature gradient or differences between the skin and ambient air. Journeay *et al.* (2004) have documented a decreased core temperature secondary to increased cutaneous blood flow and sweating when lower body positive pressure was applied, suggesting that during recovery after exercise, clothing, such as compressive garments can alter the transfer of heat from the core to the environment. Evaporation and dissipation of heat through clothing depends on the physical properties of the garment, design, fit, body movement and activity, air velocity, air temperature and humidity.

Some garments may add weight and restrict movement and this will increase metabolic heat. Also, clothing reduces sweat evaporation by increasing the saturation of the layer next to the skin, which is referred to as the microclimate. This means that compression garments may increase heat storage and reduce convective as well as evaporative heat loss (Laing and Sleivert, 2002).

Doan and co-authors (2003) showed that the skin temperature was significantly higher during warm-ups with compression shorts compared to the normal shorts (EXP: 1.09°C vs. C: 0.07°C;  $P = 0.003$ ). This increase in skin temperature could indicate an improved blood flow and muscle temperature. If the garment raises the muscle temperature during warm ups, the muscle will generate force more effectively and be less prone to injury. In addition, if the external pressure improves cutaneous blood flow, the heat evaporation via sweat could increase as well.

All these studies have been done in cool environmental conditions and therefore the increase in skin temperature would not have any detrimental effect on other physiological functions. However, it is possible that during prolonged events compression garments may be detrimental to runners' performances if the increase in temperature causes significant physiological strain



(Duffield and Portus, 2007). On the other hand, this potential negative effect may be offset by high levels of aerobic fitness. Aerobic fitness allows endurance athletes to acclimatize to heat faster due to several training induced factors, such as hypervolemia, lower resting core temperature and an increase in high core temperature tolerance. Also, reduced body fat, typically seen in endurance athletes improves heat dissipation and tolerance (Laing and Sleivert, 2002).

Compression garments may also be able to assist pre-cooling. Cooling the body prior to exercise has been shown to improve distance running performances such as 600 m to 10 km, but not sprinting events. Arngrímsson *et al.* (2004) showed that a cooling vest during a warm up will moderately increase body temperature by 0.4 °C and improve perceptual responses in hot humid conditions. The researchers also suggested that the reduced thermal and cardiovascular strain, as well as perception of thermal discomfort in the initial stages of a race allow runners to run faster at a later stage of a 5 km run.

Hauswirth and Lehénaff (2001) suggested that thermal sensations may influence running economy. However, Bringard *et al.* (2006<sup>b</sup>) found improved running economy without an associated change in temperature in runners with compression garments.

Thermal comfort or enhancing heat balance can also limit fatigue (Millet *et al.*, 2006). Houghton *et al.* (2009) found no thermoregulatory benefits in wearing tight fitting compression garments underneath normal sports attire. The initial assumption was that compression garments would increase heat storage during a simulated hockey game and thus negatively influence thermoregulation. Although cutaneous temperature was about 1°C higher ( $P = 0.03$ ) and sweat rate was slightly higher ( $P = 0.06$ ) in the experimental group with compression garments, there were no differences in terms of physiological or perceptual responses.

Thus, the compression garments did not influence performance or added additional strain and fatigue. Houghton *et al.* (2009) suggested that the increase in cutaneous temperature and higher sweat rate may be due to increased blood flow to the skin or a reduction in sweat evaporation. This research demonstrates that compression garments do not aid cooling, but also does not cause dehydration or affect performance when worn underneath sports attire.



## V. CONCLUSION

In spite of compression garments being successfully applied in the clinical field, it is still debatable whether compression garments are beneficial to sporting performance and recovery from exercise. However, after reviewing the literature, it is clear that evidence for performance enhancement is equivocal, but that there are substantial evidence that compression garments aid recovery after exercise.

Several possible mechanisms have been proposed to explain the recovery benefits of compression garments. These include improving central and local haemodynamics by assisting the muscle-pump action, immobilization of injured muscle, reducing oedema by mechanically pushing water from the tissue into the circulation, limiting muscle damage by physically supporting the involved muscle and improve proprioception thereby limiting fatigue. These mechanisms probably do not function in isolation, but rather combine in different ways and to varying degrees depending on the specific activity.



## CHAPTER THREE

### PROBLEM STATEMENT

#### I. EXISTING LITERATURE ON SPORTING COMPRESSION GARMENTS

Nusser and Senner (2010) showed in a survey that compression garments are most popular amongst endurance athletes, in particular as a recovery intervention. Although compression garments seem like a practical and cost effective recovery aid, limited scientific evidence exists to support anecdotal claims, specifically those related to enhanced performance. For the purpose of this investigation, recovery is defined as the process of returning to one's pre-exercise state (physiological and psychological), more specifically, post-exercise recovery occurs after the cessation of exercise.

Clinical studies have set the foundation for the use of garments with compressive qualities in sporting populations. Since then conventional sports-related research focused on performance benefits in sprint-like activities of short duration. About ten years ago research were more directed towards the post-exercise recovery benefits of compression garments. Initial research concentrated on healthy, untrained individuals, and gradually shifted to physically active individuals. Most research is still laboratory based and involves mostly team sports and sprinting activities.

Eight studies investigated recovery after EIMD (Kraemer *et al.*, 2000; Kraemer *et al.*, 2001<sup>a</sup>; Kraemer *et al.*, 2001<sup>b</sup>; Gill *et al.*, 2006; Trenell *et al.*, 2006; Perrey *et al.*, 2008; Jakeman *et al.*, 2010; Lepers *et al.*, 2010), while 15 investigated recovery of performance after fatiguing protocols (Chatard *et al.*, 2004; Maton *et al.*, 2006<sup>a</sup>; Maton *et al.*, 2006<sup>b</sup>; Duffield and Portus, 2007; Rimaud *et al.*, 2007; Duffield *et al.*, 2008; Montgomery *et al.*, 2008; French *et al.*, 2008; Thedon *et al.*, 2008; Davies *et al.*, 2009; Pearce *et al.*, 2009; Ali *et al.*, 2010; Duffield *et al.*, 2010; Rimaud *et al.*, 2010; Kraemer *et al.*, 2010).

The average age of subjects participating in post-exercise recovery research is  $27 \pm 10$  years and only 4 studies investigated subjects older than 30 years (Maton *et al.*, 2006<sup>a</sup>; Maton *et al.*, 2006<sup>b</sup>;





Pearce *et al.*, 2009; Ali *et al.*, 2010;). Thus far no recovery research has included subjects older than 40 years. The most popular age groups to participate in long distance events are between the ages of 30 and 50 years. In 2009 and 2010, 7401 and 11925 male runners, respectively, (in this age group) completed the Comrades marathon (about 89 km), of which ~50% were between 40 and 50 years old. In addition, the average age in the Comrades marathon was 40 years (Jones, 2010). Furthermore, athletes older than 40 years generally need longer recovery periods after eccentric type activities than their younger counterparts (Dedrick and Clarkson, 1990).

Seven studies investigated the recovery of EIMD of which all, except Gill *et al.* (2006) used an eccentric protocol in controlled conditions to induce DOMS (Kraemer *et al.*, 2001<sup>a</sup>; Kraemer *et al.*, 2001<sup>b</sup>; Trenell *et al.*, 2006; Perrey *et al.*, 2008; Jakeman *et al.*, 2010; Lepers *et al.*, 2010). None of these studies included experienced distance runners. Training reduces the magnitude of muscle damage and conclusions drawn from research based on healthy non-athletic populations would lead to false positive results. In addition, it has been argued that most competitive endurance athletes would have recovered before their next training session and therefore the use of compression garments would be senseless (Barnett, 2006). However, increasing volumes and intensities of endurance training and competitive races would result in chronic muscle injuries (Armstrong, 1986). Hence the compression garment may be beneficial as a long term preventative intervention and not only for acute injuries or acute recovery.

Ten studies investigated the effects of compression garments on distance runners (Berry and McMurray, 1987; Thorsson *et al.*, 1987; Berry *et al.*, 1990; Bringard *et al.*, 2006<sup>a</sup>; Bringard *et al.*, 2006<sup>b</sup>; Ali *et al.*, 2007; Kemmler *et al.*, 2009; Ali *et al.*, 2010; Rimaud *et al.*, 2010; Sperlich *et al.*, 2010). All studies were laboratory based with mostly short duration, incremental treadmill protocols to assess performance. The exceptions were the research done by Ali *et al.* (2007 and 2010) which included protocols up to 40 to 60 minutes (< 10 kilometers) in controlled environments. In addition, only Ali *et al.* (2010) investigated the recovery of performance in distance runners after fatiguing protocols. The rest of the research are limited to short duration, sprinting type protocols, which are typically associated with team sports and sprinting activities.

Only two sports-related studies investigated the use of compression garments in a real life situation (Gill *et al.*, 2006; Montgomery *et al.*, 2008), while four studies simulated real life



situations such as matches and practice sessions under controlled conditions (Duffield and Portus, 2007; Higgins *et al.*, 2007; Duffield *et al.*, 2008; Houghton *et al.*, 2009). All of these studies were aimed at team sports such as netball, basketball, rugby and cricket. Field studies in sport physiology research are very limited, probably because of the associated poorer experimental control and logistical challenges. Laboratory-based research is therefore more prevalent, as it is more controlled and easier to conduct (Dimsdale, 1984).

The question must be raised to what extent laboratory based research can be extrapolated to real life applications. Physiological measures are susceptible to behavioural influences which only occur during real life situation. For example, blood pressure responses differ between clinical settings and at home (Dimsdale, 1984). This means that athletes may respond differently in real life situations, which would also imply different responses in the laboratory and in the field with compression garments. Furthermore, recovery is typically studied after eccentric protocols or maximal exercise protocols, whereas most sporting disciplines, especially endurance events, occur at submaximal intensities (Cortis *et al.*, 2010).

Despite all these shortcomings in the literature, it seems that compression garments may be a realistic, viable and cost effective recovery intervention after exercise (Kraemer *et al.*, 2001<sup>a</sup>; Kraemer *et al.*, 2001<sup>b</sup>; Thedon *et al.*, 2008; Kraemer *et al.*, 2010;). However, none of the previous studies have addressed the issue of when to wear compression garments for optimal benefits or have established the ideal pressure gradient for different populations. In most studies, subjects wore the compression garment after the fatiguing or eccentric protocol, or during the exercise in the case of performance studies. In only four studies (Berry and McMurray, 1987; Berry *et al.*, 1990; Davies *et al.*, 2009; Duffield *et al.*, 2010) were compression garments worn during exercise and recovery. There is thus no conclusive evidence to show that compression garments should be worn either during exercise, or during recovery, or perhaps during exercise and recovery.

It is still necessary to establish the optimal pressures which would ensure a favourable haemodynamic response as well as enhanced proprioception and recovery in athletes. The variations in pressure classes between countries may contribute to the inconsistencies between findings of different studies. Partsch (2003<sup>b</sup>) and Perrey (2008) also stated that compression data is meaningless if the method by which compression was measured is not stated. Twenty five



of the research papers do not specify the exact pressures exerted by the compression garments. Furthermore, only two studies used a placebo garment (Higgins *et al.*, 2007; Ali *et al.*, 2010). To date most researchers used compression garments with pressures less than 30 mmHg at the ankle. Several studies, especially those on experienced athletes, have attributed the poor responses to insufficient pressure or that the exercise protocol was not of high enough intensity to elicit a response (Montgomery *et al.*, 2008; Davies *et al.*, 2009; Ali *et al.*, 2010; Duffield *et al.*, 2010; Lepers *et al.*, 2010).

Interpreting previous research and drawing definitive conclusions are problematic in light of the many factors that may affect the results. These include differences in conditioning levels of the subject populations, study designs, protocols and methodology (instrumentation, measurements and procedures), types of compression garments and the various pressure gradients, as well as differences in the application of compression. Therefore it is still debatable whether compression garments are beneficial to sporting performance and recovery from exercise. Thus, more research, especially in real life situations, are needed to investigate this matter further.

## **II. THE RESEARCH OBJECTIVES OF THE STUDY**

The present study was divided into two separate but related parts, which endeavoured:

To determine the efficacy of graduated knee-high compression socks as a post-exercise recovery modality in experienced long distance runners after an actual long-distance event, as well as the optimal timing for the application of compression to achieve the most, if any, benefits.

Specific questions:

- (i) Would compression garments reduce the recovery time of trained distance runners so that they may return to training sooner?
- (ii) Will compression socks limit skeletal muscle damage, as observed through attenuated responses in muscle damage and inflammatory markers, such as serum CK, s-Mgb and hsCRP?



- (iii) Is there a change in blood lactate concentration as a result of wearing compression socks during and/or after exercise?
- (iv) Do compression socks reduce symptoms associated with exercise induced-muscle damage, i.e. swelling, perceived muscle soreness, fatigue as well as diminished muscular strength and power, during and/or after exercise?
- (v) Does compression socks affect functional capacity of runners during the recovery period i.e. will their running economy be reduced during the 24 – 72 hour recovery period?
- (vi) Are compression socks practical and convenient for athletes to use during competition?
- (vii) Does compression during exercise have more recovery benefits than compression only after exercise?
- (viii) Is there a more attenuated recovery response when athletes wear compression socks for longer periods of time?

Part I investigated specific questions i – v, and Part II examined specific questions vi and viii. In other words part I set out to determine if compression socks aided distance runners' recovery in a real life situation, whereas part II assessed the ideal time to wear compression socks i.e. during or after exercise.

### **III. JUSTIFICATION AND BENEFITS OF THE RESEARCH OUTCOME(S).**

Compression garments may be a viable recovery intervention for experienced distance athletes who are accustomed to high volumes and intensities of workloads. The rationale behind compression garments is that it allegedly improves peripheral circulation and venous return (Agu *et al.*, 2004), improves clearance of blood lactate (Chatard *et al.*, 2004), reduces muscle



oscillation (Kraemer *et al.*, 1998<sup>a</sup>; Doan *et al.*, 2003), maintains explosive power (Kraemer *et al.*, 1996; Kraemer *et al.*, 1998<sup>a</sup>; Kraemer *et al.*, 1998<sup>b</sup>), improves clearance of markers of muscle damage, such as CK (Gill *et al.*, 2006) and reduces fatigue (Theidon *et al.*, 2008).

Prolonged running events like marathons and ultra-marathons are demanding on runners. These endurance events may deplete energy reserves and trigger EIMD and injury (Myburgh, 2003). All of these factors would lead to a long recovery period, which would mean an extended absence from races and training. Thus ineffective recovery would be detrimental to running performance and cause injury in future activities (Barnett, 2006; Meeuwisse *et al.*, 2007). Optimizing post-exercise recovery after training and races will be beneficial to the subsequent training and performance of competitive athletes over a period of time.

Participation in sport is encouraged for a range of social-economical and health reasons, nevertheless to be enjoyable participation should be safe and pose minimal risks. Furthermore, competitive athletes and their management will seek any advantage when training and preparing for events. Hence, these research questions (section II) are applicable to sports development, in view of the fact that recovery modalities form part of athletes' training regimes.

Injuries may be a recurrence of previous injuries or due to fatigue, and this makes appropriate recovery/prevention programs more crucial. This research project will focus on an appropriate population, namely serious recreational and competitive athletes, who will benefit directly from the outcomes. Most sports-injury research is conducted on the incidences and causes of injuries, while a small number of studies concentrate on implementation, prevention and post-exercise recovery strategies. However, only research that can be implemented into practice will prevent injuries and aid recovery. Another unique feature of this research is that most studies focused on a younger population (~27 years) whereas this investigation has look at a population that reflects the general age group of endurance runners more precisely.

Equipment plays a major role in injury prevention, as it can prevent injuries but at the same time can also cause injuries in sport. This means that all possible recovery gear and devices need to be well inspected to insure its authenticity. Consequently, sport scientists need to know if compression socks truly aid recovery or hinder it. Therefore by investigating compression socks



as a recovery strategy and informing athletes and their management whether compression socks are a practical recovery method, this research project aims to bridge the divide between research in sports recovery and the athlete.

## CHAPTER FOUR

### METHODOLOGY

#### I. RESEARCH DESIGN

This study followed a field-based experimental design to investigate the effects of graduated compression socks on distance runners' recovery. To assess recovery, various tests were performed before an actual road race, and for 72 hours following the race.



Figure 4.1 Schematic design of the research project.

To answer the specific research questions, as well as for practical reasons, the project was divided into two parts. Part I investigated specific questions i – v (page 66 - 67), and Part II examined specific questions vi and vii (page 67), with reference to specific questions I to V. In other words, part I set out to determine if compression socks aided distance runners' recovery in a real life situation (specific questions I to V), whereas part II assessed the ideal time to wear compression socks, i.e. during or after exercise (specific questions (VI to VII). Part I addressed the research objectives as a single blind randomized controlled trial and part II was a randomized controlled trial. To prevent conscious and/or unconscious prejudiced interpretation, subjects were masked to the actual purpose of the study.

### **a. Research Parameters**

The following parameters of recovery were assessed, namely:

- i. muscle damage
- ii. lower limb swelling
- iii. metabolic responses
- iv. functional capacity
  - a. muscular function (explosive power)
  - b. oxygen consumption at sub maximal running intensity
- v. viability of compression socks as a recovery aid

The following tests were administered to assess the aforementioned parameters:

- i. enzyme markers for s-Mgb, serum CK and hsCRP together with Visual Analogue Scales (VAS) for the perceived muscular pain and discomfort in the calf, *Quadriceps* and *Hamstrings* muscles;
- ii. lower limb circumferences in the ankle, mid-calf and mid-thigh;
- iii. blood lactate concentrations with a portable lactate analyser;
- iv. countermovement jump (CMJ) test and running economy (RE);
- v. viability questionnaires.

### **b. Place of Study**

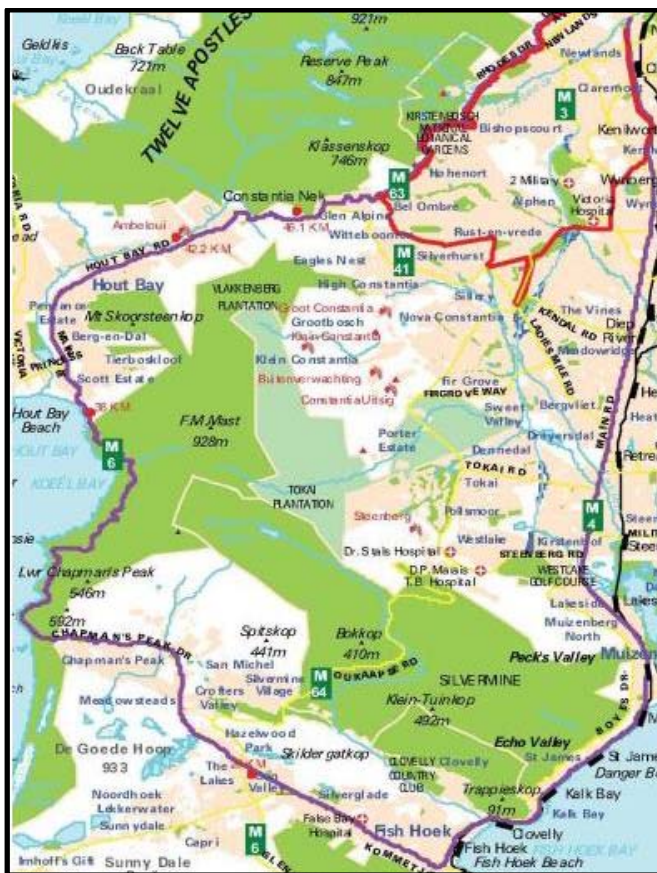
All subjects had to complete a 56 km ultra-marathon road race, followed by a 72-hour follow-up recovery period. Subjects performed testing on six different occasions (*Figure 4.1*), of which the two baselines visits (visit 0 and 1) and the three recovery phase visits (visit 3 to 5) took place at the Sport Physiology Laboratory (Stellenbosch University, South Africa). Visit 2 took place at the venue directly after the 56km road race. Testing was done at temperatures between 18 and 20 °C. Blood sample analyses were done by *PathCare* pathology laboratories in the Western Cape (South Africa).





### c. The Long Distance Event

The course is a 56 km (35 miles) IAAF (*International Association of Athletic Federations*) certified route. The same race was selected for both parts of the research to ensure subjects are tested under similar weather and environmental conditions. The average temperature during the race on the two occasions was 18.8°C and 18.4°C, respectively (South African Weather Services, Kirstenbosch weather station, Western Cape). The purple line on *Figure 4.2* indicates the 56 km route.



*Figure 4.2* The 2009 and 2010 Two Oceans ultra-marathon route. (Courtesy of the *Two Oceans* organizers).

The runners started in Newlands (elevation 20 m above sea level, ASL) and ran along the Main Road to Fish Hoek (12 m ASL), then to Chapman's Peak Drive (180 m over 5 km ASL), Hout Bay (39 m ASL), Constantia Nek (215 meters for over 4 km ASL), Rhodes Drive, and Union Avenue and they finished at University of Cape Town's (UCT) sports grounds (85 m).

Figure 4.3 illustrates the route profile. The route is flat for the first 28 kilometers, with the first major elevation at the start of Chapman's Peak, and the second elevation from Hout Bay up to the highest point (Constantia Nek). Thereafter the route is undulating up to the finish at UCT sports grounds.

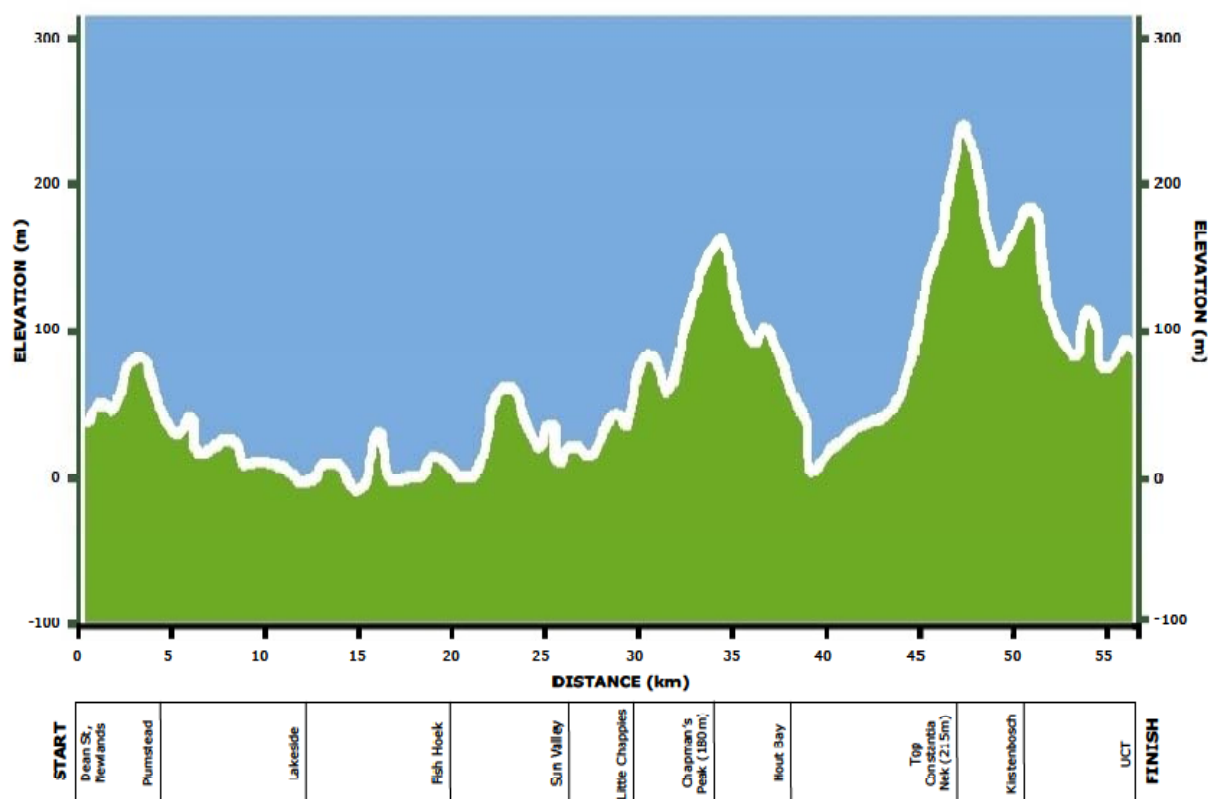


Figure 4.3 Two Oceans ultra-marathon profile. (Courtesy of the Two Oceans organizers).

#### d. Laboratory Visits

Baseline testing started 8 weeks prior to the ultra-marathon. At the time the runners were in their race preparation phase and have already reached a competitive level of fitness for the race. Visit 0 was the first of two baseline visits. Subjects were familiarized during this session with the testing equipment and procedures, i.e. the treadmill (h/p/cosmos/Saturn), metabolic analyser (Cosmed Quark CPET) and heart rate monitor (POLAR®). To determine the correct sock sizes, lower limb circumferences were also measured, according to the manufacturer's guidelines. The study protocol was carefully explained to the athletes as well as the informed consent, dietary

guidelines, and exercise guidelines for the 24 hours prior to all the visits. Furthermore, subjects completed a general health questionnaire, namely the PAR-Q in accordance with the American College of Sports Medicine's (ACSM; Whaley *et al.*, 2006) guidelines, a general information questionnaire about training, best marathon times in the last 12 months, as well as injuries in the last three months. After a written informed consent was acquired, the subject's anthropometric profile and maximum aerobic capacity ( $VO_{2max}$ ) were assessed to obtain baseline values. Visits 0 and 1 were separated by a one to seven week race preparation phase, in which the participants were allowed to train and participate in their normal running program. However, the seven days prior to the race (visit 2), subjects were asked not to perform any hill training, run up or down stairs, jumping or plyometric exercises, lower body resistance training, strenuous training (heart rate above 70% of maximum heart rate), or run any races (the participants were asked to taper the fourteen days prior to the race).

Visit 1 was the second baseline visit and took place in the 7 days prior to the race. This ensured that the subjects had reached their intended race fitness level and since they were tapering during this period, no inflammation or muscle damage were evident. The baseline muscle damage and inflammatory markers were collected, together with blood lactate concentration. Subjects completed VAS questionnaires and their baseline body composition, lower limb circumferences and running economy were assessed.

Visit 2 took place directly after the 56 km race. Runners were asked not to consume any food or fluid with calorie content during the last 5 kilometers of the race. Blood samples were taken ten to 15 minutes after the race for enzyme analysis. Blood lactate concentrations were measured 15 minutes and 30-minute after the race. Subjects completed the VAS questionnaires and body composition analysis. Subsequent to the 30-minute lactate sample, subjects performed a countermovement jump test.

During visits 3 to 5, subjects were re-assessed for three days in a controlled laboratory environment. Blood samples were taken at 24, 48 and 72 hours for blood lactate, serum CK, s-Mgb and hsCRP analysis. Subjects completed VAS questionnaires, running economy tests and countermovement jump tests to assess functional capacity. Three limb girths were measured to quantify possible swelling in the lower extremities. In the 72 hours after the race, the athletes



had to refrain from any form of exercise, until the last blood sample was taken at 72 hours post-exercise. Participants were also asked to avoid any form of recovery methods, such as massage, ice-, water or heat therapy and stretching, ultrasound, active recovery, anti-inflammatories (including non-steroidal anti-inflammatory drugs; NSAID) and nutritional supplements during the three days after the race. Subjects kept a journal to indicate daily activities and dietary intake during the 72-hour recovery period (*Appendix F*).

To standardise the subject's metabolic states during the experimental period subjects were asked not to consume any food or drink with calorie content three hours prior to testing. If participants had to eat in the three hours before any visits to the laboratory, they were asked to have a light meal. Subjects performed tests at approximately the same time of the day. Measurements were conducted in the morning, between 05:00 and 12:00. The ingestion of diuretics, such as products with caffeine and alcohol was avoided at least 12 hours prior to testing. Subjects were expected to be rested before testing. If not, the test was rescheduled. In the 24 hours before visits zero, one, three, four and five, subjects were asked to avoid exercise and vigorous activities – above 70% of maximum age predicted heart rate - or unaccustomed exercise.

## II. ETHICS

The study proposal was approved by the Ethics Committee of Research Sub-committee A (Stellenbosch University; reference number: 125/2008). Subjects were required to give their written informed consent before participating in the study, in accordance with the *Declaration of Helsinki*. The research was conducted in agreement with the *Medical Research Council (MRC)* and *South African Good Clinical Practice (GCP)* guidelines. The researcher supported the principles governing both ethical conduct of research and the protection at all times of the interest, comfort and safety of the participants.

During visit 0, the informed consent form (*Appendix A*) was explained verbally to each subject and opportunities for questions were allowed. The subjects also read the consent form in their own time. The subjects were educated about the relevance of the study but they were kept blind to the true purpose and benefits of the compression socks by only giving them limited



information. Any possible risks were explained to them and indicated in a research outline (Appendix B).

### **III. SUBJECTS**

Subjects were competitive male athletes who completed the Two Oceans ultra-marathon in 2009 and/or 2010 (see page 76 under *sub-section a*, for an explanation of competitive athletes). Male runners aged 27 to 57 years volunteered to participate in the research. Initially 54 runners volunteered for part I and 52 for part II. In part I, three of the subjects fell ill, three were injured, three were disqualified from the study (did not adhere to the protocol) and five did not complete the race. A similar pattern was seen in part II. Two of the subjects got sick, three became injured, one was disqualified from the study and three did not complete the race. In the end, a total of 40 and 43 injury free distance runners participated in part I and part II, respectively. Subjects were selected on a voluntary basis and included if they met the study inclusion criteria. Runners were divided randomly into the various experimental (EXP) and control (C) groups.

#### ***a) Inclusion and Exclusion Criteria***

Subjects were healthy male volunteers – according to the *American College of Sport Medicine's* (ACSM; Whaley *et al.*, 2006) apparently healthy category - between the ages of 30 to 57 years. Participants had no history of musculo-skeletal, metabolic, cardiovascular, respiratory, haematological or endocrine disorders. Subjects were excluded if they participated in lower body weight training exercises in the three months prior to the study. However, participants were allowed to do own body weight exercises for general strength and conditioning, such as *Pilates*. Subjects on medication were either excluded or followed a washout period of two weeks prior to the race, supervised by their general practitioner. They could resume their medication at the end of the 72-hour recovery period. Subjects had to train on averaging at least 40 kilometers and four training sessions a week for the 12 weeks prior to the start of the project. Only competitive distance runners were included, however, they were not elite or professional athletes. For the purpose of this study competitive distance runners were defined as athletes (including triathletes) that participate in running events on a regular basis, of distances longer than 21 km,



with best marathon times under four and a half hours, or completed at least one ultra-marathon in the 12 months prior to the study.

## ***b) Groups***

Participants were randomly divided into various groups for part I and part II of the research project.

### *i. Part I*

Participants were randomly divided into two groups i.e. the experimental compression sock group (CS) and the control (C) group. The control group received a placebo knee-high sock which exerted no compression. In addition, none of the subjects were ever informed of the true purpose of the study, to avoid prejudiced views that could interfere with their responses to the subjective questionnaires. However, the runners were told that the purpose of the study was to investigate the effects of different types of compression socks on the recovery of distance runners, in particular higher and lower compression socks. Runners had to run the 56 km race with the compression or placebo sock, as well as wear the compression socks after the race for 72 hours. They were allowed to take the socks off while sleeping, showering and/or bathing.

### *ii. Part II*

There were three groups in part II of the research project, i.e. (a) the recovery group (CS<sub>Rec</sub>), wearing the compression sock only during the 72 hour recovery period post-race; (b) the exercise group (CS<sub>Run</sub>), wearing the compression sock only during the race; and (c) the exercise and recovery group (CS<sub>Run&Rec</sub>), wearing the compression sock during the 56 km race and the 72 hours recovery period. Those who wore the compression sock after the race were allowed to take the socks off while sleeping, showering and/or bathing.



#### **IV. COMPRESSION AND PLACEBO SOCKS**

During the initial baseline visit (visit 0) each subject's running shoe size (UK size), lower leg length, ankle and mid-calf circumference were documented. These records were used to select the correct sock size according to the sock company guidelines. The correct compression sock size should cover the widest circumference of the calf muscle in a standing position, up to just below the patella.

##### ***a. Compression Sock Fit***

Socks were removed when the participants' dominant limb and circumferences were measured. With a steel tape measure (Rosscraft®, Canada) the narrowest circumference at the ankle just above the *malleoli* of the dominant leg was measured. The widest circumference at the calf was measured in a standing position. Lower leg length was only assessed during baseline. The length was measured from the heel, with the ankle at 90° to avoid the feet being in plantar flexion, to the bend of knee (*tibiale laterale* anatomical site). The subject was barefoot and standing.

##### ***b. Compression***

A higher than typically used compression sock was selected for this study, namely a class II compression (European *RALL* guidelines). The highest pressure (~30 mmHg) was at the foot and ankle and the lowest pressure (~20 mmHg) was just below the knee. Class II graduated compression is typically prescribed for patients with deep vein pathology. The reason for this choice in pressure is due to limited effects that have been reported in previous research, which made use of lower compression garments.

##### ***c. Compression Sock Material and Manufacture***

The closed toe compression socks (20 – 30 mmHg Class II RxFit Style; C-Sock) were supplied by Medis® (Brackenfell, South Africa). The socks are composed of Elasthane (Spandex) and *Coolmax* (Elastomide). *Coolmax* is a fabric that does not retain moisture but allows evaporation from the skin causing a cooling effect.





#### ***d. Placebo Sock Material and Manufacture***

The placebo sock for the control group, in part I of the research project, was a knee-high *All Sport Sock* purchased from the sports company Under Armour® (Baltimore, USA), and are composed of 85% Olefin, 14% Nylon and 1% Lycra® Spandex (referred to as *HeatGear®* performance). The sport sock increases airflow through vented sides, allowing cooling of the legs during running.

### **V. MEASUREMENTS AND TESTING PROCEDURES**

The subjects underwent a series of anthropometric, physiological and physical measurements before and after the 56 km road race and during the 72-hour recovery phase. All the tests and measurements are standardised tests and protocols for athletes according to the Australian sports commission (Gore, 2000; Eston and Reilly, 2003).

#### ***a. Anthropometrical Measurements***

Anthropometrical measurements were taken during the baseline visits (visit 0 and 1), as well as directly after the race and at 24, 48 and 72 hours. For all assessments, subjects were bare feet and were dressed in their clubs' running gear. Testing was done three hours post-prandial and prior to any physical activity. All anthropometrical measurements were taken on the right-hand side of the body, according to the ISAK protocol (Marfell-Jones *et al.*, 2006).

##### *i. Body Mass*

Subjects' body mass was determined using a calibrated electronic scale (UWE BW – 150 freeweight, 1997 model, Brisbane Australia), and recorded to the nearest 0.1 kg. The weighing scale was zeroed on a level surface before the measurement was taken. The subject was then asked to stand in the centre of the scale, distributing his body mass evenly without support and looking straight ahead before the body mass was recorded.





## ii. Stature

The subject was positioned against a wall and stature was measured with a sliding steel anthropometer (Siber-Hegner GPM, Switzerland). The anthropometer was held vertically to a wall and perpendicular to the floor. The subject stood bare feet with his heels together and upper back, buttocks and heels against the wall. The mid-line of the body was positioned in-line with the measuring tape, in front of the subject. The sliding anthropometer was placed firmly on the highest point of the subject's skull (Vertex), while the head was in the Frankfort plane, with the lower edge of the eye socket (*Orbitale*) in line with the indentation superior to the tragus of the ear (*Tragion*), in the horizontal plane. The measurement was taken as the subject inhaled and then exhaled. Stature was defined as the distance between the transverse planes of the highest point on the skull and the inferior aspect of the feet, at right angles. Measurements were taken to the nearest 0.1 centimeter (cm).

## iii. Bioelectrical Impedance Analysis (BIA)

A portable body composition monitor was used to assess the subjects' lean and fat mass (Bodystat® *Quadscan 4000*, 2008; Isle of Man, UK). Lean mass comprises the bony skeleton, muscle mass, innards and entire water content of the body, while fat mass is only the adipose tissue. Subjects were requested to lie in the supine position, and the electrodes were connected to the right hand and foot. The skin was wiped with an alcohol swab before placing the electrodes on the standard anatomical sites. The first electrode was placed on the dorsal side of the hand, one centimeter proximal to the knuckle of the middle finger, with the second electrode on the wrist next to the wrist joint (between the head of the *ulnar* and *radius*). The remaining two electrodes were placed on the dorsal surface at the base of the foot and one centimeter proximal to the joint of the second toe (next to the big toe), and on the ankle at the level of the protruding bones (medial and lateral *malleoli*) on the side of the ankle. The subject's limbs were not to touch the centre of their bodies or each another. Subjects had to empty their bladders beforehand and avoid exercise, drinking diuretics such as alcohol, coffee and certain teas 12-hours prior to testing. The leads were paired into red and black attachments, with the red lead always connected to the current – introducing electrode and the black lead connected to the detector electrode. After the electrodes were positioned, the paired leads were connected to the



corresponding electrodes. All measurements were taken while the subject was relaxed for approximately 20 minutes.

#### iv. Girths

All circumference measurements were taken in the anatomical position, according to the standard ISAK (International Standards for Anthropometric Assessment; Marfell-Jones *et al.*, 2006) protocols. All measurements were obtained without the compression socks. Three girths were taken to determine the circumferences of the athletes' lower limbs: calf, ankle, and mid-thigh. Two sets of measurements were obtained. If one set differed by more than 2 mm from another the measurements were taken again. Girths were measured with a spring-loaded, non-extensible anthropometric tape measure (Rosscraft®, Canada). All measurements, except the ankle, were recorded at the point where the circumference was the greatest. The measuring tape was held horizontally, at right angles to the limb and without compressing the subcutaneous tissue. A cross-hand technique was used, with the zero mark on the more lateral side of the subject at the designated anatomical landmark. Measurements were recorded to the nearest millimeter (mm). All measurements were taken while the athlete stood upright, with legs slightly apart and body mass evenly distributed on a portable wooden anthropometrical stand/box (dimensions: 40 cm (height) by 30 cm (width) by 50 cm (length)). Measurements were obtained without the compression socks on the dominant leg and were marked with a permanent marker after the race and remarked throughout the recovery period to ensure the precision of measuring sites.

Mid-thigh: The subject stood on a 40 cm box with arms crossed at the chest so that the measurement could be taken at eye level. The measurement was taken midway between the *trochanterion* and lateral border of the *tibia*, at the *mid-trochanterion-tibiale laterale* site.

Mid-calf: The subject stood on a 40cm box, with arms hanging at the sides. The steel tape was applied perpendicular to the long axis of the leg, around the maximum girth of the calf muscle (the medial calf site). The anthropometric tape was moved up and down the calf, until the maximum girth was obtained.



Ankle: The subject stood on a 40cm box, with arms hanging at the sides. The steel tape was placed tightly around the minimum circumference, proximal to the *malleolus* of the *tibia* and *fibula* of the leg and superior to the *sphyrion tibiale*. The anthropometric tape was moved up and down the lower leg, until the minimum girth was obtained.

#### v. Lengths

Lengths are measured as the vertical distances from the standing surface, while the subjects stood with their feet together, and their arms hanging at their sides in the upright position. The direct method was used. The measurement was taken from landmark to landmark. Only one length was assessed namely the *tibiale* laterale height, by using a segmometer (Rosscraft®, Canada) and a 40 cm box. The vertical distance was taken from a standing position to the *tibiale* laterale site.

#### b. Physiological Assessment

These measurements included the assessment of oxygen consumption ( $VO_2$  and  $VO_{2max}$  in millilitres per minute per body mass;  $mL \cdot min^{-1} \cdot kg^{-1}$ ), minute ventilation (VE in litres per minute;  $L \cdot min^{-1}$ ), respiratory exchange ratio (RER) and running economy (RE in millilitres per minute, per body mass to the power of 0.75;  $mL \cdot min^{-1} \cdot kg^{-0.75}$ ). All physiological measures were assessed with a metabolic analyser system (*Cosmed Quark CPET (Cardiopulmonary exercise testing)*, 2009; Rome, Italy) on an *h/p/COSMOS Saturn* treadmill (Nussdorf-Traunstein, Germany). Maximal aerobic capacity ( $VO_{2max}$ ) and peak treadmill velocity (PTV) were assessed during visit 0. These two measurements were not repeated. Running economy (RE) was assessed during visit 1 for baseline values and re-assessed during visits 3, 4 and 5 but not directly after the race (visit 2).

#### i. Maximum Aerobic Capacity Test

A progressive incremental exercise test to exhaustion was performed during the initial baseline session (visit 0) on the *h/p/COSMOS Saturn* treadmill (Nussdorf-Traunstein, Germany), to assess maximum aerobic capacity, peak treadmill velocity, anaerobic threshold and relevant heart rates



(HR in beats per minute; bpm). The treadmill was interfaced with specialized computer software (*Cosmed Quark CPET*, 2009; Italy). By using breath-by-breath analysis together with a telemetric heart rate monitor (POLAR®, Polar electro Oy, Finland), the *Cosmed* software calculates and records exercise intensity and selected cardiorespiratory parameters continuously throughout each test.

*Maximum Aerobic Capacity Protocol ( $VO_{2max}$ )*: Prior to the maximal incremental test the athletes were informed once more of the safety and emergency equipment and asked to empty their bladders. Next a heart rate monitor (POLAR®, *Polar Electro*; Oy, Finland) and an adjustable safety harness were strapped on, and positioned according to the athlete's comfort. To make sure the athletes were properly warmed up, prepared, and accustomed to the treadmill, each participant had to warm-up for five minutes at their own pace. Hereafter the treadmill was stopped and the runner was allowed to drink water before a soft plastic mask was placed over his face. The maximal test to exhaustion was performed, with increments of one kilometer per hour, every three minutes, up to thirteen kilometers per hour. Then both the speed and incline increased by one kilometer per hour ( $\text{km}\cdot\text{h}^{-1}$ ) and 1% every two minutes. At sixteen  $\text{km}\cdot\text{h}^{-1}$  the speed increased by one kilometer per hour ( $\text{km}\cdot\text{h}^{-1}$ ) every minute and the incline by 1% (6 degrees) every two minutes, until the subject reached exhaustion.

The test was terminated when the subject reached exhaustion. The standardised criteria of exhaustion are defined as the stage where two of the following criteria are met: (i) the  $VO_2$  does not increase by more than 150 ml per successive workload, (ii) a respiratory quotient (RER) value equal or above 1.15 is reached, (iii) heart rate is more than 90% of the theoretical maximal heart rate (bpm) and (iv) the rating of perceived exertion (RPE) is above 19 (Martin *et al.*, 1998). To prevent blood pooling after the maximal test, subjects were cooled down for five minutes from eight to zero  $\text{km}\cdot\text{h}^{-1}$ , until their heart rate dropped to 130 bpm or lower.

Throughout the incremental test, breath-by-breath gases were continuously recorded. The gases, flow and volumes of the expired breaths were sampled through the turbine flow meter and gas sampling line. These variables were analysed by the cardiopulmonary



metabolic analyser system (Cosmed®, *Quark CPET*; Rome, Italy). The gas analysers were calibrated prior to each test with atmospheric gas and known gas concentrations (16% O<sub>2</sub>, 5% CO<sub>2</sub>, balance N<sub>2</sub>) and the turbine flow meter was calibrated with a 3-litre (L) calibration syringe. Heart rate was measured throughout the tests via telemetry (Polar®, *Polar electro*; Oy, Finland) interfaced with the metabolic system.

*Anaerobic Threshold (AT)*: The anaerobic threshold was determined through the specialized computer software analysis (*Cosmed Quark CPET*, Rome, Italy) during the incremental maximum aerobic test. Anaerobic threshold (AT) was defined as the point where a non-linear increase in the production of carbon dioxide (VCO<sub>2</sub>) occurred when plotted against the subject's oxygen consumption (VO<sub>2</sub>) (Wassermann *et al.*, 1973). The anaerobic threshold value was expressed as an absolute value (mL.min<sup>-1</sup>.kg<sup>-1</sup>) and/or percentage of VO<sub>2max</sub> (%VO<sub>2max</sub>). The heart rate (HR) and velocity (km.h<sup>-1</sup>) at which anaerobic threshold (AT) occur were determined through computer software analysis of the *Cosmed* system. In case of an unclear inflection point, the *dual criteria* were used to verify AT. The *dual criteria* is the identification of an inflection in the ventilatory equivalent for oxygen (VE/VO<sub>2</sub>) plot whilst the ventilatory equivalent for carbon dioxide (VE/VCO<sub>2</sub>) remains constant or an inflection in the end-tidal oxygen partial pressure (P<sub>ET</sub>O<sub>2</sub>) plot whilst end-tidal carbon dioxide partial pressure (P<sub>ET</sub>CO<sub>2</sub>) remains constant (Cooper and Storer, 2008).

*Heart rate*: Maximum heart rate (HR<sub>max</sub>) and 1-minute post-exercise heart rate recovery (HRR) were measured with a heart rate monitor (POLAR®, Polar Electro Oy, Finland). Average heart rates during tests as well as during the actual race were recorded. The heart rates were used to assess the runners' recovery, as well as to determine, very basically, if there is an increase in venous return. This is based on the assumption that an increase in venous return will result in an increase in end diastolic volume and stroke volume, thus heart rate will decrease to maintain cardiac output (Ali *et al.*, 2007).



## ii. Running Economy

By measuring steady-state oxygen consumption during submaximal running at a given velocity running economy is estimated (Saunders *et al.*, 2004<sup>a</sup>). This means that running economy – the oxygen cost of running – is defined as the energy demand for a given velocity of submaximal running and is determined by measuring the steady state consumption ( $\text{VO}_2$ ) and the respiratory exchange ratio (RER). For the running economy-protocol the runner's body mass was taken into consideration ( $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-0.75}$ ). Therefore running economy is reported to the power of 0.75 of body mass, which according to various authors are important when assessing running economy between or within groups with different body mass (Saunders *et al.*, 2004<sup>b</sup>; Helgerud, 1994). Running economy was assessed on the h/p/COSMOS Saturn treadmill (Nussdorf-Traunstein, Germany) during visit 1 (baseline) and then following the ultra-marathon race at 24, 48 and 72 hours (visit 3 to 5). Even though the assessment took place in a laboratory which differs from over ground running, it will give an accurate representation of how economical the runner is. The steady-state running protocol was adapted from Chen and co-authors (2008) and a pilot study was performed with test-retest correlation coefficients for reliability ( $r = 0.89$ ).

*Running Economy (RE) Protocol:* The running economy protocol was standardised by asking subjects to wear the same shoes and clothes in which they ran the race, follow the same nutritional diet and to be tested at the same time of day. These requirements will limit typical error of measurement. The participant was not fitted with the adjustable safety harness and was not allowed to warm up. The runners ran for 5 minutes at their average Two Oceans pace with a gradient of 1%. To ensure it was submaximal running, this pace did not exceed the runner's anaerobic threshold pace predetermined during the baseline  $\text{VO}_{2\text{max}}$ . The 1% gradient simulated the external factors most accurately according to Jones and Doust (1996). The same treadmill velocity at baseline (visit 1) was used for all assessments. Heart rate was monitored via telemetry (Polar®) interfaced with the same metabolic system used during the  $\text{VO}_{2\text{max}}$  (Cosmed®, Quark CPET). The expired respiratory gas was analysed continually through the computer software. Running economy was calculated through the average steady-state values of  $\text{VO}_2$ , VE and RER parameters from the last 60 seconds (s) of the 5 minute run on each test. The heart rate (bpm) of the final 30 seconds was used for



further analysis. In addition, the  $VO_2$  and running speed data for every 10 seconds were plotted on a graph. From this data, the slope was determined, which also indicates the running economy. Running economy can be expressed as the volume of oxygen consumed per distance covered ( $\text{ml.kg}^{-1}.\text{m}^{-1}$ ) or the distance covered per volume of oxygen consumed ( $\text{m.ml}^{-1}.\text{kg}^{-1}$ ) or expressed as the rate of oxygen consumption for a given running velocity ( $\text{mL.min}^{-1}.\text{kg}^{-1}$ ). The latter will be used for this study and the subject's body mass will be taken into account ( $\text{mL.min}^{-1}.\text{kg}^{-0.75}$ ).

### ***c. Haematological Assessments***

Muscle damage and inflammation were evaluated through venous blood samples and analysed for the biological markers i.e. serum CK (unit per litres;  $\text{units.L}^{-1}$ ), s-Mgb (nanograms per millilitre;  $\text{ng.mL}^{-1}$ ) and hsCRP (milligram per litres;  $\text{mg.L}^{-1}$ ). Whole plasma lactate concentrations (LT in millimol per litre;  $\text{mmol.l}^{-1}$ ) were collected by means of a capillary sample with a finger prick. Blood samples were transported immediately after collection in a special cooler bag (Fridge-to-go®, South Africa) to the nearest *PATHCARE* (PTY) Ltd Laboratory where qualified phlebotomists performed all analyses. Samples were coded to ensure investigators were unaware of the results and were sent electronically and via hard copies to the researcher to ensure confidentiality. The electronic versions were encrypted. Specialized software provided by *PathCare* was able to decrypt the results (*PathCare DECRYPT*®). This ensured that no unauthorized person had access to the results.

#### ***i. Biological Marker Analysis***

Blood samples for enzymatic analysis were collected the week before the road race, and then 15 minutes and 24, 48 and 72 hours following the race. All the blood samples, except the samples after the race, were taken under resting and three hours post-meal conditions. Five millilitres blood samples were drawn from an antecubital vein in the forearm using a needle, syringe, and *Vacutainer* test tubes, by a trained phlebotomist. Heparinised test tubes with lithium heparin were used (green tubes) as an anticoagulant for plasma analysis and orange gel tubes with clotting agents for serum analysis. The samples were transported to the pathology laboratories



within one hour after collection. The laboratories processed and centrifuged the blood samples (1500 x g) and then analysed it for the specific enzyme markers.

Blood lactate samples were collected with a lancet device (*Softclix*®, Boehringer Mannheim) and measured with an automated blood lactate meter (*Lactate Pro*, Arkray Inc., Kyoto, Japan). A resting blood sample was collected prior to the race. Lactate samples were also collected following the race, at 15 and 30-minute intervals, as well as at 24, 48 and 72 hours.

*Skeletal Myoglobin (s-Mgb)*: Skeletal myoglobin was determined by the *Stratus CS STAT* fluorometric analyzer (Dade Behring Incorporated 1998, Newark, Denmark). The Stratus CS system is a STAT, random access analyser that provides quantitative assessment from either direct, closed tube sampling of whole blood (heparin) or plasma (heparin). A heparin (whole blood) tube is inserted into the cannula and loaded on the instrument. A method specific *TestPak* was selected. The *TestPak* contains all the reagents necessary to perform the s-Mgb test. The assay procedures are two-site sandwich assays, which use solid-phase Radial Partition Immunoassay (RPIA) technology, enhanced through the utilization of STARBURST (Dow Chemical Company, Midland, MI) dendrimers. This binds the capture antibody to the solid phase, providing a high degree of analytical sensitivity and precision. In the assay procedure, dendrimer linked monoclonal antibody is delivered to the center portion of a square piece of glass fiber paper in the reagent *TestPak*. The sample is then added to the paper and the analyte of interest is bound to the dendrimer linked antibody at a distinct antigenic site on the molecule. After a short incubation time, a conjugate reagent containing enzyme-labelled monoclonal antibody directed against a second distinct antigenic site on the analyte of interest is pipetted onto the reaction zone of the paper. During this second incubation period, enzyme-labelled antibody reacts with the bound analyte of interest, forming an antibody-antigen labeled antibody sandwich. The unbound, labelled antibody is eluted from the reaction zone by applying a substrate wash solution. By including a fluorescent substrate for the enzyme within the wash solution, initiation of enzyme activity occurs simultaneously with the wash during this step of the process. The reaction rate is measured by an optical system that monitors this rate via front surface fluorescence. The rate of the





fluorescent signal produced by the bound enzyme fraction is compared with the stored calibration curve to determine the concentration of analyte in the sample. All data analysis functions are performed by the microprocessor within the analyser.

*Serum Creatine Kinase (CK):* Creatine kinase activity was assessed with the *Beckman Synchron LX/CX* (California, United States of America). This procedure employs the original *Rosalki* method for CK analysis. CK reagent is used to measure the creatine kinase activity by an enzymatic rate method. In the reaction creatine kinase catalyzes the transfer of a phosphate group from the creatine phosphate substrate to adenosine diphosphate (ADP). The subsequent formation of adenosine triphosphate (ATP) is measured through the use of two coupled reactions catalyzed by hexokinase (HK) and glucose-6-phosphate dehydrogenase (G6PDH) which results in the production of reduced  $\beta$ -nicotinamide adenine dinucleotide phosphate (NADPH) from  $\beta$ -nicotinamide adenine dinucleotide phosphate (NADP). The CK assay contains the activator monothioglycerol. The *Beckman Synchron LX® System* (California, United States of America) automatically proportions the appropriate sample and reagent volumes into the cuvette. The ratio used is one part sample to 20 parts reagent. The system monitors the change in absorbance at 340 nanometers. This change in absorbance is directly proportional to the activity of creatine kinase in the sample and is used by the *Beckman Synchron LX® System* to calculate and express creatine kinase activity.

*Ultrasensitive C-reactive Protein:* hsCRP reagent was used to measure the hsCRP concentration by a turbidimetric method. In this reaction, C-reactive protein combines with a specific antibody to form insoluble antigen-antibody complexes. The *Synchron LX® System* automatically proportions the appropriate sample and reagent volumes into a cuvette. The ratio used is one part sample to 26 parts reagent. The system monitors the change in absorbance at 340 nanometers. This change in absorbance is proportional to the concentration of hsCRP in the sample and is used by the system to calculate and express hsCRP concentration based upon a single-point adjusted, pre-determined calibration curve.



***Blood Lactate Concentration:*** Concentrations were measured with an automated blood lactate meter (*Lactate Pro*, Arkray inc., Kyoto, Japan). Before each sample was collected the subject was requested to warm up his hands, by pulsating their fingers to enhance blood flow to the fingertips. For each sample, the subject's fingertip was cleaned with an alcohol swab prior to the finger prick. To prevent damaging blood cells and interstitial fluid discharge with the sample, the subject's fingers were on no account squeezed for blood. A cotton swab was used to wipe off the first blood droplet and then the next droplet of blood was collected on the lactate strip. Alternate fingers were used with each finger prick and cotton swabs were used to stop any additional bleeding of the subject's finger. In addition, the measurement of blood lactate via finger prick blood sampling has a measurement error of 1 – 2 mmol.l<sup>-1</sup> (Swart and Jennings, 2004), which were considered during analysis.

#### ***d. Physical Assessments of Functional Performance***

Lower body peak power was determined, as a functional ability test, with the FitroDyne® TENDO weightlifting analyzer (*TWA*; FitroDyne® Tendo Sport Machines; Trencin, Slovakia Republic). Maximal countermovement jumps (CMJ) were used to evaluate functional capacity of the lower body, specifically the explosiveness of the muscles in the lower extremities. The CMJ is typically described as a quick bend in the knees during which the body's centre of mass is lowered before being pushed upwards. During this action eccentric muscle action stores elastic energy that is released after concentric muscle action, referred to as the stretch-shortening cycle (Zatsiorsky and Kraemer, 2006).

##### ***i. Maximal Countermovement Jump Protocol***

The subjects were weighed prior to performing the maximal countermovement jump (CMJ) test. For this test, the subject stood upright, hands on the hips, with his heels and feet on the floor hip-width apart. This was the starting position for all the jumps. The FitroDyne TWA unit cord was attached to the back waistband around the runner's waist. The subject was then asked to squat down to a comfortable level and the FitroDyne TWA cord was centred behind his back. Therefore, when the runner squatted down the cord was perpendicular to the FitroDyne TWA unit. The base



of the TWA unit was positioned on the mat behind the subject. Masking tape was used as a marker behind the ankles of the runners in order for the runners to reposition them after each jump. Each subject was precisely instructed on how to perform the CMJ and it was stressed that the primary objective was to jump as high as possible. Subjects were allowed a supervised practice jump to correct any inaccurate technique. The body mass and the predetermined filter (30 cm) were inserted into the FitroDyne TWA microcomputer. This allowed the FitroDyne TWA to calculate power output in watts.

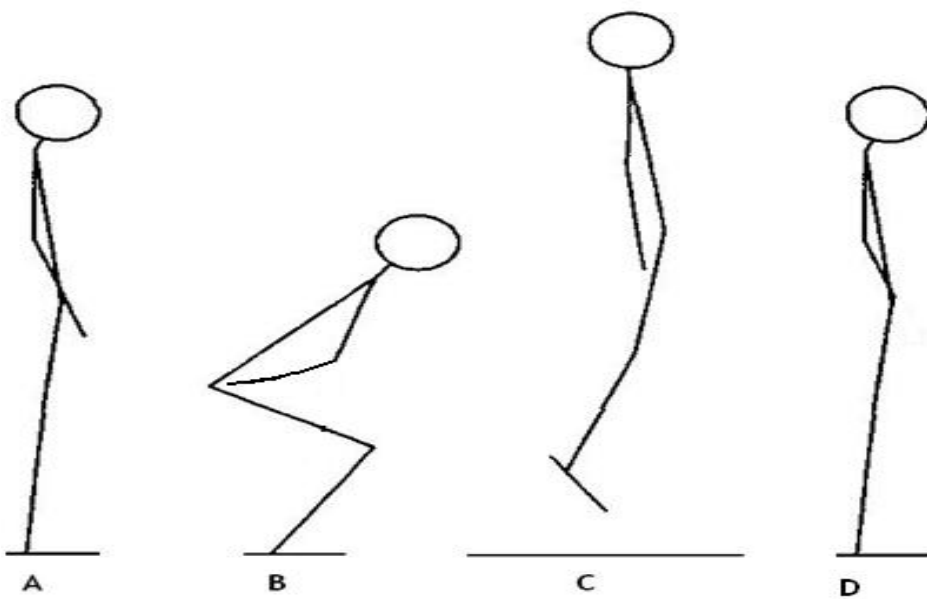


Figure 4.4 Illustration of the countermovement jump sequence.

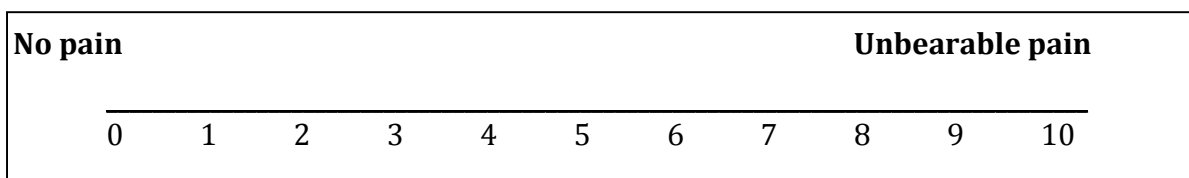
Subjects were not allowed to use their arms during the jump. After the practice jump, the next three jumps were recorded and the best of the three trials was taken as the final score. The jump was performed from an upright body, the subject's body dropped, knees bend and the subject would jump as high as possible, while keeping his arms on the hips (Figure 4.4). For all jumps the degree of knee bend was self-determined by each subject. After each jump the runner repositioned himself and waited until residual fatigue passed before attempting the next jump. Investigators supervised all jumps to ensure proper technique and safety. The CMJ test was conducted during the second baseline meeting (visit 1), after the race and at 24, 48 and 72 hours. Units of measurement were in Watts. The FitroDyne TWA unit computed peak power according to the speed of movement in the concentric phase of the jump test, and the athlete's body mass (kg).

**e. Questionnaires**

The participants were requested to complete a consent form, appropriateness-and-convenience questionnaire and a personal information form. The appropriateness-and-convenience questionnaire (*Appendix D*) evaluated the practicality and comfort of the compression socks. Whereas the data obtained from the personal information form (*Appendix C*) informed the investigator about the participants’ activity levels, training history and general health status. Subjects were also asked to complete visual analogue scales (VAS), which assess muscle pain and discomfort in the lower body at rest, in movement, while stretching and when applying pressure (*Appendix E*).

*i. Visual Analogue Scale*

The subjective Visual Analogue Scale (VAS) was used (Brunier and Greydon, 1996; Grant *et al.*, 1999), which rated the perceived muscle pain or discomfort before the race, after the race and at 24, 48 and 72 hours subsequent to the race. The VAS consists of a ten-centimeter (0 to 10 cm) line labelled with “no pain” on the extreme left end (0 mark) and “unbearable pain” on the extreme right end (10 mark). To quantify the perceived muscle pain, the subject marked the VA scale with a pencil. The score was rounded off to the nearest one millimeter from the left.



*Figure 4.5* A schematic representation of the visual analogue scale, which was used to assess perceived muscular pain and discomfort.

In part I of the research the VA scales assessed muscular pain or discomfort in the knee extensor muscles (*Quadriceps*), the knee flexor muscles (*Hamstrings*) and the calf muscle (*Gastrocnemius and Soleus*). Perceived muscle soreness scores were taken while (i) the athlete was in a resting state, lying supine on a plinth/mat, (ii) while stretching, (iii) whilst pressure was applied to the muscle belly and (iv) whilst doing daily activities.

At rest: Subjects were lying down on a plinth/mat and asked to relax. The subject was then questioned about muscular pain or discomfort in his muscles whilst he was inactive. Subjects were not allowed to move or stretch the relevant muscle group.

Pressure response: Pressure was applied for three seconds to the muscle belly site of the *Quadriceps* muscles. The muscle belly is a more suitable site for measuring pain related to pressure than the musculo-tendinous sites (Baker *et al.*, 1997). Subsequently muscle discomfort due to the pressure was assessed.

During stretching: Subjects were asked to assess the muscular distress, irritation, and/or soreness during stretching in the involved muscles. The stretch position was held for 15 seconds in both legs.

Daily activities: Subjects were asked to rate their muscle soreness during daily activities such as climbing stairs, sitting down and walking.

For part II of the research the subjects were asked to rate their perceived muscular pain and discomfort on a similar VA scale overall in the knee extensor muscles (*Quadriceps*), the knee flexor muscles (*Hamstrings*) and the calf muscle (*Gastrocnemius and Soleus*).

## ii. Journals

Subjects kept a journal of their daily activities and dietary intake during the experimental period (*Appendix F*). The journal included content of food intake, as well as the time and duration of activities. The journal was given to the runners at baseline and collected after the last session at the laboratory (visit 5).

## VI. STATISTICAL ANALYSES

The Centre for Statistical Consultation (Stellenbosch University) was consulted prior to the start of the research project. Results from a previous study, with similar subjects and parameters, were used to estimate the sample size. The recommended sample size was 12 participants per



group. The level of significance was set as  $P \leq 0.05$ , effect size = 1, and statistical power at 80% for all analysis. Statistical analysis was performed with Statistica software® (Version 9 STATSOFT, USA), GraphPad Software (GraphPad Prism® version 5.03 for Windows, San Diego California USA) and Microsoft Office Excel (Windows®, 2007; USA).

Descriptive data were reported as mean ( $\bar{x}$ )  $\pm$  SD, unless otherwise specified. Effects of the graduated compression sock on recovery (muscle damage markers, blood lactate, circumferences and peak power) before and after the distance event were illustrated as the mean change (%  $\pm$  SEM). Each change score was expressed as a percentage of the baseline test score. The exceptions to this were the visual analogue scales which are shown in raw units of measurement (*Mean* ( $\bar{x}$ )  $\pm$  SEM).

Differences between variables were assessed through either a two- way (Part I) or mixed model (part II) ANOVA for repeated measures on all outcome variables (a multivariate analysis). Significant differences among mean values were identified by using the Post-hoc Fischer Least Significant Difference (LSD) test. Effects were characterized for their practical (clinical) significance rather than simple interpretations of statistical significance and hypothesis testing. Effect sizes were assessed with the following criteria: < 0.2 trivial, 0.2 – 0.6 small, 0.6 – 1.2 moderate, 1.2 – 2.0 large and > 2.0 very large (Batterham and Hopkins, 2006; Cohen, 1990). All effect sizes were based on absolute values not relative percentage change. The Area Under the Curve (AUC) analysis is the total area under the integrated graph for serum concentration of CK, s-Mgb and hsCRP (percentage change in concentration), lower limb circumferences (percentage change in circumferences) and blood lactate concentration (percentage change in concentration) and were calculated using standardized trapezoidal methods (Pruessner *et al.*, 2003).



## CHAPTER FIVE

### RESULTS PART I

#### I. DESCRIPTIVE CHARACTERISTICS

##### a. Subject Characteristics

Forty male runners participated in Part I of the study. Twenty-one runners were in the experimental group (CS) and nineteen in the control group (C). The subjects in the CS group wore the compression socks during the race, as well as for 72 hours after the race but did not sleep in the compression socks. The subjects in the control group wore placebo socks during the race only. No significant differences were observed for age, height, body mass, percentage body fat or training status at baseline between the CS and C groups (*Table 5.1*;  $P > 0.05$ ).

*Table 5.1* The anthropometrical and training characteristics (*Mean* ( $\bar{x}$ )  $\pm$  *SD*) of the runners ( $n = 40$ ).

<i>Variables</i>	<i>Experimental (CS)</i>	<i>Ranges</i>	<i>Control (C)</i>	<i>Ranges</i>
<b>Age (years)</b>	43 $\pm$ 7	32 - 55	41 $\pm$ 9	31 - 56
<b>Height (cm)</b>	180.0 $\pm$ 6.8	163 - 190	179.6 $\pm$ 7.1	166 - 191
<b>Body mass (kg)</b>	78.5 $\pm$ 10.2	57 - 97	81.7 $\pm$ 9.6	68 - 99
<b>BMI (kg.m<sup>-2</sup>)</b>	24 $\pm$ 2	20 - 31	25 $\pm$ 3	21 - 27
<b>Body fat (%)</b>	13.6 $\pm$ 3.1	8 - 19	14.6 $\pm$ 3.3	9 - 22
<b>Training Volume (days/w<sup>-1</sup>)</b>	5 $\pm$ 1	4 - 6	5 $\pm$ 1	4 - 6
<b>Training distance (km.w<sup>-1</sup>)</b>	75.6 $\pm$ 17.1	60 - 110	73.5 $\pm$ 14.6	60 - 100
<b>AT (%)</b>	82.6 $\pm$ 4.4	74 - 91	83.6 $\pm$ 2.4	80 - 87
<b>VO<sub>2max</sub> (mL.kg<sup>-1</sup>.min<sup>-1</sup>)</b>	50.9 $\pm$ 6.9	41 - 62	49.7 $\pm$ 8.3	36 - 61
<b>V<sub>max</sub> (km.h<sup>-1</sup>)</b>	15.5 $\pm$ 1.5	13.5 - 19	15.4 $\pm$ 1.1	14 - 17

*AnT*, anaerobic threshold, *V<sub>max</sub>*, peak treadmill velocity, *BMI*, body mass index; *VO<sub>2max</sub>*, maximum aerobic capacity

In the 6 weeks prior to the 56 km race the runners trained on average between 60 to 110 km.w<sup>-1</sup> and 4 to 6 sessions a week. The best marathon time between the groups did not differ significantly (EXP: 03:36:18  $\pm$  00:39:18 vs. C: 03:35:54  $\pm$  00:29:53 hh:mm:ss;  $P = 0.34$ ) nor was there any significant difference in maximum aerobic capacity of the two groups ( $P = 0.65$ ). The



runners' aerobic capacities were classified as *Excellent* for their age and gender (Brooks *et al.*, 2005) and they had between 2 and 32 years running experience.

There were no statistically significant differences between groups at baseline for muscle damage markers, lower limb circumferences, total body water content, countermovement jump performance or running economy (Table 5.2). Baseline values for serum CK concentrations were within the normal resting range for both groups (Mougios, 2007).

Table 5.2 The baseline data for muscle damage markers, lower limb circumferences, countermovement jump performance and running economy (*Mean* ( $\bar{x}$ )  $\pm$  *SD*).

Baseline Data	Experimental (CS)	Control (C)	Effect size
<b>Creatine Kinase (units.L<sup>-1</sup>)</b>	188.7 $\pm$ 137.3	160.6 $\pm$ 80.4	0.25 <sup>S</sup>
<b>Skeletal Myoglobin (ng.mL<sup>-1</sup>)</b>	33.2 $\pm$ 12.9	36.1 $\pm$ 20.6	0.18 <sup>S</sup>
<b>Ultrasensitive C-Reactive Protein (mg.L<sup>-1</sup>)</b>	0.8 $\pm$ 0.8	2.2 $\pm$ 5.4	0.39 <sup>S</sup>
<b>Ankle Circumference (cm)</b>	22.1 $\pm$ 1.5	22.3 $\pm$ 1.4	0.12 <sup>N</sup>
<b>Mid-Calf Circumference (cm)</b>	37.8 $\pm$ 2.1	38.7 $\pm$ 2.3	0.41 <sup>M</sup>
<b>Mid-Thigh Circumference (cm)</b>	51.1 $\pm$ 3.3	52.3 $\pm$ 3.3	0.38 <sup>S</sup>
<b>Blood Lactate (mmol.L<sup>-1</sup>)</b>	1.4 $\pm$ 0.5	1.5 $\pm$ 0.5	0.20 <sup>S</sup>
<b>Total Body Water (L)</b>	46.1 $\pm$ 5.2	47.7 $\pm$ 3.8	0.37 <sup>S</sup>
<b>Running economy (ml<sup>-1</sup>.min<sup>-1</sup>.kg<sup>-0.75</sup>)</b>	115.1 $\pm$ 17.1	118.8 $\pm$ 11.2	0.30 <sup>S</sup>
<b>Peak Power (Watt)</b>	1649 $\pm$ 303	1788 $\pm$ 269	0.30 <sup>S</sup>

Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small, <sup>M</sup> medium

#### **b. The 56 km Ultra-Marathon Race**

Table 5.3 summarizes the performances of the two groups during the ultra-marathon race and indicates that there were no statistically significant differences in performance. Subjects ran on average five hours forty-nine minutes at a heart rate of ~153 bpm. Even though the runners in the CS group ran about ~13 minutes faster than those in the C group, this difference was not statistically significant ( $P = 0.34$ ) and only a small practical difference.





*Table 5.3* The performance results of the runners during the Two Oceans 56 km race  
(Mean ( $\bar{x}$ )  $\pm$  SD).

Variables	Experimental (CS)	Control (C)	Effect Size
Race Pace (min.km <sup>-1</sup> )	00:06:06 $\pm$ 00:00:43	00:06:18 $\pm$ 00:00:43	0.28 <sup>s</sup>
Race time (hh:mm:ss)	05:41:23 $\pm$ 00:44:48	05:54:36 $\pm$ 00:40:55	0.32 <sup>s</sup>
Heart rate (bpm)	155 $\pm$ 8	152 $\pm$ 6	0.28 <sup>s</sup>

Effect sizes: <sup>s</sup> small

## II. DETERMINANTS OF POST-EXERCISE RECOVERY

### a. Exercise Induced Muscle Damage

#### i. Skeletal Myoglobin (s-Mgb) Activity

*Figure 5.1* illustrates the changes in s-Mgb concentrations over the experimental period as a percentage of baseline values. A significant main effect of time ( $P < 0.01$ ) was observed, with peak levels directly after the race in both groups. There was no significant main group ( $P = 0.64$ ) or group x time interaction effect ( $P = 0.10$ ).

The absolute values for s-Mgb concentration are presented in *Table 5.4* and shows that there were significantly higher levels of s-Mgb in the C group directly after the race (46% higher) compared to the CS group ( $P = 0.04$ ). The differences at all the time points varied between small and moderate practical significance, with a negligible difference at 24 hours post-exercise. Although the total s-Mgb (AUC) concentrations between the two groups over the experimental period was not statistically significantly different (CS:  $927.4 \pm 398.6$  ng.mL<sup>-1</sup> vs. C:  $1357.0 \pm 584.8$  ng.m.L<sup>-1</sup>;  $P = 0.39$ ), the difference was, however, of large practical significance ( $ES = 0.96$ ). As mentioned before, all effect sizes are based on absolute values not relative percentage change.



Table 5.4 Skeletal myoglobin concentrations (ng.mL<sup>-1</sup>) in the control and experimental groups (Mean ( $\bar{x}$ )  $\pm$  SD).

Assessments	Experimental	Control	Effect size
Baseline	33.2 $\pm$ 13.0	36.1 $\pm$ 20.6	0.18 <sup>S</sup>
Post	675.0 $\pm$ 422.1	1072.4 $\pm$ 761.3*	0.67 <sup>M</sup>
24 hours	162.5 $\pm$ 78.7	169.5 $\pm$ 97.0	0.08 <sup>N</sup>
48 hours	52.8 $\pm$ 22.3	71.5 $\pm$ 52.4	0.47 <sup>M</sup>
72 hours	41.0 $\pm$ 15.3	51.0 $\pm$ 30.3	0.42 <sup>M</sup>

\* Significant difference between CONTROL and EXP,  $P = 0.04$ ; Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small, <sup>M</sup> medium

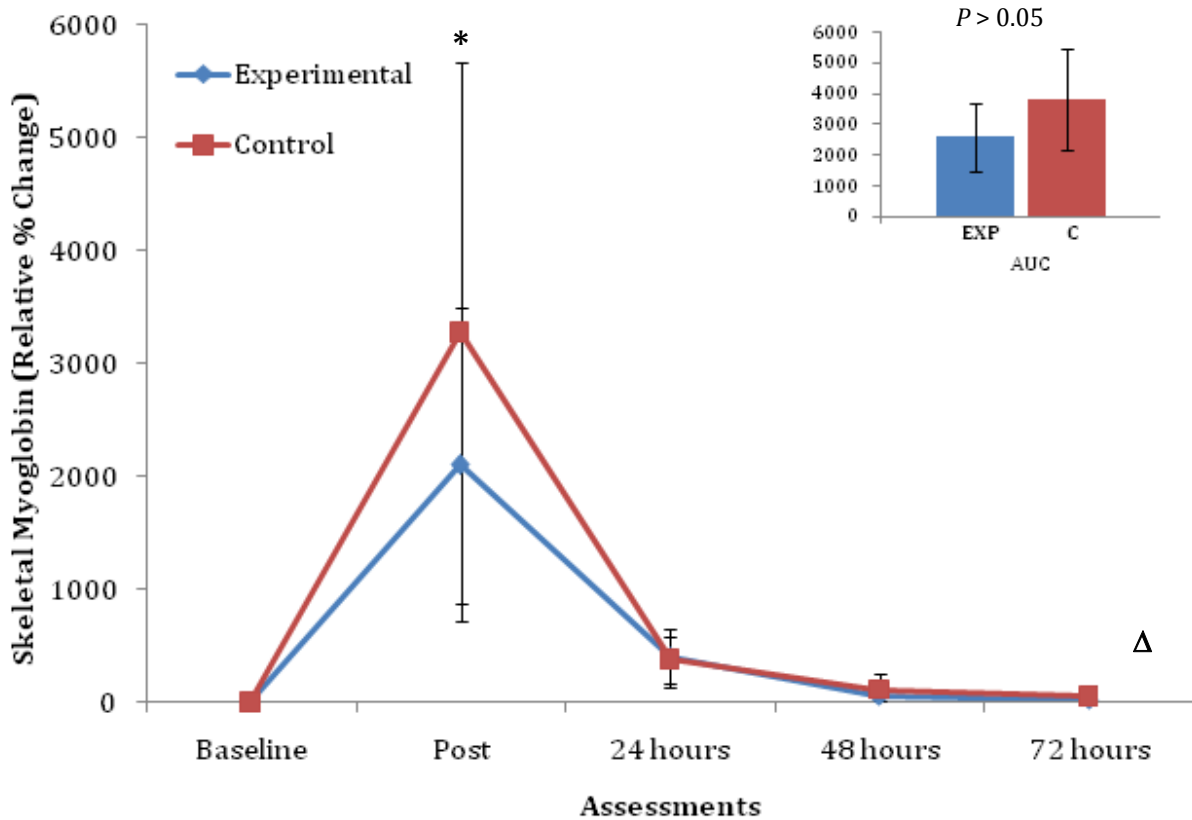


Figure 5.1 The relative percentage change in skeletal myoglobin concentration (error bars: SEM) in the CS (  $\blacklozenge$  ; EXP) and C groups (  $\blacksquare$  ; CONTROL). \*Significant difference between CONTROL and EXP;  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

ii. Serum Creatine Kinase (CK) Activity

Figure 5.2 illustrates that serum CK concentrations were significantly elevated above baseline concentrations in both groups over the study period ( $P < 0.01$ ). The CS group tended to have a lower percentage gain in serum CK levels compared to the C group at 24 hours after the race (CS:  $951 \pm 799\%$  vs. C:  $1293 \pm 971\%$ ;  $P = 0.06$ ). However, no significant interaction effect ( $P = 0.94$ ) or main group effect were found ( $P = 0.09$ ).

Table 5.5 summarizes the absolute values for serum CK over the study period, together with effect sizes between the two groups. There were only small practical differences in the absolute values between the two groups at each time point ( $ES = 0.16 - 0.35$ ). However, there was a moderate practical significant difference ( $ES = 0.46$ ) in the total serum CK concentrations over the whole study period (AUC), with the CS group showing smaller increases at all the time points (CS:  $3629.6 \pm 1560.8$  units.L<sup>-1</sup> vs. C:  $4331.9 \pm 1863.8$  units.L<sup>-1</sup>;  $P = 0.81$ ).

Table 5.5 Serum creatine kinase concentrations (units.L<sup>-1</sup>) throughout the study period (Mean ( $\bar{x}$ )  $\pm$  SD).

Assessments	Experimental	Control	Effect size
<b>Baseline</b>	188.7 $\pm$ 137.3	160.6 $\pm$ 80.4	0.25 <sup>s</sup>
<b>Post</b>	494.2 $\pm$ 240.5	532.2 $\pm$ 247.7	0.16 <sup>s</sup>
<b>24 hours</b>	1702.3 $\pm$ 1036.4	2004.3 $\pm$ 1184.9	0.28 <sup>s</sup>
<b>48 hours</b>	1039.3 $\pm$ 648.2	1306.4 $\pm$ 909.5	0.35 <sup>s</sup>
<b>72 hours</b>	598.9 $\pm$ 435.0	817.4 $\pm$ 732.4	0.37 <sup>s</sup>

Effect sizes: <sup>s</sup> small

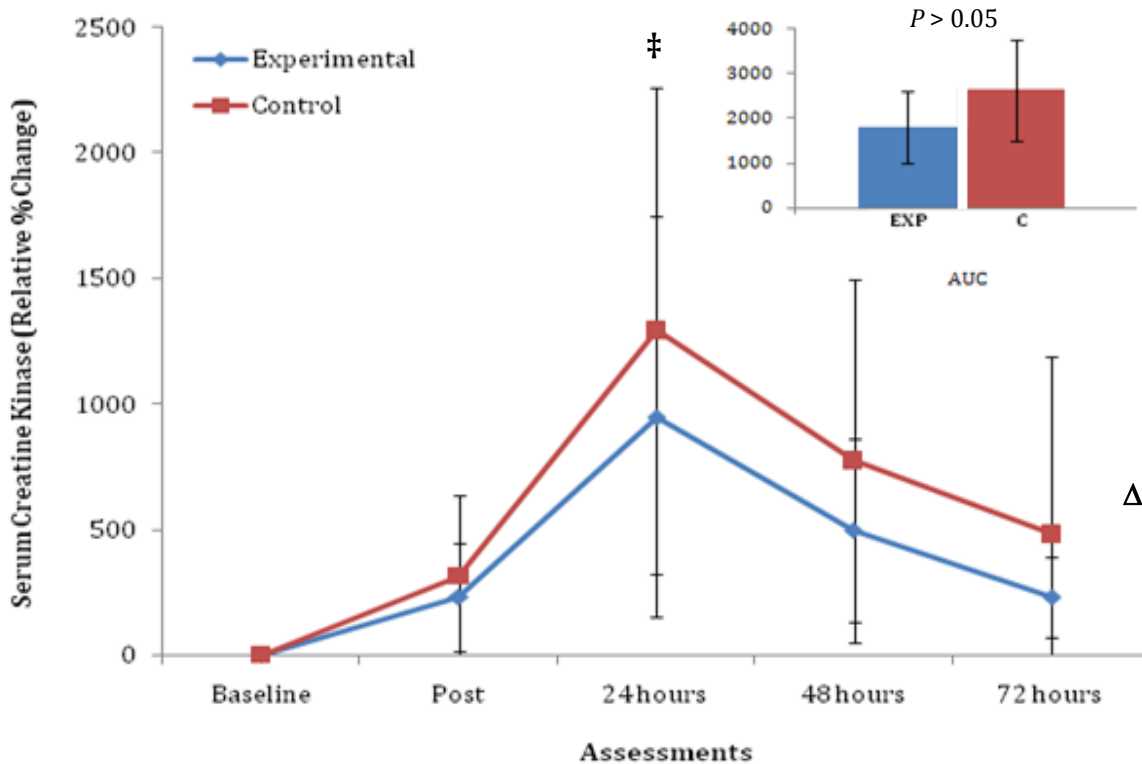


Figure 5.2 The relative percentage change from baseline in serum creatine kinase concentrations (error bars: SEM) in the CS group ( ◆ ; EXP) and the C group ( ■ ; C). ‡Tendency towards significant difference in % gain ( $P = 0.06$ ); ΔSignificant change over time ( $P \leq 0.01$ ).

### iii. Ultrasensitive C - reactive Protein (hsCRP)

Changes in hsCRP are shown in Figure 5.3 and Table 5.6. For both groups there were significant elevations in hsCRP levels above baseline after the race ( $P < 0.01$ ), with peak levels at 24 hours after the race. However, no significant main group ( $P = 0.57$ ) or interaction effect (time x group) were apparent ( $P = 0.99$ ). Furthermore, analysis of effect sizes revealed negligible to small effect sizes at all assessment points (Table 5.6).

Table 5.6 The ultrasensitive C - reactive protein (mg.L<sup>-1</sup>) activity (Mean ( $\bar{x}$ )  $\pm$  SD) levels in the runners.

Assessments	Experimental	Control	Effect size
Baseline	0.8 $\pm$ 0.8	2.2 $\pm$ 5.4	0.39 <sup>S</sup>
Post	2.4 $\pm$ 6.1	2.8 $\pm$ 6.0	0.07 <sup>N</sup>
24 hours	25.1 $\pm$ 16.6	26.8 $\pm$ 16.5	0.11 <sup>N</sup>
48 hours	13.1 $\pm$ 9.3	14.3 $\pm$ 9.1	0.13 <sup>N</sup>
72 hours	5.9 $\pm$ 3.9	6.8 $\pm$ 4.0	0.24 <sup>S</sup>

Effect sizes:<sup>N</sup>negligible,<sup>S</sup>small

There was no statistically significant difference in total ultrasensitive C - reactive protein (AUC) concentrations between the two groups (CS: 43.9  $\pm$  19.6 mg.L<sup>-1</sup> vs. C: 48.4  $\pm$  21.4 mg.L<sup>-1</sup>;  $P = 0.87$ ), and the practical difference was also small ( $ES = 0.24$ ).

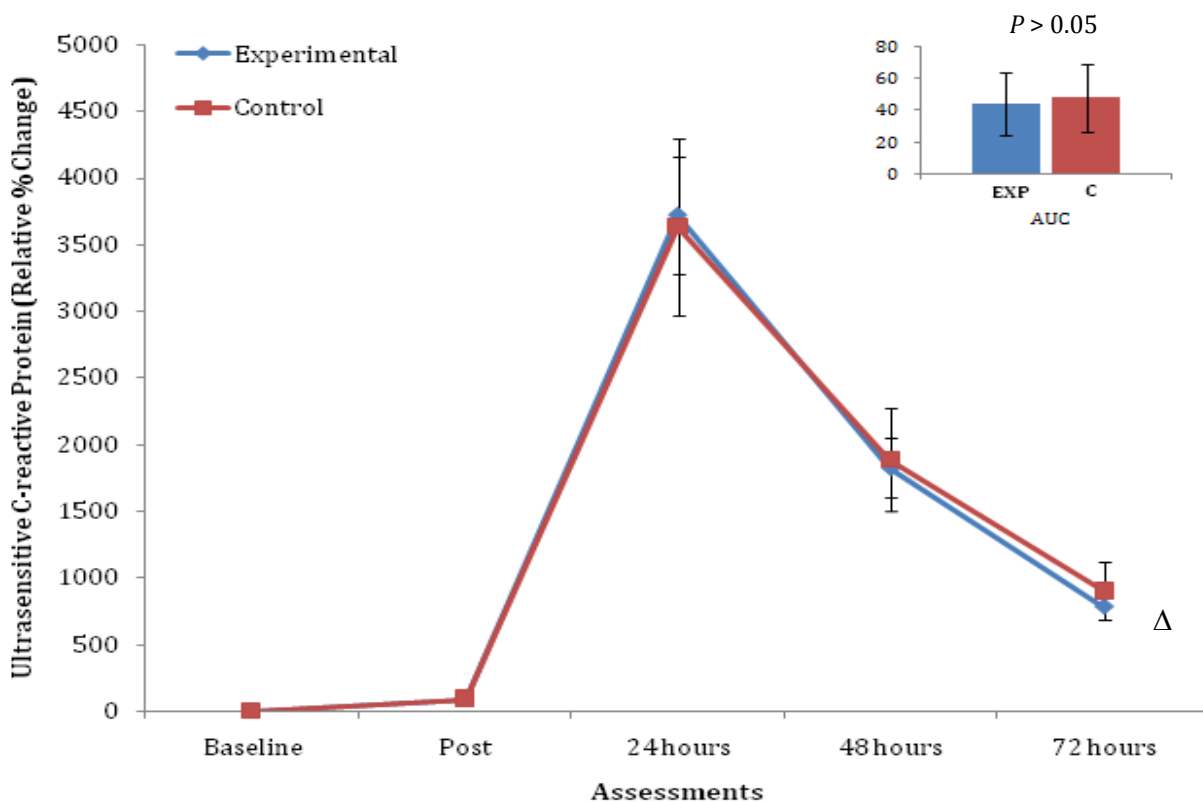


Figure 5.3 The relative percentage change in ultrasensitive C - reactive protein concentrations (error bars: SEM) in the CS group ( — ◆ — ; EXP) and the C group ( — ■ — ; CONTROL).  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

## **b. Swelling**

### *i. Lower Limb Circumferences*

Lower leg circumferences, namely ankle (*Figure 5.4*), calf (*Figure 5.5*) and mid-thigh (*Figure 5.6*) were significantly increased after the race in both groups ( $P < 0.01$ ).

The control group had on average a ~1.5% greater increase in ankle circumferences than the CS group. No significant main group effect was visible ( $P = 0.58$ ), however, there was a tendency towards an interaction effect (group x time;  $P = 0.08$ ). The area under the curve analysis revealed a strong tendency for the experimental group to gain less swelling compared to the control group (CS:  $1 \pm 1\%$  vs. C:  $4 \pm 2\%$ ;  $P = 0.06$ ).

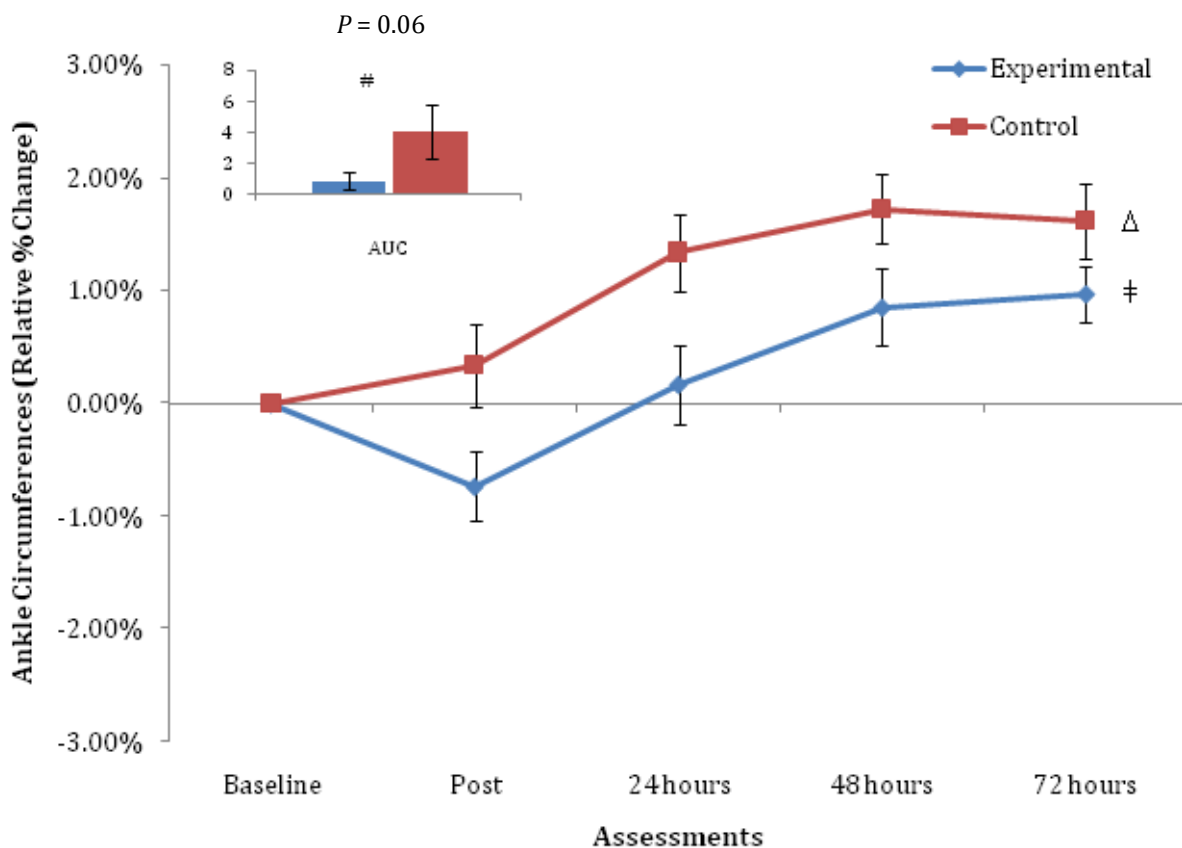
*Table 5.7* summarizes the absolute changes in ankle circumferences over the study period in the two groups. The relative percentage gain was 1% directly after the race and similar increases were found at 24, 48 and at 72 hours after the race. The CS group showed a lesser increases in ankle swelling compared to the C group. The largest difference between the groups was observed at 24 hours after the ultra-marathon.

*Table 5.7* Absolute ankle circumferences (cm) in the control and experimental group during the study period (*Mean ( $\bar{x}$ )  $\pm$  SD*).

<b>Assessments</b>	<b>Experimental (CS)</b>	<b>Control (C)</b>	<b>Effect size</b>
<b>Baseline</b>	22.1 $\pm$ 1.5	22.3 $\pm$ 1.4	0.12 <sup>N</sup>
<b>Post</b>	21.9 $\pm$ 1.3	22.4 $\pm$ 1.4	0.31 <sup>S</sup>
<b>24 hours</b>	22.2 $\pm$ 1.5	22.6 $\pm$ 1.5	0.29 <sup>S</sup>
<b>48 hours</b>	22.3 $\pm$ 1.5	22.7 $\pm$ 1.5	0.25 <sup>S</sup>
<b>72 hours</b>	22.3 $\pm$ 1.4	22.6 $\pm$ 1.5	0.22 <sup>S</sup>

*Effect sizes:*<sup>N</sup>negligible,<sup>S</sup>small





**Figure 5.4** The relative percentage change from baseline in ankle circumferences (error bars: SEM) in the CS group ( ◆ ; EXP) and the C group ( ■ ; CONTROL). #Tendency for an interaction effect ( $P = 0.08$ ); #Tendency for difference ( $P = 0.06$ );  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

Mid-calf circumferences (Figure 5.5) also showed no main group effect ( $P = 0.10$ ), but a significant interaction effect ( $P < 0.001$ ) between the control and experimental groups were found. Specifically, post-hoc analysis revealed lower circumferences at 24 hours ( $P = 0.05$ ), 48 hours ( $P = 0.06$ ) and 72 hours ( $P = 0.04$ ) after the ultra-marathon in the experimental group (Table 5.8). Overall, runners in the CS group had ~ 3% less swelling of the calf over the recovery period compared to the C group (CS:  $37.2 \pm 0.1$  cm vs. C:  $38.4 \pm 0.2$  cm).

Table 5.8 Absolute mid-calf circumferences (cm) in the control and experimental group during the study period (Mean ( $\bar{x}$ )  $\pm$  SD).

Assessments	Experimental (CS)	Control (C)	Effect size
Baseline	37.8 $\pm$ 2.1	38.7 $\pm$ 2.3	0.41 <sup>M</sup>
Post	36.6 $\pm$ 2.1	37.5 $\pm$ 2.0	0.44 <sup>M</sup>
24 hours	37.0 $\pm$ 2.3	38.5 $\pm$ 2.3*	0.65 <sup>M</sup>
48 hours	37.3 $\pm$ 2.3	38.7 $\pm$ 2.4‡	0.61 <sup>M</sup>
72 hours	37.2 $\pm$ 2.3	38.8 $\pm$ 2.4*	0.66 <sup>M</sup>

\*Significant difference between CONTROL and EXP,  $P < 0.05$ ; ‡Strong tendency towards a statistically significant difference ( $P = 0.06$ ) Effect sizes: <sup>M</sup> medium

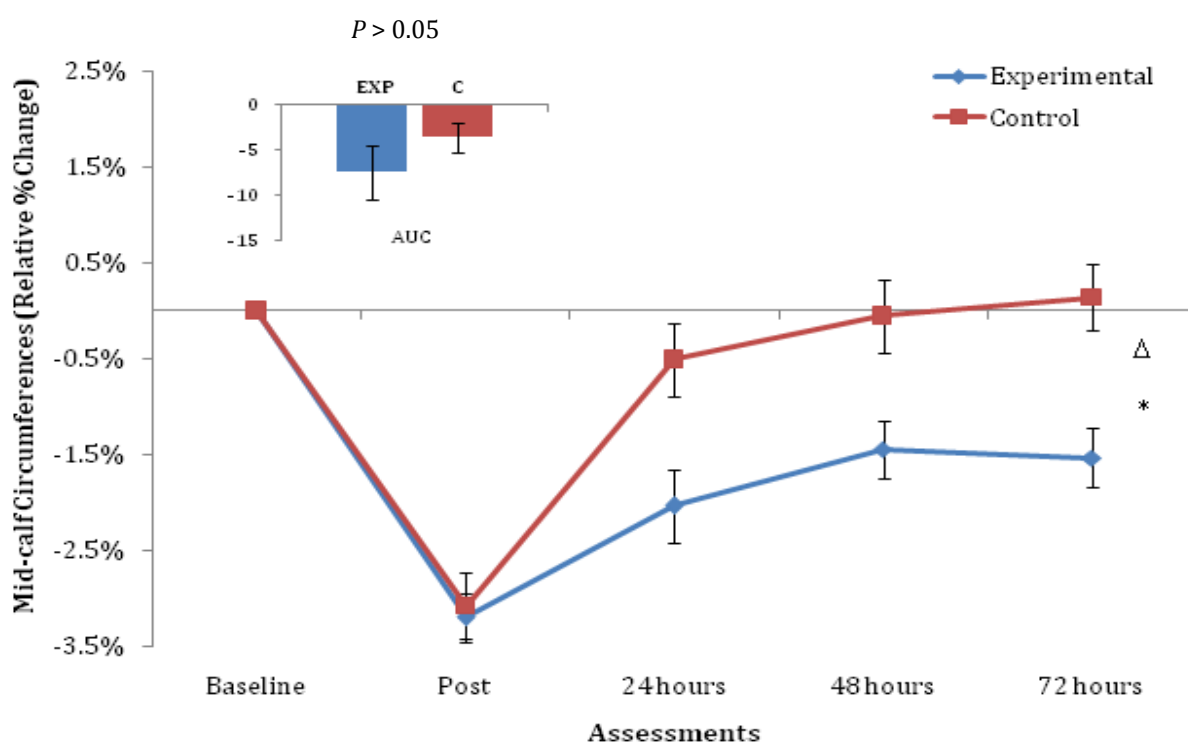
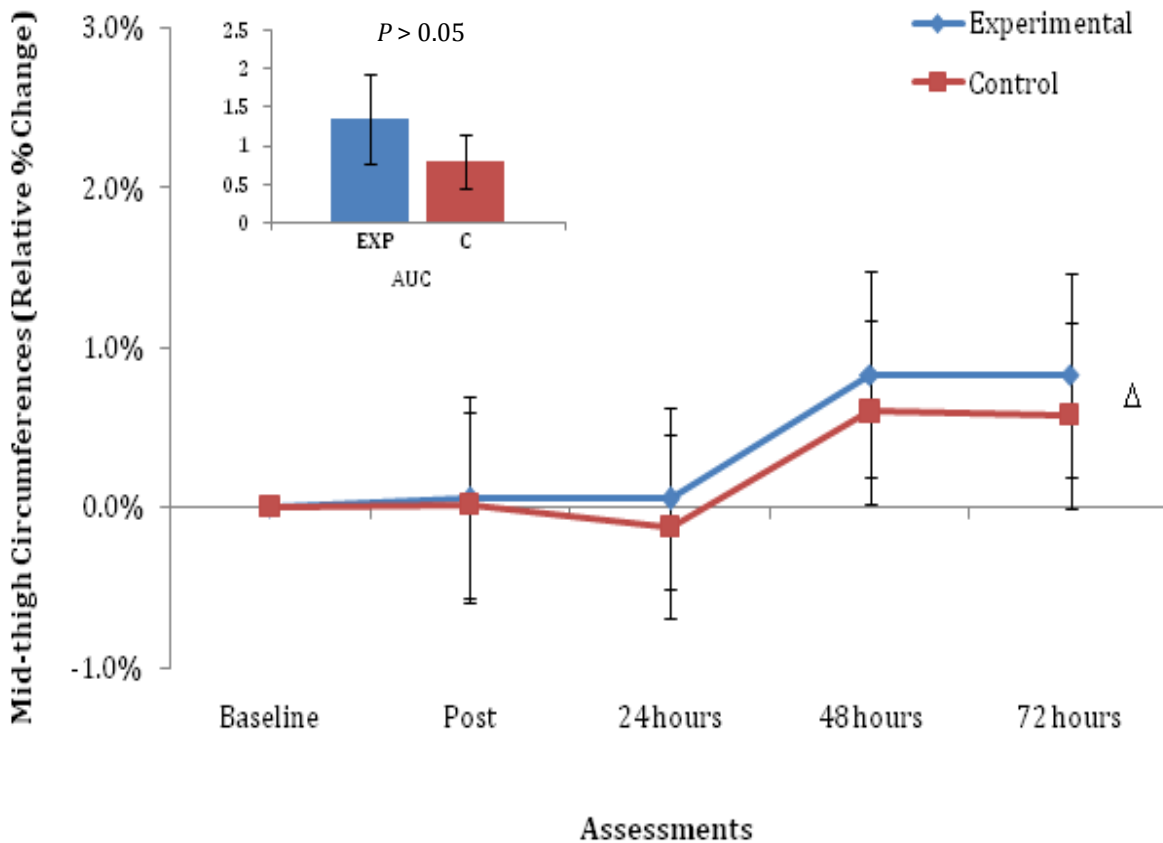


Figure 5.5 The relative percentage change from baseline in mid-calf circumferences (error bars: SEM) in the CS group (—◆—; EXP) and the C group (—■—; CONTROL). \*Significant interaction effect ( $P \leq 0.01$ ); ΔSignificant change over time ( $P \leq 0.01$ ).

Figure 5.5 illustrates that the control group had a more pronounced increase in calf swelling (expressed as relative percentage change from baseline) compared to the experimental group. The AUC analysis did not show a statistically significant difference (CS: 148.4  $\pm$  58.6 cm vs. C: 153.4  $\pm$  60.6 cm,  $P = 0.39$ ).



There was only a significant time effect in the changes in mid-thigh circumferences for both groups ( $P < 0.05$ ), but no interaction ( $P = 0.13$ ) or main group effect ( $P = 0.53$ ).



**Figure 5.6** The relative percentage change from baseline in mid-thigh circumferences (error bars: SEM) in the CS group (—◆—; EXP) and the C group (—■—; CONTROL).  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

Overall, the differences in thigh circumferences were not statistically significant (CS:  $205.0 \pm 81.0$  cm vs. C:  $209.7 \pm 82.9$  cm,  $P = 0.52$ ; AUC) with negligible practical significance ( $ES = 0.06$ ). Table 5.9 lists the absolute circumferences and effect sizes between the two groups.

*Table 5.9* Absolute mid-thigh circumferences (cm) in the control and experimental group during the study period (*Mean (  $\bar{x}$  )  $\pm$  SD*).

<b>Assessments</b>	<b>Experimental (CS)</b>	<b>Control (C)</b>	<b>Effect size</b>
<b>Baseline</b>	51.1 $\pm$ 3.3	52.3 $\pm$ 3.3	0.38 <sup>S</sup>
<b>Post</b>	51.1 $\pm$ 2.9	52.3 $\pm$ 3.2	0.41 <sup>M</sup>
<b>24 hours</b>	51.1 $\pm$ 2.8	52.3 $\pm$ 3.2	0.40 <sup>M</sup>
<b>48 hours</b>	51.5 $\pm$ 2.9	52.6 $\pm$ 3.2	0.38 <sup>S</sup>
<b>72 hours</b>	51.5 $\pm$ 2.3	52.6 $\pm$ 3.1	0.38 <sup>S</sup>

*Effect sizes: <sup>S</sup> small, <sup>M</sup> medium*

### **c. Total Body Water Analysis**

*Figure 5.7* illustrates that the relative changes in total body water were significantly elevated above baseline concentrations in both groups over the study period ( $P < 0.01$ ). However, no significant main group effect ( $P = 0.20$ ) or interaction effect was observed between the groups ( $P = 0.24$ ). *Table 5.10* lists the absolute water content values for both group and shows that the differences in absolute body water during the recovery period was of moderate practical significance ( $ES = 0.48 - 0.55$ ). At all the time points, the CS group had lower body water levels compared to the control group and these differences varied from small to medium practical differences.

*Table 5.10* Total body water (L) in the control and experimental group during the study period (*Mean (  $\bar{x}$  )  $\pm$  SD*).

<b>Assessments</b>	<b>Experimental</b>	<b>Control</b>	<b>Effect Size</b>
<b>Baseline</b>	46.1 $\pm$ 5.2	47.7 $\pm$ 3.8	0.37 <sup>S</sup>
<b>Post</b>	45.8 $\pm$ 5.5	47.1 $\pm$ 3.7	0.29 <sup>S</sup>
<b>24 hours</b>	44.8 $\pm$ 5.3	47.3 $\pm$ 3.6	0.55 <sup>M</sup>
<b>48 hours</b>	47.0 $\pm$ 5.2	48.2 $\pm$ 4.2	0.49 <sup>M</sup>
<b>72 hours</b>	46.3 $\pm$ 5.3	48.5 $\pm$ 4.2	0.48 <sup>M</sup>

*Effect sizes: <sup>S</sup> small, <sup>M</sup> medium*

The AUC analysis indicate that 61% of the change in TBW in the control group after the ultra-marathon was below baseline levels, while 100% of the total area in the experimental group was

below baseline values. The difference in AUC was not statistically significantly different (CS:  $183.8 \pm 72.5$  L vs. C:  $190.7 \pm 75.4$  L,  $P = 0.20$ ) with negligible effect sizes ( $ES = 0.10$ ).

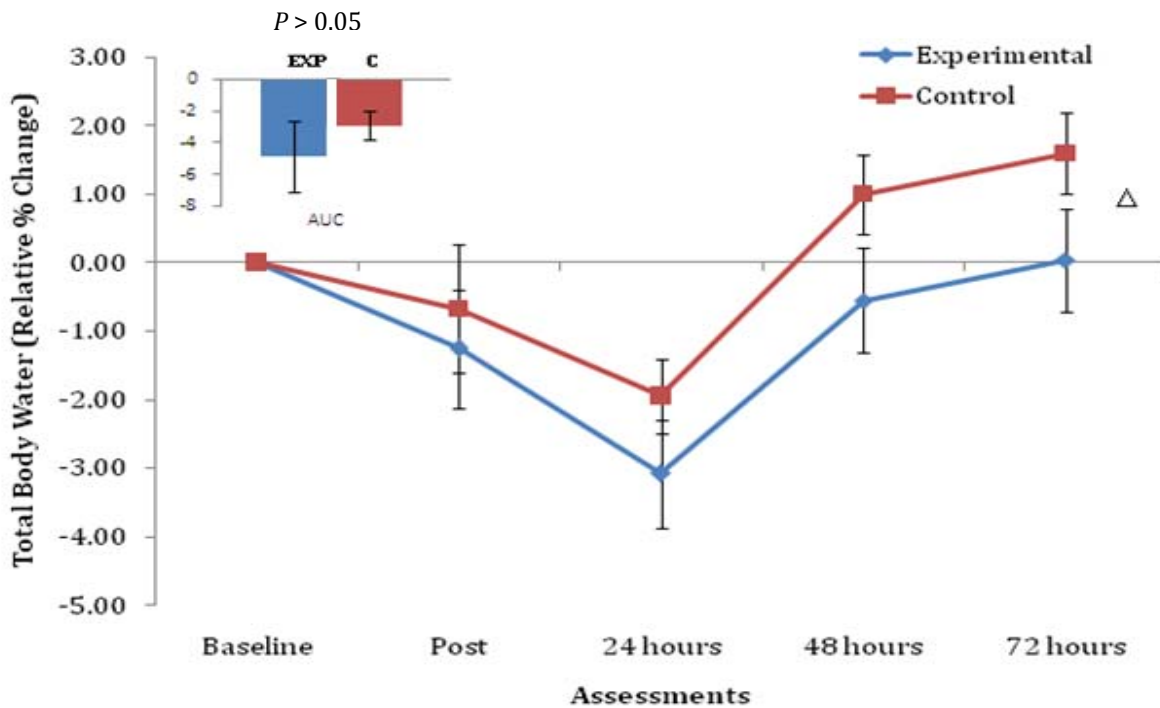


Figure 5.7 The relative percentage change from baseline in total body water (error bars: SEM) in the CS group (  $\blacklozenge$  ; EXP) and the C group (  $\blacksquare$  ; CONTROL).  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

#### d. Perceived Muscle Soreness

##### i. Visual Analogue Scales

##### Quadriceps

All the VAS scores pertaining to the *Quadriceps* muscle changed significantly over time ( $P < 0.001$ , Figure 5.8 a - d), with peak values directly after the race in both groups. There were no statistically significant treatment effects ( $P > 0.05$ ). The CS group demonstrated on average significantly less perceived pain and discomfort when stretching the *Quadriceps* muscles compared to the C group (main group effect;  $P = 0.04$ ). In particular, runners in the CS group

reported 95% less perceived pain and discomfort while stretching at 24 hours ( $P = 0.06$ ;  $ES = 0.52$ ) and 86% less at 48 hours ( $P < 0.01$ ;  $ES = 0.84$ ) after the ultra-marathon (Table 5.11a - d). Furthermore, the CS group reported 58% less perceived pain and discomfort during daily activities at 48 hours after the race compared to the C group ( $P = 0.05$ ).

Table 5.11a - d The perceived muscle soreness and discomfort (VAS scale 0 - 10) in the Quadriceps during the study period (Mean ( $\bar{x}$ )  $\pm$  SD).

Assessment	Baseline	Post	24 hours	48 hours	72 hours
<b>a) Rest</b>					
Experimental (CS)	0.4 $\pm$ 1.0	2.3 $\pm$ 2.7	1.2 $\pm$ 2.4	0.9 $\pm$ 1.4	0.5 $\pm$ 1.6
Control (C)	0.5 $\pm$ 1.0	3.2 $\pm$ 2.6	1.5 $\pm$ 2.2	1.5 $\pm$ 2.0	0.3 $\pm$ 0.7
<b>Effect Sizes</b>	0.12 <sup>N</sup>	0.34 <sup>S</sup>	0.13 <sup>N</sup>	0.37 <sup>S</sup>	0.17 <sup>S</sup>
<b>b) Stretch</b>					
Experimental (CS)	0.4 $\pm$ 1.2	3.2 $\pm$ 2.9	0.7 $\pm$ 2.0	1.3 $\pm$ 1.8	1.1 $\pm$ 1.3
Control (C)	1.0 $\pm$ 1.2	3.8 $\pm$ 2.8	2.0 $\pm$ 3.0 $\ddagger$	3.1 $\pm$ 2.8*	1.2 $\pm$ 1.0
<b>Effect Sizes</b>	0.45 <sup>M</sup>	0.22 <sup>S</sup>	0.52 <sup>M</sup>	0.84 <sup>L</sup>	0.05 <sup>N</sup>
<b>c) Pressure</b>					
Experimental (CS)	0.1 $\pm$ 0.2	2.4 $\pm$ 2.9	2.0 $\pm$ 2.5	2.0 $\pm$ 2.2	1.4 $\pm$ 1.7
Control (C)	0.7 $\pm$ 1.2	3.2 $\pm$ 2.7	2.8 $\pm$ 2.8	3.0 $\pm$ 3.0	1.0 $\pm$ 1.3
<b>Effect Sizes</b>	0.88 <sup>L</sup>	0.28 <sup>S</sup>	0.31 <sup>S</sup>	0.42 <sup>M</sup>	0.32 <sup>S</sup>
<b>Daily Activities</b>					
Experimental (CS)	0.6 $\pm$ 1.4	3.5 $\pm$ 3.0	2.7 $\pm$ 2.3	1.7 $\pm$ 1.8	1.1 $\pm$ 1.7
Control (C)	0.8 $\pm$ 1.1	4.3 $\pm$ 3.1	3.0 $\pm$ 2.8	3.1 $\pm$ 2.4*	1.2 $\pm$ 1.2
<b>Effect Sizes</b>	0.17 <sup>S</sup>	0.27 <sup>S</sup>	0.13 <sup>N</sup>	0.69 <sup>M</sup>	0.08 <sup>N</sup>

\* Significant difference between CONTROL and EXP;  $\ddagger$  Tendency towards a statistically significant difference,  $P = 0.06$ ; Effect sizes: <sup>S</sup> small, <sup>M</sup> medium, <sup>L</sup> large

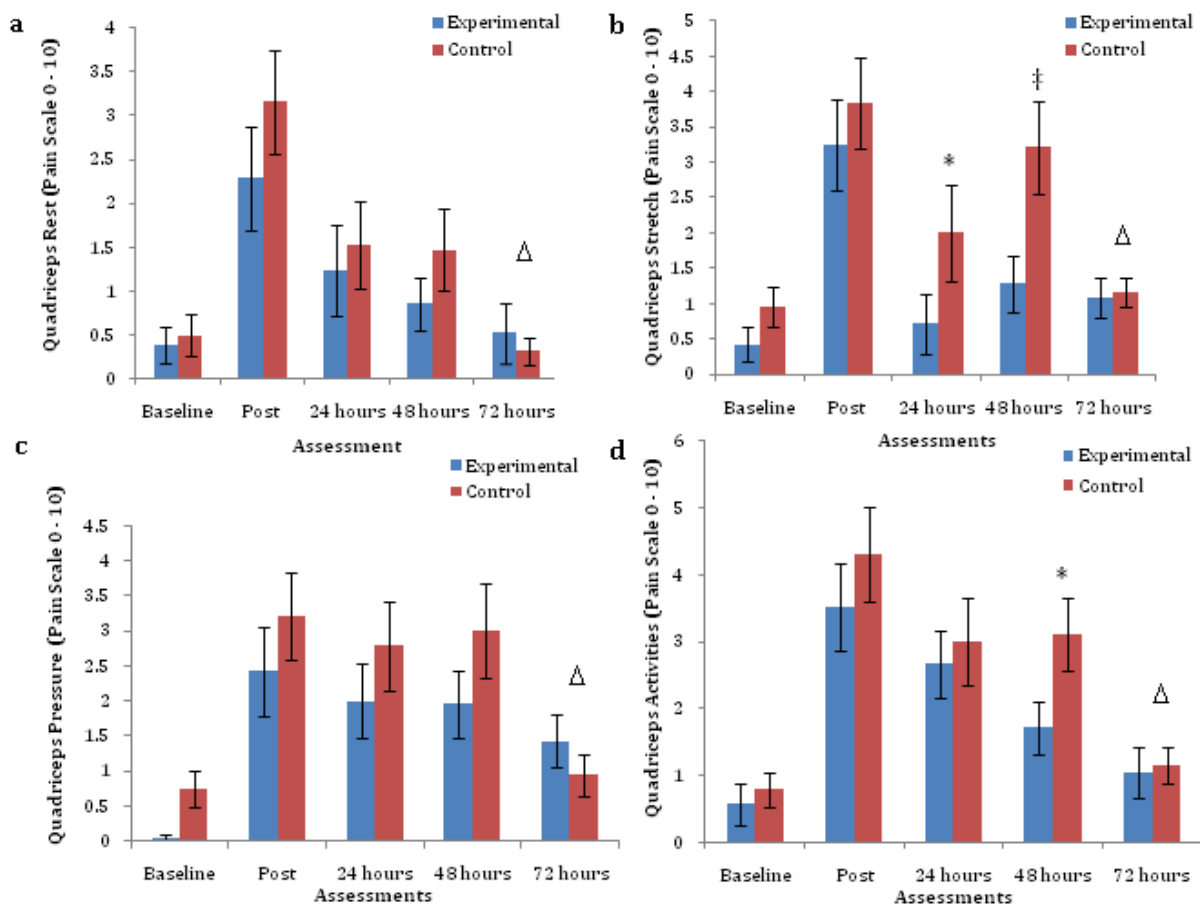


Figure 5.8 (a – d) The average scores on the visual analogue pain scale (0 – 10) in the *Quadriiceps* muscles while a) seated, b) stretching, c) when pressure is applied and d) performing daily activities (error bars: SEM) in the CS group (■; EXP) and the C group (■; CONTROL). \*Significant differences ( $P < 0.05$ ); #Strong tendency ( $P = 0.06$ ); ΔSignificant change over time ( $P \leq 0.01$ ).

### Hamstrings

Perceived soreness and discomfort of the *Hamstring* muscles increased significantly from baseline ( $P < 0.001$ ) over the study period (Figure 5.9 a – d and Table 5.12 a - d), however, no main group or interaction effects were observed in any of the scores ( $P > 0.05$ ).

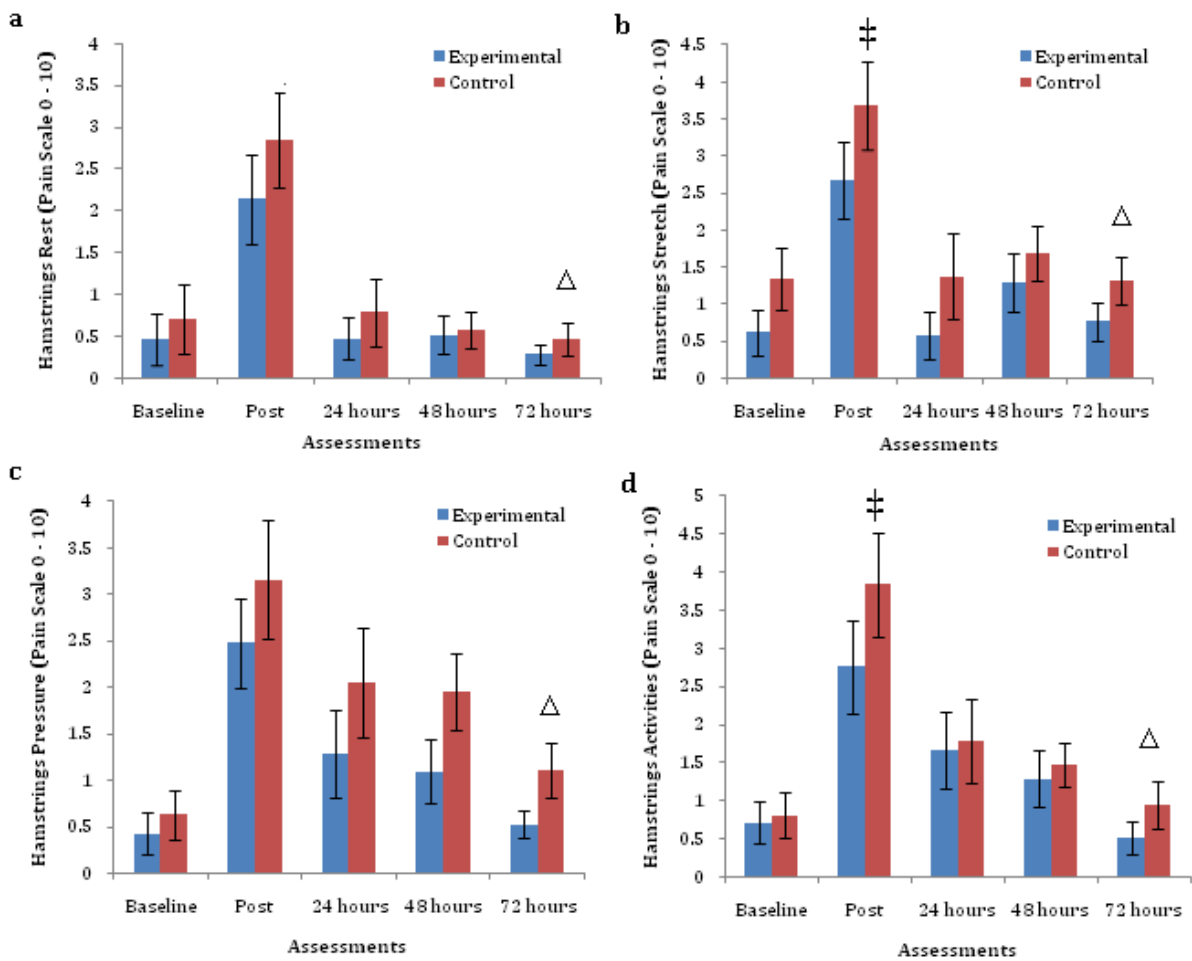


Figure 5.9 (a – d) The average scores on the visual analogue pain scale (0 – 10) in the *Hamstrings* muscles while a) seated, b) stretching, c) when pressure is applied and d) performing daily activities (error bars: SEM) in the CS group (■; EXP) and the C group (■; CONTROL). ‡Tendency towards statistically significant difference ( $P = 0.09$ ); ΔSignificant change over time ( $P \leq 0.01$ ).

Table 5.12 a - d summarizes the actual VAS scores as well as the associated effect sizes during the research period in the *Hamstring* muscles. Runners in the CS group tended to perceive less pain while stretching ( $P = 0.09$ ) as well as during daily activities ( $P = 0.09$ ) directly after the race.

Table 5.12 a - d The perceived muscle soreness and discomfort (VAS scale 0 – 10) in the Hamstrings during the study period (Mean ( $\bar{x}$ )  $\pm$  SD).

Assessment	Baseline	Post	24 hours	48 hours	72 hours
<b>a) Rest</b>					
Experimental	0.5 $\pm$ 1.4	2.1 $\pm$ 2.5	0.5 $\pm$ 1.1	0.5 $\pm$ 1.1	0.3 $\pm$ 0.6
Control	0.7 $\pm$ 1.8	2.8 $\pm$ 2.5	0.8 $\pm$ 1.8	0.6 $\pm$ 1.0	0.5 $\pm$ 0.8
<b>Effect Sizes</b>	0.15 <sup>S</sup>	0.29 <sup>S</sup>	0.22 <sup>S</sup>	0.06 <sup>N</sup>	0.27 <sup>S</sup>
<b>b) Stretch</b>					
Experimental	0.6 $\pm$ 1.4	2.7 $\pm$ 2.4	0.6 $\pm$ 1.5	1.3 $\pm$ 1.8	0.8 $\pm$ 1.2
Control	1.3 $\pm$ 1.8	3.7 $\pm$ 2.6 <sup>‡</sup>	1.4 $\pm$ 2.5	1.7 $\pm$ 1.6	1.3 $\pm$ 1.4
<b>Effect Sizes</b>	0.46 <sup>M</sup>	0.42 <sup>M</sup>	0.40 <sup>M</sup>	0.24 <sup>S</sup>	0.44 <sup>M</sup>
<b>c) Pressure</b>					
Experimental	0.4 $\pm$ 1.0	2.5 $\pm$ 2.9	1.3 $\pm$ 2.2	1.1 $\pm$ 1.6	0.5 $\pm$ 0.7
Control	0.6 $\pm$ 1.2	3.2 $\pm$ 2.8	2.1 $\pm$ 2.6	2.0 $\pm$ 1.8	1.1 $\pm$ 1.3
<b>Effect Sizes</b>	0.19 <sup>S</sup>	0.28 <sup>S</sup>	0.33 <sup>S</sup>	0.52 <sup>M</sup>	0.59 <sup>M</sup>
<b>Daily Activities</b>					
Experimental	0.7 $\pm$ 1.3	2.8 $\pm$ 2.8	1.7 $\pm$ 2.3	1.3 $\pm$ 1.7	0.5 $\pm$ 1.0
Control	0.8 $\pm$ 1.4	3.6 $\pm$ 3.0 <sup>‡</sup>	1.8 $\pm$ 2.4	1.5 $\pm$ 1.2	0.2 $\pm$ 1.3
<b>Effect Sizes</b>	0.08 <sup>N</sup>	0.38 <sup>M</sup>	0.05 <sup>N</sup>	0.13 <sup>N</sup>	0.38 <sup>S</sup>

<sup>‡</sup> Tendency towards a statistically significant difference,  $P = 0.09$ ; Effect sizes: <sup>S</sup> small, <sup>M</sup> medium, <sup>L</sup> Large

### Calf Muscles

Figure 5.10 a - d illustrates the pain and discomfort scores in the calf muscles of the runners over the study period. There were significant increases in calf muscle soreness and discomfort after the race in both groups ( $P < 0.001$ ) during resting, stretching, applying pressure and with daily activities. Runners in the experimental group experienced less pain and discomfort when stretching (main group effect,  $P = 0.03$ ), when pressure was applied to the calf muscle (main group effect,  $P = 0.05$ ) and with daily activities (main group effect,  $P = 0.01$ ).

Table 5.13a - d The perceived muscle soreness and discomfort (VAS scale 0 – 10) in the Calf during the study period (Mean ( $\bar{x}$ )  $\pm$  SD).

Assessment	Baseline	Post	24 hours	48 hours	72 hours
<b>a) Rest</b>					
Experimental	0.5 $\pm$ 1.7	2.1 $\pm$ 2.5	0.6 $\pm$ 1.2	0.4 $\pm$ 0.8	0.3 $\pm$ 0.8
Control	0.3 $\pm$ 0.6	2.9 $\pm$ 2.2‡	1.1 $\pm$ 1.9	0.6 $\pm$ 1.1	0.6 $\pm$ 1.2
Effect Sizes	0.17 <sup>S</sup>	0.37 <sup>S</sup>	0.28 <sup>S</sup>	0.16 <sup>S</sup>	0.30 <sup>S</sup>
<b>b) Stretch</b>					
Experimental	0.8 $\pm$ 1.5	2.4 $\pm$ 2.7	0.3 $\pm$ 0.7	1.2 $\pm$ 1.8	0.8 $\pm$ 1.1
Control	0.8 $\pm$ 1.2	4.1 $\pm$ 2.8#	1.3 $\pm$ 2.4	2.1 $\pm$ 2.2	1.4 $\pm$ 1.8
Effect Sizes	0.02 <sup>N</sup>	0.62 <sup>M</sup>	0.57 <sup>M</sup>	0.45 <sup>M</sup>	0.39 <sup>S</sup>
<b>c) Pressure</b>					
Experimental	0.9 $\pm$ 1.9	2.4 $\pm$ 2.7	1.2 $\pm$ 1.5	1.3 $\pm$ 1.8	0.8 $\pm$ 1.0
Control	1.0 $\pm$ 1.4	3.8 $\pm$ 2.8*	2.9 $\pm$ 2.7#	1.8 $\pm$ 1.5	1.4 $\pm$ 1.7
Effect Sizes	0.04 <sup>N</sup>	0.51 <sup>M</sup>	0.79 <sup>L</sup>	0.28 <sup>S</sup>	0.45 <sup>M</sup>
<b>Daily Activities</b>					
Experimental	0.8 $\pm$ 1.8	2.0 $\pm$ 2.5	1.8 $\pm$ 1.8	1.2 $\pm$ 1.7	0.8 $\pm$ 0.9
Control	1.0 $\pm$ 1.4	4.2 $\pm$ 2.3#	2.9 $\pm$ 2.8‡	2.1 $\pm$ 1.8	1.3 $\pm$ 1.7
Effect Sizes	0.15 <sup>S</sup>	0.92 <sup>L</sup>	0.49 <sup>M</sup>	0.51 <sup>M</sup>	0.39 <sup>S</sup>

#Significant difference between CONTROL and EXP  $P \leq 0.007$ ; \* Significant difference between CONTROL and EXP,  $P = 0.009$ ; ‡ Tendency towards statistically significant difference,  $P = 0.08$ ; Effect sizes: <sup>S</sup> small, <sup>M</sup> medium, <sup>L</sup> Large

Table 5.13 a - d reveals that the treatment group experienced significantly less muscle soreness and discomfort in the calf muscles directly after the race at rest ( $P = 0.08$ ), during daily activities ( $P = 0.0005$ ) and while stretching ( $P = 0.007$ ). At 24 hours these differences were most apparent when pressure was applied to the calf (80% less,  $P = 0.009$ ) and with daily activities (46% less,  $P = 0.08$ ). At the majority of time points, there was a moderate to large practically significant difference in perceived soreness and discomfort between the two groups, with the CS group reporting less pain and discomfort.



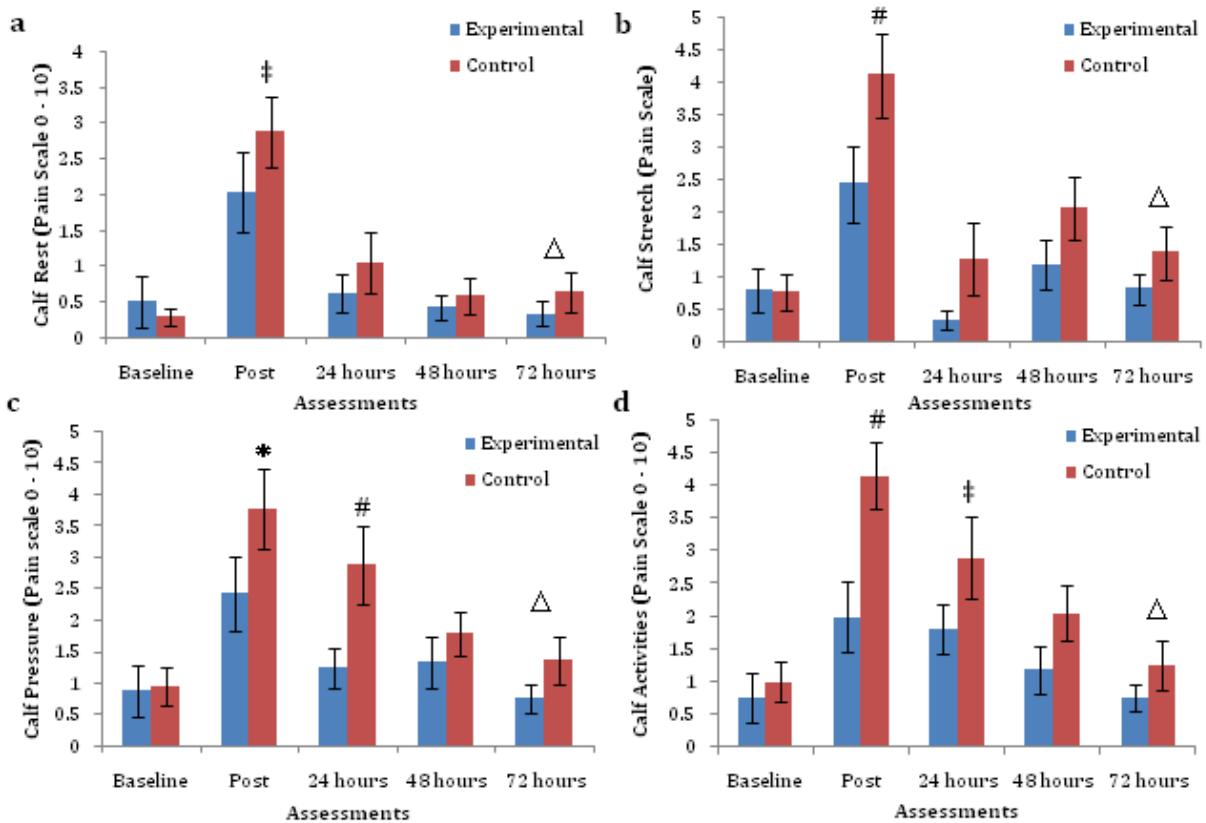


Figure 5.10 (a – d) The average scores on the visual analogue pain scale (0 – 10) in the *Calf* muscles while a) seated, b) stretching, c) when pressure is applied and d) performing daily activities (error bars: SEM) in the CS group (■; EXP) and the C group (■; CONTROL). #Significant difference between CONTROL and EXP ( $P \leq 0.007$ ); \*Significant difference between CONTROL and EXP ( $P = 0.009$ ); ‡Tendency towards statistically significant difference ( $P = 0.08$ ); ΔSignificant change over time ( $P \leq 0.01$ ).

## ii. Viability Questionnaires

Subjects were asked to complete an appropriateness-and-convenience questionnaire (Table 5.14) to assess the viability of the compression socks. Of the 21 runners that wore the compression socks (EXP), 96% reported that they will wear the socks again during their training and races. About 86% of the 19 runners in the placebo sock group (CONTROL) stated that they will wear the compression sock again.

Table 5.14 The appropriateness-and-convenience questionnaire to assess the runners' perception of the compression socks' viability as a recovery aid (%; n =40)\*.

Viability Questions	Experimental	Control
Comfortable	96%	82%
Contributing to Foot Sores	8%	18%
Difficulty Putting Garment On	48%	77%
Improve Running Confidence	52%	36%
Preventing Injuries	67%	59%
Additional Fatigue Due To CS	7%	0%
Compression Sock Aids Running	48%	48%
Compression Sock Aids Recovery	63%	36%
Sweating Excessively due to CS	4%	0%
Contribute to Irritation	7%	9%

\*The table indicates the percentage of runners who agreed with the statement.

### e. Metabolic Responses

#### i. Blood Lactate Concentration

Table 5.15 summarizes the absolute blood lactate concentrations and Figure 5.11 illustrates the relative percentage change in blood lactate concentrations over the study period.

Table 5.15 The blood lactate concentrations (mmol.L<sup>-1</sup>) during the study period (Mean ( $\bar{x}$ )  $\pm$  SD) in the experimental and control group.

Assessments	Experimental	Control	Effect Sizes
Baseline	1.4 $\pm$ 0.5	1.5 $\pm$ 0.5	0.20 <sup>S</sup>
Post	2.5 $\pm$ 0.8	2.9 $\pm$ 1.9	0.32 <sup>S</sup>
30 minutes	2.0 $\pm$ 0.9	2.5 $\pm$ 1.8*	0.43 <sup>M</sup>
24 hours	1.3 $\pm$ 0.5	1.5 $\pm$ 0.7	0.23 <sup>S</sup>
48 hours	1.5 $\pm$ 0.5	1.4 $\pm$ 0.5	0.23 <sup>S</sup>
72 hours	1.3 $\pm$ 0.6	1.5 $\pm$ 0.6	0.47 <sup>M</sup>

\*Significant difference between CONTROL and EXP,  $P < 0.05$ ; Effect sizes: <sup>S</sup> small, <sup>M</sup> medium

Blood lactate concentrations were significantly elevated above baseline levels in both groups after the race ( $P < 0.001$ ). However, no significant main group ( $P = 0.13$ ) or interaction effect (time x group) ( $P = 0.58$ ) were apparent between the control and experimental group.

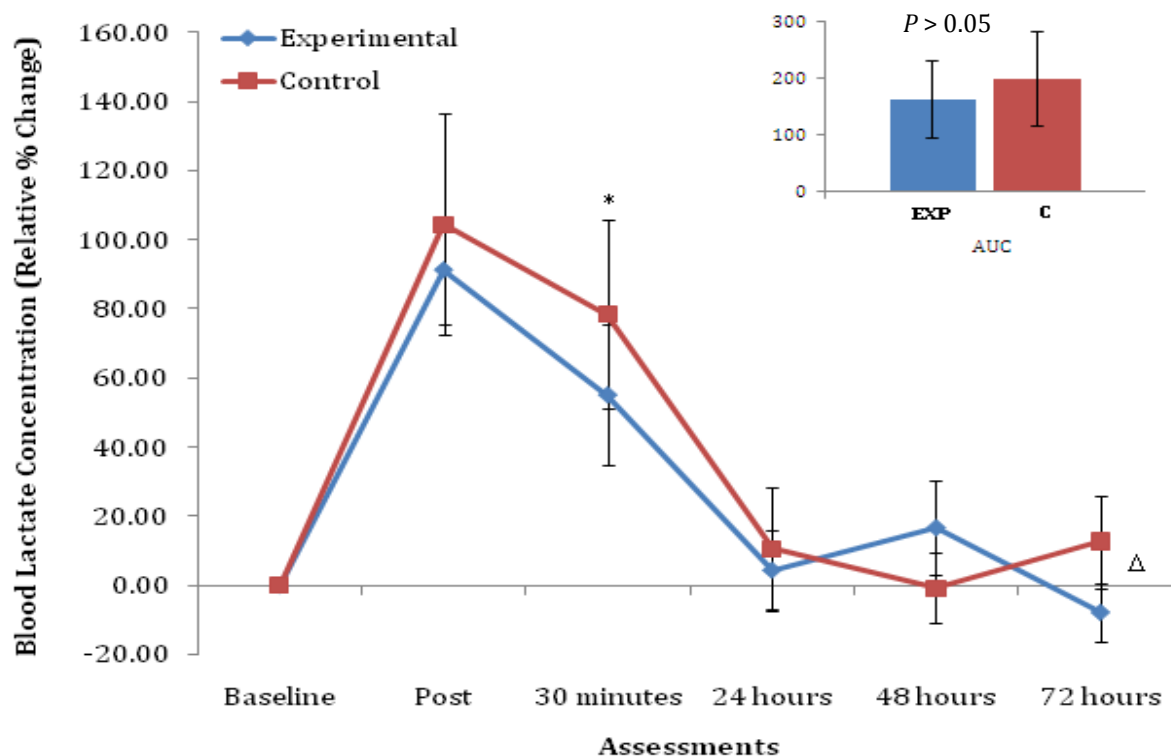


Figure 5.11 The relative percentage blood lactate concentration (error bars: SEM) in the CS group (■; EXP) and the C group (◆; Control). \*Significant difference between CONTROL and EXP ( $P < 0.05$ );  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

Blood lactate concentrations were significantly less in the CS group (26%) compared to the control group at 30 minutes after the race, which related to a moderate practically significant difference ( $ES = 0.43$ ). At 72 hours, there was still a 19% difference in blood lactate levels between the two groups, with the CS group having recovered completely ( $ES = 0.47$ ). The total blood lactate concentrations (AUC analysis) did not differ significantly between the groups (CS:  $8.6 \pm 3.2 \text{ mmol.L}^{-1}$  vs. C:  $9.8 \pm 3.7 \text{ mmol.L}^{-1}$ ,  $P = 0.61$ ), but the effect sizes of the absolute values showed a moderate practically significant difference ( $ES = 0.40$ ).

**f. Functional Ability**

**i. Running Economy**

Running economy was corrected for body mass to the power of 0.75. The relative values are reported in *Table 5.16* and graphically illustrated in *Figure 5.12* as relative percentage change from baseline. There was a significant deterioration in running economy after the race in both groups ( $P < 0.001$ ). Although the CS group had better running economy at all the time points after the race, there was no significant main group effect ( $P = 0.32$ ) or time x group interaction effect ( $P = 0.83$ ). Additional analysis only revealed small effect sizes at the various assessment points. The difference in area under the curve was not statistically significant ( $P = 0.68$ ) with negligible practical significance (CS:  $350.5 \pm 151.0 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-0.75}$  vs. C:  $363.0 \pm 156.4 \text{ mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-0.75}$ ,  $ES = 0.09$ ).

*Table 5.16* The relative running economy ( $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-0.75}$ ) adjusted for body mass during the study period ( $\text{Mean} (\bar{x}) \pm SD$ ) in the experimental and control group.

<b>Assessments</b>	<b>Experimental</b>	<b>Control</b>	<b>Effect Size</b>
<b>Baseline</b>	115.1 $\pm$ 17.1	118.8 $\pm$ 11.2	0.26 <sup>S</sup>
<b>24 hours</b>	119.8 $\pm$ 16.0	124.3 $\pm$ 13.2	0.32 <sup>S</sup>
<b>48 hours</b>	116.9 $\pm$ 17.3	120.1 $\pm$ 11.2	0.22 <sup>S</sup>
<b>72 hours</b>	112.7 $\pm$ 18.7	118.5 $\pm$ 10.4	0.39 <sup>S</sup>

Effect sizes: <sup>S</sup> small



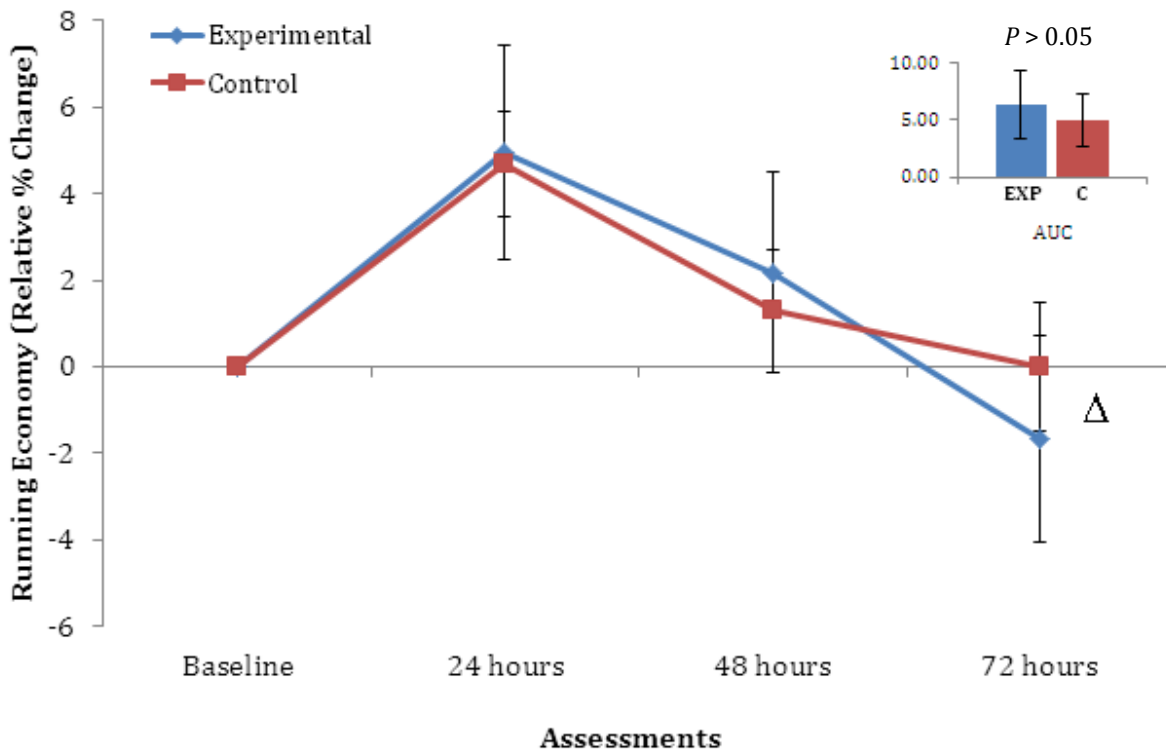


Figure 5.12 The relative percentage change in running economy (error bars: SEM) in men of the CS group ( —◆—; EXP) and the C group ( —■—; CONTROL).  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

The average heart rates during the RE tests are reported in Table 5.17 and show negligible to small practically significant differences. There were, however, no significant differences in heart rates between the groups at any of the time points ( $P > 0.05$ ).

Table 5.17 The average heart rate (bpm) responses of the runners during the running economy (RE) test (Mean ( $\bar{x}$ )  $\pm$  SD).

Assessments	Experimental	Control	Effect Size
Baseline	148 $\pm$ 12	144 $\pm$ 15	0.24 <sup>S</sup>
24 hours	155 $\pm$ 13	156 $\pm$ 18	0.07 <sup>N</sup>
48 hours	150 $\pm$ 13	152 $\pm$ 17	0.09 <sup>N</sup>
72 hours	147 $\pm$ 14	147 $\pm$ 15	0.03 <sup>N</sup>

Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small

ii. Muscle Function (Countermovement Jump for Explosive Power)

Both groups showed a significant reduction in explosive power after the ultra-marathon ( $P < 0.001$ ). No main group effect ( $P = 0.30$ ) was observed, however there was a tendency for a treatment effect ( $P = 0.07$ ).

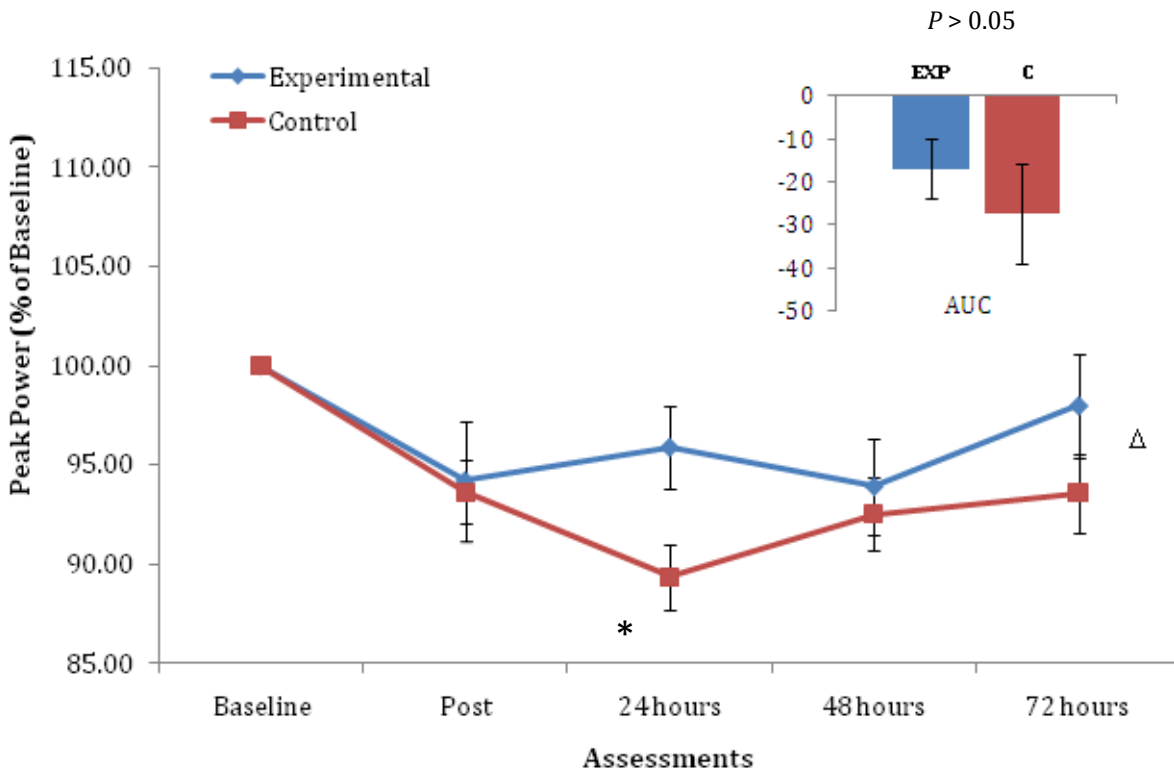


Figure 5.13 The relative decrease in peak power from baseline (error bars: SEM) in men of the CS group ( —◆—; EXP) and the C group ( —■—; CONTROL). \*Significant difference between CONTROL and EXP in % gain from baseline ( $P = 0.04$ );  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

Absolute peak power values (W) and effect sizes are reported in Table 5.18. Even though there was a negligible effect between the peak power values at 24 hours, the difference in relative gain of about 6.5% was significantly different between the groups ( $P = 0.04$ ). Furthermore, at 48 hours after the race, there was still a moderate practically significant difference in peak power between the two groups ( $ES = 0.49$ ; Table 5.18), indicating that the CS group recovered quicker.

Table 5.18 The peak power (W) of the runners during the study period ( $Mean (\bar{x}) \pm SD$ ).

Assessments	Experimental	Control	Effect Sizes
Baseline	1649 ± 303	1788 ± 269	0.50 <sup>M</sup>
Post	1537 ± 275	1669 ± 253	0.51 <sup>M</sup>
24 hours	1573 ± 285	1595 ± 263	0.08 <sup>N</sup>
48 hours	1532 ± 233	1652 ± 276	0.49 <sup>M</sup>
72 hours	1598 ± 244	1666 ± 250	0.28 <sup>S</sup>

The AUC analysis indicate that the recovery of muscle function between the groups did not differ significantly (CS: 6265 ± 2473 W vs. 6644 ± 2616 W,  $P = 0.48$ ) with the effect sizes showing a small practically significant difference ( $ES = 0.17$ ).



## CHAPTER SIX

### RESULTS PART II

#### I. DESCRIPTIVE CHARACTERISTICS

##### a. *Subjects Characteristics*

In part II, 43 runners of the initial 52 completed the research. Similarly to part I, the 6 weeks prior to the 56 km race the runners trained on average between ~60 to 120 km.w<sup>-1</sup> and 4 to 6 sessions a week. Runners were randomly divided into three treatment groups, *i.e.* 14 runners wore the compression socks only during the race (CS<sub>Run</sub>), 15 runners wore the socks only during the 72 hours recovery period after the race (CS<sub>Rec</sub>) and 14 runners wore the socks during the race as well as during the recovery period (CS<sub>Run&Rec</sub>).

The order of comparison for the following chapter is the CS<sub>Run</sub><sup>a</sup> group opposed to the CS<sub>Rec</sub><sup>b</sup> group, then CS<sub>Rec</sub><sup>b</sup> group against the CS<sub>Run&Rec</sub><sup>c</sup> group and finally CS<sub>Run&Rec</sub><sup>c</sup> group with the CS<sub>Run</sub><sup>a</sup> group. Similar to chapter five, all effect size calculations are based on absolute values and not on relative percentage change values.

The best marathon time between the groups did not differ significantly (CS<sub>Run</sub>: 03:33:29 ± 00:29:55, CS<sub>Rec</sub>: 03:31:22 ± 00:28:40 and CS<sub>Run&Rec</sub>: 03:28:36 ± 00:22:38;  $P = 0.86^{ab}$ ,  $0.79^{bc}$  and  $0.66^{ca}$ ). The runners in part II had between 3 and 27 years running experience. *Table 6.1* summarizes the physical and training characteristics of the three groups and shows that there were no significant differences in age, height, body mass, percentage body fat or training status between the three groups ( $P > 0.05$ ). The three groups did not differ statistically significantly in maximum aerobic capacity and were classified in the *Excellent* class for their age and gender ( $P = 0.95^{ab}$ ,  $0.45^{bc}$ ,  $0.36^{ca}$ ; Brooks *et al.*, 2005). In addition, there was no significant difference in the maximum aerobic capacity or training status of the runners in part I and II of the research ( $P > 0.05$ ).





Table 6.1 The anthropometrical and training characteristics (*Mean* ( $\bar{x}$ )  $\pm$  *SD*) of the runners ( $n = 43$ ).

<b>Variables</b>	<b>CS<sub>Run</sub></b>	<b>Range</b>	<b>CS<sub>Rec</sub></b>	<b>Range</b>	<b>CS<sub>Run&amp;Rec</sub></b>	<b>Range</b>
<b>Age (years)</b>	41 $\pm$ 8	32 - 57	41 $\pm$ 7	29 - 54	42 $\pm$ 7	32 - 54
<b>Height (cm)</b>	178.9 $\pm$ 6.5	169 - 189	176.8 $\pm$ 6.4	165 - 187	177.7 $\pm$ 6.6	169 - 188
<b>Body mass (kg)</b>	74.6 $\pm$ 8.5	61 - 91	77.3 $\pm$ 15.6	56 - 106	75.0 $\pm$ 7.8	61 - 90
<b>BMI (kg.m<sup>-2</sup>)</b>	24 $\pm$ 1	22 - 26	25 $\pm$ 4	21 - 29	24 $\pm$ 3	21 - 31
<b>Body fat (%)</b>	18.6 $\pm$ 2.5	15 - 22	17.1 $\pm$ 3.5	14 - 25	15.7 $\pm$ 4.6	12 - 28
<b>Training Volume (days/w<sup>-1</sup>)</b>	5 $\pm$ 1	4 - 6	5 $\pm$ 1	4 - 6	5 $\pm$ 1	4 - 6
<b>Training distance (km.w<sup>-1</sup>)</b>	81.2 $\pm$ 21.7	60 - 120	73.3 $\pm$ 18.2	60 - 120	75.0 $\pm$ 18.7	60 - 110
<b>AT (%)</b>	73.4 $\pm$ 2.7	70 - 77	74.9 $\pm$ 6.5	67 - 82	80.3 $\pm$ 4.4	76 - 88
<b>VO<sub>2max</sub> (mL.kg<sup>-1</sup>.min<sup>-1</sup>)</b>	47.8 $\pm$ 5.5	39 - 54	47.9 $\pm$ 7.4	39 - 56	50.0 $\pm$ 5.0	39 - 59
<b>V<sub>max</sub> (km.h<sup>-1</sup>)</b>	16.1 $\pm$ 1.0	14 - 17	16.3 $\pm$ 1.9	13 - 18	16.4 $\pm$ 1.3	13 - 18

*AnT anaerobic threshold, V<sub>max</sub>, peak treadmill velocity, BMI, body mass index; VO<sub>2max</sub>, maximum aerobic capacity.*



Table 6.2 summarizes the baseline values in the second part of the research. Absolute values at baseline for muscle damage markers, lower limb circumferences, countermovement jump performance did not differ statistically significantly between the three groups ( $P > 0.05$ ). However, there was a statistically significant difference in the running economy of the  $CS_{Run}$  and  $CS_{Run\&Rec}$  groups ( $P = 0.04$ ), with the  $CS_{Run}$  group having the superior running economy.

Table 6.2 The baseline values of variables assessed ( $Mean (\bar{x}) \pm SD$ ) ( $n = 43$ ).

Baseline Data	$CS_{Run}$ Group(a)	$CS_{Rec}$ Group(b)	$CS_{Run\&Rec}$ Group(c)	Effect Sizes ab, bc, ca
Serum CK (units.L <sup>-1</sup> )	146.4 ± 59.5	171.9 ± 81.7	176.9 ± 78.5	0.37 <sup>S</sup> , 0.06 <sup>N</sup> , 0.45 <sup>S</sup>
S-Mgb(ng.mL <sup>-1</sup> )	38.7 ± 7.7	47.3 ± 18.3	49.6 ± 19.5	0.62 <sup>M</sup> , 0.13 <sup>S</sup> , 0.76 <sup>M</sup>
hsCRP (mg.L <sup>-1</sup> )	0.8 ± 0.5	1.0 ± 0.7	0.7 ± 0.6	0.20 <sup>S</sup> , 0.36 <sup>S</sup> , 0.20 <sup>S</sup>
Ankle cmf (cm)	21.8 ± 0.8	21.9 ± 1.7	22.0 ± 0.7	0.11 <sup>N</sup> , 0.05 <sup>N</sup> , 0.29 <sup>S</sup>
Mid-Calf cmf (cm)	37.0 ± 2.3	38.0 ± 3.5	37.8 ± 1.7	0.32 <sup>S</sup> , 0.07 <sup>N</sup> , 0.40 <sup>M</sup>
Mid-Thigh cmf (cm)	50.8 ± 3.1	52.2 ± 4.7	51.8 ± 2.6	0.35 <sup>S</sup> , 0.11 <sup>N</sup> , 0.35 <sup>S</sup>
LT (mmol.L <sup>-1</sup> )	1.1 ± 0.3	1.4 ± 0.5	1.3 ± 0.4	0.72 <sup>M</sup> , 0.06 <sup>N</sup> , 0.76 <sup>M</sup>
RE (ml <sup>-1</sup> .min <sup>-1</sup> .kg <sup>-0.75</sup> )	87.7 ± 9.2*	92.4 ± 11.4	99.1 ± 13.9*	0.46 <sup>M</sup> , 0.55 <sup>M</sup> , 0.99 <sup>L</sup>
Peak Power (Watt)	1613 ± 262	1619 ± 315	1611 ± 203	0.02 <sup>N</sup> , 0.03 <sup>N</sup> , 0.01 <sup>N</sup>

*a, b, & c* Indicates effect sizes between respective treatment groups \* Significant difference between  $CS_{Run}$  and  $CS_{Run\&Rec}$ ,  $P = 0.04$ ; Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small, <sup>M</sup> medium, <sup>L</sup> large

### b. The 56 km Ultra- Marathon Race

Table 6.3 summarizes the performances of the runners during the ultra-marathon race and shows no significant differences in performance between the groups. Runners completed the race in an average time of five and a half hours at a heart rate of ~150 bpm. Even though the finishing times for the runners who ran the race with the compression socks ( $CS_{Rec}$  and  $CS_{Run\&Rec}$ ) were 4 to 10 minutes faster than those who did not run with the compression socks ( $CS_{Run}$ ), these differences were not statistically significant. However, analysis of the effect sizes indicates that the differences in race time constitute a moderate practically significant better performance for the runners who competed with the socks.



Table 6.3 The performance results of the three groups in the 56 km race  
(Mean ( $\bar{x}$ )  $\pm$  SD).

Variables	CS <sub>Run</sub> <sup>a</sup> Group	CS <sub>Rec</sub> <sup>b</sup> Group	CS <sub>Run&amp;Rec</sub> <sup>c</sup> Group	Effect Size ab, bc, ca
Average time (hh:mm:ss)	05:31:20 00:37:17	$\pm$ 05:48:13 00:44:19	$\pm$ 05:27:37 00:49:30	$\pm$ 0.42 <sup>M</sup> ; 0.45 <sup>M</sup> ; 0.09 <sup>S</sup>
Heart rate (bpm)	149 $\pm$ 5	153 $\pm$ 6	148 $\pm$ 9	0.80 <sup>L</sup> ; 0.69 <sup>M</sup> ; 0.08 <sup>N</sup>
Pace (min.km <sup>-1</sup> )	00:05:55 00:00:40	$\pm$ 00:06:13 00:00:39	$\pm$ 00:05:51 00:00:40	$\pm$ 0.41 <sup>M</sup> ; 0.46 <sup>M</sup> ; 0.06 <sup>N</sup>

<sup>a, b, & c</sup> Indicates effect sizes between respective treatment groups: Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small, <sup>M</sup> medium

## II. DETERMINANTS OF POST-EXERCISE RECOVERY

### a. Exercise-Induced Muscle Damage

#### i. Skeletal Myoglobin (S-Mgb) Activity

Absolute values for s-Mgb concentrations are presented in Table 6.4. The values were significantly elevated above baseline concentrations in all groups over the study period ( $P < 0.001$ ), with peak values directly after the race.

Table 6.4 The absolute skeletal myoglobin (ng.mL<sup>-1</sup>) concentrations (Mean ( $\bar{x}$ )  $\pm$  SD) in all three groups.

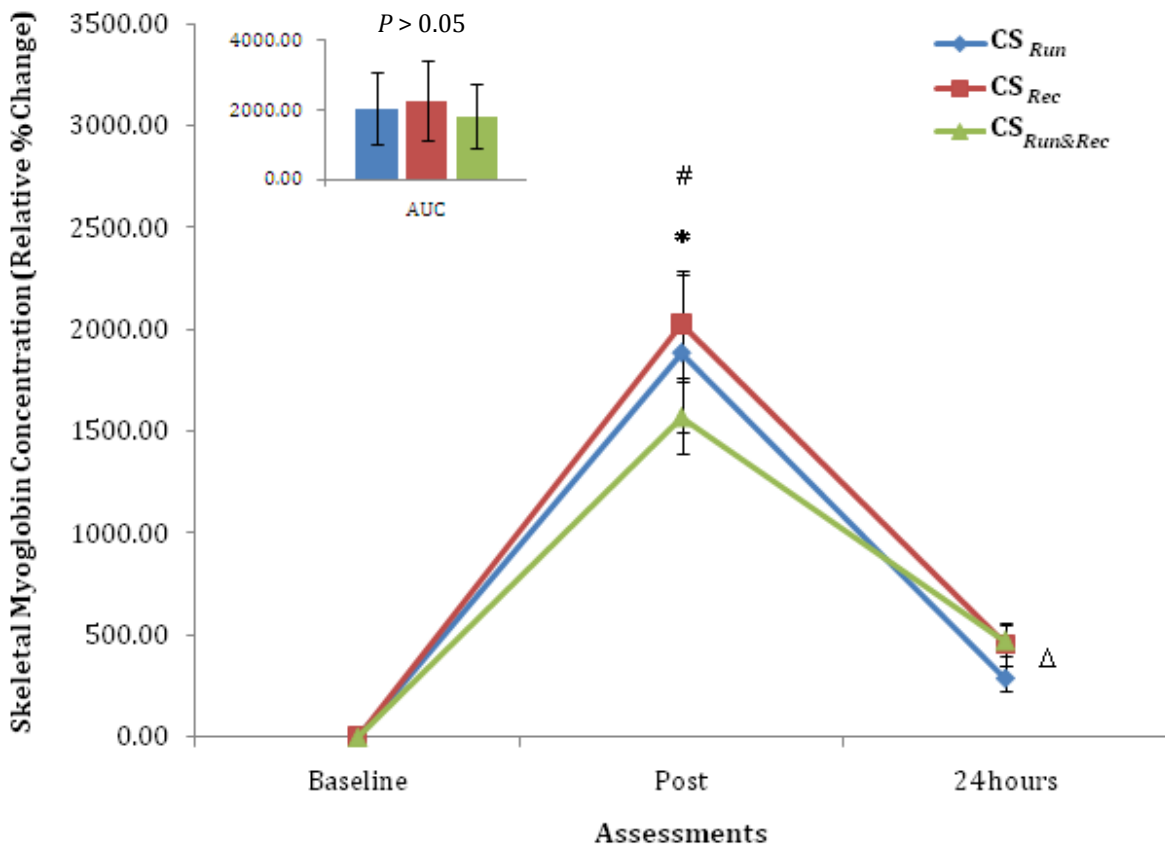
Assessments	CS <sub>Run</sub> <sup>a</sup> group	CS <sub>Rec</sub> <sup>b</sup> group	CS <sub>Run&amp;Rec</sub> <sup>c</sup> group	Effect Size ab, bc, ca
Baseline	38.7 $\pm$ 7.7	47.3 $\pm$ 18.3	49.6 $\pm$ 19.5	0.62 <sup>M</sup> , 0.13 <sup>N</sup> , 0.76 <sup>L</sup>
Post	750.9 $\pm$ 514.8*	963.7 $\pm$ 494.6*#	770.9 $\pm$ 258.1#	0.44 <sup>M</sup> , 0.55 <sup>M</sup> , 0.05 <sup>N</sup>
24 hours	156.8 $\pm$ 98.3	251.1 $\pm$ 186.1	278.9 $\pm$ 152.5	0.64 <sup>M</sup> , 0.17 <sup>S</sup> , 0.98 <sup>L</sup>

<sup>a, b, & c</sup> Indicates effect sizes between respective treatment groups: \* Significant difference between CS<sub>Run</sub> and CS<sub>Rec</sub>,  $P = 0.04$ ; #Strong tendency for CS<sub>Rec</sub> and CS<sub>Run&Rec</sub> to differ,  $P = 0.06$ ; Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small, <sup>M</sup> medium, <sup>L</sup> large.

There was a moderately strong practical difference of 25% directly after the race between the CS<sub>Run</sub> and CS<sub>Rec</sub> groups ( $ES = 0.44$ ;  $P = 0.04$ ). Similarly, the CS<sub>Run&Rec</sub> group had lower s-Mgb concentrations than the CS<sub>Rec</sub> group which bordered on statistical significance but with a medium effect size (22% moderate difference;  $ES = 0.55$ ;  $P = 0.06$ ). The CS<sub>Run&Rec</sub> and CS<sub>Run</sub> groups



differed only by 3% directly after the race ( $ES = 0.05$ ;  $P = 0.85$ ). In other words, both groups who wore the compression socks during the race had lower myoglobin values compared to those who didn't run with socks and this difference according to Cohen's effect size analysis was of moderate practical significance.



**Figure 6.1** The relative percentage change in skeletal myoglobin concentrations (*error bars: SEM*) over 24 hours in the CS<sub>Run</sub> group ( ), the CS<sub>Rec</sub> group ( ) and the CS<sub>Run&Rec</sub> group ( ). \* Significant difference between CS<sub>Run</sub> and CS<sub>Rec</sub> absolute concentrations,  $P = 0.04$ ; # Strong tendency towards statistical difference between CS<sub>Rec</sub> and CS<sub>Run&Rec</sub> ( $P = 0.06$ ); Δ Significant change over time ( $P \leq 0.01$ ).

The relative percentage changes in s-Mgb concentration are shown in *Figure 6.1*, as well as the total relative s-Mgb (AUC) concentrations (CS<sub>Run</sub>:  $2028 \pm 1015$ ; CS<sub>Rec</sub>:  $2255 \pm 1129$ ; CS<sub>Run&Rec</sub>:  $1805 \pm 905\%$ ;  $P = 0.92^{ab}$ ,  $0.80^{bc}$  and  $0.88^{ca}$ ). The AUC effect sizes were small ( $ES = 0.24^{ca}$ ) to medium ( $ES = 0.65^{ab}$ ,  $0.42^{bc}$ ) when calculated for the absolute s-Mgb concentrations (AUC: CS<sub>Run</sub>:  $848.6 \pm 424.6$ ; CS<sub>Rec</sub>:  $1112.8 \pm 557.2$ ; CS<sub>Run&Rec</sub>:  $935.1 \pm 468.7$  ng.mL<sup>-1</sup>;  $P = 0.77^{ab}$ ,  $0.84^{bc}$  and

0.93<sup>ca</sup>). No significant interaction effect ( $P = 0.39$ ) or main group effect were found between the different treatment groups ( $P = 0.29$ ).

ii. Serum Creatine Kinase (CK) Activity

Table 6.5 shows the absolute serum CK activity responses throughout the study period. The Cohen's effect size between the groups directly after the race was negligible to small ( $ES = 0.09 - 0.27$ ), however, at 24 to 72 hours after the race there were some practically significant differences of moderate strength, particularly between those who ran with the socks and those who only wore the socks during recovery.

Table 6.5 The absolute serum creatine kinase (units.L<sup>-1</sup>) concentrations (Mean ( $\bar{x}$ )  $\pm$  SD) for the three groups.

Assessments	CS <sub>Run</sub> <sup>a</sup> group	CS <sub>Rec</sub> <sup>b</sup> group	CS <sub>Run&amp;Rec</sub> <sup>c</sup> group	Effect Sizes ab, bc, ca
Baseline	146.4 $\pm$ 59.5	171.9 $\pm$ 81.7	176.9 $\pm$ 78.5	0.37 <sup>S</sup> , 0.06 <sup>N</sup> , 0.45 <sup>M</sup>
Post	589.6 $\pm$ 335.0	563.6 $\pm$ 280.4	518.7 $\pm$ 185.7	0.09 <sup>N</sup> , 0.19 <sup>S</sup> , 0.27 <sup>S</sup>
24 hours	1675.3 $\pm$ 1327.1*	2670.9 $\pm$ 2180.8*	2055.2 $\pm$ 1001.8	0.56 <sup>M</sup> , 0.37 <sup>S</sup> , 0.34 <sup>S</sup>
48 hours	1092.6 $\pm$ 887.8*	2116.9 $\pm$ 2173.8*	1650.6 $\pm$ 1366.1	0.62 <sup>M</sup> , 0.26 <sup>S</sup> , 0.50 <sup>M</sup>
72 hours	797.1 $\pm$ 828.6	1460.3 $\pm$ 1590.9	1030.2 $\pm$ 1011.2	0.53 <sup>M</sup> , 0.33 <sup>S</sup> , 0.26 <sup>S</sup>

<sup>a, b, & c</sup> Indicates effect sizes between respective treatment groups: \* Significant difference between CS<sub>Run</sub> and CS<sub>Rec</sub>,  $P = 0.02$ ; Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small, <sup>M</sup> medium

Figure 6.1 illustrates the relative percentage change in serum CK concentrations between the three treatment groups, as well as the AUC analysis. The serum CK concentrations were significantly elevated above baseline in all groups over the study period ( $P < 0.001$ ), with peak levels at 24 hours post-race. No significant main group ( $P = 0.25$ ) or interaction effect (time x group) were apparent ( $P = 0.28$ ).

The total relative serum CK (AUC: CS<sub>Run</sub><sup>a</sup>: 2118  $\pm$  907; CS<sub>Rec</sub><sup>b</sup>: 3674  $\pm$  1591; CS<sub>Run&Rec</sub><sup>c</sup>: 2139  $\pm$  933%;  $P = 0.56^{ab}$ ,  $0.53^{bc}$  and  $0.93^{ca}$ ) concentrations were not statistically significantly different between the treatment groups. However additional analysis of the absolute CK concentrations (AUC: CS<sub>Run</sub><sup>a</sup>: 3829.3  $\pm$  1630.9; CS<sub>Rec</sub><sup>b</sup>: 6167.5  $\pm$  2646.3; CS<sub>Run&Rec</sub><sup>c</sup>: 4828.1  $\pm$  2065.0 units.L<sup>-1</sup>;  $P = 0.55^{ab}$ ,  $0.74^{bc}$  and  $0.78^{ca}$ ) reveals that there was a very large practical difference between the CS<sub>Rec</sub>

and the CS<sub>Run</sub> group ( $ES = 1.19$ ). Whereas the differences observed for the CS<sub>Rec</sub> group compared to CS<sub>Run&Rec</sub> group ( $ES = 0.63$ ) and between the CS<sub>Run</sub> group and CS<sub>Run&Rec</sub> group ( $ES = 60$ ) were of a moderate practical significance.

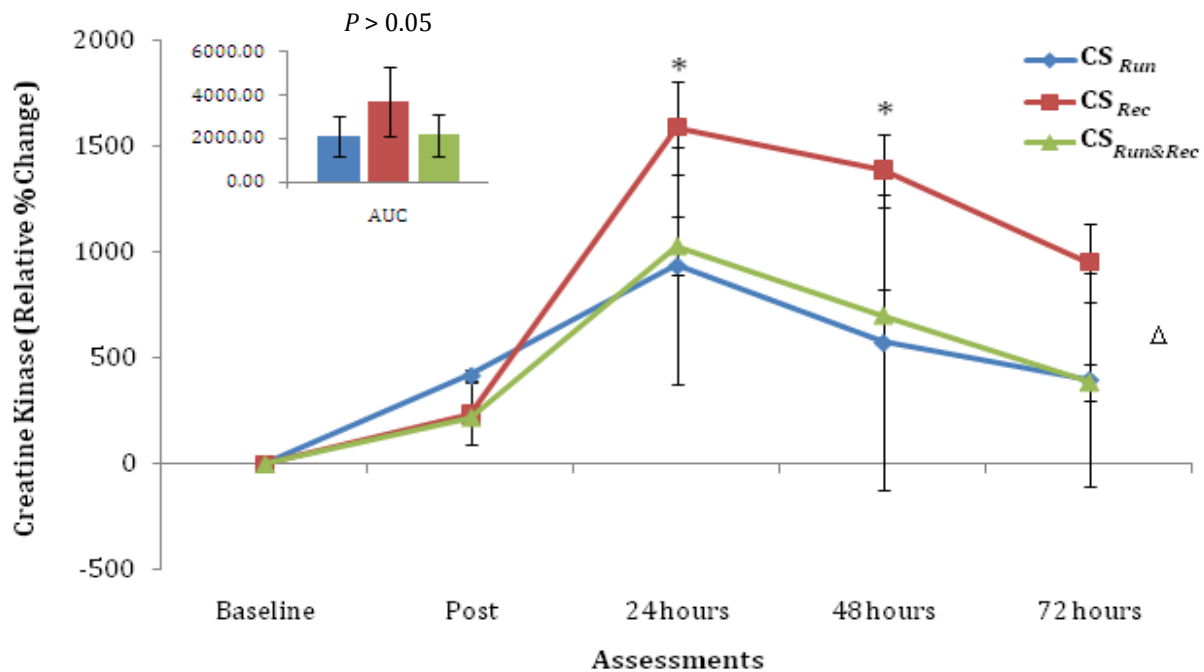


Figure 6.2 The relative percentage change in serum creatine kinase concentrations (error bars: SEM) in the CS<sub>Run</sub> group (  $\color{blue}\blacktriangle$  ), the CS<sub>Rec</sub> group (  $\color{red}\blacktriangle$  ) and the CS<sub>Run&Rec</sub> group (  $\color{green}\blacktriangle$  ). \*Significant difference between CONTROL and EXP ( $P < 0.05$ );  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

### iii. Ultrasensitive C - reactive Protein (hsCRP)

Table 6.6 lists the absolute values for hsCRP and Figure 6.3 illustrates the relative change in hsCRP during and after the race. The ultra-marathon induced a significant inflammatory response in all groups (main time effect;  $P < 0.001$ ). No main group ( $P = 0.59$ ) or group x time interaction effect ( $P = 0.60$ ) was observed between the treatment groups. Post hoc analysis revealed no difference between the three groups, and only negligible to small effect sizes.

Table 6.6 The absolute ultrasensitive C-reactive protein (mg.L<sup>-1</sup>) concentrations (Mean ( $\bar{x}$ )  $\pm$  SD) for the three groups.

Assessments	CS <sub>Run</sub> <sup>a</sup> group	CS <sub>Rec</sub> <sup>b</sup> group	CS <sub>Run&amp;Rec</sub> <sup>c</sup> group	Effect Sizes ab, bc, ca
Baseline	0.8 $\pm$ 0.5	1.0 $\pm$ 0.7	0.7 $\pm$ 0.6	0.20 <sup>S</sup> , 0.36 <sup>S</sup> , 0.20 <sup>S</sup>
Post	1.1 $\pm$ 0.7	1.1 $\pm$ 0.9	1.7 $\pm$ 3.4	0.01 <sup>N</sup> , 0.25 <sup>S</sup> , 0.25 <sup>S</sup>
24 hours	26.6 $\pm$ 9.6	25.1 $\pm$ 12.0	23.2 $\pm$ 9.8	0.14 <sup>N</sup> , 0.18 <sup>S</sup> , 0.26 <sup>S</sup>
48 hours	12.4 $\pm$ 4.3	12.8 $\pm$ 6.6	11.8 $\pm$ 5.7	0.08 <sup>N</sup> , 0.17 <sup>S</sup> , 0.13 <sup>N</sup>
72 hours	6.1 $\pm$ 2.2	6.4 $\pm$ 3.1	6.0 $\pm$ 3.0	0.12 <sup>N</sup> , 0.13 <sup>N</sup> , 0.03 <sup>N</sup>

<sup>a, b, & c</sup> Indicates effect sizes between respective treatment groups: Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small

The total relative change in hsCRP from baseline did not differ statistically significantly between the three treatment groups ( $P = 0.89^{ab}, 0.69^{bc}, 0.79^{ca}$ ). Additional analysis revealed a negligible practical difference between the CS<sub>Run</sub> and CS<sub>Rec</sub> groups ( $ES = 0.05$ ), and a small practical difference between the CS<sub>Run&Rec</sub> and CS<sub>Run</sub> groups ( $ES = 0.20$ ) and the CS<sub>Run&Rec</sub> and CS<sub>Rec</sub> groups ( $ES = 0.16$ ).

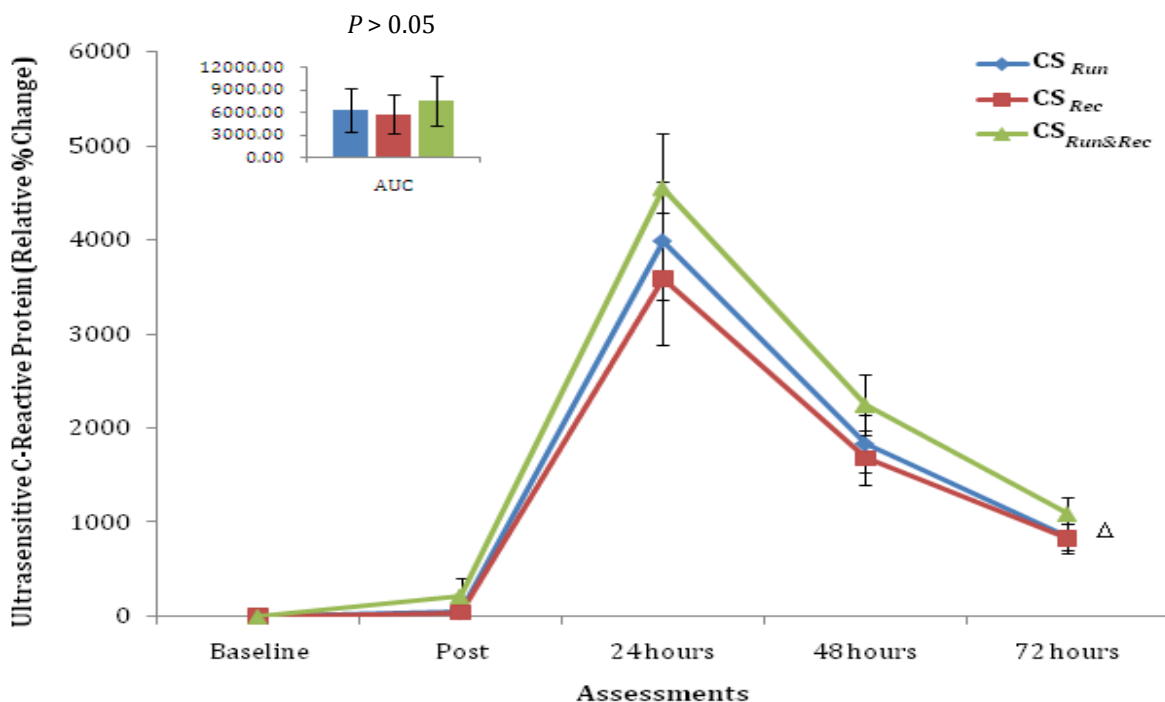


Figure 6.3 The relative percentage change in ultrasensitive C-reactive protein concentration (error bars: SEM) in the CS<sub>Run</sub> group (  $\blacklozenge$  ), the CS<sub>Rec</sub> group (  $\blacksquare$  ) and the CS<sub>Run&Rec</sub> group (  $\blacktriangle$  ).  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

**b. Swelling**

**i. Lower Limb Circumferences**

The absolute ankle circumferences are reported in *Table 6.7*. All the circumferences in the lower limbs changed significantly over time ( $P < 0.01$ ) and values generally peaked between 48 and 72 hours after the race for all the groups. There were no statistically significant differences in the ankle circumferences of the treatment groups (treatment effect,  $P = 0.99$  and group effect,  $P = 0.93$ ) and the practical differences varied between negligible to small.

*Table 6.7* The absolute values for ankle circumferences (cm; Mean ( $\bar{x}$ )  $\pm$  SD) for the three groups.

Assessments	CS <sub>Run</sub> <sup>a</sup> <i>group</i>	CS <sub>Rec</sub> <sup>b</sup> <i>group</i>	CS <sub>Run&amp;Rec</sub> <sup>c</sup> <i>group</i>	Effect Sizes <i>ab, bc, ca</i>
<b>Baseline</b>	21.8 $\pm$ 0.8	21.9 $\pm$ 1.7	22.0 $\pm$ 0.7	0.11 <sup>N</sup> , 0.05 <sup>N</sup> , 0.29 <sup>S</sup>
<b>Post</b>	21.7 $\pm$ 0.9	21.8 $\pm$ 1.9	21.9 $\pm$ 0.9	0.04 <sup>N</sup> , 0.08 <sup>N</sup> , 0.22 <sup>S</sup>
<b>24 hours</b>	22.0 $\pm$ 0.9	22.1 $\pm$ 1.8	22.1 $\pm$ 0.9	0.08 <sup>N</sup> , 0.03 <sup>N</sup> , 0.09 <sup>N</sup>
<b>48 hours</b>	22.1 $\pm$ 1.0	22.3 $\pm$ 1.9	22.2 $\pm$ 0.9	0.10 <sup>N</sup> , 0.04 <sup>N</sup> , 0.10 <sup>N</sup>
<b>72 hours</b>	22.1 $\pm$ 1.0	22.3 $\pm$ 1.7	22.3 $\pm$ 0.9	0.10 <sup>N</sup> , 0.01 <sup>N</sup> , 0.17 <sup>S</sup>

<sup>a, b, & c</sup> Indicates effect sizes between respective treatment groups; Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small

The percentage change in ankle circumferences is depicted in *Figure 6.4*. The AUC analysis revealed no statistical or practical significant differences between the three treatment groups ( $P = 0.40^{ab}, 0.57^{bc}, 0.75^{ca}$ ).



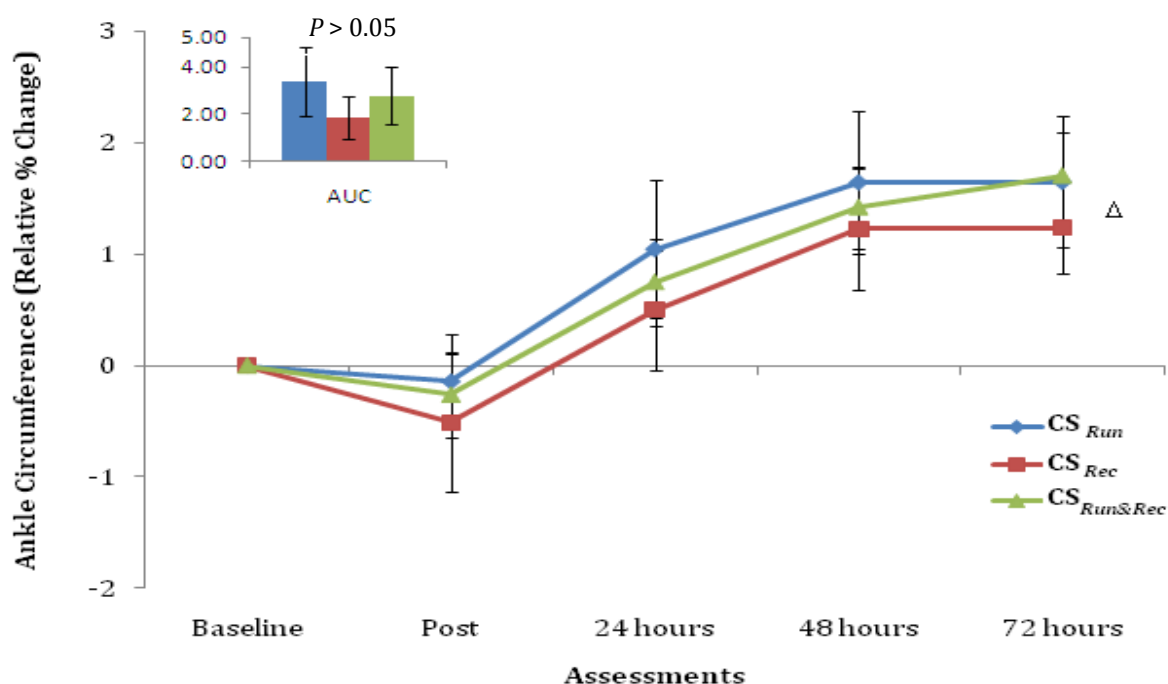


Figure 6.4 The relative percentage change from baseline in ankle circumferences (error bars: SEM) in the CS<sub>Run</sub> group ( —◆— ), the CS<sub>Rec</sub> group ( —■— ) and the CS<sub>Run&Rec</sub> group ( —▲— ). ΔSignificant change over time ( $P \leq 0.01$ ).

Table 6.8 and Figure 6.5 illustrate the changes in mid-calf circumferences. There was a significant interaction effect ( $P = 0.0003$ ), but no main group effect ( $P = 0.90$ ) among the three groups. The AUC analysis showed no statistical or practical significant differences between any of the three groups ( $P > 0.05$ ).

Table 6.8 The absolute mid-calf circumferences (cm; Mean ( $\bar{x}$ )  $\pm$  SD) for the three groups.

Assessments	CS <sub>Run</sub> <sup>a</sup> group	CS <sub>Rec</sub> <sup>b</sup> group	CS <sub>Run&amp;Rec</sub> <sup>c</sup> group	Effect Sizes ab, bc, ca
Baseline	37.0 $\pm$ 2.3	38.0 $\pm$ 3.5	37.8 $\pm$ 1.7	0.32 <sup>S</sup> , 0.07 <sup>N</sup> , 0.40 <sup>M</sup>
Post	36.2 $\pm$ 2.2	36.8 $\pm$ 3.7	36.8 $\pm$ 1.7	0.21 <sup>S</sup> , 0.01 <sup>N</sup> , 0.34 <sup>S</sup>
24 hours	37.2 $\pm$ 1.9	37.5 $\pm$ 3.6	37.3 $\pm$ 2.0	0.11 <sup>N</sup> , 0.08 <sup>N</sup> , 0.04 <sup>N</sup> ,
48 hours	37.6 $\pm$ 2.0	37.9 $\pm$ 3.7	37.7 $\pm$ 2.1	0.10 <sup>N</sup> , 0.06 <sup>N</sup> , 0.04 <sup>S</sup>
72 hours	37.7 $\pm$ 2.0	37.9 $\pm$ 3.7	37.6 $\pm$ 2.1	0.08 <sup>N</sup> , 0.12 <sup>N</sup> , 0.06 <sup>N</sup>

<sup>a, b, & c</sup> Indicates effect sizes between respective treatment groups; Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small, <sup>M</sup> medium

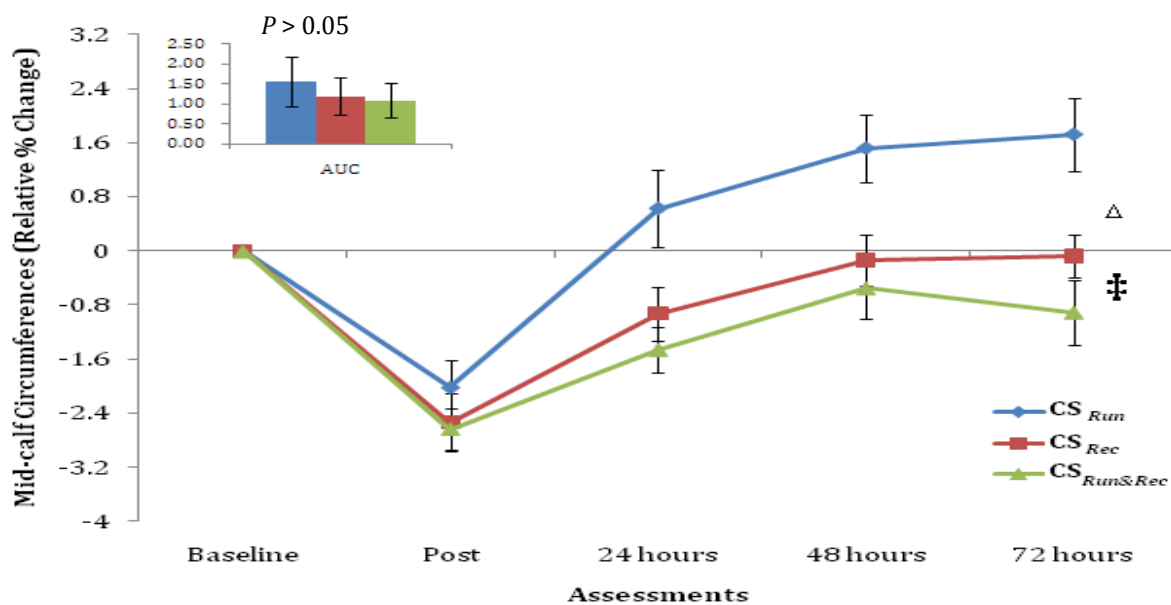


Figure 6.5 The relative percentage change from baseline in mid-calf circumferences (error bars: SEM) for men and women in the CS<sub>Run</sub> group (◆), the CS<sub>Rec</sub> group (■) and the CS<sub>Run&Rec</sub> group (▲). #Significant interaction effect ( $P \leq 0.01$ ); ΔSignificant change over time ( $P \leq 0.01$ ).

The absolute mid-thigh circumferences are reported in Table 6.9, together with effect sizes. Moderately meaningful practical differences were observed between the CS<sub>Run</sub> and the CS<sub>Rec</sub> groups ( $ES = 0.40 - 0.41$ ) during the recovery period, however, differences between the other two groups were negligible to small.

Table 6.9 The absolute mid-thigh circumferences (cm; Mean ( $\bar{x}$ )  $\pm$  SD) for the three groups.

Assessments	CS <sub>Run</sub> <sup>a</sup> group	CS <sub>Rec</sub> <sup>b</sup> group	CS <sub>Run&amp;Rec</sub> <sup>c</sup> group	Effect Sizes ab, bc, ca
Baseline	50.8 $\pm$ 3.1	52.2 $\pm$ 4.7	51.8 $\pm$ 2.6	0.35 <sup>S</sup> , 0.11 <sup>N</sup> , 0.35 <sup>S</sup>
Post	50.9 $\pm$ 3.2	52.4 $\pm$ 4.9	52.0 $\pm$ 2.6	0.36 <sup>S</sup> , 0.12 <sup>N</sup> , 0.37 <sup>S</sup>
24 hours	50.8 $\pm$ 3.2	52.5 $\pm$ 5.0	52.1 $\pm$ 2.8	0.41 <sup>M</sup> , 0.09 <sup>N</sup> , 0.47 <sup>M</sup>
48 hours	51.3 $\pm$ 3.3	53.0 $\pm$ 5.0	52.4 $\pm$ 2.9	0.41 <sup>M</sup> , 0.14 <sup>N</sup> , 0.39 <sup>S</sup>
72 hours	51.4 $\pm$ 3.3	53.0 $\pm$ 4.9	52.5 $\pm$ 2.9	0.40 <sup>M</sup> , 0.12 <sup>N</sup> , 0.39 <sup>S</sup>

<sup>a, b, & c</sup> Indicates effect sizes between respective treatment groups; Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small, <sup>M</sup> medium

Figure 6.6 depicts the relative percentage change in mid-thigh circumferences over the study period in all three groups. These circumferences only changed significantly over time for all

groups ( $P < 0.001$ ), but no interaction ( $P = 0.56$ ) or main group effect ( $P = 0.92$ ) were evident. The total relative change in mid-thigh circumferences (AUC) was not statistically or practically significant different between the groups ( $P = 0.71^{ab}$ ,  $0.87^{bc}$ ,  $0.58^{ca}$ ).

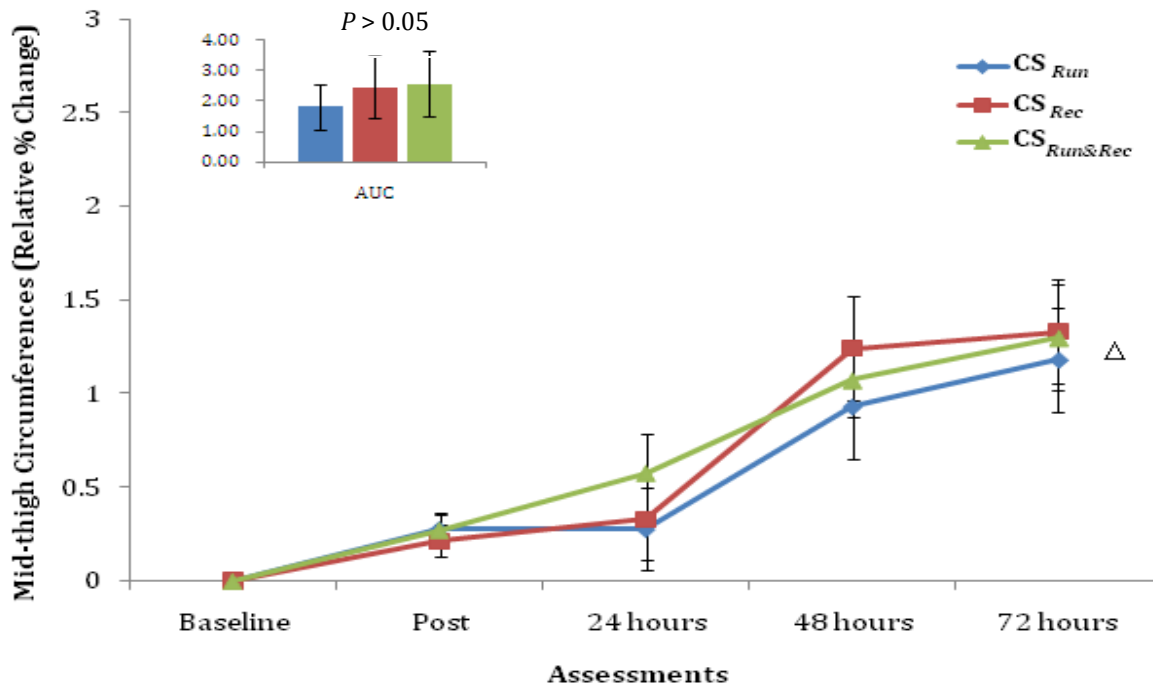


Figure 6.6 The relative percentage change from baseline in mid-thigh circumferences (error bars: SEM) in the CS<sub>Run</sub> group (—◆—), the CS<sub>Rec</sub> group (—■—) and the CS<sub>Run&Rec</sub> group (—▲—).  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

### c. Perceived muscle soreness

#### i. Visual Analogue Scales

The subjects' overall perceived muscle pain and discomfort is illustrated in Figure 6.7 – 6.9. Perceived muscle soreness for the *Quadriceps*, Hamstrings and calf muscles increased significantly from baseline to after the ultra-marathon race ( $P < 0.05$ ). The three treatment groups did not differ significantly in perceived muscle soreness at any time point except in the calf muscles between CS<sub>Rec</sub> and CS<sub>Run&Rec</sub> directly after the race ( $P = 0.04$ ).

Quadriceps

Table 6.10 and Figure 6.7 depict the absolute scores for the pain perceived in the *Quadriceps* muscles in the three groups. Pain and discomfort levels were worse directly after the race in all three groups and gradually recovered over 72 hours. There were no differences in the pain scores of the three groups ( $P > 0.05$ ) and all the effect sizes varied from negligible and small.

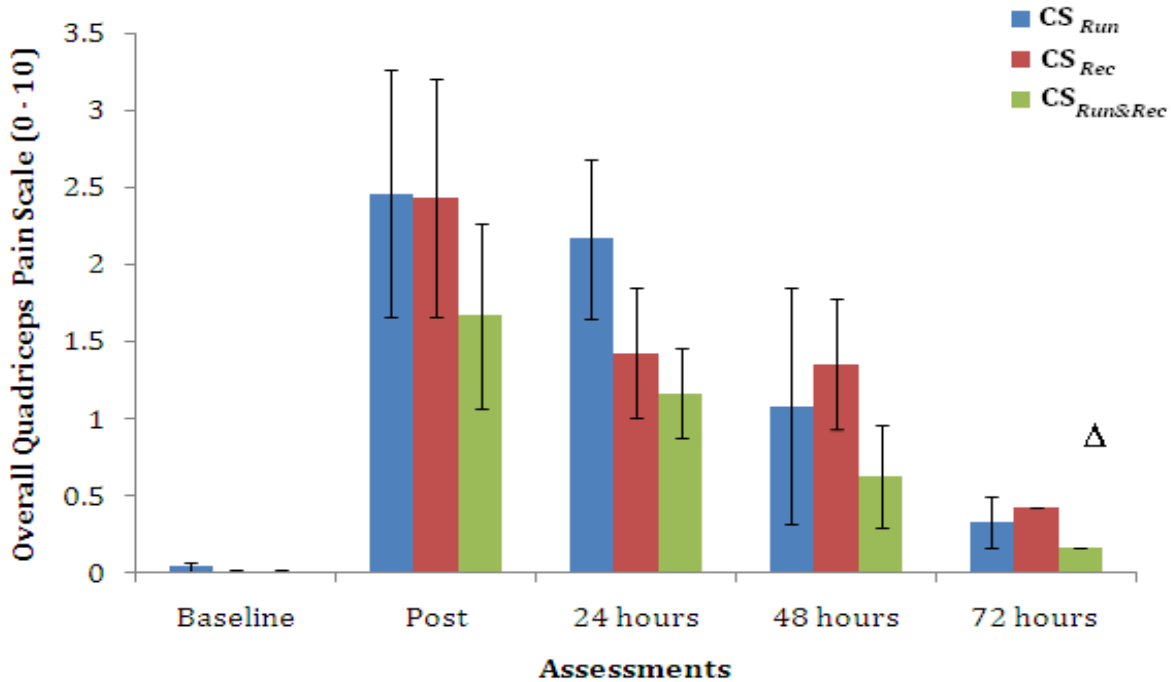


Figure 6.7 Overall perceived muscle soreness in the *Quadriceps* muscles following the ultra-marathon race in the CS<sub>Run</sub> ■, CS<sub>Rec</sub> ■ and CS<sub>Run&Rec</sub> ■.  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

Table 6.10 The overall perceived pain and discomfort (VAS pain scale 0 – 10) in the *Quadriceps* muscle (Mean ( $\bar{x}$ )  $\pm$  SD) for the three treatment groups.

Assessments	CS <sub>Run</sub> <sup>a</sup> group	CS <sub>Rec</sub> <sup>b</sup> group	CS <sub>Run&amp;Rec</sub> <sup>c</sup> group	Effect Sizes ab, bc, ca
<b>Baseline</b>	0.0 $\pm$ 1.1	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0	0.34 <sup>s</sup> , 0.04 <sup>N</sup> , 0.32 <sup>s</sup>
<b>Post</b>	2.5 $\pm$ 3.5	2.4 $\pm$ 3.7	1.7 $\pm$ 2.4	0.01 <sup>N</sup> , 0.25 <sup>s</sup> , 0.28 <sup>s</sup>
<b>24 hours</b>	2.2 $\pm$ 3.3	1.4 $\pm$ 2.2	1.2 $\pm$ 2.0	0.28 <sup>s</sup> , 0.13 <sup>N</sup> , 0.39 <sup>s</sup>
<b>48 hours</b>	1.1 $\pm$ 2.4	1.4 $\pm$ 0.4	0.6 $\pm$ 1.5	0.31 <sup>s</sup> , 0.37 <sup>s</sup> , 0.24 <sup>s</sup>
<b>72 hours</b>	0.3 $\pm$ 1.2	0.4 $\pm$ 1.6	0.2 $\pm$ 0.6	0.07 <sup>N</sup> , 0.22 <sup>s</sup> , 0.19 <sup>s</sup>

<sup>a, b, & c</sup> Indicates effect sizes between respective treatment group; Effect sizes: <sup>N</sup> negligible, <sup>s</sup> small

## Hamstrings

Table 6.11 and Figure 6.8 illustrate the overall pain and discomfort levels of the runners in the Hamstrings. The CS<sub>Rec</sub> group experienced the most pain directly after the race compared to the other two groups. Minimal pain and discomfort were reported during the three days of recovery after the race and the CS<sub>Run</sub> group was the only to report some pain and discomfort at 72 hours after the race.

Table 6.11 The overall perceived pain and discomfort (VAS pain scale 0 – 10) in the Hamstring muscle (*Mean* ( $\bar{x}$ )  $\pm$  *SD*) for the three treatment groups.

Assessments	CS <sub>Run</sub> <sup>a</sup> group	CS <sub>Rec</sub> <sup>b</sup> group	CS <sub>Run&amp;Rec</sub> <sup>c</sup> group	Effect Sizes ab, bc, ca
<b>Baseline</b>	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0	0.00 <sup>N</sup> , 0.00 <sup>N</sup> , 0.00 <sup>N</sup>
<b>Post</b>	1.4 $\pm$ 2.9	2.9 $\pm$ 3.9	0.6 $\pm$ 1.5	0.44 <sup>M</sup> , 0.78 <sup>L</sup> , 0.36 <sup>S</sup>
<b>24 hours</b>	0.3 $\pm$ 1.1	0.2 $\pm$ 0.6	0.5 $\pm$ 1.2	0.11 <sup>N</sup> , 0.32 <sup>S</sup> , 0.17 <sup>S</sup>
<b>48 hours</b>	0.2 $\pm$ 0.6	0.4 $\pm$ 0.9	0.5 $\pm$ 1.2	0.27 <sup>S</sup> , 0.14 <sup>N</sup> , 0.40 <sup>M</sup>
<b>72 hours</b>	0.6 $\pm$ 1.7	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0	0.54 <sup>M</sup> , 0.00 <sup>N</sup> , 0.52 <sup>M</sup>

<sup>a, b, & c</sup> Indicates effect sizes between respective treatment group; Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small, <sup>M</sup> medium

Directly after the race the CS<sub>Rec</sub> perceived more soreness in the Hamstrings with a large effect size ( $P = 0.40$ ) compared to the CS<sub>Run&Rec</sub> group and with a moderate effect from the CS<sub>Run</sub> group ( $P = 0.51$ ).



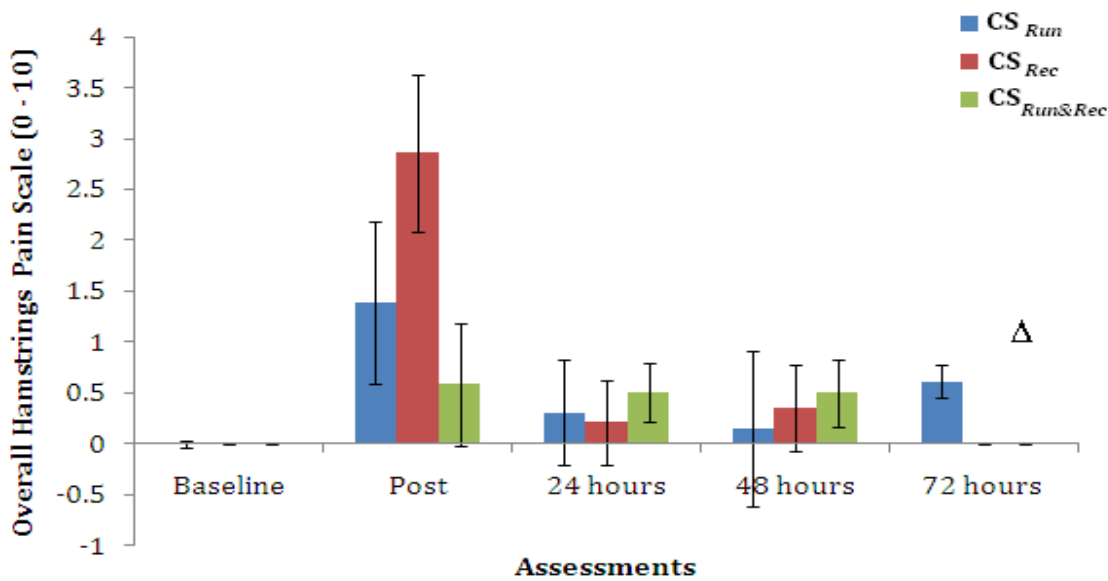


Figure 6.8 Overall perceived muscle soreness in the *Hamstring* muscles following the ultra-marathon race in the CS<sub>Run</sub> ■, CS<sub>Rec</sub> ■ and CS<sub>Run&Rec</sub> ■.  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

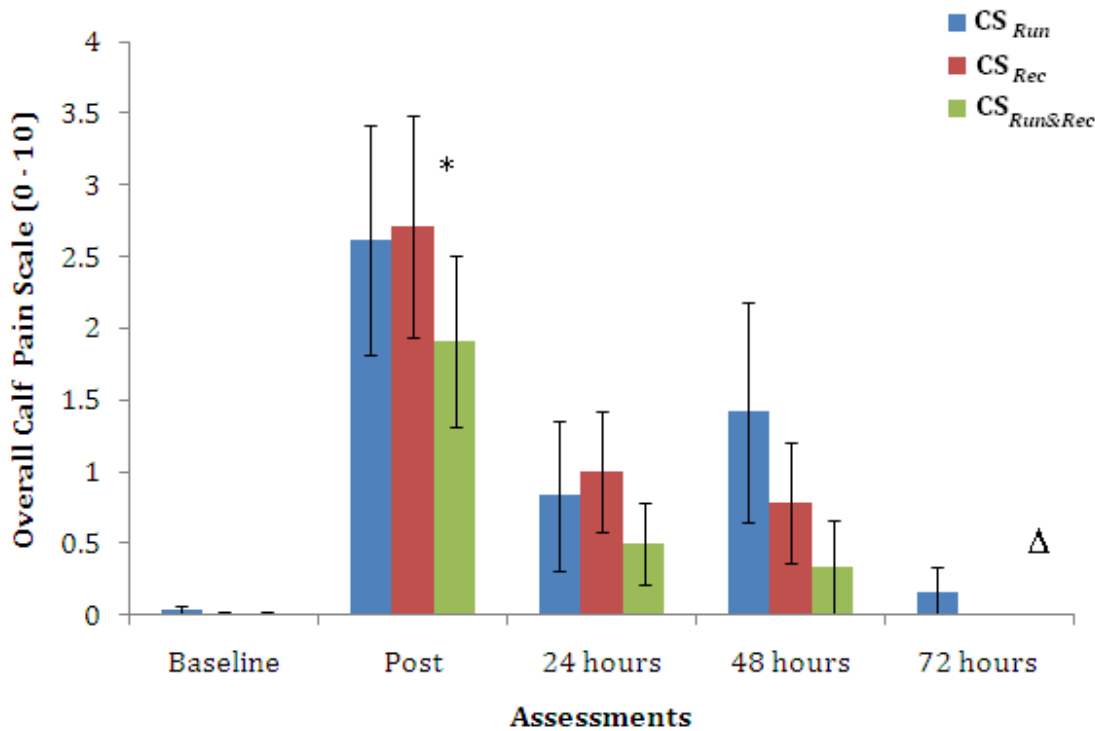
### Calf Muscles

The absolute pain scores for the calf muscle are presented in *Table 6.12* with the respective effect sizes between the three treatment groups. Runners in all groups experienced most pain and discomfort directly after the race. However, the practical differences between the groups were negligible to small. At 72 hours, the CS<sub>Run</sub> group still reported some levels of pain and discomfort, while the runners in the CS<sub>Run&Rec</sub> group and CS<sub>Rec</sub> group recovered completely by 72 hours.

Table 6.12 The perceived pain and discomfort (VAS pain scale 0 – 10) in the calf muscle (*Mean* ( $\bar{x}$ )  $\pm$  *SD*) for the three treatment groups.

Assessments	CS <sub>Run</sub> <sup>a</sup> <i>group</i>	CS <sub>Rec</sub> <sup>b</sup> <i>group</i>	CS <sub>Run&amp;Rec</sub> <sup>c</sup> <i>group</i>	Effect Sizes <i>ab, bc, ca</i>
<b>Baseline</b>	0.0 $\pm$ 0.1	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0	0.34 <sup>S</sup> , 0.04 <sup>N</sup> , 0.32 <sup>S</sup>
<b>Post</b>	2.6 $\pm$ 2.9	2.7 $\pm$ 2.9*	1.9 $\pm$ 2.1*	0.04 <sup>N</sup> , 0.33 <sup>S</sup> , 0.29 <sup>S</sup>
<b>24 hours</b>	0.8 $\pm$ 1.8	1.0 $\pm$ 1.6	0.5 $\pm$ 1.0	0.10 <sup>N</sup> , 0.39 <sup>S</sup> , 0.24 <sup>S</sup>
<b>48 hours</b>	1.4 $\pm$ 2.6	0.8 $\pm$ 1.6	0.3 $\pm$ 1.2	0.31 <sup>S</sup> , 0.34 <sup>S</sup> , 0.55 <sup>M</sup>
<b>72 hours</b>	0.2 $\pm$ 0.6	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0	0.44 <sup>M</sup> , 0.00 <sup>N</sup> , 0.43 <sup>M</sup>

*a, b, & c* Indicates effect sizes between respective treatment group; \* Significant difference between  $CS_{Run\&Rec}$  and  $CS_{Rec}$ ,  $P = 0.04$ ; Effect sizes: *N* negligible, *S* small, *M* medium



**Figure 6.9** Overall perceived muscle soreness in the calf muscles following the ultra-marathon race in the  $CS_{Run}$  ■,  $CS_{Rec}$  ■ and  $CS_{Run\&Rec}$  ■. \*Significant difference between  $CS_{Run\&Rec}$  and  $CS_{Rec}$  ( $P = 0.04$ );  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

*ii. Viability Questionnaires*

Subjects were asked to complete an appropriateness-and-convenience questionnaire to assess the viability of the compression socks. Of the 14 runners who wore the compression socks only during the race ( $CS_{Run}$ ), 73% reported that they will wear the socks again during their training and races. About 59% of the fifteen runners in the group who wore the socks only during the 72 hours recovery period ( $CS_{Rec}$ ) and 78% of the 14 runners who wore the socks during the race as well as during the recovery period ( $CS_{Run\&Rec}$ ) stated that they will wear the compression sock again. *Table 6.13* summarizes the key questions of the appropriateness-and-convenience questionnaire.

Table 6.13 The appropriateness-and-convenience questionnaire to assess the runners' perception of the compression socks' viability as a recovery aid (%; n = 43)\*.

Viability Questions	CS <sub>Run</sub>	CS <sub>Rec</sub>	CS <sub>Run&amp;Rec</sub>
Comfortable	93%	88%	100%
Contributing to Foot Sores	33%	18%	17%
Difficulty Putting Garment On	41%	41%	72%
Improve Running Confidence	78%	0%	61%
Preventing Injuries	93%	94%	94%
Additional Fatigue Due To CS	20%	12%	17%
Compression Sock Aids Running	80%	n/a	61%
Compression Sock Aids Recovery	0%	62%	70%
Sweating Excessively due to CS	7%	0%	28%
Contribute to Irritation	20%	0%	39%

\* The table indicates the percentage of runners who agreed with the statement.

### c. Metabolic Responses

#### i. Blood Lactate Concentration

Figure 6.10 illustrates the relative percentage change over time in blood lactate concentrations in the three groups. The blood lactate concentrations increased significantly after the ultramarathon race in all the groups ( $P < 0.001$ ) and peaked directly after the race. There was no interaction effect between groups over time ( $P = 0.34$ ) or main group effect ( $P = 0.42$ ).

There was a 14% lower blood lactate concentration directly after the race in the CS<sub>Run</sub> group compared to CS<sub>Rec</sub> group ( $P = 0.05$ ) and this difference was of moderate practical significance ( $ES = 0.47$ ). The CS<sub>Run&Rec</sub> group also had an 11% lower blood lactate than the CS<sub>Rec</sub> group, although this difference was not statistically significant and only of small practical significance ( $P = 0.09$ ;  $ES = 0.39$ ). A negligible difference of 2% was observed between the CS<sub>Run</sub> and CS<sub>Run&Rec</sub> groups ( $P = 0.76$ ;  $ES = 0.09$ ) directly after the race. At 72 hours the CS<sub>Run</sub> group had slightly elevated blood lactate concentrations, while the other two groups recovered completely.



**Table 6.14** The absolute blood lactate (mmol.L<sup>-1</sup>) concentrations (*Mean* ( $\bar{x}$ )  $\pm$  *SD*) for the three groups.

<b>Assessments</b>	<b>CS<sub>Run</sub><sup>a</sup> group</b>	<b>CS<sub>Rec</sub><sup>b</sup> group</b>	<b>CS<sub>Run&amp;Rec</sub><sup>c</sup> group</b>	<b>Effect Sizes ab, bc, ca</b>
<b>Baseline</b>	1.1 $\pm$ 0.3	1.4 $\pm$ 0.5	1.3 $\pm$ 0.4	0.72 <sup>M</sup> , 0.06 <sup>N</sup> , 0.76 <sup>L</sup>
<b>Post</b>	3.1 $\pm$ 0.8*	3.6 $\pm$ 1.2*#	3.2 $\pm$ 0.9#	0.47 <sup>M</sup> , 0.39 <sup>S</sup> , 0.09 <sup>N</sup>
<b>30 minutes</b>	2.5 $\pm$ 0.7	2.6 $\pm$ 0.7	2.4 $\pm$ 0.6	0.15 <sup>S</sup> , 0.36 <sup>S</sup> , 0.22 <sup>S</sup>
<b>24 hours</b>	1.8 $\pm$ 0.5	1.7 $\pm$ 0.5	1.5 $\pm$ 0.4	0.38 <sup>S</sup> , 0.27 <sup>S</sup> , 0.66 <sup>M</sup>
<b>48 hours</b>	1.5 $\pm$ 0.4	1.7 $\pm$ 0.6	1.6 $\pm$ 0.5	0.42 <sup>M</sup> , 0.17 <sup>S</sup> , 0.29 <sup>S</sup>
<b>72 hours</b>	1.5 $\pm$ 0.4 $\Upsilon$	1.3 $\pm$ 0.5	1.1 $\pm$ 0.5 $\Upsilon$	0.52 <sup>M</sup> , 0.44 <sup>M</sup> , 1.07 <sup>L</sup>

<sup>a, b, & c</sup> Indicates effect sizes between respective treatment groups: \* Significant difference between CS<sub>Run</sub> and CS<sub>Rec</sub>, *P* = 0.05; ;# Tendency to differ between CS<sub>Rec</sub> and CS<sub>Run&Rec</sub> (*P* = 0.09);  $\Upsilon$  Tendency to differ between CS<sub>Run&Rec</sub> and CS<sub>Run</sub> (*P* = 0.08);  $\Delta$  Significant change over time (*P*  $\leq$  0.01). Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small, <sup>M</sup> medium, <sup>L</sup> large

The AUC analysis for the total relative percentage change in lactate concentrations (*Figure 6.14*) revealed no statistically significant differences between the three groups (CS<sub>Run</sub><sup>a</sup>: 406  $\pm$  166, CS<sub>Rec</sub><sup>b</sup>: 329  $\pm$  135, CS<sub>Run&Rec</sub><sup>c</sup>: 283  $\pm$  114%; *P* = 0.67<sup>ab</sup>, 0.62<sup>bc</sup>, 0.38<sup>ca</sup>). In practical terms there were small differences between the CS<sub>Run</sub> and CS<sub>Rec</sub> groups (*ES* = 0.16), and the CS<sub>Run&Rec</sub> and CS<sub>Rec</sub> groups (*ES* = 0.26). A negligible practical difference were found between the CS<sub>Run</sub> and CS<sub>Run&Rec</sub> groups (*ES* = 0.1). This was calculated from the overall absolute blood lactate concentrations (CS<sub>Run</sub><sup>a</sup>: 10.2  $\pm$  3.9; CS<sub>Rec</sub><sup>b</sup>: 10.8  $\pm$  4.1; CS<sub>Run&Rec</sub><sup>c</sup>: 9.8  $\pm$  3.8 mmol.L<sup>-1</sup>).



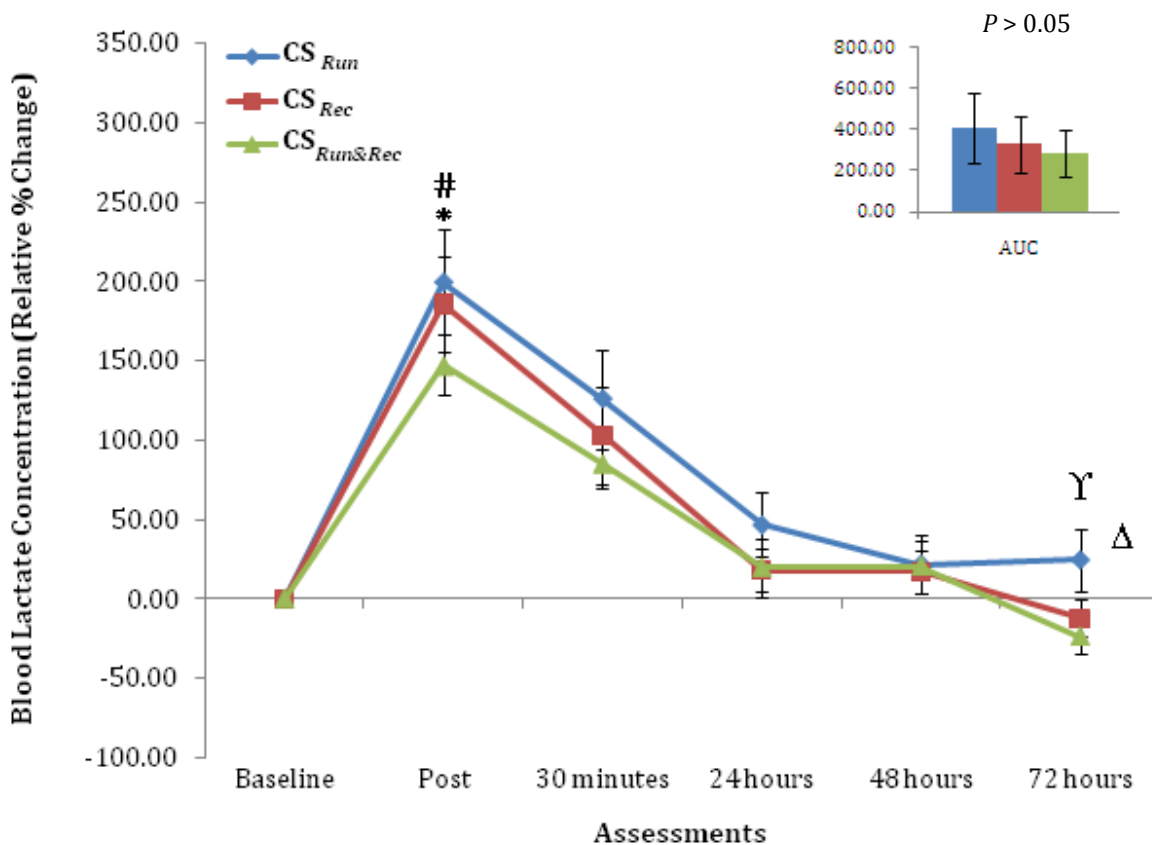





Figure 6.10 The relative percentage change in blood lactate concentration (error bars: SEM) in the CS<sub>Run</sub> group ( , the CS<sub>Rec</sub> group ( ) and the CS<sub>Run&Rec</sub> group ( ). \*Significant difference between CS<sub>Run</sub> and CS<sub>Rec</sub>, ( $P = 0.05$ ); #Tendency towards statistically significant difference between CS<sub>Run</sub> and CS<sub>Rec</sub>, ( $P = 0.05$ ); #Tendency towards statistically significant difference between CS<sub>Rec</sub> and CS<sub>Run&Rec</sub> ( $P = 0.09$ );  $\Upsilon$ Tendency towards statistically significant difference between CS<sub>Run&Rec</sub> and CS<sub>Run</sub> ( $P = 0.08$ );  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

**d. Functional Ability**

*i. Running Economy*

Table 6.15 and Figure 6.11 show the absolute values and relative percentage changes in running economy over the study period. Running economy was negatively affected by the ultra-marathon race and showed a significant time effect ( $P < 0.001$ ). Overall, there was neither a significant interaction effect ( $P = 0.23$ ), nor a significant main group effect ( $P = 0.45$ ).

Absolute oxygen consumption during the baseline running economy test did not differ statistically significantly between the  $CS_{Run}$  group and  $CS_{Rec}$  group, however it did differ significantly between the  $CS_{Run}$  group and the  $CS_{Run\&Rec}$  group ( $P = 0.04$ ). The effect sizes for these differences varied between moderate to large (Table 6.14). The total relative change in running economy (AUC) was not practically or statistically significant ( $P = 0.67^{ab}$ ,  $0.80^{bc}$  and  $0.52^{ca}$ ).

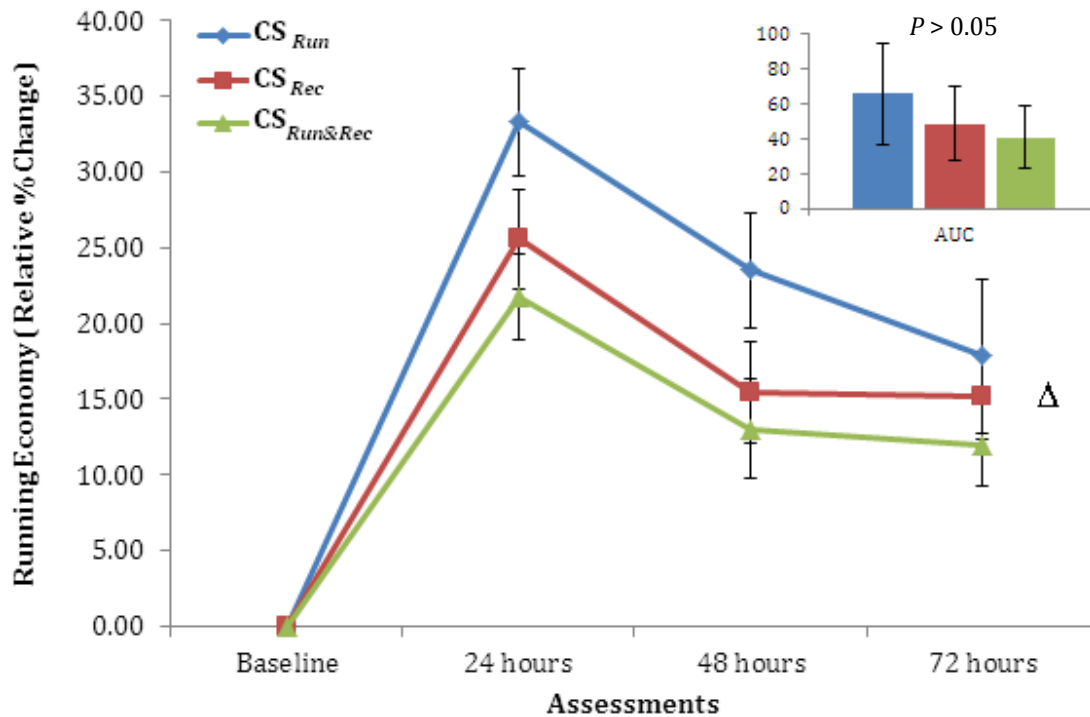


Figure 6.11

The relative change in running economy after the ultra-marathon race in the  $CS_{Run}$  group (  $\color{blue}\blacklozenge$  ), the  $CS_{Rec}$  group (  $\color{red}\blacksquare$  ) and the  $CS_{Run\&Rec}$  group (  $\color{green}\blacktriangle$  ). \*Significant difference between  $CS_{Run}$  and  $CS_{Run\&Rec}$  ( $P = 0.04$ );  $\Delta$ Significant change over time ( $P \leq 0.01$ ).

**Table 6.15** The absolute oxygen consumption ( $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-0.75}$ ) during the running economy test after ultra-marathon ( $\text{Mean}(\bar{x}) \pm \text{SD}$ ).

Assessments	$\text{CS}_{\text{Run}}^a$ group	$\text{CS}_{\text{Rec}}^b$ group	$\text{CS}_{\text{Run\&Rec}}^c$ group	Effect Sizes ab, bc, ca
<b>Baseline</b>	$87.7 \pm 9.2^*$	$92.4 \pm 11.4$	$99.1 \pm 13.9^*$	$0.46^M, 0.55^M, 0.99^L$
<b>24 hours</b>	$118.8 \pm 13.4$	$115.6 \pm 14.9$	$120.0 \pm 14.7$	$0.23^S, 0.32^S, 0.09^N$
<b>48 hours</b>	$108.3 \pm 16.3$	$106.1 \pm 13.8$	$111.1 \pm 12.7$	$0.15^S, 0.39^S, 0.20^S$
<b>72 hours</b>	$102.9 \pm 16.8$	$106.2 \pm 15.4$	$110.3 \pm 13.3$	$0.21^S, 0.29^S, 0.51^M$

*a, b, & c* Indicates effect sizes between respective treatment groups; \* Significant difference between  $\text{CS}_{\text{Run}}$  and  $\text{CS}_{\text{Run\&Rec}}$ ,  $P = 0.04$ ; Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small, <sup>M</sup> medium, <sup>L</sup> large

Table 6.16 shows that there were no statistically significant differences in the heart rates of the runners during the running economy test. Although there were significant changes over time ( $P < 0.001$ ), there was no significant interaction effect between the three groups ( $P > 0.05$ ).

**Table 6.16** The average heart rate (bpm) response during the running economy (RE) test after ultra-marathon ( $\text{Mean}(\bar{x}) \pm \text{SD}$ ).

Assessments	$\text{CS}_{\text{Run}}^a$ group	$\text{CS}_{\text{Rec}}^b$ group	$\text{CS}_{\text{Run\&Rec}}^c$ group	Effect Sizes ab, bc, ca
<b>Baseline</b>	$146 \pm 15$	$141 \pm 15$	$134 \pm 7$	$0.36^M, 0.62^M, 1.07^L$
<b>24 hours</b>	$157 \pm 14$	$150 \pm 14$	$143 \pm 14$	$0.51^M, 0.47^M, 0.98^L$
<b>48 hours</b>	$151 \pm 13$	$146 \pm 14$	$141 \pm 17$	$0.38^S, 0.36^S, 0.36^S$
<b>72 hours</b>	$147 \pm 13$	$145 \pm 15$	$139 \pm 14$	$0.12^N, 0.47^M, 0.63^M$

*a, b, & c* Indicates effect sizes between respective treatment groups; \* Significant difference between  $\text{CS}_{\text{Run}}$  and  $\text{CS}_{\text{Rec}}$ ,  $P = 0.02$ ; Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small, <sup>M</sup> medium, <sup>L</sup> large

ii. **Countermovement Jump (Explosive Power)**

Peak power (Watts) relative to baseline was significantly affected by the ultra-marathon race over time ( $P < 0.001$ ). No significant group x time interaction ( $P = 0.69$ ) and group effect was observed ( $P = 0.94$ ), indicating that the treatment groups were similarly affected by the exercise (Table 6.17). By 72 hours, the  $\text{CS}_{\text{Run}}$  group recovered completely in terms of explosive power, while the values for the other two groups were still below baseline. The AUC analysis reveals no practical or statistically significant difference between the three treatment groups ( $P = 0.43^{ab}, 0.26^{bc}, 0.62^{ca}$ ).

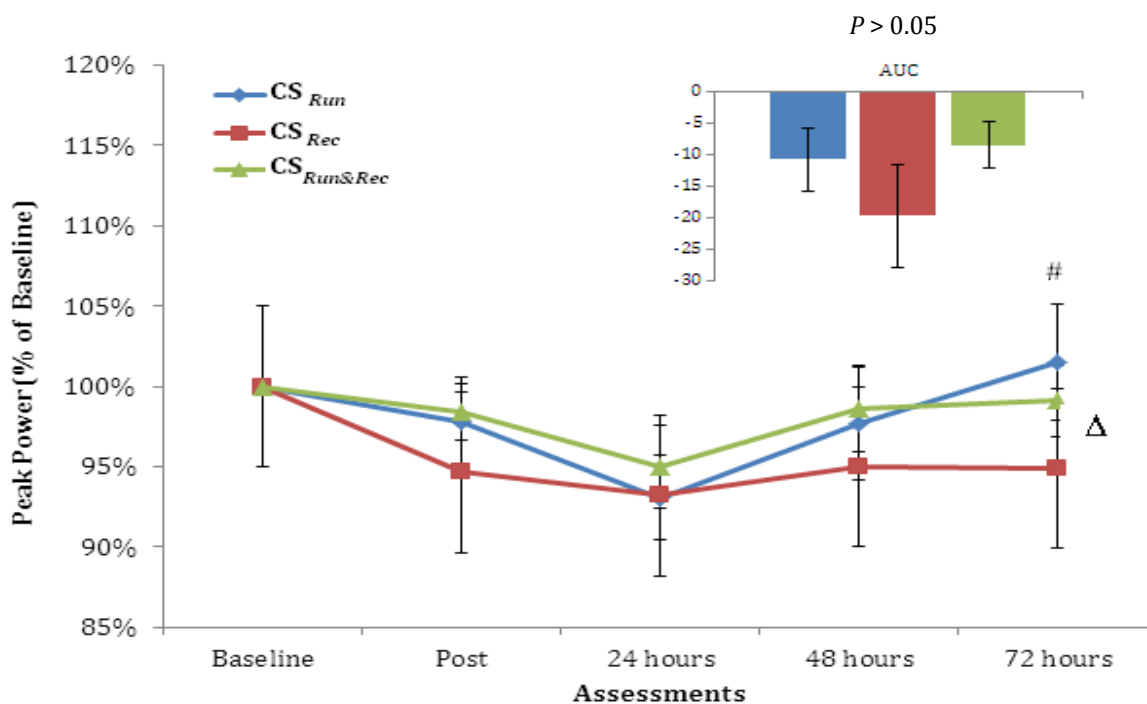


Figure 6.12 Countermovement vertical jump peak power (error bars: SEM) relative to baseline following the ultra-marathon in the three groups. #  $CS_{Run}$  and  $CS_{Rec}$  tend to differ from baseline ( $P = 0.07$ );  $\Delta$  Significant change over time ( $P \leq 0.01$ ).

Table 6.17 Peak power (Watts) measurements ( $Mean (\bar{x}) \pm SD$ ) for the three groups.

Assessments	$CS_{Run}^a$ group	$CS_{Rec}^b$ group	$CS_{Run\&Rec}^c$ group	Effect Sizes ab, bc, ca
Baseline	1613 ± 262	1619 ± 315	1611 ± 203	0.02 <sup>N</sup> , 0.03 <sup>N</sup> , 0.01 <sup>N</sup>
Post	1577 ± 292	1536 ± 362	1587 ± 237	0.13 <sup>N</sup> , 0.17 <sup>S</sup> , 0.04 <sup>N</sup>
24 hours	1495 ± 259	1526 ± 329	1520 ± 275	0.11 <sup>N</sup> , 0.02 <sup>N</sup> , 0.10 <sup>N</sup>
48 hours	1565 ± 254	1555 ± 343	1572 ± 248	0.03 <sup>N</sup> , 0.06 <sup>N</sup> , 0.03 <sup>N</sup>
72 hours	1633 ± 299	1559 ± 364	1576 ± 205	0.23 <sup>S</sup> , 0.06 <sup>N</sup> , 0.23 <sup>S</sup>

<sup>a, b, & c</sup> Indicates effect sizes between respective treatment groups; Effect sizes: <sup>N</sup> negligible, <sup>S</sup> small, <sup>M</sup> medium

## CHAPTER SEVEN

### DISCUSSION

#### I. INTRODUCTION

Knee-high graduated compression socks have become a commonly used recovery strategy for endurance athletes, but to date there are little scientific evidence to validate this practice in well-conditioned athletes (Jakeman *et al.*, 2010; Sperlich *et al.*, 2010). The aim of this two part investigation was to examine the efficacy by which graduated compressive knee-high socks can modulate the recovery of muscle damage and athletic performance in well-trained distance runners.

In the first part of the research (part I) the objective was to compare the use of graduated compression socks and placebo socks during a real life ultra-distance event. The next part of the investigation (part II) endeavoured to establish the optimal time to wear graduated compression socks i.e. during and/or after endurance exercise. Each recovery parameter will be discussed in this order. For the purpose of this investigation optimal time was defined as the most advantageous interval to apply external pressure that is practical and safe, as well as produces the greatest regeneration benefits and shortest recovery time.

A major contribution of this study is that a real-life ultra-distance event was used as experimental protocol and the results of this study therefore contribute directly to the practical application of sport science recovery research (ecological validity). Previous research has typically used laboratory or simulated environments, with little attention focusing on actual sporting situations. Therefore, a level of soft tissue damage (exercise induced muscle damage, EIMD) was induced which can be assumed to be typical for experienced, well-trained distance runners who are accustomed to high volume exercise. The results of this study are therefore also applicable to the majority of runners who regularly compete in distance events.

Laboratory or simulated activities typically investigate muscle damage by inducing DOMS with an eccentric activity, such as downhill running/walking and eccentric resistance activities (Clea



and Eston, 1992; Kraemer *et al.*, 2001<sup>a</sup>; Kraemer *et al.*, 2001<sup>b</sup>; Trenell *et al.*, 2006; Bailey *et al.*, 2007; French *et al.*, 2008; Pearce *et al.*, 2009; Jakeman *et al.*, 2010). This practice is based on findings from previous research that have found more pronounced muscle damage with eccentric protocols, due to more forceful contractions, compared to isometric and concentric actions (Byrne *et al.*, 2004; Proske and Allen, 2005).

However, isolated eccentric muscle action rarely occurs in natural human movement (Byrne *et al.*, 2004). Instead, natural muscle function occurs in a sequence of active eccentric muscle action followed by an active concentric muscle action, better known as the stretch shortening cycle (Chambers *et al.*, 1998; Komi, 2000; Tee *et al.*, 2007). The stretch shortening cycle (SSC) occurs during daily activities and especially during activities like running. With running, the individual's body is subjected to high impact and/or stretch due to external forces such as gravity. Consecutive stretching of muscles during running results in high mechanical strain and transient breakdown of ultra-structures in muscles (Fridén *et al.*, 1983; Kuipers *et al.*, 1989). As a result the SSC activities cause muscle damage which interrupts contractile function. Furthermore, long distance running events, such as the 56 km race used in this investigation, have been shown to induce myofibrillar material and cytoskeleton damage because of the large eccentric component (Strachan *et al.*, 1984; Cleak and Eston, 1992). During the 56 km race the runners would experience on average about 2363 stretch-shortening cycles and together with the large percentage of downhill running during this specific race, it is very likely that the runners in this study experienced a significant amount of mechanical stress.

Some researchers suggested that eccentric activities typically used to induce muscle soreness may differ from dramatic or sudden acute injuries, such as strains and sprains attained during actual races (Kraemer *et al.*, 2004; Byrne *et al.*, 2004; Miller *et al.*, 2004; Zainuddin *et al.*, 2005; Takahashi *et al.*, 2006). Strains are also more severe than eccentric induced muscle damage (Zainuddin *et al.*, 2005). Furthermore, researchers suggested that the maximum impact forces experienced by runners on a treadmill are less compared to over ground running on hard surfaces, such as tarmac (Ali *et al.*, 2007; Ali *et al.*, 2010). Consequently, assessing runners during an actual real-life situation would take these higher ground reaction forces into account.



The aims of recovery research are not limited to the manipulation of recovery time, but also to improve the quality of recovery that would prevent future injuries or chronic strains. As a consequence, research in this field should address the benefits of recovery during both training and competition. Long distance runners accumulate muscle and cartilage damage over their running lifetime from strains and sprains, as well as by accumulated fatigue (Kuipers *et al.*, 1989; Kim *et al.*, 2009). The changes in the ultra-structure of the muscle tissue are due to continuous degeneration and regeneration of skeletal muscle (Hikida *et al.*, 1983; Warhol *et al.*, 1985). Hence, it may be speculated that any reduction in acute muscle damage during training and competition, would minimize the accumulated muscle damage experienced by athletes during their running career. Furthermore, the occurrence of injuries and muscular overuse in long distance runners are associated with the distance covered per week rather than the intensity of the run (Hikida *et al.*, 1983; Warhol *et al.*, 1985; Kuipers *et al.*, 1989). Despite the risks and discomfort, participation in distance events by runners of all walks of life seems to increase in popularity (Kim *et al.*, 2009). Thus, an effective recovery strategy will not only limit exercise induced muscle damage and alleviate the associated symptoms during and/or after races, but also during training. Consequently, runners should have less structural damage or overuse injuries in the long term.

There is limited evidence to support the use of compression socks during and following dynamic exercise. Dynamic activities are considered by Bailey *et al.* (2007) to be ecologically more valid when providing recommendations in a sport performance environment. Hence, investigating the effects of a recovery modality in a real-life situation such as the 56 km race would be more realistic and ecologically valid than controlled laboratory research. It is hypothesized that endurance trained runners may benefit from a recovery modality such as compression garments, by limiting recurring muscle damage or secondary damage due to inflammation associated with exercise induced muscle damage. Also, it has been reported that endurance athletes often develop increased vascular compliance, which would predispose them to venous insufficiencies (Donaldson, 1990). Wearing compression garments during running may possibly prevent, or at least slow down this process.





## II. THE PARTICIPANTS

Most recovery research has been done on healthy untrained or sedentary individuals since it is easier to induce an adverse response in these participants and they are more readily available for these types of interventions than well-trained athletes. However, there are many reasons why results from an untrained population cannot unconditionally be extrapolated to a well-trained population. For instance, in the context of this study, it is important to note that the soft tissue recovery in untrained individuals do not reflect the same recovery responses of conditioned athletes (Tee *et al.*, 2007; Kraemer *et al.*, 2010). Yet the irony is that it is mostly well-trained athletes and active individuals who make use of the recovery strategies despite the fact that most research is limited to sedentary individuals.

One of the critical aspects differentiating this investigation from previous studies is the training status and training volume of the volunteers that participated. This means that these runners will not only need a higher intensity to elicit an adverse response, but will also recover faster. All the runners in this study had more than 2 years endurance training experience (range 2- 32 years in part I and 3 to 27 years part II). With the exception of 10 runners, all have completed at least one ultra-distance event (~90 km) in the year prior to the start of this study. Those runners who have not completed a ~90 km distance event in the 12 months before the research were evenly distributed between the various groups of part I and II. All the runners participated in at least three distance events longer than 30 km in the 12 months before the actual testing race. It can thus be concluded that this extensive training experience will probably result in a prophylactic resistance to physical strain in these runners, which is called the repeated bout effect (Nosaka and Clarkson, 1995). This brings the focus again to the question whether or not compression socks are a viable recovery method for trained endurance athletes. Especially since most research has been on untrained athletes.

The participants of this study were healthy, fit men who trained regularly (4 to 6 days a week). In the 6 weeks prior to the 56 km race, the runners in part I averaged about 75 km.w<sup>-1</sup> training and had about 12 years running experience. In part II, all the runners averaged 76 km.w<sup>-1</sup> training and had about 11 years running experience. This is similar to other studies which involved well-



trained ultra-distance runners (Speechly *et al.*, 1996; Bam *et al.*, 1997; Nieman *et al.*, 2006; Kim *et al.*, 2007; Kim *et al.*, 2009).

Previous research by Hoffman (2008<sup>a</sup>) reported body mass index values between 21.6 and 24.6 for competitive male ultra-marathon runners. This is similar to the BMI reported in the current research; with the exception of one runner in the *CS<sub>Rec</sub>* group and one runner in the *CS<sub>Run&Rec</sub>* group in part II of the research who had a BMI above 29. Hoffman (2008<sup>a</sup>) explained that participants in ultra-marathon events may vary widely in physical characteristics with BMI values that would classify individuals even as underweight or overweight. Body fat percentage, height and body mass in both parts of the research were similar than previously reported for experienced long and ultra-distance runners (Bam *et al.*, 1997; Nieman *et al.*, 2006; Kim *et al.*, 2007; Hoffman, 2008<sup>a</sup>; Hoffman, 2008<sup>b</sup>; Kim *et al.*, 2009).

The average age for long distance runners are between 35 and 59 years (Bam *et al.*, 1997; Nieman *et al.*, 2006; Kim *et al.*, 2007; Hoffman, 2008<sup>a</sup>; Hoffman, 2008<sup>b</sup>; Kim *et al.*, 2009) and the sample of this study is therefore representative of this popular age range. There were no differences in the aerobic capacities between any of the groups in the study and the runners were all classified with excellent aerobic capacity for their age and gender (Brooks *et al.*, 2005). In addition, Speechly *et al.* (1996) reported similar aerobic capacities in their study for ultra-distance athletes of the same age and gender.

### **III. THE 56 KM ULTRA-MARATHON**

According to Bam *et al.* (1997) any distance longer than the standard 42.2 km marathon is considered an ultra-marathon event. Since ultra-marathon running is frequently associated with muscle damage and various cellular changes (Kim *et al.*, 2007), a well-known 56 km race in Cape Town was chosen for this intervention study. This race takes place over a tough course consisting of undulating hills and at least three demanding downhill sections. Since eccentric muscle actions contribute more to downhill running, it was anticipated that this type of route would induce more muscle damage and soreness, even in well-trained runners, than a flat or predominantly uphill race.



The average heart rate during the race did not differ statistically significantly between any of the groups, or the two parts of the research (152 to 155 bpm in part I and 148 to 152 in part II). This is also similar to findings from previous research (Ali *et al.*, 2010). This, together with the fact that the weather conditions were similar for the two consecutive years, suggests that the runners in the two parts of this study were probably similarly stressed during the two different races.

According to Kraemer *et al.* (2010) most physical training does not result in a level of traumatic damage that would influence performance, except when endurance events like marathons and eccentric exercises are performed. Thus, it was expected that the chosen 56 km race would induce a great deal of muscle damage because of the higher and longer force requirements for motor unit recruitment, as well as the high metabolic demand. This means that the current research is the first attempt to make meaningful and practical conclusions on the effects of compression in distance runners during a real-life event where it is expected that the athletes would experience a certain level of muscle trauma.

The same relative stress and response patterns for the different variables of part I and II indicate that the race was successful in producing an identical and relative specific exercise stress in the runners. The only exceptions were the slightly higher relative percentage change in blood lactate activity in part II compared to part I, and somewhat more pronounced increases in oxygen consumption during submaximal running in part II compared to part I. These slight discrepancies could be attributed to the faster average race times in part II than in part I. However, the experimental group in part I who wore the graduated compression socks (CS group), mediated a similar recovery pattern as those runners who wore the graduated compression socks during the race and during recovery in part II of the investigation (CS<sub>Run&Rec</sub>).

#### **IV. POST-EXERCISE RECOVERY PARAMETERS**

Long distance running events such as marathons and ultra-marathons have become increasingly popular with the general population, but are frequently associated with numerous cellular changes due to the high levels of strain on the musculoskeletal system (Byrne *et al.*, 2004; Kim *et al.*, 2009). Eccentric exercise typically induces muscle damage when the individual is unaccustomed to the activity or when the activity is performed for prolonged periods of time



and/or at a high intensity (Cleak and Eston, 1992; Chambers *et al.*, 1998; Howatson and Van Someren; 2008). The latter is possibly more applicable to experienced runners who are accustomed to regular training, such as the runners in this study.

Athletes are familiar with the symptoms related to EIMD following eccentric muscle actions and high training volumes. Indicators of muscle damage include disruption of muscle structure, the sarcolemma and extracellular matrix, muscle enzyme increases in blood, extended impairment of muscle function (i.e. muscular strength), delayed onset of muscle soreness (DOMS), perceived fatigue and pain, reduced flexibility and muscle stiffness and swelling (Fridén *et al.*, 1983; Noakes, 1987; Byrne *et al.*, 2004; Howatson and Van Someren; 2008; Zainuddin *et al.*, 2005; Davies *et al.*, 2009). Recovery strategies therefore typically focus on ameliorating these symptoms of EIMD.

#### ***a. Exercise Induced Muscle Damage***

Both serum CK and s-Mgb have been extensively used in previous recovery research as indirect biological markers of myofibrillar damage (Kraemer *et al.*, 2001; Gill *et al.*, 2006; Bailey *et al.*, 2007; Goodall and Howatson, 2008; French *et al.*, 2008; Davies *et al.*, 2009; Ali *et al.*, 2010; Kraemer *et al.*, 2010). CK and myoglobin are both cytoplasmic proteins that are released after acute muscle fibre damage, with muscle membrane leakage into the plasma and followed by a resealing of the membrane (Cummins *et al.*, 1987; Kraemer *et al.*, 2004; Mougios, 2007).

Unfortunately the physiological interpretation of changes in myocellular proteins is not as clear-cut. Various researchers caution that the high inter- and intra-subject variability of serum CK activity may prevent an unambiguous interpretation of serum CK levels on its own. The accuracy of estimating the magnitude of muscle damage with serum CK is especially debatable (Bailey *et al.*, 2007; French *et al.*, 2008; Jakeman *et al.*, 2010). Also, it is difficult to compare myofibrillar protein plasma activity between studies, since the delay of release and the concentrations varies greatly between subjects, the type and intensity of activity and the training status of the subjects (Sorichter *et al.*, 1997). It is believed that serum CK concentrations in the circulation reflect both its release from specific origins, like myocytes, which would indicate membrane disruption, as well as the clearance of CK from the circulation (Wilcock *et al.*, 2006). CK concentrations will also



be affected by exercise-induced hemoconcentrations and/or hemodilution, as well as alterations of tissue clearance because of blood function and flow changes (Wilcock *et al.*, 2006; French *et al.*, 2008). Consequently, various researchers have suggested that serum CK is used as an indicator of the presence of muscle damage, rather than a tool to determine its magnitude.

Mougiou (2007) maintains that serum CK demonstrates a far more pronounced effect than any other damage markers and therefore it is easier to interpret. In 2007, Mougiou revised the resting CK limits for trained athletes and claimed that these revised ranges are more applicable for trained athletes than was previously the case. He also suggested that when these limits are exceeded, it may indicate an increased risk for over exertion or injury. In addition, the revised CK values for well-conditioned athletes will make interpretation more accurate than previously. Kraemer *et al.* (2009) recently established via MRI's of damaged muscles that serum CK follows a similar pattern to the observed structural damage of the muscles and concluded that it is therefore a good indicator of muscle damage.

In this research s-Mgb activity were assessed together with serum CK, to give a better indication of the muscle damage induced. Furthermore, the inflammatory response may contribute to secondary muscle damage hours rather than days later, and for this reason the immediate response of myoglobin may be a more accurate indicator of subsequent injury (Lapointe *et al.*, 2002; Bailey *et al.*, 2007). The significant change over time observed in both variables indicates that the 56 kilometre road race was sufficient to cause an efflux of myocellular proteins into the circulation of well-conditioned endurance athletes. Therefore, an assessment of knee-high compression socks as a relevant muscle damage recovery intervention could be effectively made in this two part study.

#### *i. Skeletal Myoglobin Activity*

The baseline s-Mgb concentrations observed in this study were within the normal resting ranges for men (17 – 106 ng.ml<sup>-1</sup>), although it was slightly lower than those reported in Ali *et al.* (2010), but similar to French *et al.* (2008).



In part I, the baseline s-Mgb concentrations increased 20 fold in the experimental group and 30 fold in the control group. Similarly, values increased 15 to 20 fold in the various treatment groups in part II of the research. Compared to other investigations in which eccentric-type exercises were used to induce muscle damage, for instance Ali *et al.* (2010) and French *et al.* (2008), the increase in intracellular proteins were more pronounced in the current study (peak s-Mgb: ~678 – 1072 ng.ml<sup>-1</sup>). Ali *et al.* (2010) reported only slight increases in myoglobin concentrations post-exercise (peak s-Mgb: ~120 - 125 ng.ml<sup>-1</sup>) in competitive runners, while French *et al.* (2008) reported moderate increases in resistance trained men (peak s-Mgb:~ 284 - 352 ng.ml<sup>-1</sup>). However, similar time course responses were observed in all studies, with peak values directly after the race and near baseline values by 24 hours (Table 5.1 and 6.4).

These results not only indicate that the 56 km race was successful in producing muscle damage, but that this response was also repeatable over two consecutive races. In both cases the muscle damage was more pronounced than in previous research. This is to be expected since the time course and severity of muscle soreness, muscular dysfunction and appearance of muscle damage markers in the systemic circulation varies according to the duration, intensity and type of exercise performed (Proske and Allen, 2005; Bailey *et al.*, 2007). Therefore the current research did induce a sufficient response in athletes even though they were accustomed to high training volumes and intensities.

In part I, the peak myoglobin concentrations in the CS group were significantly lower directly after the race compared to the placebo group. The myoglobin concentrations in the experimental group were almost half of that of the placebo group, with effect sizes showing a moderate practical significance. The results of part II are in agreement with those in part I. Both groups who ran with the compression socks (CS<sub>Run</sub> and CS<sub>Run&Rec</sub>) revealed moderately lower myoglobin concentrations compared to the CS<sub>Rec</sub> group who only wore the socks during recovery.

These results are in contrast to what French *et al.* (2008) reported. In their research the full length ankle to waist compression garment (12 to 10 mmHg; calf to thigh) resulted in significantly higher myoglobin activity in resistance trained men compared to the control group. Possible reasons for the discrepancies in findings are that the current research made use of a



different and higher pressure garment than French *et al.* (2008). In addition, there are also differences in the time period that the socks were worn. The younger men in French *et al.* (2008) did not wear the compression garment during the eccentric activities, but only after the activities for 12 hours overnight. In the current study, runners in part I wore the compression socks during the race and for about ~16 hours during the day time and only removed the compression socks while sleeping. In part II, the  $CS_{Run}$  and  $CS_{Run\&Rec}$  groups wore the compression socks (CS) during the race and  $CS_{Run\&Rec}$  and  $CS_{Rec}$  wore the CS for ~16.5 hours during the day and took the socks off while sleeping. Other differences that may explain the differences in results pertain to the training status and age range of the participants.

The study by Ali *et al.* (2010) was similar to the current research with regards to the age range of the runners, as well as the type of compression socks used (graduated compression of 23 – 32 mmHg). In addition, Ali *et al.* (2010) also included a placebo garment (0 mmHg) in their study. Yet, their results do not support the findings of the current study with regards to the myoglobin response after exercise. In their investigation the trained endurance runners had to perform three 40 minute treadmill runs at 80% of their predetermined aerobic capacity, randomly with a CCL I stocking (~8 - 11 mmHg), CCL II stocking (~15 – 26 mmHg) and with the control stocking (~4 mmHg). Ali *et al.* (2010) conceded that their protocol might not have been effective in producing a response in their trained runners and this may therefore explain the discrepancy in findings.

On the other hand, Trenell *et al.* (2006) found lower skeletal PDE one hour after eccentric exercise using a lower body compression garment, suggesting faster cellular repair. These results thus support the findings of the current research that compression socks worn during a long distance event significantly lower myoglobin concentrations directly after exercise in trained distance runners.

Additionally the results show that the higher pressure compression socks did not result in a tourniquet effect. As Jørgensen (1987) reported myoglobin is noticeably elevated when compression results in a tourniquet effect, since the ischemia will cause cell damage in the muscles.



The AUC analysis in part I showed a faster clearance rate, of large practical significance, of myoglobin from the circulation with the compression socks compared to the placebo group. This finding was confirmed in part II of the study where the runners who did not run with CS had moderately slower clearance of myoglobin activity from the circulation compared to the runners that wore the compression socks throughout the run as well as during the run and over the recovery period. There may be two possible reasons for this finding. Firstly, the faster clearance of myoglobin activity may be attributed to reduced muscle damage as a result of the compression sock limiting muscle oscillations and impact during the run and thus improving soft tissue repair, or secondly, due to an increase in peripheral and venous blood flow that would remove the Mgb faster. If the compression socks reduce or lessen the inflammatory response, then secondary muscle damage will be attenuated and hence result in less leakage of myoglobin into the circulation. The reduced s-Mgb directly after the race, may suggest repair throughout the body's musculature even at higher levels of soft tissue damage. Less muscle damage would also mean better contractile functioning after strenuous exercise (Cheung *et al.*, 2003; Goodall and Howatson, 2008) and this may translate in faster recovery of functional capacity (see pages 96 – 97 for part I and pages 130 – 132 for part II).

ii. *Serum Creatine Kinase Activity*

The baseline values for both parts of the current investigation were within the currently accepted normal resting values for male athletes (range: 82 – 1083 units.L<sup>-1</sup>; Tables 5.2 and 6.1) as reported by Mougios (2007). The baseline values were higher than previously reported for healthy sedentary individuals, which confirms that conditioned long distance runners tend to have more pronounced resting serum CK levels compared to untrained individuals (Mougios, 2007). Other researchers have found even higher resting CK activity (347- 278 U.L<sup>-1</sup>) in long distance runners (Takahasi *et al.*, 2006), which again highlights the large between-subject variability in CK levels and which was also evident in the current research.

The 56 km race significantly increased serum CK activity in all groups of the study. However, no treatment or main group effects were observed in either part I or II, which means that the CK responses were not influenced by the compression socks. However, as indicated earlier, the large





inter-individual differences in CK concentrations may have masked the true effects of the compression socks.

CK activity following the race was within the range of previously reported values for a 56 km race (Strachan *et al.*, 1984). Therefore, the level of CK together with s-Mgb appearance suggest that the ultra-marathon promoted a leakage of myocellular proteins comparable to that observed during similar distance events.

In both parts of the research, the CK concentrations followed the typical response after exercise (Mougios, 2007), with a slight increase after the race, peak values at 24 hours and thereafter a steady decline, although pre-race levels were not yet reached by 72 hours. This is in accordance with the findings of Hikida *et al.* (1983) who showed that ultra-structural changes in muscle fibres are most prevalent at 24 to 72 hours after a marathon. However, previous research on physically active individuals and/or trained athletes reported far lower peak CK concentrations at 24 hours after exercise than the current study. For instance, Ali *et al.* (2010) found serum CK levels between ~270 and 290 units.L<sup>-1</sup> for all groups and Kraemer *et al.* (2010) reported serum CK levels in resistance trained men of ~310 units.L<sup>-1</sup> and ~600 units.L<sup>-1</sup> in the experimental and control group, respectively. This would again suggest that runners experience more pronounced muscle damage during real-life exercise compared to simulated laboratory exercise.

In part I of the current study, there was a small practical difference in serum CK levels between the CS group and the placebo group at 24 hours, which was not statistically significant ( $P = 0.08$ ). Similarly, Jakeman *et al.* (2010) also did not find significantly lower CK concentrations in active individuals wearing compression socks, even though there were significant improvements in perceived muscle soreness and muscle function with the compression socks. The researchers attributed the lack of statistically significant results to the inter- and intra-subject variability of CK activity. This may therefore also explain the findings of this study, as CK concentrations at 24 hours varied between 291 – 3759 u.L<sup>-1</sup> in the experimental group and between 571 - 4127 u.L<sup>-1</sup> in the placebo group. However, AUC analysis showed a moderate practical difference ( $ES = 0.46$ ) between the total CK activities in the circulation of the two groups, with the CS group having a



more reduced activity. This may therefore suggest that the compression socks have indeed resulted in a significant treatment effect.

Gill *et al.* (2006) were the only other researchers who used an actual match to induce muscle damage. The researchers reported significantly less CK activity at 36 and 84 hours after the match in well-trained rugby players. However, unlike the current research, the rugby players wore a lower body compression garment for only 12 hours overnight and they used a non-validated method to assess transdermal exudate creatine kinase activity (Barnett, 2006). The runners in the current study wore the compression socks for longer and the compression socks were worn over the calf muscle which is most affected by prolonged running. Furthermore, rugby union is a high impact contact sport that involves not only the lower body but also the upper body. Hence the reported high CK values is more likely due to the trauma associated with the frequent contact, as well as muscular strains and sprains. This conclusion is confirmed by French *et al.* (2008) and Barnett (2006). Therefore the results of Gill *et al.* (2006) are limited to rugby or similar contact sports and are not applicable to endurance athletes.

Most research protocols have been ineffective to induce muscle damage in well-trained athletes and as a result reported no differences between experimental and control groups. Ali *et al.* (2010) found no difference between groups either directly after exercise or up to 48 hours recovery. Davies *et al.* (2009) also reported no significant differences in CK between groups – even when the CK was log-transformed to satisfy assumptions of sphericity associated with repeated measures ANOVA. The researchers only found a change over time in perceived muscle soreness and sprint performance. Davies *et al.* (2009) investigated trained netball and basketball players and only found a significant change from pre-exercise to 24 hours post-exercise in CK in the women of the control group, but not in the experimental group. However, when the results of the men and women were pooled, there was no significant change in CK from pre-exercise to 24 hours post-exercise.

In part II of the current research the three treatment groups responded similarly until directly after the race. However, at 24 to 48 hours after the race the CS<sub>Run</sub> group had significantly lower CK concentrations of 46% and 64%, respectively, compared to the CS<sub>Rec</sub> group. Effect size analysis revealed moderate differences between the two groups at 24 and 48 hours, and a large



practical difference at 72 hours. In addition, it is evident from the AUC analysis that the  $CS_{Run}$  group had far less CK activity compared to the  $CS_{Rec}$  group ( $ES = 1.19$ ), which constituted a very large practical difference. Again, the large inter-individual variability in CK values could explain the lack of statistically significant differences between groups.

It is interesting to note that in most research on compression garments, the participants wore the garments only after EIMD protocols when recovery was the main interest, whereas participants wore the compression garments during the exercise when performance outcomes were the primary question. In this study, both the s-Mgb and serum CK results in part II indicate that when athletes run with compression socks, they had less muscle damage compared to those not running with the socks. Thus the results of this study suggest that wearing the compression socks during exercise rather than only after exercise, are more beneficial for the recovery of skeletal muscle damage in trained distance athletes.

Of the seven recovery studies where compression garments were worn during exercise, four investigated muscle damage and the associated symptoms in trained athletes (Ali *et al.*, 2007; Duffield *et al.*, 2008; Ali *et al.*, 2010; Duffield *et al.*, 2010). None of these studies reported any beneficial or detrimental effects of compression garments on CK levels during exercise. Duffield *et al.* (2008) and Duffield *et al.* (2010) investigated performance decrements and fatigue associated with muscle damage after strenuous high intensity simulated team sport activities, while Ali *et al.* (2007) and Ali *et al.* (2010) studied the recovery of athletes during and after running activities while wearing graduated compression socks. Ali *et al.* (2010) in particular used similar high pressure compression socks as in the current study and investigated trained runners of the same age. In both studies it was found that the protocols to induce muscle damage and its effects on the recovery responses in experienced athletes were not effective. Their lack of results was thus attributed to the chosen protocol and the training status of the participants.

Other recovery research on physically active individuals where compression garments were worn after EIMD used mostly eccentric protocols (Trenell *et al.*, 2006; French *et al.*, 2008; Jakeman *et al.*, 2010; Kraemer *et al.*, 2010). Most of these studies resulted in conflicting results that are mostly attributed to different protocols and varying training levels of athletes. In the studies by Gill *et al.* (2006), French *et al.* (2008) and Jakeman *et al.* (2010) compression garments



were worn for 12 hours overnight, i.e. after the exercise. French *et al.* (2008) reported a non-significantly higher total CK concentration (AUC of absolute CK) in the compression garment group compared to a contrast bath recovery group and a control group. This is similar to the findings of Thorsson *et al.* (1997), as well as part II of the current study. The researchers found that applying high pressure compression bandages (40 – 80 mmHg) within 5 minutes after muscle damage occurred to the thigh and calf muscles of club level soccer players did not result in any reduction in the hematoma or recovery time compared to no treatment (Thorsson *et al.*, 1997).

In contrast, some research on healthy sedentary individuals found that wearing compression sleeves after eccentric protocols aids soft tissue recovery. For instance, Kraemer *et al.* (2001<sup>a</sup>) found significant differences in CK concentrations between control and experimental groups at 48 hours in healthy untrained women, as well as a significant difference between the control and experimental groups at 72 hours in healthy untrained men and a significantly lower change over time from baseline (Kraemer *et al.*, 2001<sup>b</sup>). This may suggest that the application of compression garments and the effects thereof are very specific to training status.

Kraemer *et al.* (2004) proposed three possible mechanisms for the lower serum CK levels with compression. The compression sock may increase blood flow and therefore increase the removal rate of myofibrillar proteins from the circulation, or the muscle damage markers are retained within the muscle, thereby reducing the leakage of CK into the circulation, or the compression garment acts as a dynamic cast (particularly during recovery), preventing additional muscle damage after the initial muscle damage by stabilizing the muscle fibres' alignment and promoting regeneration. Bringard *et al.* (2006<sup>a</sup>), however, showed that a lower body compression garment (~ 20 mmHg) improves calf muscle tissue oxygenation and did not limit blood flow in the muscles. This would suggest that CK is not retained within the muscles. It has been reported that pressure garments between 10 – 30 mmHg causes increases in venous blood flow by reducing the superficial and deep venous systems' cross-sectional areas in both healthy individuals, as well as those with venous insufficiencies during resting protocols (Litter, 1952; Jonker *et al.*, 2001; Bringard *et al.*, 2006<sup>a</sup>). Therefore, the possibility cannot be ruled out that compression socks increase the blood flow in well-trained athletes and that this mechanism may explain the findings



of the current study. However, since blood flow was not measured, this conclusion remains speculative.

Given the available results of this study, another possible mechanism may explain the findings, namely that compression socks mechanically limit muscle damage during stretch-shortening cycle activities such as running. This postulation is based on the findings of Doan *et al.* (2003), Bringard *et al.* (2006<sup>b</sup>) and Kraemer *et al.* (1998<sup>b</sup>) in which it was established that compression garments reduce muscle oscillations and vibration in the area where it is applied. Hence, less impact and more support during the repetitive stretch activities would limit muscle damage during the run by minimizing forceful muscle actions and associated micro trauma. This explanation is supported by the evidence in part II of the current investigation.

It was also suggested that CK enters the circulation from the injured muscle fibres through the lymph system (Zainuddin *et al.*, 2005; Brancaccio *et al.*, 2007; Brancaccio *et al.*, 2010) and consequently the CK response would reflect lymph flow activity. As a result, some researchers suggested that an attenuated increase in CK will be due to reduced lymph flow when compression is applied (Sayers and Clarkson, 2003; Zainuddin *et al.*, 2005). Sayers and Clarkson (2003) and Sayers *et al.* (2000) reported that CK activity increased when a cast was removed from an immobilised limb, probably due to the activity-related efflux of accumulated muscle exudates from lymphatic vessels (Sayers and Clarkson, 2003). In part II of the current study overall CK concentrations were especially less pronounced in those groups who ran with the compression socks. However, when the compression socks were removed in the CS<sub>Run</sub> group there was no sudden increase in CK activity over the 72 hour recovery period, even with the sudden increase in circumferences in this specific group. In fact, the CS<sub>Run</sub> and CS<sub>Run&Rec</sub> groups responded similarly, and had a less pronounced CK activity compared to the CS<sub>Rec</sub> group. These findings therefore suggest that compression socks do not retain the CK within the affected muscle as previously suggested by Kraemer *et al.* (2001<sup>a,b</sup>). This also supports the notation that the runners who ran with the compression socks had less muscle damage compared to those who did not run with the compression socks.



To summarize, the evidence available from this study suggests that the lower CK activity in athletes wearing compression socks during exercise were due to less muscle damage during the run.

### iii. *Ultrasensitive C-reactive Protein*

Inflammation occurs as a result of mechanical muscle fibre injury and the purpose is to clear the debris from the injured area. Even though the inflammatory response may amplify initial muscle injury by releasing reactive oxygen species and by activating phospholipases and proteases at the injured site, the inflammatory response is also important for regeneration of muscle fibres (Clarkson and Hubal, 2002). The acute phase inflammatory responses can be assessed by measuring C-reactive protein activity (Strachan *et al.*, 1984; Kim *et al.*, 2007). Neubauer *et al.* (2008) claimed that it is a sensitive marker of inflammation and tissue damage. Ultra-sensitive CRP (hsCRP) was used in this study since research has shown that regular exercise may reduce baseline CRP values (Kasapis and Thompson, 2005), while the hsCRP test can measure very small amounts of CRP in the blood (i.e. from 0.5 mg.L<sup>-1</sup>).

Baseline hsCRP values in this study corresponded to previously reported values in well-conditioned distance runners (Weight *et al.*, 1987; Siegel *et al.*, 2001; Kim *et al.*, 2007; Kim *et al.*, 2009). HsCRP increases with muscle necrosis which is associated with long distance events and peak CRP has been shown to have a distance-related response for distances from 15 km to 88 km (max ~27 mg.L<sup>-1</sup>) (Strachan *et al.*, 1984). The greatest magnitude of increase in hsCRP activity in well-trained distance runners is typically seen at 24 hours following endurance events (Strachan *et al.*, 1984; Pedersen and Hoffman-Goetz, 2000; Kasapis and Thompson, 2005; Kim *et al.*, 2009). In the current study the hsCRP concentrations directly after the race was only slightly increased, but peaked at 24 hours. This is in agreement with the results found for distance runners after a 56 km race (Strachan *et al.*, 1984) and after a 42.2 km race (Kim *et al.*, 2009). Although the hsCRP values of the current study were slightly higher at 24 hours (~ peak 22.7mg.L<sup>-1</sup>) than those reported by Strachan *et al.* (1984), it was similar in magnitude to two other studies following a marathon (Weight *et al.*, 1987; Kim *et al.*, 2009). Furthermore, the CRP activity in the current study did not return to pre-race values by 72 hours, which is also consistent with previous



research where it was suggested that CRP takes four to five days to recover to pre-race values (Strachan *et al.*, 1984; Kim *et al.*, 2009).

There were no differences in CRP responses between the experimental and control group in part I or between the three treatment groups in part II of this research, suggesting that the compression socks had no effect on CRP levels, neither during nor after exercise. Duffield *et al.* (2010) found similar results in eleven trained team sport athletes (with and without compression garments) after an exercise fatiguing protocol, even though CRP activity was also between ~140% and ~177% less than in the current study.

The increase of CRP in all groups of the current study may indicate the existence of contractile trauma which was not prevented or minimized by the compression socks. The existence of contractile trauma is substantiated by the increase in myoglobin, CK and perceived pain and discomfort subsequent to the race. Muscle trauma caused by running will be further exacerbated by the subsequent inflammatory response (Chen and Nosaka, 2006). In other words, if the compression sock reduces the inflammation it will limit secondary muscle injury due to inflammation. Furthermore, altered fluid shifts have been typically associated with reduced inflammation (Kraemer *et al.*, 2001<sup>a</sup>, Kraemer *et al.*, 2004; French *et al.*, 2008). However, the results indicate that the reduction in hsCRP activity during recovery did not correlate with the reduction in circumferences with the compression socks in part I, nor did it reflect similar responses in the various treatment groups in part II. Initially this may seem contradicting; however, it may mean that the compression socks did not reduce inflammation through augmentation of the calf muscle pump action. Admittedly, this conclusion is in contrast to the results of Bringard *et al.* (2006<sup>a</sup>) that reported improved calf oxygenation and reduced venous pooling with graduated lower body compression garments at rest. Furthermore, following the theory of Sayers *et al.* (2000) and Zainuddin *et al.* (2005) that compression would increase lymph flow, it could be hypothesized that increased lymph drainage would remove the pain generating inflammatory by-products from within the injured muscle and therefore reduce pain level and swelling. However, the results of this study also do not support this theory, as CRP levels were not less in those individuals who recovered with the compression socks.





There are a few possible explanations for the inconclusive results in CRP responses of this study. Only a few studies have examined the changes in CRP after eccentric activities or ultra-distances and therefore the exact relationship between exercise intensity, the amount of muscle damage and the relative production of inflammatory mediators in the tissue have not been elucidated yet (Margeli *et al.*, 2005; Ingram *et al.*, 2009; Duffield *et al.*, 2010).

CRP is an acute phase protein produced in the liver and is indicative of a systemic inflammatory response (Ostrowski *et al.*, 1999). It is secreted from the hepatocytes, under the control of the cytokine Interleuken-6, in response to various forms of infection, tissue damage, trauma and inflammation. In other words, the C-reactive protein is part of the non-specific acute phase response (Pepys and Hirschfield, 2003). This means that the CRP concentrations indicate systemic inflammation and is not muscle damage specific, unlike serum CK.

Accordingly, various factors may influence CRP levels after exercise other than muscle damage. For example, airway inflammation, often experienced by runners after long distance events (Bonsignore *et al.*, 2001), tendonitis, damage to cartilage (Kim *et al.*, 2009) and excessive endurance exercise or overtraining can lead to chronic systemic inflammation (Swanson, 2006). Swanson (2006) also reported that several studies on inflammatory markers such as CRP and intensive exercise demonstrate a release of CRP in the brain, skeletal muscle and/or connective tissue in response to prolonged long distance running. The reason being that exhaustive endurance exercise causes stress upon the different systems (hormonal, metabolic, thermal and oxidative systems) which results in the release of cytokines and other acute phase proteins (CRP), in addition to the up-regulation of different immune cells (Nebauer *et al.*, 2008). Also, the athletes' diets were not strictly controlled in the current study and elevated carbohydrate intake post-exercise may actually increase local inflammatory responses but not skeletal damage markers (Depner *et al.*, 2010; Ross *et al.*, 2010). However, the latter is a contentious issue which needs further investigation.

Furthermore, it has been said that post-race CK reflects a combination of trans-membrane leakage and muscle necrosis, but according to Strachan *et al.* (1984) CRP may be a more accurate index of muscle necrosis than CK. However, the CRP response is not necessarily linked to the CK response (Kasapis and Thompson, 2005). This means that the magnitude by which CRP increases





does not necessarily reflect the magnitude of change in serum CK. Nosaka and Clarkson (1996) reported a 107 fold increase in serum CK ( $111 \pm 8 \text{ u.L}^{-1}$  to  $11932 \pm 1731 \text{ u.L}^{-1}$ ) four days after eccentric exercise in elbow flexors with no increase in inflammation ( $\sim 0.22 \pm 0.03 \text{ mg.L}^{-1}$  average CRP over 5 days). The researchers also reported an increase in the upper arm circumferences after the eccentric exercise which indicated swelling with no change in CRP. The researchers suggested that CRP is related to the type of exercise and the muscle mass involved. Similarly, Warhol *et al.* (1985) performed muscle biopsies on runners after a marathon and reported various structural damages to the *Gastrocnemius* muscle, but no accompanying signs of local inflammation. However, this is in contrast to the study of Hikida *et al.* (1983) who reported inflammatory responses in *Gastrocnemius* biopsies after a marathon. These conflicting findings indicate that the CRP responses during and after exercise warrant further investigation.

## **b. Swelling**

### *i. Lower Limb Circumferences*

Increased lower limb circumferences after strenuous exercise indicate oedema and could therefore be used as a simple and indirect marker of muscle damage and acute inflammation (Smith, 1991; Zainuddin *et al.*, 2005; Kraemer *et al.*, 2001<sup>a</sup>; Kraemer *et al.*, 2001<sup>b</sup>; Davies *et al.*, 2009; Kraemer *et al.*, 2010). The purpose of an inflammatory response is to repair the muscle damage induced by the exercise. This inflammatory response will recruit several types of cells such as macrophages and lymphocytes to the injured area. The increased capillary permeability will allow exudate to leak into the damaged area (Smith, 1991; Zainuddin *et al.*, 2005). The increased protein and enzyme leakage disrupt the oncotic osmotic pressure in such a way that fluid movement to the interstitial space is enhanced (Smith, 1991; Cheung *et al.*, 2003). This will result in swelling of the lower limb and cause an increase in the ankle, calf and mid-thigh circumferences. This was confirmed by the results of the current study, as the circumferences of all the runners changed significantly over time.

Overall the runners wearing the compression socks during the 72 hour recovery period seemed to have more reduced circumferences in their ankle and calves compared the group that did not



wear the compression socks (Part I) and the group that took the compression socks off after the race (Part II).

Also the circumferences did not return to baseline by 72 hours in any of the groups in both parts of the investigation. This response pattern in part I and II is normal. Limb circumferences typically increase within a couple of hours after strenuous exercise and tend to be most pronounced 2 to 3 days after strenuous exercise due to fluid accumulation (Kraemer *et al.*, 2001<sup>b</sup>). The increase in circumferences within 24 and 48 hours reflects tissue swelling and inflammation after exercise (Smith, 1991; Kraemer *et al.*, 2004; Zainuddin *et al.*, 2005). Thus, the exercise induced swelling initially appears intramuscularly (Kraemer *et al.*, 2004).

The changing pattern in the limb circumferences matched the pattern of change in CK concentrations better than the changes in hsCRP. In a recent study Kraemer *et al.* (2010) assessed muscle swelling that was associated with tissue damage with ultrasound. They found that both swelling and CK were significantly less in resistance trained men at 24 hours after eccentric exercise with a compression garment. They concluded that this reduced muscle tissue swelling is evidence for the dynamic cast theory which they proposed earlier (Kraemer *et al.*, 2004). Furthermore, Jakeman *et al.* (2010) also suggested that reduced swelling would have an effect on subsequent secondary muscle damage resulting from the inflammatory process.

The initial reduction in mid-calf circumferences after the race was about ~1.2 cm and is consistent with the findings of Knechtle and Kohler (2007) who reported a ~1.1 cm reduction in calf circumferences after a 62 km stage of a multistage ultra-marathon. The researchers attributed this acute reduction to water, fat and mostly skeletal muscle mass loss. Typically, the loss in body mass after distances longer than a standard marathon is due to dehydration. However, Knechtle *et al.* (2010) reported that ultra-distance runners may lose skeletal muscle mass of about ~1 kg and fat mass of ~0.5 kg. The researchers suggested that the reduction in skeletal muscle mass was due to the high eccentric muscle actions involved during an ultra-distance which would damage skeletal muscle fibres (Knechtle and Kohler, 2007).



The calf circumferences followed a normal response, with peak values at 48 hours in the CS group followed by a moderate reduction in swelling by 72 hours ( $P < 0.05$ ). In contrast, runners in the placebo group experienced a further moderate increase in circumferences at 72 hours. This latter increase is probably more subcutaneous swelling and could be due to the synthesis of connective tissue which would suggest muscle regeneration (Fridén *et al.*, 1983; Jones *et al.*, 1986; Kraemer *et al.*, 2004). The results would suggest that wearing the higher than typically used compression restricted the movement of the calf muscle, resulting in less movement and for this reason better recovery than no compression. Immobilization of damaged muscle for four days has been shown to minimize the increases in circumferences seven days after exercise (Zainuddin *et al.*, 2005). The rapid reduction in tissue swelling would follow the formation of new granulation tissue and thus supports the dynamic cast theory of Kraemer *et al.* (2004).

In contrast to the current study, French *et al.* (2008) did not observe more reduced circumferences in the calves of trained athletes with compression socks after an eccentric protocol. Two possible reasons for this discrepancy are that i) the current study used a much higher pressure at the calf than French *et al.* (2008) (~ 25 mmHg vs 12 mmHg, respectively), and ii) the calf muscle is prone to muscle damage during running activities, whereas the resistance protocol followed by French *et al.* (2008) would have caused more muscle damage in the mid-thigh. Consequently, the results stress the importance of selecting the correct pressure gradient, as well as highlight the fact that the actions of the garments are specific to the physical activity and the muscles involved.

Kraemer *et al.* (2004) recommended that lower body compression garments should exert pressures between 60 and 100 mmHg to elevate venous blood flow. However, the results of the current study suggest that lower pressure would be just as effective in reducing swelling. The results of this study thus favour the theory that the increased pressure restricts the accumulation of oedema within the muscle by mechanically reducing the space available for accumulation. This mechanical reduction of space available for fluid accumulation is also supported by the findings of reduced upper arm circumferences by Kraemer *et al.* (2001<sup>b</sup>) and Kraemer *et al.* (2001<sup>a</sup>). Furthermore, the 20 – 30 mmHg of the compression socks is lower than the normal diastolic blood pressure of 37 - 80 mmHg and this lead to the conclusion that the mechanical compression



is probably the main contributor to the reduction in swelling and not a possible increase in blood flow.

However, since blood flow in the lower limbs was not measured in the current study, the possibility of some improved blood flow cannot be summarily dismissed. Increased blood flow would remove extracellular debris to facilitate recovery from injury by attenuating the inflammatory associated oedema (French *et al.*, 2008; Kraemer *et al.*, 2004; Kraemer *et al.*, 2001<sup>b</sup>). Previous research by Kraemer *et al.* (2000) has shown that by applying appropriate external pressure, the compression garments reduce the cross-sectional area of the popliteal and posterior tibial veins in the lower limbs. As a result peripheral and venous blood flow, as well as lymph drainage is increased.

The calf circumferences in part II of the current study demonstrated a similar but more pronounced response than the ankle circumferences in part II. Both groups that wore the compression socks during the 72 hour recovery period showed a lesser increase in swelling than the CS<sub>Run</sub> group. Thus, the results of the current study indicate that ankle and calf circumferences are reduced as long as the compression socks are worn, regardless of whether there is a reduction in the systemic inflammatory marker CRP or not. Thus compression socks limit lower limb swelling by physically reducing the space available for fluid accumulation.

Various researchers made suggestions regarding the optimal time to wear compression garments for reduced swelling and the associated benefits. French *et al.* (2008) suggested that compression garments should only be worn for 12 hours overnight and not longer, given that athletes would find wearing it for longer impractical. However, the results of this study indicate that compression garments are only effective when actually applied, and sleeping with the garments is not necessary. Kraemer *et al.* (2001<sup>a</sup>) suggested that compression sleeves should be applied after exercise and for at least 72 hours. This corresponds to the current study which shows that the longer the compression socks are applied, the more pronounced the therapeutic effects.

No significant differences were found in the mid-thigh circumferences of any of the groups in this study. This consequently provides indirect evidence that the intervention was unsuccessful in bringing about vascular changes in the mid-thigh. This could actually be expected as the



compression sock was not applied to the upper thigh; hence it will only limit swelling where it is applied. These results further support the hypothesis that it is the mechanical external pressure exerted by the compression sock that reduces the swelling.

Although Kraemer *et al.* (2000) used a lower body compression garment that extended to the thigh, they also only found significantly reduced ankle and calf circumferences. They concluded that the pressure on the thigh (~5.2 to 9.0 mmHg) was insufficient to cause any effects in this muscle. Watanuki and Murata (1994) suggested that at least 17.6 mmHg in the lower leg and 15.1 mmHg in the thigh are needed to improve venous return in healthy individuals. Similar results were reported by Davies *et al.* (2009) who also found no differences in the average mid-thigh circumferences with compression garments (15 to 9 mmHg). The researchers suggested that peak swelling would only have occurred at day 5 and since they only measured circumferences on day two they speculated that they would have missed the increase in circumferences or that the protocol was insufficient to induce muscle damage in the well-trained team sport athletes.

The reduced swelling could mean the runners with the compression garment perceived less pain and/or were able to move more freely. Given that swelling is related to reduced range of motion (Takahashi *et al.*, 2006), localised swelling may contribute to perceived muscle discomfort and pain due to the additional increase in intramuscular pressure (Fridén *et al.*, 1986; Cleak and Eston, 1992; Jakeman *et al.*, 2010). Similarly increased external pressure by the compression sock may result in an even further increase in intramuscular tissue pressure, which has been associated with increased DOMS (Smith, 1991). However, this was not the case since the experimental group perceived less calf muscle soreness compared to the placebo sock group. Also the placebo sock minimized the possibility of a placebo effect. Furthermore, only the calf muscles benefited by the applied compression. Thus, the reduction in circumferences through the mechanical reduction of oedema would explain the lower perceived muscle soreness with the compression socks.

The findings of this study therefore indicate that knee-high compression socks reduce swelling after prolonged exercise in well-trained distance runners. In addition, wearing the compression garment for a period after a race or training would be more beneficial than only wearing the socks during a training session or a race. Furthermore, the results favour the mechanical



reduction of swelling by limiting the space available for fluid accumulation. However, increased blood flow due to the mechanical compression of the veins, cannot be excluded completely. Consequently, the externally applied pressure may increase lymph drainage and improve blood flow with associated fluid shifts and reduced inflammation. The compression sock circumference data coincided with greater force production recovery (see pages 101 – 105, as well as pages 117 – 118 for part I and pages 135 – 138 with 147 – 148 for part II) and follows a similar pattern as serum CK activity.

### ***c. Total Body water***

Total body water was only assessed in part I of the current investigation. Total body water typically demonstrates a reduction of about 1% directly after strenuous exercise (Knechtle *et al.*, 2010). In the current study, both the control and the experimental group showed a similar reduction in the total body water content after the race than was reported in previous studies (1.3% and 0.7%, respectively).

The CS group showed a more pronounced reduction in TBW at 24 hours than the control group. A possible explanation for this is that the compression sock is made of a material (Coolmax®) that would have kept the runner's legs cool during the race, by increasing the athlete's sweat rate and thus these runners could have experienced greater water losses during the race. This may also have had an effect on the performance of the runners. Barnett (2006) reported that precooling is beneficial for the performance of 600m to 10000m athletes. Therefore, it could be speculated that the cooling of the legs contributed to the slightly faster pace of the CS runners.

Interestingly, even though not statistically significant, the runners in the control group had on average a 5% higher water content than the CS group at 24 to 72 hours after the race. Furthermore, there was a slight increase in water content up to 72 hours in the control group, while TBW content was maintained at the same level in the CS group. This is in agreement with the findings of Kraemer *et al.* (2000) after a standing fatigue protocol with three different lower body compression garments and a control group and further supports the argument that the sweat rate, and thus water loss, was greater in the CS runners compared to the control group.



#### **d. Perceptual Responses**

##### *i. Perceived Muscle Soreness (PMS)*

The results of the visual analogue scale assessments are consistent with previous research on distance runners (Vickers, 2001). Perceived muscle soreness increased significantly following the 56 km race indicating that muscle damage did occur in the *Quadriceps*, *Hamstrings* and calf muscles, in both parts of the investigation.

In contrast to eccentric laboratory protocols, perceived muscle soreness in this study did not peak between 24 and 48 hours after the 56 km race. This is in agreement with the findings of Vickers (2001) that distance runners typically experience most muscle soreness directly after the race and then gradually return towards baseline values after about 72 to 96 hours. The difference in the time course of PMS after distance events and eccentric activities may be due to the different types of muscle actions and muscle groups involved during distance running, as well as metabolic fatigue after the race (Komi, 2000; Vickers, 2001).

Takahashi *et al.* (2006) reported more muscle soreness in the posterior calf muscles compared to the anterior thigh muscles after a 3 x 5 minute downhill run (-10%) in trained long distance runners. The researchers explained that the calf muscle is exposed to more reaction forces from the ground during downhill running since it is closer to the ground and has fewer elements to absorb the shock caused by gravity (Takahashi *et al.*, 2006). Other researchers also confirmed that long distance running poses great strain on the *Gastrocnemius* (Hikida *et al.*, 1983), *Soleus* and *Quadriceps* muscles (Warhol *et al.*, 1985; Millet and Lepers, 2004). Even though most muscle damage is typically observed in the thighs of distance runners, Kuipers *et al.* (1989) suggested that metabolic and mechanical strain posed on the *Gastrocnemius* muscle is higher than that on the *Quadriceps*. Evidence to support Kuipers *et al.* (1989) is that a more pronounced inflammatory response was observed in the *Gastrocnemius* muscle of runners after distance events (Hikida *et al.*, 1983).

The results of this study are in line with the above findings. Of the weight bearing lower limbs assessed in part I of the study, the greatest perceived muscle soreness was reported for the



*Quadriceps* muscles in both the compression and placebo sock group. Interestingly, the *CS<sub>Run</sub>* group experienced the least amount of muscle soreness in the calf muscles, similar to the hamstrings. The placebo sock group reported only slightly lower pain levels in the calf muscles compared to the *Quadriceps* and least pain in the *Hamstrings*. Similar results were also reported by Ali *et al.* (2007).

In part I, the control group reported significantly greater soreness at 48 hours in the *Quadriceps* muscles while stretching, when pressure was applied to the muscle and during daily activities. There was also some tendency for the control group to report less muscle discomfort and pain in the Hamstrings directly after the race compared to the compression sock group. This initial perception of muscle soreness and discomfort may have been due to fatigue rather than muscle damage.

The most pronounced reduction in muscle soreness, however, was found in the calf muscles of the CS group and the degree of discomfort was lower than for the placebo group. Furthermore, the CS runners perceived significantly less muscle pain in the calf muscle at 24 hours while pressure was applied and during daily activities. These results may be explained by the fact that the compression sock was applied to the calf muscle.

Even though the time course of the perceived muscle soreness was different compared to other studies, the results are still consistent with previous research indicating the potential benefits of compression garments to reduce muscle soreness (Kraemer *et al.*, 2000; Kraemer *et al.*, 2001<sup>a</sup>; Kraemer *et al.*, 2001<sup>b</sup>; Ali *et al.*, 2007, Duffield and Portus, 2007; Jakeman *et al.*, 2010). However, not all researchers are in support of this view (Trenell *et al.*, 2006; French *et al.*, 2008; Ali *et al.*, 2010; Sperlich *et al.*, 2010).

Swelling as a result of muscle damage is associated with the acute inflammatory response and may be the underlying cause of muscle soreness and discomfort (Smith, 1991). The compression socks significantly reduced the swelling in the ankles and calves in part I of the study. Similarly, Kraemer *et al.* (2010) found less muscle swelling in trained athletes wearing compression socks after high intensity resistance training. The reduction in swelling would have decreased the runners' perceptions of soreness in the calf muscles. The use of compression to manage oedema





may also have an effect on subsequent secondary muscle damage resulting from the inflammatory process.

An increase in blood flow may also be a possible explanation for the reduced perception of pain in the *Quadriceps* at 48 hours. Various researchers have shown that compression socks improve tissue oxygenation (Bringard *et al.*, 2006<sup>a</sup>, Thedon *et al.*, 2008; Sear *et al.*, 2010). The knee high compression sock reduces the cross-sectional area of the deeper veins, as well as forces blood from the superficial veins and then shunts a greater blood volume towards the heart. This means that the compression socks augment the calf muscle pump, which would improve blood flow, remove waste products and transport nutrients as well as oxygen towards the injured muscles, such as the *Quadriceps* and *Hamstrings*. This is similar to active recovery.

Another possibility is that the difference in perceived pain and discomfort is only a placebo effect. Duffield *et al.* (2010) found, with the exception of lower perceived muscle soreness at 24 hours in the compression group, no significant differences in any other variables, including muscle damage markers after a fatiguing protocol between a control and compression garment group. Hence they concluded that the experimental group reported a placebo effect. However, this is unlikely the reason for the results in this study, as the CS group who perceived less muscle soreness was compared with the control group who wore a knee-high sock that did not exert any pressure, while the participants were naive to the true difference between the socks.

Despite a similar pattern in perceived muscle soreness in part II of the study, namely peak values directly after the race and a gradual return to baseline values, no differences were observed between any of the treatment groups at any time point. The CS<sub>Run</sub> group reported moderately more muscle soreness and discomfort in the calf and hamstrings at 48 hours and in particular at 72 hours compared to the CS<sub>Rec</sub> group. These findings may be as a result of the increased swelling when the sock was removed, as explained in *section b* of this chapter (page 168), increased secondary muscle damage due to inflammation, as well as the lack of increased blood flow which the other groups would have experienced as they wore the compression socks during recovery. Another possibility is that the compression socks may have formed a dynamic cast as suggested by Kraemer *et al.* (2004) and stabilized the injured muscles, as well as assisted alignment and regeneration of the damage muscles during recovery.



ii. *Viability of Compression Socks as a Recovery Aid*

Runners were asked to rate the practical use of the compression sock and placebo sock using a self-developed viability questionnaire. The purpose of the questionnaire was to assess the athletes' perception of fit, comfort and the practicality of the compression sock.

In part I the practicality of the compression socks was compared to the placebo sock. About 4% of the experimental group did not find the compression sock comfortable and 18% found the placebo sock uncomfortable. Runners in both groups reported similar perceptions with regards to running performance. For instance, 64% in the control group and 58% in the experimental group said the garment they wore during the run improved their running confidence. Similarly, 48% of runners in both groups felt that the garment they wore improved their running performance. However, there were slight differences between the groups when their perception of recovery was assessed. Runners were asked if the garment they wore reduced possible injuries, to which 67% in the CS group and 59% in the control group responded positively. In addition, when the runners were asked if the garment aided their overall recovery, 63% in the CS group and 36% in the control group said the garment did. More runners in the control group (17%) compared to the CS group (7%) indicated that the garment contributed to additional fatigue during the run. A few runners, 7% and 9%, in the experimental and control groups, respectively, indicated that the garment caused excessive rubbing and blisters.

When the runners in the various treatment groups of part II were asked if they would wear the compression socks again, 73% of the  $CS_{Run}$  group, 59% of the  $CS_{Rec}$  group and 78% of the  $CS_{Run\&Rec}$  group said they would. Those who didn't want to wear the socks again said it was because the socks were too tight and uncomfortable over the 72 hour recovery period. Two thirds of the runners who ran with the socks claimed that the compression socks improved their running confidence during the race, while 60% felt the socks reduced their recovery time.

Sperlich *et al.* (2010) reported no benefits in wearing compression socks to reduce perceived exertion and suggested that the different perceptual outcomes between various studies is because eccentric protocols where muscle soreness is induced may differ from protocols using



running activities, or that athletes training 60 – 90 km per week may be accustomed to fatigue. However, this was not supported by the current research since less than 20% of all the runners felt the compression socks contributed to their fatigue and 71% said the socks aided their running performance during the race. The results support the findings of Kraemer *et al.* (2010) which revealed that compression garments significantly reduced perceptions of fatigue and improved vitality in resistance trained athletes who wore compression garments after strenuous exercise.

Only 3% of runners in the  $CS_{Run}$  and  $CS_{Run\&Rec}$  groups reported that the compression socks were uncomfortable. This is opposite to the results reported by Ali *et al.* (2010). The researchers also assessed the perceived comfort of two different compression socks, of which the class II compression sock (similar than the current study) was rated as less comfortable than the control socks ( $P < 0.05$ ). The class II compression socks were also perceived as tighter than the lower compression socks and the control ( $P < 0.05$ ). However, the differences in perceptions between the studies are most likely because the runners in the current investigation did not have the opportunity to try a lower compression sock. Of the three groups, the  $CS_{Run\&Rec}$  group, who wore the socks for the longest period, indicated that they found it particularly hard to put the socks on after the race. 25% of the runners who ran with the compression socks and 18% of those who only wore the socks during recovery reported that the socks contributed to footsores. Approximately 29% of the runners indicated that the compression sock caused chafing during the run, in particular at the top part of the foot near the ankle joint. This may be explained by the fact that the highest pressure of the compression sock is at the anterior side of the ankle, while the movement of the ankle during running could also aggravate the rubbing (Liu *et al.*, 2005).

Overall it appears that runners perceived compression socks as a viable recovery aid. However, there appears to be a psychological benefit as well, since the control group with the placebo sock as well as the compression sock group in part I of the study reported similar perceptions on the “sock’s” ability to aid running performance.

#### ***e. Metabolic Responses***

##### *i. Blood Lactate Concentration*



Baseline blood lactate values in part I and II corresponded to previously reported values in well-conditioned long distance runners of the same age and gender (Kim *et al.*, 2007). In addition, blood lactate concentrations after the 56 km race corresponded to values reported after a 100 km race. This is possible, since Kim *et al.* (2007) reported similar blood lactate concentrations after a 100 km and 200 km distance race and all ultra-distance events, irrespective of the distance, are typically run at a slow comfortable pace.

In part I of the research, the CS group had 26% lower blood lactate concentrations at 30 minutes after the race compared to the placebo sock group ( $P < 0.05$ ). The absolute blood lactate concentrations were not only significantly lower during the acute phase (30 minutes) after the distance race with the compression socks, but it was also overall (AUC) moderately lower with the compression socks compared to the placebo sock ( $ES = 0.40$ ). The results in part I was similar to the findings of Berry and McMurray (1987) who reported 31% lower lactate values at 15 minutes after exercise in trained men who wore compression socks during and after exercise, compared to the control who only exercised with the compression socks ( $P < 0.05$ ). The lower lactate values were not accompanied by any changes in plasma volume and therefore the researchers suggested that the lower lactate values were as a result of the tourniquet effect of the compression stocking, and/or that the increased intramuscular tissue pressure caused the lactate to be retained within the muscle.

In part II of the study, the  $CS_{Run}$  and  $CS_{Run\&Rec}$  groups had 11 – 14% lower blood lactate values at 15 minutes after the race compared to the  $CS_{Rec}$  group. Furthermore, the  $CS_{Run\&Rec}$  group had moderately lower lactate concentrations at 72 hours after the race compared to the other two groups. Although the  $CS_{Run}$  group had significantly lower blood lactate levels directly after the race, they were also the group with the most elevated relative change in lactate levels during recovery. However, these higher values could not be as a result of more muscle damage incurred during the race, as this is also the group who had significantly lower CK levels during recovery. Rather, it may indicate that the lack of compression during the recovery phase attenuated venous return to the heart and thus inhibited lactate clearance rates. This argument is supported by the fact that those runners, who wore the compression socks during recovery, had lower lactate levels. These findings are also in agreement with Chatard *et al.* (2004) who reported lower



absolute blood lactate concentrations during an 80 minute recovery period after a maximal cycling protocol in subjects who wore compression socks.

The results of this study is therefore in agreement with most research, namely that compression garments cause diminished blood lactate concentrations during the acute phase after exercise (Berry and McMurray, 1987; Chatard *et al.*, 2004; Rimaud *et al.*, 2007). However, there are two studies in which no difference in blood lactate concentrations during exercise were reported (Kemmler *et al.*, 2009; Sperlich *et al.*, 2010).

There are a few possible explanations for the above findings. It is possible that while wearing the compression socks the lactate is retained within the muscle. This may be due to the added intramuscular pressure which limits blood flow towards the muscle and thus reduces lactate exchange ability with other muscle or the circulation (Berry and McMurray, 1987). Rimaud *et al.* (2010) made a similar conclusion when they reported a higher retention of muscle lactate (29%) rather than an increased clearance rate (22%) with the compression garment. On the other hand, the mechanical compression provided by the socks may improve peripheral circulation and thus lactate can be more readily removed and oxidized (Berry and McMurray, 1987; Chatard *et al.*, 2004). This argument is supported by the fact that lymph flow (via serum CK) and myoglobin concentrations while at rest after exercise did not reveal a tourniquet effect. Hence wearing the compression sock during recovery may clear lactate faster due to improved blood flow and not retain the lactate within the tissue. Lastly, due to the high level of muscle damage during the ultra-event, muscle oxidative function is impaired and the runner relies more on anaerobic metabolism, thus producing higher resting blood lactate values (Gleeson *et al.*, 1998).

## ***f. Performance Recovery***

### *i. Running Economy and Heart Rate*

Previous research has shown that exercise induced muscle damage negatively affected running economy in well-trained distance runners and triathletes up to 48 hours after a downhill running protocol (Braun and Dutto, 2003). The researchers attributed the reduced economy to the decrease in stride length and greater reliance on anaerobic metabolism due the induced muscle



damage. On the other hand, Bringard *et al.* (2006<sup>b</sup>) reported improved running economy when trained athletes ran at 12 km.h<sup>-1</sup> with compression stockings (~20 mmHg) and suggested that compression garments would be beneficial to endurance performance. It was proposed that the improvement in running economy is due to the physical support provided by the compression stocking which would reduce muscle oscillations and improve circulation via the enhancement of the calf muscle pump function. Consequently, the running economy test was used in the current investigation to track functional regeneration in the runners and not as a performance measure *per se*.

Running economy was significantly elevated after the race and during recovery in all the groups and in both parts of the study. This increase in oxygen consumption was associated with a significant increase in heart rate over the same time period. These results support the findings of Braun and Dutto (2003) who found that DOMS affects running economy in well-trained athletes. The increase in oxygen consumption may be attributed to the muscle damage and acute inflammatory response which could have affected stride length, since the increased swelling that was observed would have been associated with a reduction in the runners' range of motion.

However, the current investigation does not support the findings of Bringard *et al.* (2006<sup>b</sup>) that compression garments improve running economy. It must be noted that this improvement was only observed at one specific running speed, namely 12 km.h<sup>-1</sup>, even though the researchers also investigated oxygen consumption at 10, 14 and 16 km.h<sup>-1</sup>. No difference was found between the submaximal oxygen consumption of the two groups in part I, or between the three treatment-groups of part II of the study. This is in agreement with the findings of Bringard *et al.* (2006<sup>b</sup>) who didn't find statistically significant improvements in running economy at 10 km.h<sup>-1</sup>, which was about the same speed at which all the athletes ran in this study. There are also a few discrepancies between the two studies which may explain the results. Firstly, the subjects in Bringard *et al.* (2006<sup>b</sup>) were rested and did not have muscle damage, unlike the runners in this investigation. Secondly, they tested a small sample size ( $n = 6$ ) and thirdly, the protocols to assess running economy were different. For instance, Bringard and co-investigators (2006<sup>b</sup>) tested running economy on a 200 m indoor track with a portable metabolic system (Cosmed K4b<sup>2</sup>) at the four running speeds mentioned before.



A reduced heart rate is a crude method to indirectly indicate improved venous return (Ali *et al.*, 2007) during or after exercise. However, there were no differences in heart rate during the race, or during the running economy test, between any of the groups in this study. Other studies have also reported no significant differences in physiological responses such as heart rate, RER,  $\text{VO}_2$  and blood pressure between compression garment and control groups. Sperlich *et al.* (2010) found no difference in submaximal oxygen consumption in 15 well-trained endurance athletes running with three different types of compression garments (~20 mmHg), including a compression stocking. Bernhardt and Anderson (2005) reported no difference in athletes' oxygen uptake during a 20m shuttle run with compression shorts. Rimaud *et al.* (2010) did not find any differences between heart rate, blood pressure or submaximal oxygen consumption in trained endurance athletes during an incremental treadmill test. Ali *et al.* (2010) also reported no improvement in running economy or difference in heart rate of competitive runners running at  $14 \pm 1.40 \text{ km}\cdot\text{h}^{-1}$ . Kuipers *et al.*, (1989) found that athletes have adequate blood flow from the lower leg towards the heart. Therefore, the unchanged cardiovascular response may indicate that compression garments do not augment venous return during dynamic contractions.

## ii. Muscular Function

Running and jumping biomechanics are similar in that both rely on the stretch-shortening cycle (SSC) with a stretch-reflex component that is important for force generation (Komi, 2000). Muscle damage due to eccentric muscle action is associated with an acute (immediate) and prolonged reduction in the runner's muscle function and in particular, reduced maximal force generating capacity (Fridén *et al.*, 1983; Byrne *et al.*, 2004; Millet *et al.*, 2002; Howatson and Van Someren; 2008; Zainuddin *et al.*, 2005). Warren *et al.*, (1999) even suggested that the reduction in muscle function is a better indication of muscle damage and recovery than blood markers such as serum CK. Previous researchers explained that both DOMS and the acute inflammatory response after EIMD will influence muscle power (Smith, 1991; Byrne *et al.*, 2004). The swelling as a result of the acute inflammatory response will interfere with the muscle mechanics and the pain perceived after EIMD may in some cases act as a protecting mechanism against excessive movement by immobilizing the injured muscles (Smith, 1991).





The current study did not make use of a typical laboratory based eccentric protocol and several differences to traditional EIMD protocols have been identified which need to be considered when interpreting the data. For instance, the perceived muscle soreness peaked directly after the race in all the runners and hence did not follow a typical DOMS response as is usually observed in laboratory studies. Furthermore, the 56 km race required the use of low to moderate intensity, but prolonged duration SSC activity and was not limited to eccentric muscle actions. Byrne *et al.*, (2004) highlighted several factors, other than EIMD, that will influence muscle function after long distance running, such as metabolic depletion, Ca<sup>2+</sup> influx, reactive oxygen species and musculo-tendinous stiffness. Initially, EIMD results in the disruption of the contractile components of the sarcomere and interference with excitation-contraction coupling (Warhol *et al.*, 1985; Jones *et al.*, 1997; Byrne *et al.*, 2004). Therefore the loss of muscular performance after EIMD is the result of a reduced number of functioning motor units (French *et al.*, 2008). This is then followed by the degeneration-regeneration process after DOMS and swelling, due to acute inflammation, have subsided (Hikida *et al.*, 1983; Warhol *et al.*, 1985; Armstrong, 1986; Byrne *et al.*, 2004). This regeneration process may explain why there were non-inflammatory related increases in circumferences still at 72 hours (connective tissue) in the current study, as well as the non-typical perceived muscle soreness response which did not correlate with the recovery of muscle function. Additionally, the CMJ protocol that was used in this study as a functional test includes both an active eccentric muscle action followed by a concentric muscle action (SSC). Thus, both the *Quadriceps* and the plantar flexors (*Gastrocnemius* and *Soleus*) are actively involved during the CMJ (Bobbert *et al.*, 1986; Maffiuletti *et al.*, 2002). Laboratory studies typically focus on one muscle and exclusively eccentric actions, while the runners in the current study utilized more than one muscle group and used SSC. These factors therefore need to be considered when interpreting the findings on muscle function.

In part I of the study, runners in both groups experienced a significant but similar drop in peak power output during countermovement jumps directly after the race (7% and 9% in the placebo and CS groups, respectively). At 24 hours, the control group experienced a further drop in peak power (- 5%), compared to the CS group who actually showed a slight increase (+1%) towards pre-exercise values (see page 117 - 118). This difference indicates that the control group experienced more pronounced muscle damage than the CS group. In addition, the control group may also have demonstrated more pronounced muscle damage due to secondary muscle damage





associated with the inflammatory response as evident by the more pronounced swelling and perceived muscle soreness. However, this was not substantiated by the hsCRP activity in the current study. The CS group showed a strong tendency towards a treatment effect over the study period ( $P = 0.07$ ), meaning that these runners tended to maintain muscle function better during recovery than the placebo group.

The reduction in the ability to generate power during vertical jump movements after the ultramarathon is expected (Byrne *et al.*, 2004; Komi, 2000). The initial reduction is most likely due to both muscle damage and metabolic disturbances directly after the race (Komi, 2000). This is evident in the increase in perceived muscle soreness and discomfort in both groups directly after the race. Interestingly, Komi (2000) reported a strong correlation between the recovery of SSC activity and serum CK activity ( $r = 0.99$  and  $0.94$ ) which is supported by the current study (part I and II). At 24 hours, the CS group reported significantly less perceived muscle soreness during daily activities in the *Quadriceps* compared to the control group. Similar results were found for the calf muscles during applied pressure and daily activities at 24 hours. Thus the more pronounced reduction in muscle function in the control group may be due to the protective mechanism of pain as a result of more severe muscle damage (Cleak and Eston, 1992; Howatson and van Someren, 2008; Zainuddin *et al.*, 2005).

Previous research by Kraemer *et al.* (1996) and Doan *et al.* (2003) have shown that compression garments helped maintain repetitive maximum jumping power in individuals by reducing muscle oscillations. However, these researchers used compressive tights in their studies (covering the *Quadriceps* muscle) and not knee-high socks and the results are therefore not directly comparable to the current study. Ali *et al.* (2010) investigated the effects of compression socks on CMJ performance in experienced well-conditioned runners, but found that compression socks had no effect on muscle function. However, their protocol was insufficient to induce muscle damage and associated DOMS. On the other hand, the recent study by Jakeman *et al.* (2010) reported significant improvements in muscle function in physically active women with lower limb compression tights after an EIMD protocol. Therefore, the results of this study support the theory of Kraemer *et al.* (1996) and Perrey *et al.* (2008) that compression socks mechanically support the muscles (specifically those prone to damage during running, i.e. the calf), as well as



reduce muscle oscillations, thereby limiting the mechanical strain placed on the fibres and thus minimizing muscle damage (Tee *et al.*, 2007).

It was also interesting to note that the CS group showed a slight biphasic response in muscle function. A similar response in perceived pain and discomfort (VAS) of the *Quadriceps* muscle were found when pressure was applied and during daily activities. This is supported by the findings of Komi (2000) who explained that this biphasic response in force generation after long distance events is typically associated with SSC fatigue and that the immediate response after the distance run is due to metabolic fatigue, while the second reduction is due to inflammation and muscle damage.

Other studies reported that neural disruption due to exercise is associated with subsequent inhibition of muscle function (Byrne *et al.*, 2004; Jakeman *et al.*, 2010). As a result, reduced perceived muscle soreness will indicate improved muscle function, because muscle soreness due to EIMD is associated with reduced neural drive. The findings in part I of this study, namely less perceived muscle soreness associated with better muscle function, would support this explanation. This would also be in agreement with the findings of Kraemer *et al.*, (2010) who reported significant faster recovery in bench press throw power (W) at 24 hours after exercise in well-trained resistance trained men who wore compression garments compared to a control group. The researchers attributed the smaller reduction in power due to enhanced recovery from the neuromuscular deficit. However, the same researchers did not find any improvements in CMJ power performance with the compression garments.

Peak power was reduced after the ultra-distance race up to 24 hours in all three treatment groups in part II of the study. Unlike part I, there was no difference at 24 hours after the race between the groups and one group also did not recover at a faster rate than the others. Muscle function returned to pre-race levels at 72 hours in the CS<sub>Run&Rec</sub> group and recovered to slightly higher values than baseline in the CS<sub>Run</sub> group. The CS<sub>Rec</sub> group did not recover by 72 hours. These changes in peak power output of the three groups followed a similar pattern than the changes in myoglobin and serum CK activity. This means that regardless of the variability in the serum concentrations of muscle damage markers, the indication of muscle damage correlated to the changes in muscle function.



The runners who ran with the compression socks completed the race in faster times than the  $CS_{Rec}$  group, although the group differences in race times were not statistically significant. This is indirect evidence that wearing the compression socks during the race improves muscle function and SSC activity in the *Quadriceps* and calf muscles. Komi (2000) also stated that loss of muscle function and SSC activity during repetitive SSC actions will contribute to fatigue during endurance activities. Thus, the compression socks may reduce the impact on the muscles and provide stability to the limb. Pearce *et al.*, (2009) stated that the compression socks will improve proprioception and thus increase muscle activation and motor control. A concern was also raised that compression socks may cause a tourniquet effect which could potentially affect neuromuscular function below and distal to the tourniquet (Mohler *et al.*, 1999). However, better race times, as well as faster recovery of muscle function in those runners who competed with the compression socks indicate that it is unlikely that the socks caused a tourniquet effect in the runners of this study.



## CHAPTER EIGHT

### CONCLUSION

#### I. INTRODUCTION

A variety of treatments have been advocated as possible recovery strategies after strenuous exercise i.e. active recovery, hyperbaric oxygen therapy, electromyostimulation, stretching, ultrasound, massage, antioxidant supplementation, NSAID, water immersion therapy (hot, cold and contrast) or a combination of these modalities (Barnett, 2006). Still a consistent therapy - the gold standard - for recovery from exercise induced muscle damage and associated symptoms has not been established. The greatest challenge with recovery research is that there is limited understanding of the exact mechanisms or aetiology related to EIMD and the associated symptoms. As a result finding an effective recovery modality is like trying to find a light switch in an unfamiliar dark room. This also emphasizes once more the intricate aspects of the human body. Perhaps the solution is to use a combination of treatments for the numerous DOMS symptoms, of which compression garments seem to be a definite must.

Even though improved blood flow cannot be excluded as a possible mechanism to aid recovery after exercise, the current investigation (part I and II) supports the hypothesis that compression garments limit the magnitude of muscle damage by providing mechanical stability to the involved musculature and furthermore acts as a dynamic cast after exercise (Kraemer *et al.*, 2001<sup>a</sup>) to manipulate associated symptoms of muscle damage. In other words the compression socks reduced structural tissue damage during exercise and aided regeneration after exercise by reducing swelling and assisting cellular repair. Doan *et al.* (2003) and Bringard *et al.* (2006<sup>b</sup>) found that compression garments reduce muscle oscillation and vibration during activities. Other more recent research also supports this hypothesis (Pearce *et al.*, 2009; Perrey *et al.*, 2008; Jakeman *et al.*, 2010; Kraemer *et al.*, 2010; Sperlich *et al.*, 2010).

There are four principal findings from this study. The first finding advocates the use of knee-high compression socks as recovery aid and as a preventative method more than a treatment method. The runners wearing compression socks during the ultra-distance event showed signs of less



muscle damage compared to the runners that did not run with the compression socks. This supports the finding of Doan *et al.* (2003) and Bringard *et al.* (2006<sup>b</sup>). The physical support would have reduced impact and muscle oscillation thereby possibly limiting muscle contractile dysfunction. Perrey and co-authors (2008) found the peripheral contractile properties had significantly recovered by 24 hours in the calf muscles when wearing graduated compression socks and suggested that the compression sock compress the muscle tissue so that less muscle damage occurred. This would to some extent explain the improved muscle function over the recovery period in the current investigation.

Secondly, wearing the compression sock during the recovery period contributed to less swelling, and possibly reduced additional muscle tissue disruption during the recovery period. The dynamic cast hypothesis of Kraemer *et al.* (2001<sup>a</sup>) stipulates that the compression garment's mechanical support provides a more stable alignment of muscle fibres during regeneration and attenuates the inflammatory response, which may explain the faster functional recovery and improved the feelings of tenderness and pain in the calf muscles. Even though the investigation in part II did reveal benefits when wearing the compression sock after muscle damage were induced, i.e. post-exercise, these positive effects seem to be less than when running in the socks.

Thirdly, most recovery benefits were observed in the *Gastrocnemius* and *Soleus* muscles which would mean that the compression socks are more effective were it is applied. In addition this also supports the hypothesis that the compression socks limited the structural damage in the calf muscle while contracting and during impact in the run.

Finally, some researchers have suggested that commercially available garments do not exert enough pressure (Davies *et al.*, 2009). In this investigation a higher pressure than typically applied compression socks were used and resulted in a beneficial response. This is different than the findings of a recent study by Ali *et al.* (2010). The researchers suggested that clinically recommended graduated compression garments (30 – 15 mmHg) may not be appropriate for athletic populations due to the high pressure. However the current investigation shows no negative impact on recovery or performance in athletes wearing a higher pressure class II graduated compression sock (CCL II; 32 – 23 mmHg).



## II. PRACTICAL APPLICATION

Quicker recovery is thought to be an important factor in successful training and performance (Kraemer *et al.*, 2010). Exercise induced muscle injuries and the associated symptoms may be an impediment to continued activity and optimal performance. Thus recreational as well as competitive athletes will benefit from a reliable recovery strategy for DOMS. Unlike team sports athletes, most endurance athletes might not have to compete every 48 hours, still most would want to return to training by day two. Inflammation and metabolic demands would be the worst during this time frame as well. As a result the initial 48 hours after strenuous endurance activities is a critical period for not only metabolic but also functional recovery in athletes. The findings of this study show that wearing compression socks during training and when racing would promote rapid recovery, but wearing the compression socks after the activity will also add to the benefits in experienced athletes during this critical time frame after exercise. Thus compression socks may contribute to a better pre-exercise capacity, which would translate into more effective and beneficial training.

As mentioned in the previous section, from the investigation the most likely mechanisms is the mechanical support provided by the compressive force applied by the socks, which would explain the reduced muscle damage and limiting swelling. Wearing the compression sock during training and races may contribute to the prevention of chronic overreaching, accumulated fatigue and long term injuries in endurance athletes by reducing muscle damage during training and races. Conversely the results indicate that the compression sock is also effective as a post-exercise recovery aid to ameliorate symptoms associated with acute muscle damage. This is important since the days after muscle injury has occurred the athlete is exposed to swelling of the involved limb, muscle trauma, pain and tenderness as well as muscle weakness. This would make the athlete more susceptible to additional muscle injury or retard healing of the initial tissue injury. Lastly most recovery research has focused on reducing the acute inflammatory response. But the inflammatory response is a necessary process in muscle regeneration and remodelling after injury. Interfering with the natural process could be detrimental to long term muscle health and recovery. The research in this study suggests that wearing compression socks after exercise would physically assist the involved musculature in recovering without excessively interfering with the inflammatory response.



These findings promote the use of graduated compression knee high socks as a preventative measure of chronic muscle strain in experienced athletes as well as a recovery aid during the acute phase after exercise.

### III. LIMITATIONS AND FUTURE DIRECTIONS

This investigation addressed some of the limitations associated with previous research such as whether well-trained endurance athletes would benefit from wearing compression garments, when the optimal time is to wear the compression garments, as well as, do real life events support findings from laboratories.

One possible limitation to this investigation is that recovery time for endurance events depends on running distance and tissue type (Kim *et al.*, 2009). Hence this might make this study specific for endurance athletes and not resistance trained athletes. Furthermore, even though the two parts of the investigation was similar with regards to subjects, race and procedures, the lack of a control group in part II has made interpretation of the results less objective. This study also did not measure the actual pressure underneath the compression sock thus the exerted pressure may have been higher or lower than the prescribed value depending on the individual limb differences. Ali *et al.* (2010) found that a CCL II CS exerted a pressure range of 26 to 15 mmHg instead of 32 to 23 mmHg. Also most studies do not report the pressure exerted by the garments that were tested and commonly accepts that all garments are equal. This however is not true. There are various types of compression garments i.e. shorts, tops, sleeves and some are graduated and others are not. This too has made comparison between studies difficult. Even though this study did address optimal time to wear compression socks, more information is needed on this topic still. Finally, this study advocates the mechanical-pressure support theory and to some extent disregards the improved blood flow theory. Similar to muscle oscillation, blood flow was not assessed hence this possibility cannot be excluded so readily.

Some of the prominent issues that came to light during this investigation were the need for better non-invasive markers of muscle damage, since muscle damage varies from one individual to another (Warhol *et al.*, 1985). Also different statistical methods of interpreting data have made



interpretation difficult. Various studies assessed small sample populations. However, future researchers should also beware of lower quality studies for the sake of better statistical power.

Study methodology differs across studies on well-conditioned athletes. As a result the various research protocols, compression garments, fit, design (i.e. applied compressive area and pressure) and materials, as well as the individuals physiological and psychological aspects, has made it difficult to determine the specific physiological mechanisms involved by which compression garments may improve performance and/or aid recovery. In particular blood flow during exercise and the possibility of blood flow occlusion due to added intramuscular pressure. Hence more controlled studies with sophisticated techniques are warranted. In addition, homogeneity of procedures will be more reliable and give valid results. Sperlich *et al.* (2010) also emphasized that sponsorship of research may have made investigations bias.

Finally future research may investigate whether there is some form of dependence or reliance and what would the regular use of compression garments entail? Hence the impact of adaption and repeated bout effect has yet to be investigated, especially in athletes. One's ability to recovery could be a consequence of training status of the subject population. Well-trained athletes are used to discomfort associated with challenging exercises and are able to reproduce baseline performances within a short period after exercise induce muscle damage, due to the repeated bout effect. Furthermore is the use of compression garments really cost effective compared to other recovery strategies?

#### **IV. FINAL PERSPECTIVE**

In conclusion and to the best of our knowledge this was the first study to report the effects of compression socks on EIMD following an actual distance race, as well as to address the optimal time to wear compression socks for the most recovery benefits.

While previous research has shown that compression garments have the potential to effectively aid recovery, the efficacy is often undermined by disparity between applied pressures. Hence the success of compression socks as a regeneration strategy depends on an optimal period of application. When the optimal time is to wear compression garments for shorten recovery time is





a question that has not been addressed in research prior to this investigation. In addition a lack of effect in previous studies on trained populations may be attributed to ineffective protocols to induce muscle damage and/or fatigue in well-conditioned athletes, or the mismatch of the garment to the individual or type of sport (Kraemer *et al.*, 2010). This was also successfully addressed in the current study.

The results of this investigation suggest that knee-high compression socks worn during exercise are effective in reducing deleterious symptoms associated with EIMD such as the reduction in muscle function. In addition the longer the compression sock is worn after strenuous exercise the more added benefits there are such as reduced swelling and perceived pain. The results also suggest a strong psychological factor in wearing compression garments. The precise mechanism responsible for the benefits requires further investigation. Nonetheless the findings of this investigation emphasize the multitude of factors in the aetiology of EIMD.



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## APPENDIX A:

### INFORMED CONSENT FORM (ENGLISH VERSION)

Department of Sport Science  
Sport Physiology Laboratory  
Sport Science Department  
Coetzenburg  
Stellenbosch  
7600  
Telephone 021 808 28 18  
Facsimile 021 808 48 17



**Stellenbosch  
University**

### C o n s e n t   t o   P a r t i c i p a t e   i n   R e s e a r c h   P r o j e c t

**Title of the research project:** The value of graduated compression socks as a post-exercise recovery modality in long distance runners.

#### Researchers and Contact Address

Karen Welman (PhD student, Sport Science)

Phone: **082 098 5387** or 021 808 28 18; email: 13091115@sun.ac.za

Prof. E Terblanche (Promoter; Chairperson: Department of Sport Science)

Phone: 021 808 27 42

Licensed physicians Dr. Viviers/Dr. Williams and Dr. Scwabbe (Sport Medicine Centre, Sport Science Department)

Phone: 021 808 33 92

**Research Project Correspondence: [researchproject2009@gmail.com](mailto:researchproject2009@gmail.com)**

**Reference number:** *(office use)*

**Test administrator:** *(office use)*

TO#

Karen Welman

**Objective:** To determine whether compression socks are an effective post-exercise modality that facilitates the recovery process of experienced long distance runners, after exercise in the field.

**Research will be conducted according to the declaration of Helsinki, Medical Research Council (MRC) guidelines and SA Good Clinical Practice (GCP).** The researcher conducting this study support the principles governing both ethical conduct of research and the protection at all times of the interest, comfort and safety of the participants. The form and the accompanying information sheet are given to you for your own protection. They contain a detailed outline of the project procedures.

**Statement by the subject:**



I, the undersigned, \_\_\_\_\_ [ID no. \_\_\_\_\_],

of (address) \_\_\_\_\_

---

have been invited by **Stellenbosch University's Sport Science Department** to participate in the research project in which the researcher endeavours to investigate the possible effects of compression socks on the recovery of long distance runners after a race, i.e. the **Two Oceans Ultramarathon (56km)**.

**with this statement I confirm that:**

1. **I have been given and understood** an explanation and purpose of the research study. The information was explained to me in **English/Afrikaans** by **Karen Welman**.
2. **I have read the participant information sheet**, and the researcher has carefully explained to me all the procedures involved, as stated on the participant information sheet.
3. I have had an opportunity to **ask question** and they were **satisfactorily answered**.
4. I was informed that the information, which will be obtained through this project, would be handled **confidentially**, but that the results will be published in **research journals**.
5. I understand that no material that could identify me will be used in any reports on this study.
6. I have had time to consider whether to take part in this research project. It was **explained to me** that my participation in this project is **voluntary** and that I may withdraw myself, or information traceable to me, from the study at any time, without giving a reason and that ,this in no way will affect my future involvement with Stellenbosch University.
7. I also understand that the researcher or medical doctor may withdraw me from the study if deemed necessary for medical or study purposes.
8. I was informed that there are **no costs** involved for my participation in this project.
9. I am aware of that I will **receive a voucher at the completion of the project**, which entitles me to a maximum aerobic capacity test with lactate analysis, BIA analysis, two sport massage sessions and report with training guidelines i.e. heart rate zones and training intensities specifically tailored to my physiological results when I complete the study.
10. **I take the responsibility** to complete all the visits to the laboratory for anthropometrical assessments, functional testing, questionnaires and the three consecutive days for blood sample collection.
11. I am aware that the **anthropometrical assessments** include **body mass, stature and body composition analysis (BIA analysis)**, as well as **lower limb circumferences**.
12. I am aware that the **functional tests include a maximal aerobic capacity test, running economy test and a maximal leg power jump test**.



13. **I undertake** to enter the **Two Oceans Ultramarathon 2009**  **or 2010** , as well as to complete the testing prior and after the race.
14. **I understand** that I will have to complete **six visits** in total. Five of which will be at the **Sport Physiology Laboratory (Sport Science Department, Stellenbosch)** and one at the **Two Oceans Ultramarathon race**.
15. **I take the responsibility** to be and stay **highly motivated** during the **testing programme**.
16. **I agree** to complete my **daily activity and nutritional journal**, throughout the project, and hand it back to the researcher at the end of the study.
17. the researcher explained to me **the restrictions in my training prior to**, such as the tapering protocol **and during** the assessments, such as that I have to avoid any form of recovery methods, such as massage, ice-, water or heat therapy and stretching, any activities, anti-inflammatory and nutritional supplements during the three days after the race.
18. I will **not participate in any events or races the 72 hours** after the third visit (the race).
19. **I will tell the researcher** if I have any muscle fatigue or soreness prior to the tests.
20. **My second (running economy baseline) and the race (third)** will be separated by at least **seven days**, but not more than **21 days**.
21. I do not have any problem wearing a **heart rate monitor** or **compression socks** during the study.
22. **I was warned** that there is a possibility that I may experience one or more **signs or symptoms** during the aerobic capacity test. The possible **symptoms were explained** to me, such as light-headedness, dizziness, fainting, chest, jaw, neck or back pain or pressure, severe shortness of breath, wheezing, coughing or difficulty breathing, nausea, cramps or severe pain or muscle ache and severe prolonged fatigue or exhaustion during the maximal aerobic capacity test and some slight discomfort and tenderness after the blood samples are collected. I understand that I may stop the tests at any time when I experience any of these symptoms or if I feel unfit to continue.
23. **I am aware** that the researcher will require **15 blood samples** (5 samples across the study period x three 5 ml tubes) from **my forearm vein (total of 75 mL blood)** and **12 blood samples from finger pricks (total of 12 µL)**.
24. the researcher has explained to me that the **blood samples** will be collected by **qualified personnel** and will **not interfere** with my running ability.
25. **I am aware of the risks** involved in this study.
26. the researcher has explained to me the **safety and emergency procedures** which are in place, in case of an emergency situation.
27. **I have knowledge of the research doctor's contact number (021) 808 33 92** at the Sport Medicine Centre next to the Sport Physiology Laboratory.



28. **I am aware** that if I have any complaints or if I am not treated with respect, I may phone the human research committee member **Ms Maryke Hunter-Husselman** at **(021) 808 46 23**.
29. I will receive a **copy of the participant information sheet and informed consent** form for my own records.
30. **I understand that** this research project has been approved by **Stellenbosch University's Ethics Subcommittee A** [reference number:125/2008].

Signed at \_\_\_\_\_ on .

\_\_\_\_\_  
Researcher

**Karen Welman**

\_\_\_\_\_  
Participant

**STATEMENT BY RESEARCHER(ENGLISH VERSION)**

Department of Sport Science  
Sport Physiology Laboratory  
Sport Science Department  
Coetzenburg  
Stellenbosch  
7600

Telephone 021 808 28 18  
Facsimile 021 808 48 17



**Stellenbosch  
University**

**S t a t e m e n t   b y   r e s e a r c h e r**

**Title of the research project:** The value of graduated compression socks as a post-exercise recovery modality in long distance runners.

Researcher and Contact Address

Karen Welman (PhD student, Sport Science)

Phone: 082 098 5387 or 021 808 28 18; email: 13091115@sun.ac.za

**Research Project Correspondence: [researchproject2009@gmail.com](mailto:researchproject2009@gmail.com)**

**TO #\_\_\_\_\_**

I, ***Karen Estelle Welman***, declare that I:

1. Explained the information in this document to \_\_\_\_\_;
2. Requested the participant to ask questions if anything was unclear;
3. That this conversation took place in English/Afrikaans.

I, the researcher, furthermore declare that the research will be conducted according to the



**International Declaration of Helsinki, Medical research Council (MRC) guidelines and SA Good Clinical Practice (GCP).** That this study supports the principles governing both ethical conduct of research and the protection at all times of the interest, comfort and safety of the participants.

Signed at \_\_\_\_\_ on \_\_\_\_\_.

\_\_\_\_\_  
Researcher Witness

Karen Welman



## APPENDIX B:

### RESEARCH OUTLINE: GENERAL PARTICIPANT INFORMATION SHEET

(ENGLISH VERSION)

Department of Sport Science  
Sport Physiology Laboratory  
Sport Science Department  
Coetzenburg  
Stellenbosch  
7600



Stellenbosch  
University

Telephone 021 808 28 18  
Facsimile 021 808 48 17

### S p o r t   S c i e n c e   R e s e a r c h   P a r t i c i p a t i o n   I n f o r m a t i o n

**Title of the research project:** The value of graduated compression socks as a post-exercise recovery modality in long distance runners.

#### Researchers and Contact Address

Karen Welman (PhD student, Sport Science)

Phone: **082 098 5387 or 021 808 28 18; email: 13091115@sun.ac.za**

Prof. E Terblanche (Promoter; Chairperson: Department of Sport Science)

Phone: 021 808 27 42

Licensed physicians

Dr. Viviers/Dr. Williams and Dr. Scwabbe (Sport Medicine Centre, Sport Science Department)

Phone: 021 808 33 92

**Research Project Correspondence: [researchproject2009@gmail.com](mailto:researchproject2009@gmail.com)**

#### Background Information

If an athlete does not recover sufficiently after a race or training, future problems may develop. Thus, recovery after training and competition is an accepted practice by athletes and their management. However, the literature shows that there is a need for more scientific research on post-exercise recovery strategies, as most research has demonstrated inconclusive findings. A practical and inexpensive post-exercise recovery method will not only aid recovery in trained athletes but also will (i) prevent future injuries and (ii) indirectly improve athletic performance by allowing the athlete to recover more efficiently and return to training sooner.



## Project Objectives

To determine whether compression socks are an effective post-exercise modality that facilitates the recovery process of experienced long distance runners, after exercise in the field as well as when the optimal time would be to wear the compression socks.

## Subject Requirements

To be included in this study you need to be in excellent health and between the ages of 30 to 57 years, without a history of musculo-skeletal, metabolic, cardiovascular or endocrine disorders. Only men are allowed to volunteer for the study. You are not allowed to have participated in any lower body weight training exercises (gym) in the three months prior to the study, or be dependent on chronic medication. You must train on a regular basis, i.e. four or more times a week. Only experienced athletes, running or triathletes for at least two years are allowed to participate. Best marathon times should be 04:30:00 or less OR you have done one ultramarathon in the 12 months prior to the study.

## Payment for participation

As a participant you will not receive any financial reimbursement or payment to participate in the study and there will be **no costs** involved for your participation in this project.

## Benefits

You will receive interesting information on your general fitness level that can be beneficial to improving sport performance, i.e. **maximum aerobic capacity, training pace and heart rate zones**. On completion of the study, you will also receive a voucher for another **maximal aerobic capacity test with lactate threshold measurement, body composition assessment and two 30-minute sports massages**. The voucher is valid until **30/11/2010** and is not transferable. Participants will be reimbursed for the **Two Oceans Ultramarathon** entry fee after completion of the study. Participants completing the study will receive a report summarizing the main findings of this study and will be invited to a presentation of the completed study. In the case of athletes traveling from 70 km outside the Stellenbosch area, the voucher will be substituted with a travel voucher.

## Research procedures

The research project is undertaken by the **Sport Science Department at Stellenbosch University**. You will need to visit the **Sport Physiology Laboratory** on **five** different occasions and **one** visit will be at the **Two Oceans Ultramarathon** event (total of 6). During these visits, the following tests will be done:

**First visit:** This visit to the Sport Physiology Laboratory is for baseline testing and to familiarize you with the apparatus and procedures. You will need to complete a consent form, questionnaire regarding your health status and activity level and muscle soreness and fatigue questionnaire. Your height and weight will be taken. Then your mid-thigh, mid-calf- and ankle circumferences as well as leg length will be measured to provide you with the correct compression sock. Other tests include determination of body fat percentage, fat free mass and hydration levels, a maximum aerobic capacity test for oxygen consumption, and a jump test for lower body power. None of these tests are invasive. This session may take between 60 to 90 minutes.



**Time in between visits:** In-between the first and second assessment is 7 to 21 days. During the 14 days before the race you will need to follow a training taper protocol.

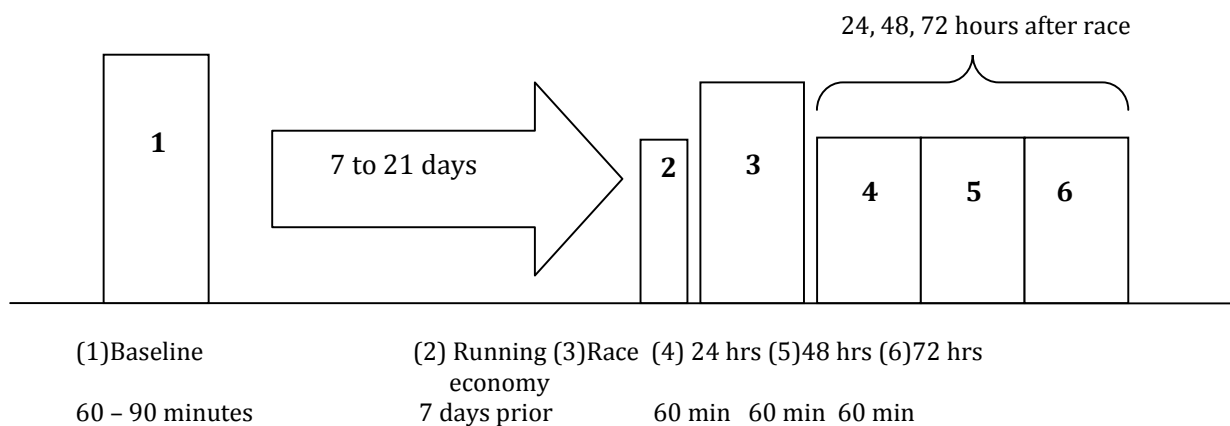
**Second visit:** During the second assessment you will have to complete a running economy test. This is a 10 minute test at your marathon pace. You must wear the compression sock and the running shoes and clothes which you will wear during the 56 km ultramarathon. Also blood samples will be collected.

**Third visit:** During the third assessment you will have to complete the **56 km Ultramarathon**, as well as an appropriateness-and-convenience survey and muscle soreness questionnaire. Please refrain from any fluid or food with calorie content the 5 km before the finish line. Only water is allowed. Blood samples will be taken for lactate and enzyme markers (this involves finger pricks and drawing blood samples by a qualified phlebotomist/nurse). Limb circumferences will be taken for lower limb swelling.

**Time in between visits:** The third visit will be followed by three consecutive days of testing and collecting data.

**Fourth to the sixth visit** (24 to 72 hours after race): Blood samples will be collected. An appropriateness-and-convenience survey, along with all of the tests, from the first visit, except the maximum aerobic capacity test, will be assessed. After the sixth visit you may return the compression sock as well as the activity and nutrition journal.

**Illustration of Visits**



## Guidelines During the Research Project

You may not take any medication two days prior to or during the tests. In-between the first and second assessment, as well as the seven days prior to the second assessment, you may only perform **moderate to low intensity exercises**, by following the taper protocol/your own. You will not be allowed to run hilly or mountainous trails and/or perform lower body weight training or participate in any high intensity training, the seven days prior to the second assessment date and during the study period. Participants have to avoid any form of recovery methods, such as **massage, ice-, water or heat therapy and stretching, any physical activities/exercise, anti-inflammatory and nutritional supplements** during the three days after the race. If you receive additional equipment or gear from the Sport Physiology laboratory, during the study, you must return it to the University of Stellenbosch at the termination of the study. During the study, you will need to record a logbook of your daily activities and nutrition and hand it back to the researcher by the end of the testing (visit six).

## Potential Risks

The researcher will do all within her power to reduce possible risks. If you fall in a risk population you would be excluded from the study. Dr P. Viviers is available at the *Sport Medicine Centre* to discuss any issues that may arise. There is a possibility that you may experience one or more signs or symptoms during the aerobic capacity tests. These symptoms include light-headedness, dizziness, fainting, chest, jaw, neck or back pain or pressure, severe shortness of breath, wheezing, coughing or difficulty breathing, nausea, cramps or severe pain or muscle ache and severe prolonged fatigue or exhaustion, since this is a maximal test to exhaustion. You may stop at any time you feel that you cannot continue the activity. A sterile environment will be maintained at all times. The blood sample collection for muscle damage markers and lactate may cause slight discomfort. A qualified phlebotomist, nurse or doctor will collect all the samples. Latex gloves and new needles will be used at all times. Carefully cleaning the skin and keeping the area clean and dry until the skin heals will minimize the risk for infection. A few subjects have experienced local soreness and stiffness in the arm or tender fingertips for two or three days after the blood sample are taken, it feels similar to a bruise. If you experience any problems you must contact the principle researcher or sport physician. However, if for some reason, you are not able to contact the researcher/physician then you should contact your family doctor or go to the emergency department of your nearest hospital. The researchers are competent and experienced in sport testing and do not expose research participants to unnecessary risks or discomfort. Health and safety procedures are in place to deal with emergencies that may arise during the tests.

## Rights of Research Subjects

You can choose whether to be in this study or not. You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, please contact **Ms Maryke Hunter-Husselmann (contact number: (021) 808 46 23 or mh3@sun.ac.za)**.

## Freedom of Consent



The researcher's intent is to only include subjects that freely choose to participate in this study. Thus participation is voluntary and you are free to withdraw consent at any time. Withdrawal will have absolutely no influence on your present and or future involvement with Stellenbosch University. Your consent to participate in this research will be indicated by your signing and dating of the consent form. Signing the consent form indicates that you have freely given your consent to participate, and there has been no coercion to participate.

### **Confidentiality**

All data collected for this research will be treated with absolute confidentiality. All questions and data sheets will be numerically coded and no names will be included in the data collection or analysis. This means that reported results will not include any names by any means.

### **Data & Results**

Recorded data will be securely retained for a period of six years at the Sport Science Department. No one except the researcher and project supervisor will be able to access these raw data. Please take note that overall data may be published in a peer review scientific journal.

### **Identification of Investigators**

If you have any questions or concerns about the research, please feel free to contact the principle researcher Ms. Karen Welman (**021 8082818, 082 098 53 87 or 13091115@sun.ac.za**) or the project supervisor, Prof E. Terblanche (**021 808 27 42 or et2@sun.ac.za**) at any time if you feel a topic has not been explain to your complete satisfaction. The official research e-mail is [\*\*researchproject2009@gmail.com\*\*](mailto:researchproject2009@gmail.com).



**APPENDIX C:  
PERSONAL INFORMATION**

**PART A: THE HEALTH HISTORY SECTION IS ADAPTED FROM THE STANDARDIZED PHYSICAL ACTIVITY READINESS PAR-Q & YOU QUESTIONNAIRE (AMERICAN COLLEGE OF SPORT MEDICINE, 2000) (ENGLISH VERSION)**

Department of Sport Science  
Sport Physiology Laboratory  
Sport Science Department  
Coetzenburg  
Stellenbosch  
7600  
Telephone 021 808 28 18  
Facsimile 021 808 48 17



**Stellenbosch  
University**

**Sport Science Research Subject Health Screening Form**

**Researchers and Contact Address**

Karen Welman (PhD student, Sport Science)  
Phone: 082 098 5387 or 021 808 28 18; email: 13091115@sun.ac.za  
Prof. E Terblanche (Promoter; Chairperson: Department of Sport Science)  
Phone: 021 808 27 42  
Dr. Viviers/Dr. Williams and Dr. Scwabbe (Medical doctors, Sport Medicine Centre)  
Phone: 021 808 33 92

**Research Project Correspondence: [researchproject2009@gmail.com](mailto:researchproject2009@gmail.com)**

**TO #**

**Reference code** *(office use)*

**Test administrator** *(office use)*

Karen Welman

**HEALTH HISTORY**

Please complete the following questions.

<b>Contact number of general physician/ doctor</b>	
<b>Has your doctor ever said that you may not do any physical activity?</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>
<b>Do you feel pain in your chest when you do physical exercise?</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>
<b>Do you smoke?</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>
<b>Have you had any chest pains in the past month?</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>
<b>Do you lose your balance because of dizziness?</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>
<b>Do you experience the loss of consciousness?</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>
<b>Do you have a bone or joint problem that could be aggravated with exercise?</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>
<b>If yes, please specify:</b>	
<b>Are you using any medication?</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>
<b>If yes, please specify: Name and indicate if chronic</b>	
<b>Do you know of any reason why you should not do this study?</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>




Do you suffer from any of the following conditions? Please specify if necessary.		
<b>Musculo- skeletal problems</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>	
<b>Metabolic- and endocrine disorders</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>	
<b>Immune deficiencies</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>	
<b>Cardiorespiratory disorders</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>	
<b>Cardiovascular disorders</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>	
<b>Haematological problems</b>	No <input type="checkbox"/> Yes <input type="checkbox"/>	

If you have said yes to one or more questions, please consult your doctor by phone or in person. If your health status changes during the study period, please inform the principle investigator.

Prior to any of the visits, please avoid any exercise 24 hours before, caffeine and alcohol 12 hours before and stop eating and drinking 3 hours before the testing – except water. During the 72 hours after the Two Oceans' do not do any exercise or recovery techniques.

**Participation to this study is voluntary and you may withdraw from the study at any time.**

Please do not hesitate to ask any questions. You can contact the principle research, Karen Welman:

 [archproject2009@gmail.com](mailto:archproject2009@gmail.com) (e-mail)



082 098 5387 (cell phone) or 021 808 2818



021 808 4718 (fax)

Thank you



Karen Welman



**PART B: PARTICIPANT INFORMATION**

Department of Sport Science  
 Sport Physiology Laboratory  
 Sport Science Department  
 Coetzenburg  
 Stellenbosch  
 7600  
 Telephone 021 808 28 18  
 Facsimile 021 808 48 17



**Stellenbosch  
 University**

**Sport Science Research Subject Activity Screening Form**

**Researchers and Contact Address**

Karen Welman (PhD student, Sport Science)  
 Phone: 082 098 5387 or 021 808 28 18; email: 13091115@sun.ac.za  
 Prof. E Terblanche (Promoter; Chairperson: Department of Sport Science)  
 Phone: 021 808 27 42  
 Dr. Viviers/Dr. Williams and Dr. Scwabbe (Medical doctors, Sport Medicine Centre)  
 Phone: 021 808 33 92

**Research Project Correspondence: [researchproject2009@gmail.com](mailto:researchproject2009@gmail.com)**

**Reference code:** *(office use)*

**Test administrator:** *(office use)*

**TO #**

Karen Welman

**GENERAL INFORMATION QUESTIONNAIRE: assessing health and running history.**

**Research project:** The value of graduated compression socks as a post-exercise recovery modality in long distance runners.

To help us collect general information about you, please complete the following questions. Please read the questions carefully and answer each one honestly.

**PERSONAL INFORMATION**

Please complete the following questionnaire and return it to [✉ researchproject2009@gmail.com](mailto:researchproject2009@gmail.com)

<b>Full name</b>		<b>Date:</b>	
<b>Physical Address</b>		<b>Postal code</b>	
		<b>Work telephone no.</b>	
<b>Sex</b>		<b>Home telephone no.</b>	
<b>Cell</b>		<b>Date of birth</b>	<i>dd/mm/yyyy</i>
<b>Email</b>			
<b>Identification number</b>			

Please ✓select the best way to contact you



## TRAINING HISTORY

The following questions are relevant to the 12 months prior to this study.

<b>Other sport except running in which you participate:</b>		
Please name <b>3 Marathons or other long distance events( &gt;30 km)</b> and when you participated in these events, during the last 12 months:		
<b>Name of marathon(s)</b>	<b>Race time(s)</b>	<b>Participation date(s)</b>
<b>Personal best for a marathon (PB) and the date:</b>		
<b>Do you train 4 or more sessions a week?</b>		No <input type="checkbox"/> Yes <input type="checkbox"/>
Please, specify: <i>hours or days AND distance per week</i>		
<b>When did you start running competitively?</b>		
<b>Have you had any injuries in the past three months?</b>		No <input type="checkbox"/> Yes <input type="checkbox"/>
If yes, please specify: <i>what and when</i>		
<b>Do you often do hill training/run mountainous trails?</b>		No <input type="checkbox"/> Yes <input type="checkbox"/>
If yes, please specify: <i>times per week</i>		
<b>Have you done/will you do <u>lower body weight training (gym)</u> in the three months prior to the Two Oceans?</b>		No <input type="checkbox"/> Yes <input type="checkbox"/>
Please consider the following:		
<b>Will you be able to taper reduce your training volume the 14 days before the race?</b>		No <input type="checkbox"/> Yes <input type="checkbox"/>
After the Two Oceans' ultramarathon race, follow up assessments will be done the following 72 hours; this includes blood samples and functional tests.		
<b>Will you be able to visit the sport physiology laboratory between 5:00 and 12:00am, the 72 hours after the ultramarathon for about an hour?</b>		No <input type="checkbox"/> Yes <input type="checkbox"/>



**APPENDIX D:**

**APPROPRIATENESS-AND-CONVENIENCE QUESTIONNAIRE**

Group \_\_\_\_\_ TO # \_\_\_\_\_

1. Did the compression sock feel comfortable?  
Not at all      a Little      Moderately      Quite a bit      Extremely

2. Did it feel like compression sock was slipping?  
Not at all      a Little      Moderately      Quite a bit      Extremely

3. Did the compression sock contribute to foot sores?  
Not at all      a Little      Moderately      Quite a bit      Extremely

4. Was it easy to put the compression sock on?  
Not at all      a Little      Moderately      Quite a bit      Extremely

5. Did the compression sock improve your running confidence?  
Not at all      a Little      Moderately      Quite a bit      Extremely

6. Did it feel safe to wear the compression sock? - preventing injuries.  
Not at all      a Little      Moderately      Quite a bit      Extremely

7. Did you experience any additional fatigue from the compression sock?  
Not at all      a Little      Moderately      Quite a bit      Extremely

8. Do you feel the compression sock aided your running?  
Not at all      a Little      Moderately      Quite a bit      Extremely

9. Did the compression sock help to recovery after the ultramarathon?  
Not at all      a Little      Moderately      Quite a bit      Extremely

10. Did the sock make you sweat excessively/more than usually?  
Not at all      a Little      Moderately      Quite a bit      Extremely

11. Did the compression sock chafe / irritate you in any why? If yes, specify.  
Not at all      a Little      Moderately      Quite a bit      Extremely

Would you use the compression sock again, if not specify? Yes/No

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**APPENDIX E:**  
**VISUAL ANALOGUE SCALES (VAS)**  
**PART I:**

**VAS SCALE**  
Assessing Pain and Muscular Discomfort

Subject name: \_\_\_\_\_ Ref. no. \_\_\_\_\_

Muscle: e.g. Quadriceps (front of thigh)

No pain \_\_\_\_\_ Unbearable pain  
0 \_\_\_\_\_ 10  
Pain at rest (lying/seated)

No pain \_\_\_\_\_ Unbearable pain  
0 \_\_\_\_\_ 10  
Pain during daily activities (like walking or stairs)

No pain \_\_\_\_\_ Unbearable pain  
0 \_\_\_\_\_ 10  
Pain during stretching

No pain \_\_\_\_\_ Unbearable pain  
0 \_\_\_\_\_ 10  
Pressure Pain (apply pressure to the belly of the muscle)

**PART II:**



**VISUAL ANALOGUE SCALES (VAS)**

**PART II**

**VAS SCALE**

Assessing Pain and Muscular Discomfort

Subject name: \_\_\_\_\_ Ref. no. \_\_\_\_\_

Identify over all pain and discomfort in e.g. Quadriceps muscles(front of thigh)

No pain

Unbearable pain

0

10

Overall Pain and Discomfort



**APPENDIX F:  
FOOD AND ACTIVITY JOURNAL**

<b>Day of race</b>	<b>24 hours</b>	<b>48 hour</b>	<b>72 hours</b>
<b>Breakfast:</b>	<b>Breakfast:</b>	<b>Breakfast:</b>	<b>Breakfast:</b>
<b>Lunch:</b>	<b>Lunch:</b>	<b>Lunch:</b>	<b>Lunch:</b>
<b>Dinner:</b>	<b>Dinner:</b>	<b>Dinner:</b>	<b>Dinner:</b>
<b>Snacks:</b>	<b>Snacks:</b>	<b>Snacks:</b>	<b>Snacks:</b>
<b>Activities</b>	<b>Activities</b>	<b>Activities</b>	<b>Activities</b>
<b>Alcohol:</b>	<b>Alcohol:</b>	<b>Alcohol:</b>	<b>Alcohol:</b>