THE EFFECT OF MINIMALIST SHOE TRAINING ON THE NEUROMUSCULAR CONTROL OF RECREATIONAL DISTANCE RUNNERS

by

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DECLARATION

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ABSTRACT

Neuromuscular control (NMC) plays a critical role in dynamic movement regulation such as running (Nyland *et al.*, 2011) and injury prevention (Hübcher *et al.,* 2010). This experimental study set out to determine whether an eight-week minimalist shoe training program influences NMC in recreational distance runners.

Eleven experimental (EXP) (5 women; 6 men) (age 23.4 ± 2.98 yrs; VO_{2max} 43.55 ± 5.04 $ml.min^{-1}.kg^{-1}$; BMI 22.61 ± 3.08 $kg.m^2$; Training 17 ± 5$km.w^{-1}$) and 12 control (CON) runners (7 women; 5 men) (age 25.42 ± 5.57 yrs; VO_{2max} 43.67 ± 4.38 $ml.min^{-1}.kg^{-1}$; BMI 22.38 ± 3.12 $kg.m^2$; Training 18 ± 6$km.w^{-1}$) randomly completed an eight-week training program in either minimalist shoe (EXP) or their usual trainers (CON). Neuromuscular control components were measured before and after the intervention i.e. postural sway (Balance Biodex®), using the Athletic Single Leg (ASL) and modified Clinical Test of Sensory Integration and Balance (mCTSIB) tests, joint position sense (JPS) using joint angle reproduction tests (Biodex® Isokinetic Dynamometer), frontal and sagittal planes isokinetic strength testing, lower body electromyography (EMG) and kinematic measurements while participants ran on a treadmill.

Plantar-dorsiflexion (PF/DF) or inversion eversion (IN/EV) proprioception did not differ between groups ($p > 0.05$). In selected trials EXP showed less deterioration in IN/ EV foot position error, when compared to CON, with medium to large practical significance. Athletic Single Leg scores for non-dominant ($p < 0.01$) and dominant M/L ($p = 0.05$) sway, and dominant overall sway ($p = 0.04$) improved in CON, with marked differences between genders. Dorsiflexor strength improved for 30°.sec^{-1} and 60°.sec^{-1} speeds in CON ($p < 0.01$ & $p = 0.04$, respectively) and in the slower speed for EXP ($p = 0.04$). Plantar-flexion (PF) strength improved in EXP men (30°.sec^{-1} $p = 0.02$; 60°.sec^{-1} $p = 0.02$), while EXP women demonstrated a 7% deficit. At initial contact PF increased in EXP (8$km.h^{-1}$ $p = 0.01$; 10$km.h^{-1}$ $p = 0.01$; 12$km.h^{-1}$ $p = 0.01$), with women showing a greater change in ankle angle (8$km.h^{-1}$ $p = 0.03$; 10$km.h^{-1}$ $p = 0.02$; 12$km.h^{-1}$ $p = 0.01$) compared to men (8$km.h^{-1}$ $p = 0.05$; 10$km.h^{-1}$ $p = 0.06$; 12$km.h^{-1}$ $p = 0.05$). Greater knee flexion (8$km.h^{-1}$ ES = 0.64; 10$km.h^{-1}$ ES = 0.49; 12 $km.h^{-1}$ ES = 0.51) in EXP. Plantar-flexor pre-activation improved in EXP women, while co-activation improved in EXP men and total activation improved in both genders.

Results suggest that women may require more time to transition into minimalist shoes. While minimalist shoes may moderately reduce foot position error, improve strength and muscle activation patterns, excessive plantar flexor muscle damage may reduce strength and muscle spindle proprioceptive feedback.

Keywords: neuromuscular control**,** minimalist running, electromyography, proprioception.

ABSTRAK

Neuromuskulêre beheer (NMC) speel 'n kritieke rol in dinamiese beweginsregulasie, soos met hardloop (Nyland *et al.,* 2011) en beseringsvoorkoming (Hübscher *et al.,* 2010). Hierdie eksperimentele studie het uit gesit om te bepaal of 'n agt-week minimalistiese skoen oefenprogram NMB kan beïnvloed in rekreasie langafstand atlete.

Elf eksperimentele (EXP) (5 vrouens, 6 mans) (ouderdom 23.4 ± 2.98 jr; VO_{2maks} 43.55 ± 5.04 $ml.min^{-1}.kg^{-1}$; BMI 22.61 ± 3.08 $kg.m^{2}$; Oefening 17 ± 5$km.w^{-1}$) en twaalf kontrole (CON) hardlopers (7 vrouens, 5 mans) (ouderdom 25.42 ± 5.57; VO_{2maks} 43.67 ± 4.38 $ml.min^{-1}.kg^{-1}$; BMI 22.38 ± 3.12 $kg.m^{2}$; Oefening 18 ± 6 $km.w^{-1}$) het lukraak 'n agt-week oefenprogram voltooi, óf in minimalistiese skoene (EXP) of in hul gewone hardlooptekkies (CON). Neuromuskulêre beheer komponente was gemeet voor en na die intervensie i. e. posturale wieg (Balans Biodex®), met gebruik van Atletiese Enkelbeentoets (ASL) en die gemodifiseerde Kliniese Toets van Sensoriese Integrasie en Balans (mCTSIB), gewrigs posisie bewustheid (Biodex® Isokinetiese Dinamometer), frontale en sagitalle vlak isokinetiese kragtoetsing, onderlyf elektromiografie (EMG) en biomeganiese metings terwyl deelnemers op 'n trapmeul gehardloop het.

Plantaar dorsifleksie (PF/DF) of inversie eversie (IN/EV) propriosepsie het nie verskil tussen groepe nie ($p > 0.05$). In selektiewe proewe het EXP IN/ EV 'n verminderde afname gehad in foutiewe voet posisieplasings, in vergelyking met CON, terwyl medium na groot praktiese betekenisvolle verskille. . Atleet enkel been toets tellings vir nie-dominant ($p=0.001$) en dominante M/L ($p = 0.05$) wieg, en dominant algehele wieg ($p = 0.04$) het verbeter in CON, met gemerkte verskille tussen geslagte. Dorsifleksor krag het verbeter vir 30°.sec^{-1} en 60°.sec^{-1}spoed in CON ($p = 0.01$ en $p = 0.04$, onderskeidelik) en in die stadiger spoed vir EXP ($p = 0.04$). Plantaarfleksie (PF) krag het verbeter in EXP mans (30°.sek^{-1} $p = 0.02$; 60°.sek^{-1} $p = 0.02$), terwyl EXP vrouens 'n 7% tekort gedemonstreer het. By initïele kontak het PF toegeneem in EXP (8$km.h^{-1}$ $p = 0.01$; 10$km.h^{-1}$ $p = 0.01$; 12$km.h^{-1}$ $p = 0.01$), met vrouens wat 'n groter verandering getoon het (8$km.h^{-1}$ $p = 0.03$; 10$km.h^{-1}$ $p = 0.02$; 12$km.h^{-1}$ $p = 0.01$), in vergelyking met mans (8$km.h^{-1}$ $p = 0.05$; 10$km.h^{-1}$ $p = 0.06$; 12$km.h^{-1}$ $p = 0.05$). Groter kniefleksie (8$km.h^{-1}$ ES = 0.64; 10$km.h^{-1}$ ES = 0.49; 12 $km.h^{-1}$ ES = 0.51) in EXP. Plantaarfleksie pre-aktivering het verbeter in EXP vrouens, terwyl ko-aktivering verbeter het in EXP mans, en totale aktivering verbeter het in beide geslagte.

Hierdie resultate stel voor dat vrouens moontlik meer tyd sal vereis om na minimalistiese skoene oor te skakel. Terwyl minimalistiese skoene matige verbetering in foutiewe voetposisieplasing, verbeterde krag en spieraktiveringspatrone kan veroorsaak, kan oormatige plantaarfleksie spierskade krag en spierspoel proprioseptiewe terugvoer ook verminder.

Sleutelwoorde: Neuromuskulêre beheer, minimalisties hardloop, elektromyografie, propriosepsie.

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ABBREVIATIONS

AMPA	:	American Medical Podiatric Association
ANOVA	:	Analysis of Variance
A/P	:	Anterior Posterior
AT	:	Anaerobic Threshold
BF	:	Biceps Femoris
BMI	:	Body Mass Index
bpm	:	Beats per minute
BM	:	Body Mass
CNS	:	Central Nervous System
COG	:	Centre of Gravity
CON	:	Control group
COP	:	Centre of Pressure
Cm	:	Centimetre
$Deg.sec^{-1}$	:	Degrees per Second
EMG	:	Electromyography
ES	:	Cohen's Effects Sizes
EXP	:	Experimental group
FFS	:	Forefoot Strike
GLUT	:	Gluteus Medius
GRF	:	Ground Reaction Force
H-reflex	:	Hoffman's Reflex
HR	:	Heart Rate
HR_{max}	:	Maximal Heart Rate
HR_{AT}	:	Heart Rate at Anaerobic Threshold
Hrs	:	Hours
Hz	:	Hertz
ITB	:	Iliotibial band

Kg	:	Kilogram
$Km.h^{-1}$	:	Kilometres per Hour
$Km.w^{-1}$	:	Kilometres per Week
LG	:	Lateral Gastrocnemius
LLCI	:	Lower Limb Comfort Index
mCTSIB	:	Modified Clinical Test of Sensory Integration and Balance
MG	:	Medial Gastrocnemius
Min	:	Minutes
ms	:	Milliseconds
MTSS	:	Medial Tibial Stress Syndrome
M/L	:	Medial Lateral
MFS	:	Midfoot strike
n	:	Number of Subjects
NMC	:	Neuromuscular control
p	:	Probability
PFPS	:	Pattelofemoral Pain Syndrome
PER	:	Peroneus Longus
PF	:	Plantar-flexion
PTTD	:	Posterior Tibial Tendon Dysfunction
RFS	:	Rearfoot Strike
RRI	:	Running Related Injury
SD	:	Standard Deviation
SEM	:	Standard Error of Measure
TA	:	Tibialis Anterior
VE_{AT}	:	Minute Ventilation at Anaerobic Threshold
VE	:	Minute Ventilation
VO_{2AT}	:	Oxygen Consumption at Anaerobic Threshold
VO_{2max}	:	Maximal Oxygen Consumption

OPERATIONAL DEFINITIONS

Dynamic postural control:	The ability to execute a movement task, on different types of surfaces, with minimal superfluous movements (Hrysomallis, 2011).
Dynamic proprioception:	Defined as kinaesthesia, and the sense of rates of movements, both segmentally (joint stability) and in regards to postural equilibrium (Xian Li *et al.,* 2009; Jerosch & Prymka, 1996)
Forefoot strike:	A running technique where the forefoot contacts the ground first.
Joint motion sense:	The threshold value of passive motion required to detect motion in a joint (kinaesthesia).
Joint position sense:	The accuracy of passive and active joint reproduction.
Neuromuscular control:	Coordinative strategies aimed principally at improving quality and efficiency of movements.
Rearfoot strike:	A running technique in which the heel contacts the ground first.
Recreational Runner:	A person who has not been running regularly during the previous year (Nielsen *et al.,* 2013; Buist *et al.,* 2008). The cut-off to define regularity is set at 20km of total training volume per week.
Running related injury:	Running-related lower extremity or back musculoskeletal pain limiting running for at least one week, that is, three scheduled consecutive training sessions.
Midfoot strike:	A running technique in which the heel and forefoot contact the ground at approximately the same time.
Static postural control:	The process by which the centre of gravity is kept vertically above and within the limits of the base of support (Hosseini *et al.,* 2012; Paillard, 2012).
Static Proprioception:	Usually defined as position sense, which refers to the conscious perception of the orientation of different parts of the body with respect to each other.

CHAPTER ONE: INTRODUCTION

A. Overview

Recreational distance running have become an ever-increasing pastime, both for the associated psychological benefits and positive health-related effects (Garber *et al.,* 2011). Running provides an enjoyable and easily practiced form of exercise, applicable to almost any age or level. The South African climate and landscape is ideal for endurance-type sports. Marathons like the 56 km Two Oceans or 90 km Comrades races have become an annual affair for more experienced runners.

However, sudden increases in training volume or prolonged overload, often seen with novice athletes or those competing at high levels, places stress on the system. This load may result in repetitive strain injuries (Hreljac, 2004). Rehabilitation of injuries can be timely and frustrating to runners wanting to maintain their fitness levels. Therefore early intervention or prevention of running-related injuries (RRI's) is preferential (Hreljac, 2004). Risk factors for running-related injuries can be broadly separated into extrinsic and intrinsic categories (Doaud *et al.,* 2012). While certain intrinsic risk factors like age, gender, and anatomical abnormalities are unavoidable, modification of extrinsic risk factors like shoes, surfaces and training variables may provide a protective effect.

Methods commonly used to prevent and treat RRI's include the various forms of orthotics, bracing and taping, program alterations, pre-exercise warm-ups and stretching, as well as shock absorbing heel inserts (Yeung & Yeung, 2001). These prevention modalities aim at correcting biomechanical alignment, providing mechanical stability, and/or alleviating shock absorption. However, on the whole, high injury rates have remained to be a large concern among runners, despite intervention methods (Buist *et al.,* 2008).

While these intervention methods may be helpful, most aim at treating RRI symptoms, leaving underlying cause unidentified. It has been suggested that neuromuscular control (NMC), coordination and timing between antagonistic and synergistic muscles play a critical role in dynamic movement regulation, including running and landing (Nyland *et al.,* 2011; Lephart & Riemann, 2002). Inefficient movement patterns may result in insufficient shock attenuation, increased energy cost, and excessive strain on muscles and joints (Lieberman *et al.,* 2010).

The rationale behind minimalist shoes as a NMC restoring modality is dependent on three theoretical concepts. Firstly, the thinner sole of a minimalist shoe increases sensory information from the plantar aspect of the foot, resulting in increased afferent proprioceptive information reaching the central nervous system (CNS) (Robbins & Waked, 1997). This provides the CNS with better information regarding the joint position, leading to better movement regulation, reduced foot placement errors, and possibly reduced long-term injury rates (Wakeling *et al.,* 2002; Nurse & Nigg, 2001; Robbins, Waked & McCLaren, 1995). Secondly, by increasing the strength of the intrinsic musculature of the foot, minimalist shoes acts similarly to wobble board training (Nigg, 2009). Proprioceptive wobble-board training is used in rehabilitation following sports related injuries (O'Driscoll & Delahunt, 2011) and is becoming recognized as an important element in injury prevention in sport (DiStephano, 2010; O'Driscoll *et al.,* 2011). Wobble board training has been positively associated with a reduction in injury rates. Emery and colleagues (2005) found that a 6-week wobble board intervention study resulted in decreased injury rates after a six month follow-up period. Lastly, harder surfaces, as a consequence of reduced cushioning, results in neuromuscular adaptations. These adaptations include attenuated ankle stiffness (Bishop *et al.,* 2006; Robbins & Waked, 1997) and greater pre-activation of the plantar-flexory muscles (Divert *et al.,* 2005[a]; Giandolini *et al.,* 2013). This improvement in feed-forward control significantly aids shock attenuation (Divert *et al.,* 2005[a]).

Most research has focused on the extrinsic measurement of shock attenuation in barefoot running, with little attention being paid to the underlying neuromuscular mechanism, which brings about running adaptations. Although improved proprioceptive ability have been indirectly implied in many studies (Squadrone & Galozzi, 2011; Rose *et al.,* 2010; Divert *et al.,* 2005; Robbins & Waked, 1997), little research has been done specifically investigating the long-term proprioceptive effect of minimalist training. Further, the majority of studies are of cross-sectional nature with little information regarding the long-term effects of minimalist training.

Therefore, the present study will set out to determine the effect of minimalist training on the NMC, proprioception, dynamic balance, strength and biomechanics of recreational runners new to minimalist shoes, over an 8-week intervention period.

CHAPTER 2: THEORETICAL BACKGROUND

A. Introduction

Any form of effective movement relies on precise coordination. Neuromuscular control (NMC) mechanisms aim principally at improving quality and efficiency of movements (Ageberg *et al.,* 2013). Effective NMC is critical during distance running not only to ensure economical gait patterns, but also to avoid incorrect running kinematics which could lead to increased injury risk. By investigating the specific components of NMC, one can identify several factors that may contribute to more productive movement patterns, or alternatively, possibly lead to RRI's. This section will start by outlining the current state of RRI occurrences, followed by the identification of several injury risk factors associated with running, as well as possible underlying mechanisms. This review aims to fill potential knowledge gaps by providing practical information that can be easily applied by coaches and sport scientists. It aims to highlight factors that contribute to improved NMC, using the intervention methods discussed. Therefore, minimalist running claims will not be specifically supported or refuted, however, advantages of either running style will be emphasized so that the athlete will benefit maximally from the study findings. Further, taking into account what is known and where limitations in current knowledge might be found, the primary problem statement will be developed.

B. Running Related Injuries And Risk Factors

Running has gained popularity both as a form of enjoyable exercise, and as a way of improving health and wellbeing. This may be attributed to the fact that running is a relatively simple exercise form, without the need for additional apparatus or instrumentation and can be performed almost anywhere, either alone or as a social gathering. Benefits of regular cardiovascular exercise, such as running includes reduced risk of Chronic Heart Disease (CHD), type II Diabetes, some cancers, as well as reduced blood pressure, improved insulin activity, preservation of bone mass, and improvement in mental health (Garber *et al.,* 2011). However, running also brings with it some disadvantages. Running related injuries occur at an incidence rate of approximately 19% to 79% (Van Gent *et al.,* 2007). Similarly, Macera and colleagues (1989) reported annual injury rates of 24 to 65%. The wide range is due to different definitions being used in reviews, including running experience, running load, period of follow up, and study design (prospective or retrospective) (Lun *et al.,* 2003; Van Mechelen, 1992; Lysholm & Wiklander, 1987). Buist and colleagues (2008) defines RRI's as running-related lower extremity or back musculoskeletal pain limiting running for at least one week, that is, three scheduled consecutive training sessions.

Repetitive strain, or overuse injuries occurring in the lower extremities most frequently associated with long distance running include Pattellofemoral Pain Syndrome (PFPS), Iliotibial Band Syndrome (ITB), Meniscal injury and Pattelar Tendinitis in the knee, whereas Medial Tibial Stress Syndrome (MTSS), Plantar Fasciitis and Achilles Tendinopathies most frequently occur in the foot (Ferber *et al.,* 2009; Taunton *et al.,* 2002; Lieberman *et al.,* 2010). Stress fractures have also become a recent concern, with an incidence of approximately 21% in runners, suggesting that impact attenuation is a problem (Zadpoor & Nikooyan, 2011; Nattiv *et al.,* 2000). With 40% of all RRI's occurring in the foot, attention needs to be paid to contributory factors to injury, in the ankle and lower leg specifically (Van Gent *et al.,* 2007).

Reasons for these excessively high injury rates are multi-factorial, and generally fall into either extrinsic or intrinsic categories (Daoud *et al.,* 2012). Examples of intrinsic risks include biomechanical abnormalities (alignment), flexibility, core strength, previous injuries, running experience, gender and body mass index (BMI). Extrinsic factors include shoes, surface characteristics and training variables (Daoud *et al*., 2012).

A retrospective study was conducted by Taunton and colleagues (2002), aimed at identifying gender specific risk factors for various injuries. Of special interest, being under the age of 34 years was reported a risk factor across the sexes for PFPS, and in men, for ITB, Patellar Tendinopathy, and MTSS. Being active for less than 8.5 years was positively associated with injuries in both sexes for MTSS, and women with a BMI less than 21 kg.m^2 were at risk for Tibial Stress Fractures and spinal injuries. Certain injuries occurred with a statistically higher frequency in one sex than the other (Taunton *et al.,* 2002). For example, anthropometric measures such as Q-angles have been used to quantify lower extremity segment alignment. Schache and colleagues (2003) found significant differences in Q-angles and larger standing pelvic tilt angles in women (20° ± 4°), compared to the men (17° ± 4.°). While women have up to two times the risk of sustaining an injury during running (Chumanov *et al.,* 2008), it appears that the reasons are multi-factorial, although probably linked to greater Q-angles. The greater Q-angle places the lower extremity in increased genu valgum, hip adduction and foot pronation. These kinematic differences increase the risk of injury, specifically Infrapatellar Tendinitis and Chondromalacia Patella (Hamill *et al.,* 1999). Given the anatomical differences, it may also be expected that NMC differs between men and women, and that these differences are amplified under dynamic situations. Therefore, it might be suggested that researchers exercise caution when investigating dynamic NMC by separating genders during data analysis.

Foot strike patterns have also received much attention in regard to injury risks. In a retrospective study, Daoud and colleagues (2012) compared foot strike patterns with injury history in collegiate athletes competing at national level. Researchers found that runners who rear foot strike incurred mild to moderate injuries up to two and a half times more frequently than do runners who forefoot strike. The authors reasoned that running style, and NMC, has a greater impact on injury rates than does shoes, or orthotics. It may be possible that a forefoot striking pattern encourages improved NMC, resulting in improved impact attenuation and reduced foot placement errors. This could possibly lead to reduced injury rates over time.

Another major factor which increases the risk of running related injury is excessive or prolonged pronation. When pronation extends beyond the mid-stance phase, it interferes with the foot's ability to become rigid at push off, thereby increasing the risk of instability and injury, particularly to the forefoot structure (Goble *et al.,* 2013). The larger loads produced on the first metatarsal, and other medial structures, increases the risk of injuries to the first metatarsal or sesamoid bones. An increased demand is also placed on the posterior tibial tendon, which is responsible for calcaneal valgus during plantar-flexion. Patellofemoral joint dysfunction, Achilles tendinopathy, metatarsalgia and medial longitudinal arch strains can also result from excessive pronation (Goble *et al.,* 2013). When looking further up the kinetic chain, excessive pronation in combination with other biomechanical factors may also be an additional causative factor leading to injuries (Morley *et al.,* 2010). Stergiou and Bates (1999) suggested that a lack of coordinative or synchronous action between pronation of the subtalar joint and knee (tibial) motion might have greater potential for predicting runners with susceptibility to injury. This suggests that NMC between the subtalar joint and knee needs to be optimal, in order to avoid injuries. The mechanism of injury is explained by modelling the subtalar joint as a mitered hinge. According to this model, pronation or supination of the foot is transferred into tibial external or internal rotation, resulting in injury to bone or soft tissue if overly excessive (Pohl *et al.,* 2006).

Additionally, the concept of variability seems to produce interesting debates among researchers. Hamill *et al.,* (1999) proposed that injured runners exhibit reduced joint coupling variability, which reduces flexibility in the system and increases the potential for musculoskeletal injury. Logically, reduced variability results in an increased frequency of repetitive impacts on specific local joint segments. In contrast to this reasoning, Ferber and partners (2011) found reductions in the stride-to-stride knee joint kinematic pattern variability following a 3-week strength training protocol, in runners with PFPS. It was suggested that strength training restored a more consistent and predictable movement pattern. Whether variability contributes to injury mechanisms or reduces injury risk remains uncertain. Considering that runners with different injury histories were used in the above mentioned studies, which makes comparisons complex, it can be assumed that injury can alter running kinematics considerably (Dubin, 2007; Noehren *et al.,* 2006). Variability can be viewed as the relative degree by which the neuromuscular system deviates from its ideal movement pattern, or alternatively, the flexibility in the system. The fact that researchers sometimes find conflicting results regarding variability could suggest that the underlying mechanisms of NMC is not well understood and that further research is warranted.

In conclusion, risk factors for running related injuries can generally be attributed to either altered neuromotor skill (coordination), or unfavourable environments (such as sloped running roads) which cause biomechanical abnormalities (Lieberman *et al.*, 2010). While biomechanical misalignments may lead to injuries, Nigg, as early as 1985, speculated that "dynamic functional abnormalities" are equally important contributing risk factors predisposing a runner to injuries. Brooke and Zehr (2006) further suggested that the transmission of sensory feedback is fundamentally different from that seen when a subject is at rest, when compared to movement. Neuromuscular control is thus dynamically regulated during movement, resulting in different outcomes. It is for this reason that this study will focus on various components of NMC and running kinematics during both static and dynamic conditions.

C. Methods Of Injury Prevention

Several preventative measures have been adopted in the past in an attempt to reduce the incidence rate and alleviate symptoms of RRI's. Briefly these include knee braces, shock absorbing heel inserts, improving hamstring flexibility, decreasing distance, pre-exercise stretching, warm ups and cool downs (Shrier, 2008; Yeung & Yeung, 2001; Bengal *et al.,* 1997; Rudzki, 1997; Hartig & Henderson, 1999; Van Mechelen *et al.,* 1993; Fauno *et al.,* 1993).

Due to the correlation found between different running styles, and specific injury risks, several runners are now turning their attention to dynamic running factors (i. e. running form). Gait retraining has proven to be a viable intervention method for the prevention of Tibial Stress Fractures. Noehren and colleagues (2010) gave runners with Patellofemoral Pain real-time feedback of hip adduction moments, reduced hip adduction, contra lateral pelvic drop and pain during an 8-week intervention period. This resulted in improvement in function and reduction in pain, which was retained after a 1-month follow-up. Rixe and partners (2012) speculated that addressing the underlying mechanics associated with injury might be beneficial for other injury types as well.

On the contrary, when comparing the intervention effect of minimalist shoes to gait retraining over a 13-week period, Giandolini and colleagues (2013) did not find agreeable results. The gait retraining intervention did not produce reduction in the loading rate, peak heel acceleration, or shock wave propagation speed. However, the minimalist shoe intervention proved to reduce peak heel acceleration and shock wave propagation speed significantly. The only concern was that heel acceleration was measured during a midfoot strike. Squadrone and Gallozzi (2009) observed that peak pressure under the heel was decreased, while that under the forefoot increased when subjects ran barefoot or with Vibram FiveFingers™. The measurement technique could thus be questioned for runners who midfoot strike.

Unfortunately efforts to alleviate the effects that injury risk factors have on injury rates, using graded training program, orthotics or shock absorbing shoes have not shown promising results (Hume *et al.,* 2008; Buist *et al.,* 2008; Schwellnus & Stubbs, 2006) and injury rates have remained at an alarmingly high level, suggesting that additional solutions remain unfound.

In conclusion, several risk factors have been identified which are believed to increase the risk of RRI's. These risk factors can generally be divided into either intrinsic or extrinsic catagories. Unfortunately RRI's have remained at disquieting levels, despite every attempt by the health care community to evade injuries. Commonly used methods of intervention have focused mostly on the use of extrinsic methods of attenuation such as orthotics, footwear or bracing. It may be suggested that by altering the intrinsic NMC within a runner, corrections of their running technique may bring about reductions in RRI's. However, research in this area is limited, and further studies are required to provide a conclusive answer.

D. Neuromuscular Control (NMC)

During the next section, the various components of NMC will be defined, and the specific function of each component will be briefly discussed, in the context of running and its related injuries. A short synopsis of what is known regarding NMC and injuries will then be presented. As much of what is currently known regarding healthy NMC is inferred from specific injuries or proprioceptive deficits, movement consequences occurring as a result of injury or poor NMC will also be highlighted. The theory behind various attenuation methods of abnormal control will next be conferred. While emphasis will be placed on factors surrounding the somatosensory system, biomechanical consequences of altered NMC will also be explored.

1. Defining Neuromuscular Control

Neuromuscular control is the interaction between the nervous and musculoskeletal systems to produce a desired effect or response to a stimulus (Enoka, 2008). Thus it involves the efferent motor response to sensory information, and is responsible for multi-joint movement and postural control (PC). As early as the 1950's certain neurologists noted that it is impossible to separate the sensory and motor systems in the control of human movement, and that changes within one section of the system are reflected by adaptations elsewhere in the system (Page, 2006; Jull & Janda, 1987). It is from this observation that the term *sensorimotor system* was derived, which essentially combines the two systems into one. Sensorimotor training, and methods used to improve NMC typically result in an improvement in coordinated motor strategies, ultimately reducing injury risks, by way of protecting joints from excessive strain and providing prophylactic mechanism(s) to recurrent injury (Smith *et al.,* 2012; Zech *et al.,* 2010; McKeon *et al.,* 2008).

There are four critical elements involved in optimal NMC, namely i) pre-active and reactive control, ii) conscious and unconscious motor control, iii) joint position sense (JPS) and iv) dynamic stability. Dynamic stability is only achieved when pre-active and reactive motor control is present, at both conscious and unconscious control levels, with adequate JPS in all situations. These elements are inter-relating and complimentary in the function of NMC, and will form part of the discussion to follow on the next section.

2. Overview of Control Systems

Information received from the somatosensory system is integrated, processed and interpreted at several levels within the CNS and are considered to be the foundation of effective NMC. Mechanoreceptors relay afferent information upward toward the cortex and cerebellum via the dorsal column and spinothalamic tracts, respectively. In a matter of milliseconds, unnecessary information is "gated out" by interneurons and thalamus. Hereafter, the message is processed spatially, similar experiences are assembled from memory using associate areas of the brain, contributory visual and vestibular input is incorporated, and a motor response is sent out (Riemann & Lephart, 2002) (Figure 2.1).

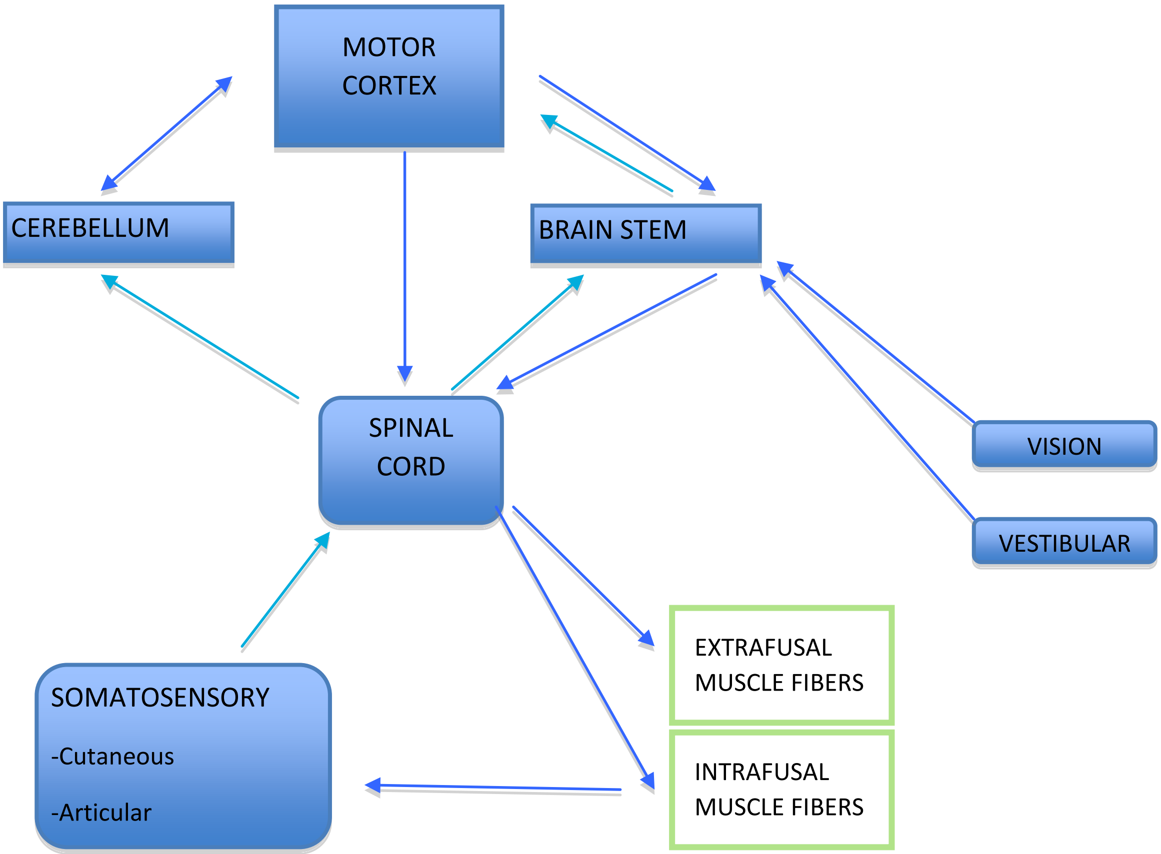


Figure 2.1. Summary of the various components involved in NMC, as well as afferent and efferent pathways found within the sensorimotor system.

3. Motor Control Mechanisms

In general, there are two motor control mechanisms involved in the interpretation of afferent information, and in the coordination of efferent response. These control mechanisms, namely reactive and pre-active, relate more specifically to the direction of control. The two control mechanisms are illustrated in Figure 2. 2. The closed-loop system (reactive control) provides feedback through a reflex arc initiated from the mechanoreceptors in the ankle joint, against a reference of correctness, determination of error and subsequent correction (Pruzinsky, 2011). This mechanism is put into action, after a stimuli activates a response. The feedback mechanism attempts to correct muscle activation patterns throughout the movement process, and has been extensively studied in regards to activation of evertor muscles in response to inversion moments (Hertel, 2008). However, this method requires a great deal of time in order for a stimulus to be processed and to yield a response. Typically, this method is mainly used when learning a new skill, and is more effective for slower, continuous movements. Brooke and Zehr (2006) proposed that certain limits exist in fast-conducting somatosensory control, and that dynamic modification of feedback inflow requires an increased reliance on internal models for movement control.

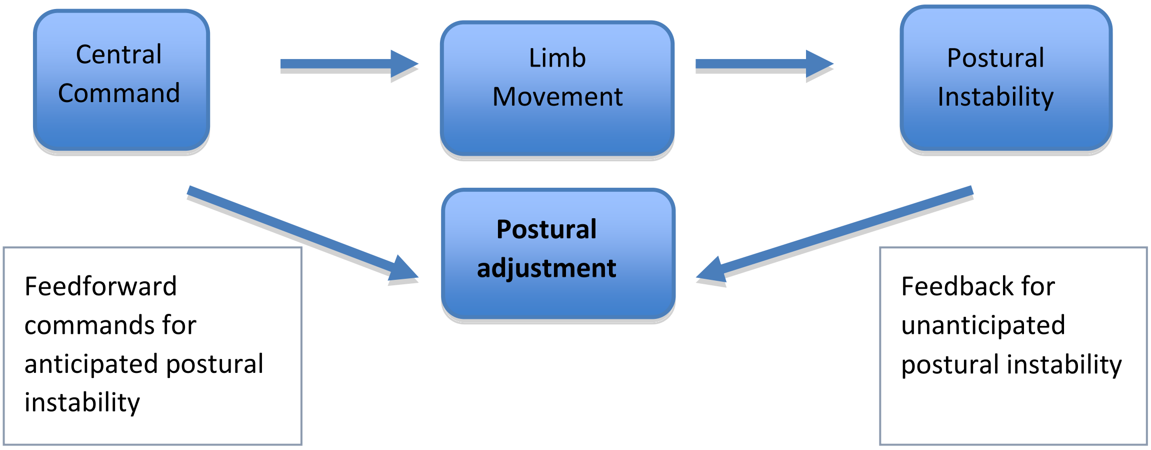


Figure 2.2. An illustration depicting the differences between open–loop and closed-loop feedback in movement control.

The second control mechanism is known as the open-loop system, or pre-active movement response. This control mechanism involves an anticipatory (i.e. before stimulus onset) generation of an action plan and subsequent muscle activation in preparation of the upcoming stimulus (Tsao & Hodges, 2007). Pre-activation responses typically occur in muscles involved in PC, whereby they activate prior to the extremities to ensure a stable base for locomotion (Tsao & Hodges, 2007). Pre-active movement responses are also especially important in the ankle, as musculature surrounding the joint must be active at landing, to control dynamic stability (Nakazawa *et al.,* 2004; DeMont & Lephart, 2004). The CNS can, in anticipation of the movements and joint loads, exploit the spring-like qualities of a muscle through pre-activation, providing quick compensation for external loads by increasing the stiffness properties of the entire muscle unit (Lohman *et al.,* 2011; Lieberman *et al.,* 2010) (Please refer to the section *Improvements in Leg Stiffness* page 32). Pre-activation also readies the system for upcoming closed-loop feedback.

In conclusion, these two mechanisms act to bring about control in very different ways; they are both essential to the neuromuscular system and function complimentarily to bring about pre-active and reactive muscle characteristics, respectively.

4. Levels of Motor Control

While there are two main directions of motor control, three levels of motor control also exist. As these responses are mediated by different areas in the brain, a single stimulus can elicit different responsive movement patterns, namely spinal reflexes, automatic responses (brainstem activity) and voluntary movement (cognitive programming) (Enoka, 2008; Riemann & Lephart, 2002, Willems *et al.,* 2002). Each type of movement is responsible for a specific aspect of NMC. The activation of motor neurons may occur in direct response to peripheral sensory input (reflexes) or from descending motor commands, both which may be modulated or regulated by associate areas.

i. Spinal Reflexes

As a load is placed on joint mechanoreceptors, spinal reflexes are activated causing stabilizing muscular contractions (Nakazawa *et al.,* 2004; Duysens, 2000; Lephart *et al.,* 1997). Myostatic or monosynaptic reflexes take 30 to 50 ms, while functional stretch reflexes take 50 to 80 ms and trigger reactions take 80 to 120 ms. Reflex pathways help in sustaining continuous (closed-loop) activation patterns during locomotion, aid in responding rapidly to disturbances in gait, and assist in PC. For example, pre-synaptic inhibition modulates the H-reflex, particularly during the latter part of the stance phase (Kao *et al.,* 2010; Schneider *et al*., 2000). This inhibitory method may seem contradictory, when trying either to sustain activation patterns or respond to perturbations, however, excessive feedback could result in instability caused by over-excitement of the segmental stretch reflex (Krauss & Misiaszek, 2007). Hence, reflexes allow for subconscious control of static and dynamic balance (Nurse & Nigg, 2001).

The foot is the only point of direct contact between the body and external environment when standing. The sensory feedback originating from cutaneous receptors in the foot can result in swift reflex response mechanisms, which has a role in upholding the gait cycle (Nurse & Nigg, 2001). Therefore, reduced sensation from the plantar surface of the foot may contribute to gait abnormalities.

Van Wezel and colleagues (2000) investigated whether reflexes during gait is altered in patients with clinically established sensory polyneuropathy with predominant loss of large myelinated, low-threshold Aß sensory fibers. By applying non-nociceptive stimulation to the sural nerve in the leg during early and late swing phases, it was observed that reflexes at a latency of ~80 ms in the bicep femoris and tibialis anterior, were significantly smaller in patients with sensory polyneuropathy. Van Wezel and partners (2000) concluded that during walking the low-threshold cutaneous mechanoreceptors provide information about phase transitions and/or ground surface irregularities. In addition, these reflexes could participate in corrective responses.

Polysynaptic reflexes can modify motor output within 70 to 110 ms, and are also reversible at various points in the step cycle. These reflexes are used to respond to unexpected perturbations or obstacles in locomotion. For example, stimulation of the superficial peroneal nerve that activated cutaneous afferents depressed EMG activity in the tibialis anterior during the swing phase, whereas stimulation of the tibial nerve increased the EMG activity of the biceps femoris and vastus lateralis muscles during the swing phase (Zehr *et al.,* 1997). Similarly, stimulation of the sural nerve increases electromyographic (EMG) activity in the tibialis anterior early swing phase and decreases it later in the swing phase (Van Wezel *et al*., 1997). These findings demonstrate that cutaneous reflexes can certainly alter muscle activation patterns, but that response varies greatly according the gait cycle phase and the type or location of the cutaneous receptor. Information from these cutaneous receptors may also be passed on to higher cognitive centres, where it is used for planning of subsequent steps (Van Wezel *et al.,* 2000), thereby readying the system via a feed-forward mechanism.

ii. Automated Movements

Automated responses occur relatively fast subconsciously, but are more complex than reflex responses. The highest level of CNS function is evoked in cognitive programming, whereby motor plans are stored in the brainstem and repeated as central commands, or more specifically central pattern generators (McKay-Lyons, 2002). This allows movement tasks to be executed with complete spatial awareness of the joint or limb in motion, without constant reference to consciousness (Nurse & Nigg, 2001; Lephart, 1997).

Ivaneko and colleagues (2006) conducted an experiment whereby a factor analysis of EMG recordings from 32 muscles on the same side of the body during walking indicated that central commands are stored in the brain as five specific events: weight acceptance, propulsion, trunk stabilization during double support, lift-off and touchdown. With that being said, a large proportion of NMC occurs at subconscious level.

iii. Voluntary Movement

Voluntary reaction time usually takes between 120 and 180 ms, due to the extensive integration of proprioceptive information by higher cognitive areas. The higher cognitive areas are "saved" for learning new tasks, switching between multiple tasks, and improving current stored motor plans (Lawrence *et al.,* 2011; Kiesel *et al.,* 2010). Therefore, while voluntary movement requires more time to perform, more accurate and complex movement tasks are possible at this level.

5. The Somatosensory System

The CNS relies on sensory input from mechanoreceptors in the lower extremities, as well as the visual and vestibular centres, to generate effective motor patterns and stable joints during locomotion (Nurse & Nigg, 2001; Fitzpatrick & McCloskey, 1994). The functions of the somatosensory system include JPS (proprioception) and joint motion sense (JMS) (kinaesthesia) (Swanik *et al.,* 2004). Kinaesthesia refers to the threshold value of passive motion required to detect motion in a joint. Joint position sense on the other hand, refers to the accuracy of passive and active joint reproduction. By detecting internal cues from joint and muscle mechanoreceptors, as well as external cues from cutaneous mechanoreceptors, the somatosensory system is responsible for relaying sufficient information to the CNS. This proprioceptive information is required to bring about a sense spatial and body awareness (i.e. JPS) (Wingert *et al.,* 2009). Accurate JPS is also essential during both pre-active and reactive control of movement.

Static proprioception is usually defined as position sense, which refers to the conscious perception of the orientation of different parts of the body with respect to each other. Dynamic proprioception is defined as kinaesthesia, and the sense of rates of movements, both segmentally (joint stability) and in regards to postural equilibrium (Xian Li *et al.,* 2009; Jerosch & Prymka, 1996). There are several types and location of mechanoreceptors, each with a specific function. Individual mechanoreceptors will be briefly discussed below.

i. Muscle Spindles

The spindle receptor is located within the muscle and sends afferent information to the CNS regarding muscle length. An unexpected increase in muscle length activates a stretch reflex, causing excitation of homonymous motorneurons, which can contribute to maintenance of the gait cycle during running (Rosales & Dressler, 2010). Muscle spindles are also efferently innervated by gamma motor neurons, whereby the CNS can control the sensitivity of the muscle spindle over large changes of muscle length (Needle *et al.,* 2013; Rosalles & Dressler, 2010).

ii. Golgi Tendon Organs

The tendon organ is much simpler, and is located at the junction of the muscle and tendon. When a muscle and its connective tissues are stretched, either through passive pulling or muscle contraction, the strands of collagen pinch together, exciting the afferent neuron and producing an inhibitory postsynaptic potential in homonymous motor neurons as well as an excitatory postsynaptic potential in antagonistic motor neurons (Mugge *et al.,* 2013; Kistemaker *et al.,* 2013).

iii. Joint Receptors

In contrast to muscle spindles and tendon-organs, joint receptors are not well-defined entities. It is believed that activation of joint mechanoreceptors is triggered by the deformation and loading of the soft tissues that compose the joint (Macefield, 2005; Lephart, 1997). Ruffini endings are typically categorized as static or dynamic mechanoreceptors, capable of signaling joint position and displacement, angular velocity, and intra-articular pressure (Flemming & Luo, 2013). Pacinian corpuscles have a lower threshold to mechanical stress and detect acceleration of the joint (Macefield, 2005). Golgi tendons monitor tension in ligaments, especially at the ends of range of motion. Free nerve endings are widely distributed and constitute the joint nociceptive system, which is activated when the joint is subjected to abnormal stress or to chemical agents (Flemming & Luo, 2013).

The significance of joint receptors for the control of movement has been convincingly demonstrated by the effect of joint pathology on muscle activation. For example, knee osteoarthritis can induce arthrogenous muscle inhibition and muscle weakness in the quadriceps (Li *et al.,* 2000).

Mechanoreceptors demonstrate adaptive properties depending on a particular stimulus types, indicating that they have even more diverse functions in a dynamic sense. The properties of the quick-adapting mechanoreceptors lead to the notion that they mediate the sensation of joint motion because they are very sensitive to changes in position. Muscular mechanoreceptors and Ruffini ending joint receptors are slow-adapting mechanoreceptors and are thought to mediate the sensation of joint position and changes in position because they are maximally stimulated at a specific joint angle (Lephart *et al.,* 1997).

iv. Cutaneous Mechanoreceptors

Five different cutaneous receptors provide information regarding external events and are sensitive to pressure, stretch, temperature, and pain and contribute to proprioception significantly (Bunnett *et al.,* 2006). The five types of cutaneous receptors are Merkel discs, Meissner corpuscles, Ruffini endings, Pacinian corpuscles and free nerve endings (Brooke & Zehr, 2006).

Research has shown that PC and stability is significantly affected by proprioception in the lower extremities (Xian *et al.,* 2009). Further, enhanced proprioceptive ability is directly related to better foot placement and fewer errors, leading to a decrease in lateral ankle sprain occurrence (Jenkins & Cauthon, 2011). It has been suggested that muscle, skin and joint mechanoreceptors are complementary in providing a constant source of information regarding loading, joint kinematics, and pressure distribution on the plantar surface of the foot (Nurse & Nigg, 2001; Lephart *et al.,* 1997). It therefore needs to be emphasized that, in order for the body to maintain its centre of gravity (COG) over the base of support (BOS), a combination of afferent inputs are required (Dietz & Duysens, 2000).

6. Functions of Neuromuscular Control

The neuromuscular system is mainly responsible for coordination and smooth execution of movement. Firstly, joint stability is attained by means of feedforward co-activation and pre-activation of muscles, which produce dynamic restraint within a given range of motion. Joint stability is critical not only for segmental control of dynamic movements, but also for postural equilibrium. Static PC can be described as the process by which the COG is kept vertically above and within the limits of the BOS (Hosseini *et al.,* 2012; Paillard*,* 2011). When NMC is not optimal, as in the case of deficient proprioceptive, visual or vestibular input, postural sway will be amplified (Pendergrass *et al.,* 2003). Postural sway can be thought of as a constant fine-tuning process, as equilibrium is lost, adjustments and counter-adjustments need to be made continuously (Pendegrass *et al.,* 2003). Dynamic postural control can be defined as the ability to execute a movement task, on different types of surfaces, with minimal superfluous movements (Hrysomallis, 2011).

Numerous studies have reported that static balance improves with PC training (Pluchino *et al.,* 2012). It is also speculated that dynamic proprioceptive training may improve NMC and PC in athletic situations (Zech *et al.,* 2010), which could in turn prevent injuries (Emery *et al.,* 2005). Emery and colleagues (2005) further continued to prove that a 6-week home-based balance training program, using wobble boards is effective in improving static and dynamic balance, and in reducing the incidence of self reported injury rates (number of injuries per 100 adolescents) between intervention 3 (95% CI 0 to 12) and control 17 (95% CI 8 to 29) groups. Similarly, McKeon and colleagues (2008) studied the effect of a 4-week progressive balance-training program that emphasized dynamic stabilization, on static and dynamic PC and self reported functional outcomes in patients with chronic ankle instability (CAI). A significant improvement in self reported function, static and dynamic PC was observed, when compared to the control group. The authors concluded that balance training might significantly enhance the ability of the sensorimotor system to overcome the sensorimotor constraints related to CAI.

O'Driscoll and colleaugues (2011) made use of a 6-week dynamic neuromuscular training program which incorporated postural stability, strengthening, plyometric and speed/agility drills. Improved parameters of ankle joint sensorimotor control were found, including reduced ankle plantar-flexion at landing, indicating that the ankle is at a less vulnerable position. Although the study was limited to a single case study report, findings showed significant practical value, especially in regards to NMC in dynamic situations.

However, when looking at the motor control strategies used to maintain static balance, interesting findings were also made. To illustrate the different movement strategies employed when maintaining static balance, researchers make use of two models. Model one is referred to as the ankle strategy, which explains whole body postural sway using movement around the ankle joint only. The body is represented as an inverted pendulum, with anterior and posterior body movements occurring as the ankle dorsiflexes and plantar-flexes, respectively. Model two (the hip strategy) expresses whole body movements by considering hip, ankle, knee and lumbosacral joint movements. The ankle strategy is utilized more often, in response to smaller perturbations, whereas the hip movement strategy is recruited when perturbations are larger and movements around the ankle are deemed not to be sufficient (Clifford & Holder-Powell, 2010).

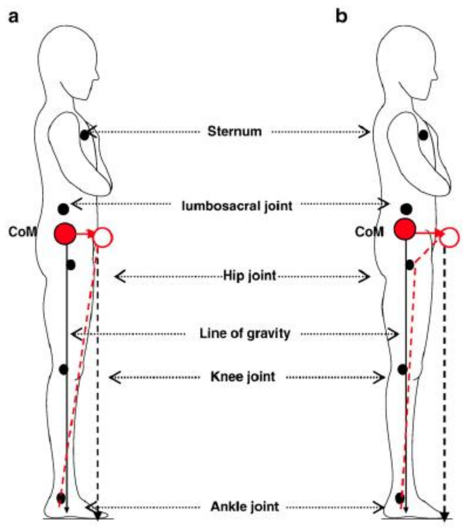


Figure. 2.3. Illustration of a) the ankle balancing strategy, b) the hip movement strategy. Image from Clifford and Holder-Powell (2010).

While Clifford and Holder-Powell (2010) found no significant differences in athletic single leg sway index scores, between dominant and non-dominant legs of healthy active individuals, analysis of joint angle data within the entire lower extremity confirmed that the non-dominant leg preferentially utilized the ankle strategy, and the dominant leg prefers the hip movement strategy. This proves that the neuromuscular system is adaptable, and may at times choose to use different motor control strategies for the same task. Further, 95% of the participants in the study was right-footed, suggesting that most humans use their right foot (dominant) for mobilization purposes, and the left foot (non-dominant) for postural stabilization activities. If central commands, which are learnt and stored earlier in life, are capable of affecting simple tasks so profoundly, one can possibly also question the effect that these commands have on more comlex, dynamics tasks such as running?

7. Neuromuscular Control and Injuries

Injury can result in de-afferentation and incomplete sensorimotor information to the CNS, which inhibits neuromuscular feedback. The additive effect of reduced NMC and mechanical instability can significantly increase the risk of re-injury. Proprioception is therefore a form of injury prophylaxis, and is essential in avoiding extreme joint movements in all planes (Gribble *et al.,* 2012; Caulfield *et al.,* 2012; Jerosch & Prymka, 1996).

The ability to detect change of position in the foot and make adjustments in response to movement is thought to be crucial in the prevention of ankle injury. Willems and partners (2002) found significant differences in the exact error of active joint positions testing, in patients with CAI. Willems and colleagues (2002) further postulated that the ability to detect the position of the foot before contact is important, and that improper positioning may be due to the loss of proprioceptive input from the mechanoreceptors.

Robbins and Waked (1997) suggested that the underlying cause of ankle sprains is a reduction in foot position sense and impaired proprioception, that results in the inability to respond to actual loading events within the given time period due to inadequate use of anticipatory muscular activation under dynamic conditions. Not only does de-afferentation result in reduced feedback quality, kinaesthesia and JPS, but spinal reflexes are also weakened. This could cause progressive degeneration of joints due to excessive or inappropriate loading, which in turn contributes to a further decline in joint dynamics, balance and coordination (Xian *et al.,* 2009; Ergen & Ulkar, 2008; Lephart, 1997).

However, some researchers believe that improvements in proprioception do not necessarily result in reduced injury. It is argued that, in some instances, the inversion force occurs in such a small interval of time, that it is impossible to produce an effective muscular response, either with or without prior proprioceptive training. It is known that ground reaction forces can reach its peak magnitude within 50 ms, and that ankle inversion can reach 17 degrees within 40 ms. There simply is not enough time even for spinal reflexes to execute an adequate motor response to prevent injury. Although certain myotiatic reflexes can react within 30 to 50 ms, these reflexes cannot produce enough force to combat the inversion moment (Ashton-Miller *et al*., 2001; Konradsen *et al.,* 1997).

It could then possibly be argued that pre-activation is all the more important, especially for the prevention of injuries for which reflex responses will not be sufficient.

8. The Effect of Long Distance Running on Neuromuscular Control

Overall PC is used to determine efficiency of NMC in runners. Excessively increased postural sway is indicative of deficient neuromuscular integration or insufficient afferent information from a component. Changes in NMC can be caused by numerous factors including fatigue, tightness or weakness of specific muscles, partial or complete de-afferentation of nerve signals due to injury, temperature or incorrect motor learning. Each factor will be discussed briefly in this section.

On the whole, fatigue can cause profound increases in postural sway, which likely add to the already high injury risk and incidence previously noted in runners (Pendegrass *et al.,* 2003). Subsequent to long distance running, clinicians have recorded several ankle sprains and miss-step injuries occurring throughout training. It would thus be important to determine both the effect of long distance running on NMC (as measured by postural sway), as well as the effect that improvements in PC has on injuries in long distance runners.

Firstly, running increases energy demands, metabolism, and the rate of breathing (hyperventilation). As the rate of breathing increases a decline in blood CO_2 levels occur along with a lowered pH level, which promotes a change in vascular tone and ultimately leads to altered PC mechanisms (Palliard *et al.*, 2012; Sakellari *et al.,* 1997). Hyperventilation results in a significant increase in the excitability of peripheral nerve fibers but not the vestibulo-spinal function, suggesting that the mechanism affecting PC is outside the vestibular instrumentation (Sakellari *et al.,* 1997). In addition, proprioceptive receptors may send modified input information during periods of hyperventilation (Sakellari *et al.,* 1997). For example, lower back proprioceptive information becomes remarkably less precise when inspiratory muscles are fatigued (Palliard *et al.,* 2012; Janssens *et al*., 2010).

In order to meet with the metabolic demands of an aerobic or anaerobic exercise, cardiac and muscular contraction throughout the body increases abruptly, which has been shown to result in increased postural sway (Palliard *et al.,* 2012; Fox *et al.*, 2008; Yaggie & Armstrong, 2004). A distance as short as 3.2 km can significantly affect PC (Pendergrass *et al.*, 2003). Interestingly, Nardone and partners (1997) observed that PC deteriorates following a walk/run above the lactate accumulation threshold, however, exercising at lower than 60% heart rate max has no effect on postural sway (Mello *et al.,* 2010). Similarly, Zemkova and colleagues (2005) found more extensive deterioration to postural sway following shorter, high intensity exercise, when compared to lower intensity training. However, recovery time for high intensity exercise was significantly shorter than for longer, low-intensity exercise.

Fatigue-induced impairments in NMC may adversely alter joint proprioception (Ribiero *et al.,* 2008) and are believed to be a potential cause for increased injury rates (Hassanlouei *et al.,* 2012). Hassanlouei and partners (2012) found that muscle fatigue in the knee resulted in a reduction in amplitude and a delay in the activation of both the quadriceps and hamstring muscles in response to rapid destabilizing perturbations, potentially reducing stability around the knee. Caron (2003) induced a fatiguing protocol on the soleus muscle, where after the effect of COG and centre of pressure (COP) was investigated. Results indicated that fatigue of the soleus muscle causes increases in COP velocity and some change in COP amplitude. However, postural stability was not altered (as measured by COG), whereby the author suggested that a modification of PC is not always systematically followed by a change in postural stability.

In a similar study, COP excursion was significantly increased in the fatigued condition, especially in the anterior posterior (A/P) plane, when compared to the non-fatigued condition both on a foam surface and on a firm surface (Gimmon *et al.,* 2011). These authors hypothesized that lower limb muscle fatigue may impair the proprioceptive and kinaesthetic properties of joints by increasing the threshold of muscle spindle discharge, disrupting afferent feedback, and subsequently conscious joint awareness (Gribble & Hertel, 2004; Gribble *et al.,* 2004). Generally the CNS would discard unreliable proprioceptive information by increasing reliance on visual information or haptic cues from the fingers (Derave *et al.,* 2002; Lackner *et al.,* 2000; Ivanecko *et al.,* 2000; Ivanecko *et al.,* 1999).

However, Gimmon and partners (2011) removed visual feedback with closing eyes, forcing the subjects to rely on possibly distorted proprioceptive information from the ankles. As an adaptive mechanism, increased co-activation between antagonistic muscles were increased, which have been shown to correlate with increased postural sway (or COP excursion) (Laughton *et al.,* 2003). Greater co-activation may assist in enhancing joint proprioception by increasing the firing rate and recruitment of primary afferents, thereby enhancing the functional behaviour of the associated closed-loop PC mechanism (Gimmon *et al.,* 2011).

Similarly Roerdink and colleagues (2011) found increases in postural sway (and COP excursion) with plantar flexor fatigue. However, these authors proposed that while there is an increase in attentional demand functioning to closely monitor and control posture, as well as a decrease in automized movement, the CNS effectively adapts to the reductions in proprioceptive feedback by increasing the regularity of postural sway, in order to amplify information possibly extracted from the vestibular system.

As mentioned above, according to the hypothesis of sensory re-weighting theory, when a specific type of proprioceptive input is reduced, the PC system can adaptively reweight the relative contribution of particular posture specific modalities, depending on the availability and reliability of the various sensory inputs, so as not to affect overall NMC or PC (Nashner *et al.,* 1982). For example, visual input can be increased when proprioceptive contributions are altered, ultimately avoiding miscalculations in daily tasks and movements (Palliard, 2012; Derave *et al.,* 2002; Nardone *et al.,* 1997). Unfortunately, visual input during running is usually already maximally utilized, due to constant stimulation by a fast moving field of vision. Additionally, the visual input often contradicts proprioceptive information by suggesting a movement in opposition to the perceived direction of movement. Consequently, the utilization of visual input for compensatory mechanisms is not ideal in the running situation, and mechanisms that optimize other available proprioceptive information are more desirable.

Endurance training is also known to result in neuromuscular adaptations that alter the production or clearance of metabolic substrates, which results in reflex inhibition of the motor neuron pool (Ergen & Ulkar, 2008). These afferents are known to decrease extensor α-motorneurons, but increase flexor α-motorneurons (Martin *et al.,* 2006; Garland & Kaufman, 1995). Other afferents exert indirect actions on α-motorneurons via the γ-loop, affecting facilitation from muscle spindle afferents, and thus the efficiency of the myotatic loop during postural regulation (Ament & Verkerke, 2009).

Further, eccentric muscle contractions produce more muscle damage and soreness than concentric contractions (Vissing *et al.,* 2008). Muscle damage deteriorates proprioception and particularly disturbs sense of force production and limb position (Paschialis *et al.,* 2007). Therefore, logically, movements involving high usage of eccentric contractions would produce a greater decline in proprioception and PC, when compared to concentric exercise. For example, running would produce greater proprioceptive deficits than walking, and downhill running would produce greater proprioceptive deficits than uphill running. Torres and colleagues (2010) found that JPS and force sense was significantly reduced following unaccustomed eccentric exercise. The authors suggested that muscle damage alters proprioception, which might be due to the impairment of muscle spindles and tendon organs (Torres *et al.,* 2010). Similarly, Villa Cha and partners (2011) found impaired proprioception up to 24 hours following unaccustomed eccentric exercise. These impairments in proprioceptive ability are detrimental to movement regulation and may lead to an increased risk of injury.

Dynamic NMC also differs notably between genders. Chumanov and partners (2008) included EMG along with a biomechanical analysis to compare gender differences during running at different speeds and inclines. Women demonstrated a greater hip-width to femoral length ratio, resulting in greater lateral pelvic tilt excursion, peak hip internal rotation, and adduction excursion throughout all running speeds and inclines. Chumanov and partners (2008) also found that women demonstrated almost double gluteus maximus activity across the entire stride, while men responded more dramatically to increased inclines by increasing gluteus maximus activity. In contrast, although gluteus medius activity was similar during flat surface running, women responded better by increasing gluteus medius activity to a greater extent during increasing speeds. Greater vastus lateralis activity was recorded during the terminal swing phase and initial loading phase in women, for all speeds and inclines. These differences in muscle activity patterns suggest that women may utilize different NMC strategies, and differences may be amplified with increasing inclines or speeds. Therefore it is recommended that the NMC of men and women be analyzed separately.

In summary, long distance running affects most components of the neuromuscular system, resulting in increases in postural sway. However, several adaptation techniques have been described by which the neuromuscular system attempts to curb unwanted effects.

9. Methods to Enhance Neuromuscular Control

Following the background on the function of the NMC system, methods often used in rehabilitation which are believed to improve NMC, will now be investigated. As with the many components and levels of control found in the neuromuscular system, there are several modes of attenuation which may hold benefits.

The practice of certain sports can affect proprioceptive ability. Xian Li and colleagues (2013) examined whether proprioceptive abilities differed between regular practitioners of ice hockey, ballet and running. The authors found that the ice hockey and ballet groups had significantly better passive joint motion sense in the medial lateral (M/L) plane, when compared to runners and sedentary control individuals. Also, no significant difference was found between control and running groups, in any of the measurements. The authors concluded that the benefits of ice hockey and ballet dancing on proprioception might be associated with their movement characteristics (Xian Li *et al.,* 2013). Similarly, in a study comparing proprioceptive ability between those practicing Tai Chi, running and swimming, the Tai Chi group was shown to demonstrate better JPS and JMS (Chan *et al.,* 2004).

Furthermore, orthotics, bracing, taping, compression garments and surface variables can act as a filter, transforming the afferent input from the sensory receptors to the CNS, and thereby altering the motor output (Nurse & Nigg, 2001). Ankle bracing and orthotic support have been shown to reduce the incidence and severity of ankle injuries, in both retrospective and prospective studies (Terrier *et al.,* 2013; Kemler *et al.,* 2011; Zinder *et al.,* 2009). Researchers believe that bracing and taping reduces the risk of injury by one of three mechanisms, including decreased range of motion, improved mechanical stability, and/or enhanced proprioception (Zinder *et al.*, 2009).

Taping or bracing is thought to connect the skin around the foot with the plantar surface of the foot, effectively amplifying sensory cues from the plantar surface, resulting in fewer foot placement errors (Spanos *et al.,* 2008; Ergen & Ulkar, 2008; Robbins *et al.,* 1995). The effect of taping may be especially beneficial in the injured ankle, which lacks proprioceptive ability. By facilitating effective reflex activity in the peroneus longus stretch reflex, risk of re-injury while wearing a brace or tape might be reduced (Cordova & Ingersoll, 2003). Additionally, even though taping has been found to rapidly stretch during exercise, reducing its resistance and proprioceptive assistance, protection from extreme ranges of motion can still be provided (Manfroy *et al,* 1997). Zinder and colleagues (2009) further investigated the underlying neuromuscular factors influencing joint stiffness when various braces were worn. It was hypothesized that increased ankle stiffness has three basic causes, including increased pre-activation, increased reflex gain, or increases in general, passive mechanical stiffness (Zinder *et* *al.,* 2009). Their findings contradicted previous research showing that increases in ankle stiffness lacked a neuromuscular change as measured by surface EMG, suggesting that braces only passively contribute to the stability of the system.

Interestingly, in a study comparing proprioceptive ability between barefoot, control, and taped ankles, the taped group did show improved proprioceptive ability and JPS when compared to baseline levels, however, the taping group still had 58% less awareness than the barefoot group (Robbins *et al.,* 1995). This might suggest that being barefoot allows optimal proprioceptive information to be collected from cutaneous mechanoreceptors. Waddington and Adams (2003) reported similar findings when they found that elite barefoot soccer players were much better able to discriminate ankle inversion movement than were shod individuals. In this case, the researchers inserted textured insoles to the boots, in which case the position sense was restored to barefoot levels.

The effect of compression garments is believed to aid proprioceptive ability similarly to taping and bracing, by improving afferent sensory feedback. In a study by Pearce and colleagues (2009), compression garments were found to improve functional motor control following eccentric exercise. This either suggests that the compression garments reduced muscle damage and thereby improved proprioception or the added tactile and pressure provided by the garment increased somatosensory feedback.

Lastly, this section will now consider the effects of footwear on several parameters of NMC. It is believed that footwear can act as a mechanical barrier between the ground and cutaneous receptors, thereby effectively reducing afferent information and altering NMC at several levels (Hsu, 2012; Robbins *et al.,* 1995).

i. Footwear and Neuromuscular Control

Firstly, when investigating the effect of footwear on NMC in general, as evaluated by postural stability, a definite increase in postural sway can be noted when wearing shoes. Robbins and partners (1994) found that athletic footwear impairs stability in older men. Postural stability was inversely related to shoe midsole thickness, and softness. In 1997, Robbins and Waked expanded their investigations to general surface characteristics, and found that both stability and vertical impact was a negative function of surface stiffness. They concluded that soft, cushioned athletic footwear encourages changes in gait characteristics in an attempt to improve stability, and that these changes are responsible for increases in vertical impact.

Brenton-Rule and colleagues (2011) compared the differences in postural stability, between the barefoot condition and two types of footwear. The barefoot condition demonstrated significantly less A/P postural sway, compared to both shoe conditions. Brenton-Rule (2011) postulated that "increased postural sway in the A/P direction could have been accounted for by the effect of the footwear on the somatosensory system". However, this cross-sectional study design was administered on elderly individuals, making generalization to younger populations difficult. On the contrary, Witney and Wrisley (2004) found no significant differences in the Modified Clinical Test of Sensory Integration and Balance (mCTSIB) scores when administered on the Biodex Balance with or without shoes, and concluded that the mCTSIB test can be performed in either condition, with equal sensitivity and specificity.

When investigating the effects of shoe characteristics on dynamic stability, Menant and partners (2008) found M/L sway to be significantly increased both in shoes with elevated heels, and in shoes with a softer sole. It was hypothesized that shoes with higher collars might improve postural sway by increasing sensory input around the ankle. However, no significant improvements were noted in this condition. Similarly, using a drop landing protocol onto a force plate, Rose and colleagues (2011) found dynamic balance to be significantly better in bare feet, compared to both standard trainers and minimalist shoes. The authors further found no significant difference between minimalist shoes and trainers, and suggested that any type of footwear acts as a mask, effectively filtering sensory input and decreasing dynamic postural stability.

In addition, ankle position sense may be affected by footwear. Squadrone and Gallozzi (2011) compared the ability to estimate ankle position sense, between barefoot, minimalist and cushioned footwear, in both static and dynamic conditions. In the static condition, cushioned shoes resulted in significantly greater error ranges. Minimalist shoes demonstrated better ankle position sense in the dynamic condition, compared to both barefoot and cushioned shoes. The study design, however, was not longitudinal and adaptation over time was not considered.

When considering reflex activation patterns, Hosada and partners (1997) investigated the effect that various types of footwear have on an immobilized foot-ankle joint. Both a delayed reaction time and decreased strength of reaction was found in direct relation to height of heel and various types of footwear. In particular, so called "health sandals" (with sole stimulating nodules) were expected to improve reaction time by increasing sensory information sent to the cerebral cortex. In contrast to expectations, the shock-absorbent properties of the sandals increased reaction time.

In conclusion, the effect of shoes on the neuromuscular system is evident in the majority of the above studies. Similarly, when wearing the correct footwear, improvements in NMC can be expected.

E. RUNNING KINEMATICS

1. Introduction

Given the fact that the importance of efficient NMC and coordination is emphasized for any person wishing to participate in sport or physical activity, and that it is often a neglected component, many are turning to minimalist footwear in an attempt to improve NMC. Further, despite improvements in running technology and footwear design, coinciding reductions in RRI's have not been observed. It is for this reason that minimalist running has gained popularity with many claims of added benefits, including anecdotal claims of reduced injury occurrence. The promoting argument is that minimalist shoes may increase proprioceptive information from the cutaneous receptors of the feet, facilitating improvement within many facets of NMC, including JPS, muscular activation patterns, reflex mechanisms, and PC, which possibly leads to prevention of RRI's. Nevertheless, the subject regarding minimalist running generally elicits two opposing views:

Those advocating barefoot running claim that humans have adapted an advantageous gait as a result of barefoot stimulation, and the insertion of a cushioned heel can be unfavourable from an evolutionary perspective (Hsu *et al.,* 2013). Shoes decrease the perception of impact, which leads to overload injuries resulting from excessive actual impact forces (Vormittag *et al.,* 2009; Robbins & Gouw, 1991; Robbins & Hanna, 1987).

However, those against barefoot running claim that conventional footwear is helpful in cushioning high impact forces, especially those caused by faulty running techniques (Vormittag *et al.,* 2009). It is also thought to be an exercise fad that could be harmful to those not properly trained, and lacking in scientific evidence. Further, there may be an increased initial risk of injury due to extremely abrupt transitions often seen in enthusiastic beginners (Hsu *et al.,* 2012).

As both lines of reasoning present valid arguments, the following section will simply explore the differences noted between minimalist footwear and regular trainers in regards to running kinematics and gait characteristics. Key findings regarding the use of conventional cushioned footwear, and running in minimalist shoes will be assimilated, with attention being drawn to biomechanical differences as well. Issues regarding optimal transition and practice in minimalist shoes will be argued, with the use of anecdotal claims where scientific evidence is lacking. Observed risks and hazards will be mentioned briefly, followed by a systematic presentation of claimed benefits noted in scientific studies.

2. Definition of Minimalist Shoes

When looking at the physical and material characteristics of the minimalist shoe, several differences can be noted. Minimalist shoes typically provide less support to the foot arch, are flexible and have lighter, thinner soles (Vormittag *et al.,* 2009). Further, they offer considerably less confinement and restriction to the foot, allowing the foot to move freely and naturally (Bonacci *et al.,* 2013). Unlike conventional trainers that have a thick, cushioned heel, minimalist shoes have a thinner sole, with a dropped heel. Several manufacturers have developed minimalist shoes that aim to transfer some of the barefoot running advantages into the minimally shod condition. These barefoot characteristics include the shape of the bare foot compared to the shape of the shoe, the specific kinematics of barefoot and shod movements, and the feeling of barefoot movements (Nigg, 2009). Minimalist shoes are effective in producing at least one aspect of barefoot running while protecting the plantar aspect of the foot against traumatic injuries (Goble *et al.,* 2013).

In contrast, the invention of the cushioned shoe was designed to assist in the attenuation of shock. In an attempt to reduce injury rates, manufacturers of cushioned footwear have designed three types of running shoes, aimed at different arch types: motion control for low-arched feet, high cushioned for high arched feet and stability for normal arched feet. Unfortunately, regardless of these technological advances in shoe invention, limited data exists suggesting a decrease in overall injury rates (Rixe *et al.,* 2012).

3. Risks Associated With Minimalist Running

Minimalist shoes have both acted as an additional training tool for those trying to improve their running, and have provided many runners with a last resort in attempting to avoid further injury. However, these benefits are accompanied by several risks.

The most obvious risk factor for the barefoot runner might be hazardous or sharp surfaces that cause injury to the plantar aspect of the foot. Plantar puncture wounds are relatively common and are experienced by persons of all ages. Minimalist shoes are not only effective in protecting the plantar aspect of the foot, without added weight, but also allow runners to gain more traction than barefoot running (Squadrone & Gallozzi, 2009). Additionally, barefoot running may also be considered unsuitable in extreme temperatures or environments, due to the risk of exposure.

However, the greatest concern revolves around overloading of bone or intrinsic musculature, caused by overenthusiastic training, and/or lack of sufficient recovery time. When correct quantities of stress are applied to the musculoskeletal system, adaptation over time will result in strengthening and improved performance. On the contrary, excessive overload or inadequate recovery time will result in tissue weakening and increased risk of injury (Goble *et al.,* 2013; Hreljac, 2004). Initially, when converting either to minimalist shoes or a midfoot striking pattern, this concept of overloading is typified in runners, increasing the risk of injury.

Another large risk factor is the lack of a proper minimalist gait implementation program to transition from a rearfoot to forefoot strike pattern (Hsu, 2013). Therefore, these runners start training in their minimalist footwear, but maintain their rearfoot strike, subjecting their feet to excessive repetitive peak impact forces, increasing injury risks dramatically (Hsu, 2013; Robbins & Gouw, 1990)

Furthermore, diabetic patients and individuals with peripheral neuropathies should not participate in barefoot activities as sensory and motor deficits are often present, such as Posterior Tibial Tendon Dysfunction (PTTD), which may lead to altered gait, poor balance and shifted plantar pressure distribution (Jayasinghe *et al.,* 2007).

In conclusion, minimalist running poses threats of injury to those unaccustomed to the running style, or those uneducated about the dangers of hasty transitioning. Also, certain physical or environmental conditions may be viewed as contra-indications to minimalist running. Therefore it is essential that those wishing to experiment with minimalist running are made aware of the possible risk factors and educated about transitioning protocols.

4. The Effect of Minimalist Training on the Biomechanics of Running

Minimalist shoes are gaining increasingly popularity, since several anecdotal claims have been made in regards to improvements in running performance and fitness benefits. This section will provide a brief review regarding what is currently known, or debated in the literature. Several changes in gait characteristics can be noted when one transitions to minimalist shoes, which may, or may not provide improvements in running performance or injury incidence. Each characteristic change will be discussed below.

i. Strike Pattern and Improved Shock Attenuation

The most noticeable observation when running in minimalist shoes is that runners are more inclined to run with a midfoot strike (Lieberman *et al.*, 2010; Squadrone & Gallozzi, 2009). This is in contrast to the traditional rearfoot striking pattern usually seen in runners wearing traditional trainers. Many of the advantages of minimalist running recorded in the literature can be accounted for by the alterations made to the strike pattern (Jenkins & Cauthon, 2011). During rearfoot striking, the heel of the foot typically makes contact with the foot first. Conversely, the front third of the foot contacts the ground first during forefoot striking, whereas the whole foot contacts the ground simultaneously during midfoot striking (Lieberman *et al*., 2010). Contemporary distance runners who routinely make use of trainers predominantly use a heel-toe running style, as classified at the 10 km mark of a half marathon (Larson *et al.,* 2011). Larson and colleagues (2011) found that 88.9% of runners were classified as rearfoot strikers, 3. 4% as midfoot strikers and 1.8% as forefoot strikers.

Figure 2.4. Examples of A) forefoot striking pattern, B) midfoot striking pattern, C) rearfoot striking pattern (Photographs from Larson *et al.,* 2011).

Mullen and Toby (2013) noted that with increasing speeds, the barefoot condition allows earlier transition into the forefoot or midfoot strike pattern, whereas running in trainers does not encourage the running style to deviate from the rearfoot striking pattern. As ground reaction forces increase with increasing speeds, it is considered to be favourable to transition from a reafoot strike to a mid-or forefoot strike at greater speeds. The reasoning why runners convert to a more plantar-flexed landing position during minimalist running may be to decrease peak impact forces exerted on the heel pad (Bishop *et al.,* 2006). Further, by landing on the forefoot, the surface area of contact made with the ground is increased, which causes force to be distributed more evenly and effectively (Hanson *et al.,* 2010). This increase in surface area can also improve proprioceptive feedback from cutaneous receptors in the foot, and as mentioned previously, will result in better foot placement. The thick cushioning below the heel of a trainer may also promote a rearfoot striking pattern by orienting the ankle into approximately 5° less dorsiflexion, emphasizing heel drive while running (Lieberman *et al*., 2010).

Although the above findings are generally accepted in the literature, there are some exceptions. A biomechanical comparison between barefoot, minimalist and shod conditions bore somewhat different results in elite adult athletes. Apart from changes in stride length and frequency Bonacci and partners (2013) found very little differences in minimalist versus shod conditions. Interestingly, no difference in ankle angle at contact was noted between minimalist and regular trainers. This suggests that athletes already competing at a high level generally have well-established patterns of NMC, with well-developed and uniform running mechanics, which is not as easily altered by shoe type.

ii. Stride Length and Frequency

A second characteristic change is that, across running speeds, when compared to traditional running footwear, stride length decreases and stride frequency increases in the minimalist condition, due to the more plantar-flexed ankle at initial contact. Consequently, contact and flight time is significantly lower in the minimalist condition, resulting in a reduction in average stride time (Divert *et al.,* 2005a). Barefoot runners can spend up to 33% more time airborne, signifying a simultaneous reduction in contact time (Lohman *et al.,* 2011; Jenkins & Cauthon, 2011). The significance of this finding is that reductions in stride lengths have been associated with a decreased mechanical energy absorbed by the joints (Derrick *et al.,* 1998). Mercer and partners (2003) similarly found that shock attenuation is more closely correlated to stride length than to stride frequency. With the knee joint being most sensitive to changes in stride length, Derrick and colleagues (1998) postulated that with increasing stride length, the increased perpendicular distance from the line of action of the resultant ground reaction force to the knee joint centre was involved in the increased energy absorption. However, Heiderscheit and colleagues (2011) warned that as the stride length decreased, a corresponding increase in the number of steps is required for any given distance. Therefore, although there is a definite reduction in the loading rate for each individual step, the overall frequency of loading is increased by the number of steps over a set distance, resulting in a possible equal cumulative load.

Nevertheless, reductions in stride length have been effective in reducing the risk of tibial stress fractures, proving that reducing the magnitude of impact is more important that reducing the total number of impact cycles (Edwards *et al.,* 2009). Whether these benefits are carried over to other injuries remain uncertain.

iii. Knee and Ankle Kinematics

The initial pressure under the heel is higher in heel-striking trainers, and joint excursion will be less in the ankle throughout the gait cycle, whereas the minimalist condition will typically produce greater pressure under the toes, with larger joint excursion at the ankle (Squadrone & Gallozzi, 2009; Divert *et al.,* 2005; De Wit *et al.,* 2000[ab]).

Another observed difference is that excursion into dorsiflexion increases among barefoot runners as speed increases, whereas shod runners show a more dorsiflexed contact position, with decreasing excursion into dorsiflexion as speed increases (Bishop *et al.,* 2006). Bishop and colleagues (2006) observed the opposite in knee kinematics, where increased joint excursion was seen with increasing speed in the shod condition and decreasing joint excursion was noted in the barefoot condition. De Wit and partners (2000[a]) studied the biomechanical differences between barefoot and shod condition, during the stance phase specifically and found similar results. In the shod condition peak flexion in addition to overall knee flexion was increased, when compared to barefoot.

In short, this demonstrates that during minimalist running work at the ankle is increased, placing greater demand on the triceps surea, while work at the knee is decreased. Bonacci and partners (2013) calculated a 19 to 24% decrease in negative work done at the knee when running in minimalist shoes. Similarly, a 13 to 15% increase in peak power generation as well as a 16 to 19% increase in positive work done at the ankle was noted during minimalist running. Practically, this might explain the countless number of anecdotal reports of calf and Achilles discomfort during transition to minimalist running. Also the decrease in work done at the knee may have therapeutic benefits for runners with knee pain and injuries (Bonnaci *et al.,* 2013).

iv. Running Economy

Barefoot running (both over ground and on a treadmill) is significantly more economical than running with shoes. Hanson and colleagues (2010) found that running barefoot was 3. 8% more economical that running shod. Both heart rate and perceived rating of exertion were found to be scored lower during barefoot running. Improved NMC (as seen with changes in leg stiffness) and reduced shoe weight are considered to be contributing factors to this increase in running economy (Divert *et al.,* 2008).

v. Ground Reaction Forces

By modelling the foot as a simple L-shaped double pendulum, one can effectively describe two of the most important adjustments that affect the magnitude of impact forces when running. These adjustments include alterations in the initial point of contact, and changing of ankle stiffness (Lieberman *et al.*, 2010).

If, as in rearfoot striking, the point of initial contact is too close to the point below the centre of mass, little translational energy is converted into rotational energy and is lost in the impact. By landing on the forefoot, the lever arm is increased, and the ankle dorsiflexes under eccentric control of the calf muscles, effectively attenuating at least a portion of the impact energy. As the foot torques around the ankle, translational kinetic energy is changed into rotational energy (Lieberman *et al.,* 2010). By allowing some of the impact energy to be translated into rotational energy, effective impact is decreased.

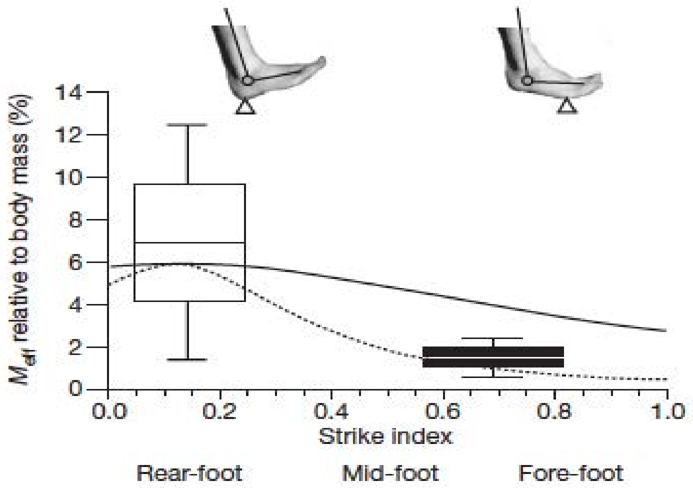


Figure 2.5. The relationship between foot strike pattern and effective mass decelerated at impact. The foot lever length also demonstrated the inverted pendulum model proposed by Lieberman and partners (2010) (Picture from Lieberman *et al.,* 2010).

When running with a rearfoot striking pattern, two impact peaks are observed. The first peak (2.2 BM), is termed as the impact peak, and occurs just after initial contact during the weight acceptance period. The second peak (2.8 BM), known as thrust peak, occurs at midstance. Having two impact peaks results in an “impact transient”. Impact transients are associated with rearfoot striking, and are sudden forces of high rates and magnitudes of loading. These forces travel rapidly up the body and thus may contribute to the high incidence of RRI’s, especially tibial stress fractures and plantar fasciitis (Lieberman *et al.,* 2010; Pohl & Davis, 2008; Wearing *et al.,* 2006). The impact peak in trainers typically occurs much later than in minimal running (33 vs. 11 ms) and is associated with the point of maximal knee flexion in the shod condition (De Wit *et al.,* 2000[b]). Not only does a midfoot strike pattern generate ground reaction forces approximately three times lower than rearfoot strikers (Lieberman *et al.*, 2010), but it may also be effective in eliminating the “impact transient”, possibly reducing knee joint loads and injuries (Goss & Gross, 2012). However, as previously mentioned increased mechanical work demand is placed on the plantar-flexors during a midfoot strike, resulting in a possible increase in injury at or around the ankle (Goss & Gross, 2012).

Following the benefits discussed by the change from rearfoot strike to midfoot strike, the question can be raised whether it is the type of footstrike or the type of footwear that produces the greatest improvement in shock absorption and impact forces. Giandolini and partners

(2013) found improvements in impact reduction when using dropped-heel running shoes as an intervention method, compared to a gait retraining intervention method aimed at altering the footstrike pattern to a midfoot strike that showed no improvement after 3 months. The authors stated that minimalist shoes are more effective in encouraging a midfoot strike, and that runners find it difficult to change to a midfoot strike in trainers, even with gait retaining. This, in turn, affects the ability to attenuate shock.

vi. Improvements in Leg Stiffness

Most of what is known currently regarding impact attenuation in barefoot running is as a result of external measures of force, using mainly force plates and biomechanical analyses. However, the internal NMC strategies used to absorb impact is not as clearly defined. Different muscle activation and coordination patterns are expected to occur, as the contact position changes during minimalist running (Lohman *et al.,* 2011).

In coming back to the inverted pendulum described by Lieberman and colleagues (2010), the second variable that is vital to efficient impact attenuation is ankle stiffness. By ensuring adequate muscle stiffness, optimal advantage can be taken from the spring-like qualities of lower extremity muscles, in which energy can be easily stored. By attaching strong, short muscles to elongated spring-like tendons, force production can be increased at a reduced metabolic cost (Lohman *et al.,* 2011).

Conceptually, the spring model is considered as follows: as the foot contacts the ground, the COM is lowered by a yielding joint motion around the ankle, knee and hip. Energy is absorbed by the musculoskeletal system, and the linear spring is compressed. Then, during the push off phase, energy is regenerated and the lower extremity is extended, while the spring recoils (Bishop *et al.,* 2006).

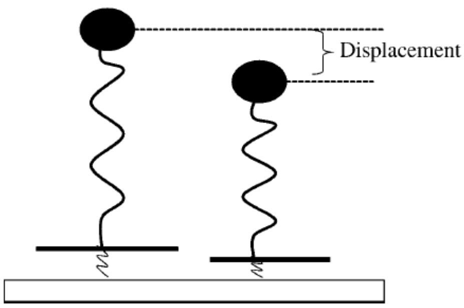


Figure 2.6. The conceptual model of the muscle spring system. As with bouncing or running, compression occurs after initial contact, into weight acceptance, with the centre of mass (COM) lowering to some extent (Image from Bishop *et al.,* 2006).

The muscle-tendon springs of the lower extremities are estimated to reduce the metabolic cost of running by approximately 50% (Lohman *et al.,* 2011; Alexander, 2005). It can be noted that propulsion during running is not primarily a function of concentric muscle contraction, but rather a combination of spring energy absorption and regeneration, followed by well-timed concentric contraction (Hamner *et al.,* 2010; Dickenson *et al.,* 2000). Additionally, Perl and colleagues (2010) claimed that unshod runners are better suited to utilize the elastic energy storage in the Achilles and arch of the feet, when compared to shod runners. The increased strength of the intrinsic musculature provides better support to the medial longitudinal foot arch. In time, these foot arches become higher and thus more pliable, allowing them to absorb shock more efficiently (Robbins & Hanna, 1987). However, Nigg (2009) did not find a correlation between peak impact force, which occurred at 30 to 50 ms, and maximal arch deformation generally occurring at 400 ms. One would then have to consider whether other factors are involved in the improvement of utilization of elastic energy noted in barefoot runners.

Nevertheless, when muscle spring stiffness is not ideal impact attenuation is deficient, possibly leading to increased injury rates. For example, it has been found that high-arched runners showed greater leg and knee stiffness than low-arched runners. When examining these runners' injury histories, it is agreed that runners with high stiffness levels are more prone to bony injuries like stress fractures, whereas runners with overly low stiffness levels present with a higher occurrence of soft-tissue injuries, especially on the medial side (Fiolowski *et al.,* 2005).

In an attempt more clearly define the role that lower extremity stiffness has on injury rates and shock attenuation, recent research has concentrated a great deal on soft tissue compartment vibrations in the lower extremities created from the initial contact point onwards, throughout the stance phase (Wakeling & Nigg, 2001[ab]). According to Wakeling and partners (2001), "muscle tuning" suggests that the body attempts to minimize soft tissue vibrations initiated at impact by inducing muscle activity prior to heel strike, which changes the mechanical properties of the lower extremity.

These modifications of NMC allow the vertical motion of the COM and therefore the ground reaction force to remain relatively constant over a wide range of surface stiffness' (Divert *et al.,* 2005[b]). As the COM lifts and lowers, energy is stored and released in muscles, tendons and ligaments (Fiolowski *et al.,* 2005). Vertical stiffness can be defined as the ratio of maximal vertical force (F_{max}) to maximal vertical displacement (Divert, 2005[b]). Logically, as the force (GRF) is increased, the stiffness within the system is required to increase, in order to minimize the vertical displacement of the COM.

Total system stiffness can be managed according to the following equation:

Total stiffness (K_{total}) is the inverse of the sum of the inverse leg stiffness ($1/K_{leg}$) and inverse surface stiffness ($1/K_{surface}$): $1/K_{total} = 1/K_{leg} + 1/K_{surface}$ (Bishop *et al.,* 2006).

Therefore, by altering leg stiffness the neuromuscular system can compensate for changes in surface stiffness, effectively keeping the total system stiffness within a desirable range. Theoretically, a harder shoe sole should increase ground reaction forces, as demonstrated by experimental mechanical models. However, actual ground reaction forces in runners remain stable regardless of shoe type, due to the fact that the CNS predicts the GRF input signal and adjusts muscle activity prior to moment of contact, accordingly. Muscle activation up to 50 ms prior to contact can effectively produce leg stiffness and thus minimize vibrations, as predicted from the anticipated impact. It is known that as speed increases impact forces increases, and likewise muscle activity also intensifies. Therefore the body dissipates vibrations through *a priori* CNS regulated pre-activation of muscles in order to maintain impact forces at a constant level or at the frequency of the next running stride (Lohman *et al.,* 2011)

Increased leg stiffness when running barefoot is demonstrated by higher EMG activity in the triceps surea during the pre-activation phase, when compared to running in regular trainers (Giandolini, 2013; Jenkins & Cauthon 2011; Divert *et al,* 2005[a]). No difference in peroneus or tibialis anterior pre-activation was demonstrated in the same study by Divert and partners (2005). However, the tibialis anterior was found to have lower amplitude pre-activation levels during barefoot running (prior to heelstrike), but to have earlier maximal EMG activity following heelstrike (25 ms barefoot vs. 60 ms shod) (Giandolini, 2013; Von Tscharner, 2003). Higher tibialis anterior pre-activation intensities when wearing shoes are thought to be due to the increased thickness and the mass of the shoe. Bishop and colleagues (2006) found significantly higher ankle stiffness levels in shod runners, when compared to barefoot runners, and there is a possibility that ankle stiffness is related to the higher pre-activation of the tibialis anterior.

The above findings are of importance as an overly stiff ankle during running in trainers, results in increased knee flexion at faster speeds, as mentioned in the section *Knee and Ankle Kinematics* (page 29). Running with excessive knee flexion angles forces the runner to attenuate more shock between the shank and head of the tibia, increasing the risk of tibial stress fractures (Edwards *et al.,* 2009; Milner *et al.,* 2006). Further, increased knee flexion causes the overall stiffness to decrease. “Stiff” runners spend less time in contact with the ground (Giandolini *et al.,* 2013; De Wit *et al.,* 2000[b]) and attenuate less shock (Daoud *et al.,* 2012).

Clinically, shoe prescription would be of importance as shoes could be utilized to manipulate lower extremity stiffness, and thereby avoid specific injury risks, which are implicated for either type of runner (high arched vs. low arched). In regards to leg stiffness, minimalist shoes may be helpful and could be utilized to decrease the lower extremity stiffness in runners with a history of stress fractures (Bishop *et al.,* 2006).

a. Plantar Feedback and Leg Stiffness

In lieu of what is known regarding feedback from cutaneous mechanoreceptors and reflex activity during locomotion (refer to *Levels of Motor Control, Spinal Reflexes,* page 11), some researchers have investigated the effect of cutaneous feedback on the stiffness of the lower extremity.

Fiolowski and colleagues (2005) found that when implementing a tibial nerve block, the overall stiffness of the lower extremity was significantly decreased, effectively increasing contact time. This indicates that feedback from the plantar aspect of the foot is important for regulating load behaviour, especially during dynamic activity. Dynamic coupling of the neural system with the mechanical properties of the leg and locomotor system are essential for efficient gait patterns. Since minimalist shoes have a harder, thinner sole, providing less obstruction between the plantar aspect of the foot and the ground, it could possibly be argued that regulation of leg stiffness will be optimal (Bishop *et al.,* 2006). This would ensure correct adjustment to surfaces (foot position sense) and improvements in running economy, by utilizing the muscle spring system more effectively (Perl *et al.,* 2012).

In conclusion, desirable levels of leg stiffness are a critical component of shock attenuation and injury prevention. Information from cutaneous mechanoreceptors may play a role in the regulation of leg stiffness and should thus be optimized, where possible. Minimalist shoes are thought to provide more accurate information to the CNS from the plantar aspect of the foot, aiding proper attenuation of leg stiffness by the neuromuscular system.

vii. Increased Muscle Strength

Minimalist training is believed to strengthen the whole muscular system, including larger muscles such as the biceps femoris and gastrocnemius, as well as smaller muscles such as the soleus and peroneus (Nigg, 2009). Therefore minimalist shoes have been used as an additional training tool in the past, as balanced development of all muscles crossing a joint is crucial for optimal performance and injury prevention (Nigg, 2009). Firstly, greater plantar-flexor force output is noted during forefoot striking, which places greater eccentric loads on the plantar-flexors during the initial part of stance. Because eccentric loads generate more muscle hypertrophy than concentric loads, it is reasonable to predict that runners who forefoot strike or midfoot strike will have stronger plantar-flexor muscles (Perl *et al.,* 2012).

In regards to the smaller musculature, it is believed that tight, motion-restricting footwear can reduce the use of plantar intrinsic foot musculature, leading to atrophy and weakness in the muscles over time (Jenkins & Cauthon, 2011; Robbins & Hanna, 1987). By preferentially using the smaller muscles, JPS can be detected with greater accuracy. These smaller muscles are closer to the axis of rotation, detecting changes in position faster. Smaller muscles therefore require less force to readjust the ankle joint, as a smaller modification is required. If larger muscles were to be used (for example the triceps surea), joint loading will increase, as the line of action is further away from the joint axis of rotation and therefore greater concentric force production will be required from these muscles (Nigg, 2009). Therefore, an improvement in NMC should conceptually be noted, as the ankle is able to respond to perturbations faster and with greater accuracy.

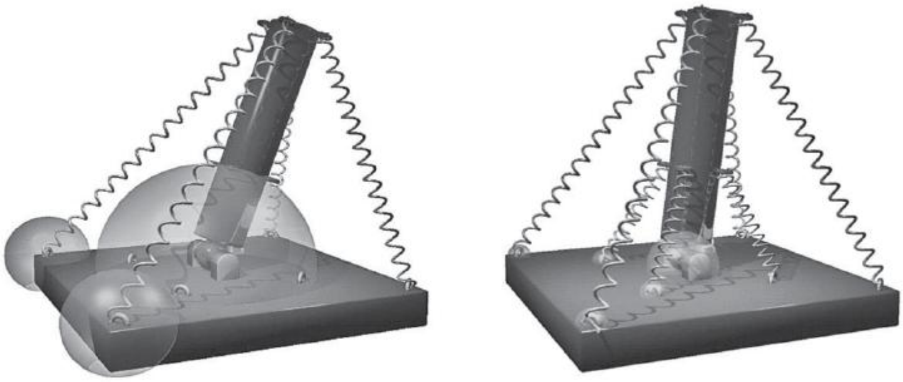


Figure 2.7. Effects of strong and weak small springs (muscles) on forces in the joint and in the attachment locations of the springs (insertion forces). The simulations were made assuming that the small springs react faster than the large springs (Taken from Nigg, 2009).

Ferber and Pohl (2011) found increased variability between the tibia, rearfoot and forefoot motion when the tibialis posterior was fatigued. Asynchronous joint coupling has been implicated in increased injury risk. The use of minimalist shoes may be beneficial in strengthening small muscles such as the tibialis posterior, possibly restoring well-coordinated running patterns.

Intrinsic foot musculature is also implicated in PC. Kelly and partners (2012) found that activation of the plantar intrinsic muscles increases with increasing postural demand. The authors suggested that these muscles are recruited in a highly coordinated manner to stabilize the foot and maintain balance in the M/L direction, particularly during single leg stance. Atrophied intrinsic musculature may therefore result in unstable ankles and poor PC, increasing the risk of injury. As mentioned before in the section *Functions of NMC* (page 15), Emery and colleagues (2005) provided evidence for the importance of training small muscles, by observing a noted decrease in sport-related injury occurrences in adolescents partaking in regular wobble board training. Similar to minimalist training, wobble board training improves the strength of the ankle intrinsic musculature (Nigg, 2009) and could thus possibly aid in the reduction of injuries over time.

viii. Joint Coupling Patterns

It has been suggested that a dynamic functional abnormality may be more important than a static misalignment in predisposing a runner to injury (Nigg, 1985). Ankle coordinative strategies are controlled by the CNS and are aimed at optimizing unconscious modifications of the subtalar joint to maximize gait efficiency (Kurz *et al.,* 2004).

When looking at the concept of gait variability, the hypothesis is that an increase in variability will be seen in barefoot runners, due to the fact that improved plantar feedback from cutaneous receptors will allow for fine unconscious modifications of foot position during each step, resulting in fewer foot position errors and improved efficiency (Kurz *et al.*, 2003; 2004). Kurz and partners (2003) found that barefoot runners demonstrated increased variability, suggesting that there is an increased ability of the foot mechanoreceptors to adjust the joint pattern and avoid repetitive impact forces.

Pohl and colleagues (2006) found that rearfoot motion was coupled to tibial internal rotation in barefoot runners; however, forefoot motion often occurred out of phase to rearfoot movement. This suggests that as the rearfoot begins to invert, the forefoot counters the movement and continues to abduct and dorsiflex, effectively collapsing the medial longitudinal arch (Pohl *et al.,* 2006; Hunt *et al.,* 2001). As discussed in the previous section *Increased Muscle Strength* (page 35), the flexibility and collapse of the longitudinal arch during the stance phase has been implicated in shock absorption. Whether there are differences in lower extremity coupling patterns between minimalist and shod runners, remains relatively uncertain.

Stacoff and colleagues (2000) did not find any differences in tibial-calcaneal movement patterns between the barefoot and shod condition, when using skeletal markers. However, only heel-toe running was used, and trails were not counted if participants deviated from this running style. Further, the number of participants was very limited.

In conclusion, several potential benefits have been discussed, relating to minimalist running. Several studies have investigated the underlying biomechanical mechanisms by which the changes observed with minimalist running brings about its advantages in shock absorption, ankle strength and running economy. While these possible benefits may be alluring to a runner wanting improve performance or to try something new, the transitioning into minimalist running has been somewhat cumbersome for some. The benefits of minimalist running may be outweighed by the risk of injury during transitioning.

E. Transition to Minimalist Running

Despite efforts of barefoot devotees, current evidence is insufficient to indicate that barefoot runners are faster, perform better, or are any less prone to rearfoot striking gait. The major podiatric societies agree that evidence is insufficient to support barefoot running and that health care providers or coaches should be prudent when recommending patients to experiment with barefoot or minimalist training (Goble *et al.,* 2013; APMA position statement, 2009).

Unfortunately, transition into minimalist shoes has proven to be a problematic topic, as there are currently no clinical guidelines helping patients to transition safely and effectively to minimalist running (Hsu, 2013). The general consensus is that clients seeking advice regarding transitioning from a rearfoot striking to a forefoot or midfoot striking style should be cautioned to progress slowly to avoid lower extremity soreness or injury (Lohman *et al.,* 2011). It is important that all runners should be considered individually; consider the case report of a forefoot striking runner with shin splints, who improved after the physical therapist changed the strike patterns to rearfoot contact (Lohman *et al.,* 2011; Cibulka *et al.,* 1994). While some runners may be injury free for extended periods, the vast majority will experience at least one injury a year that will restrict or suspend their training. For some of those runners, switching to barefoot technique may be the solution to pain and injury (Goble, 2013).

When advising patients about the risks and benefits of barefoot running, clinicians should reiterate the importance of choosing a soft surface and maintaining a slow introduction to barefoot running, similar to beginning a jogging program. The principle that the volume of exercise should be gradually increased over time is widely regarded as critical for reducing the risk of an overuse injury (Thompson *et al.,* 2003). Runners should be advised to follow the 10% rule – weekly increases in volume should not exceed 10% (Johnson *et al.,* 2003). This gradual introduction of the barefoot technique allows adequate time for adaptation by the osseous and soft-tissue structures of the foot.

Additionally runners should have a distinct reason for transitioning. Runners who train habitually in well-supported shoes, without any problems, and who don't have a specific reason for transitioning, should possibly be discouraged to put their usual trainers to rest (Goble, 2013). There are also certain exceptions, where runners might not be advised to transition to barefoot running:

As in the case with runners who overpronate and transition too quickly from pronation controlling shoes. The abrupt transition and severe overload may amplify the demand placed on the weakened medial structures, enlarging the injury risk. Athletes wanting to transition to minimalist shoes, who have successfully been treated with motion controlled shoes for pronation conditions (such as PTTD) may simply be taunting injury and increasing the risk of instability (Goble, 2013).

Furthermore cyclically loading the toes for long periods of time (as in long distance running) produces toe flexor fatigue early, in runners not accustomed to forefoot striking. This may result in a load-bearing shift from the toes to under the metatarsal heads, effectively increasing the risk of metatarsalgia or metatarsal stress fractures (Lieberman, 2012; Rolian *et al*., 2008; Nagel *et al.,* 2008).

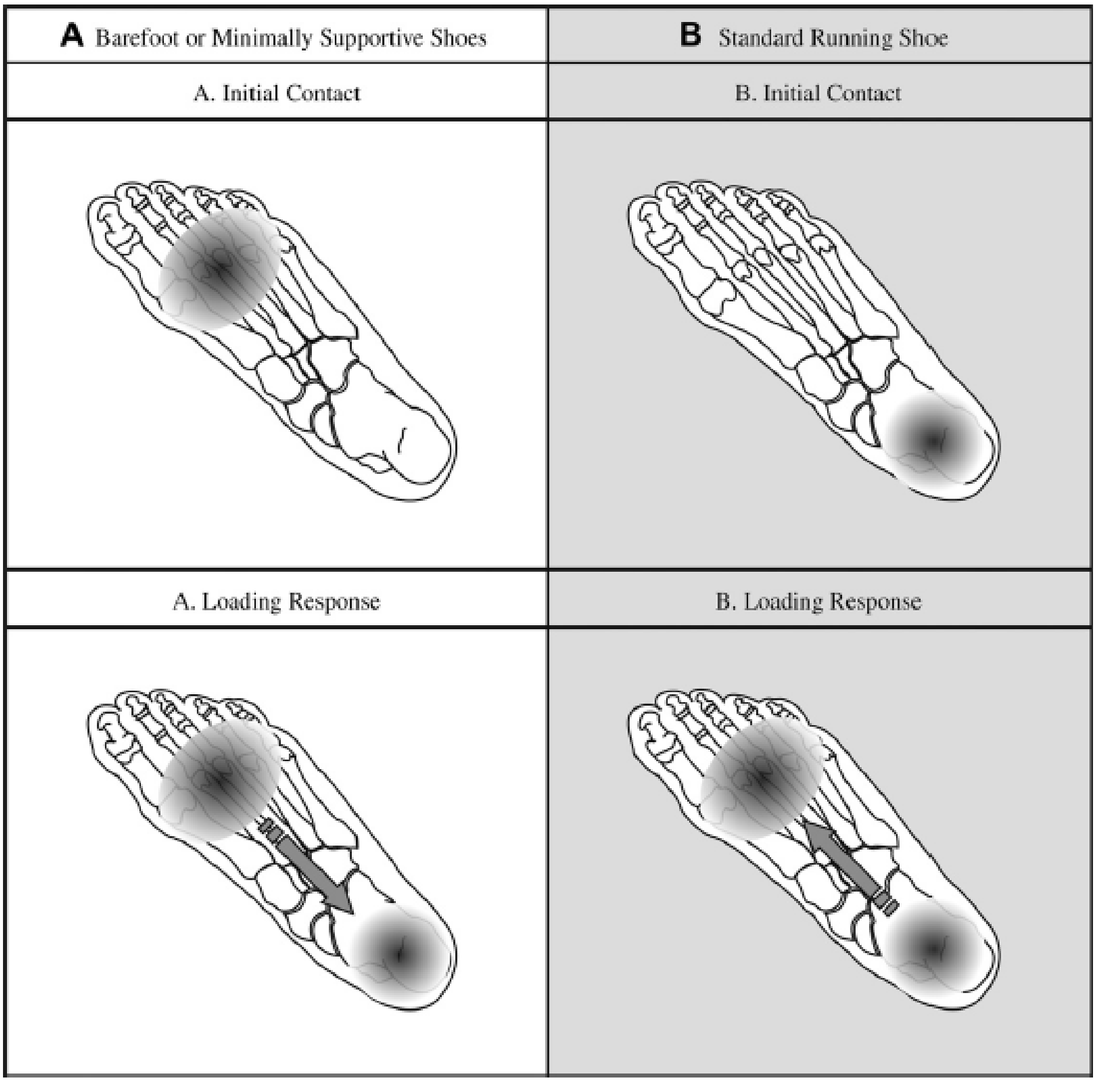


Figure 2.8. Centre of pressure during running. Minimalist shoes demonstrates an initial load on the forefoot, with the loading response travelling toward the heel, while running with trainers demonstrates a loading pattern from the heel towards the toes (Taken from Lohman *et al.,* 2011).

Women, in particular, were found to have significantly higher peak pressures under the first metatarsal. Wunderlich and colleagues (2008) questioned whether wearing various types of footwear while engaging in athletic training and movement might amplify the problem as peak overall forces are significantly increased. It remains uncertain what the exact cause is for the differences observed in peak pressures between men and women, however, it should be recommended that minimalist researchers consider the specific running kinematics of each gender separately. Whether athletic footwear contributes to injury mechanisms or not, any discomfort experienced around the metatarsal heads should be scrutinized with utmost caution during the transition period. Ankle injury history and foot conditions might exclude persons from barefoot running, including CIA, history of Achilles tendinopathy, plantar fasciitis or PTTD, osteo-, rheumatoid or posttraumatic arthritis (Goble, 2013).

Giandolini *et al.* (2013) reported localized pain at the triceps surea in runners transitioning from rearfoot strike to midfoot strike. Calf and Achilles tendon pain is thought to be associated with tissue adaptation caused by unusual and high triceps surea activation, emphasizing the importance of progressivity during transition (Daoud *et al.,* 2012). Bonacci and partners (2013) conducted a study comparing the biomechanical differences during overground running while barefoot and in three shod conditions (minimalist shoe, racing flats and the athlete's regular shoe). The authors emphasized the fact that that the increase in work done at the ankle must be considered when transitioning to barefoot running as too rapid a transition may overload the triceps surea complex. Conversely, the reduction in joint moments and work done at the knee while running barefoot may provide benefits for the management of knee pain and injury.

Vibram® published a 13-week step by step run guide in 2011, intended to aid runners in transitioning to minimalist shoes. Recommendations included mechanical stimulation of tactile receptors, proprioceptive exercises on different surfaces, simple exercises to strengthen intrinsic and extrinsic muscles, description of running technique and ideal surface selection, walking and familiarization periods, as well as a general training plan involving gradual increases in distance over 13 weeks. It was further advised that every run should be followed by self-stretching and massaging techniques (www.vibramfivefingers.com).

Although the barefoot gait is best learned with the help of a trained eye to correct improper technique, beginners can protect against injury by keeping the body upright and making sure the foot never extends past the knee when taking a step (Goble *et al.,* 2013). While patients may experience some discomfort during the transition to barefoot running, they should be advised to consult their health care provider if any pain is experienced that persists for more than 48 hours (AMPA).

Rixe and partners (2012), at the University of Pensylvania developed the "BAREFOOT essentials" run guide, with the aim of assisting runners in making the transition successfully:

Table 2.1 Barefoot running essentials: guidelines for transition into minimalist shoes. Taken from Rixe and partners (2012).

Essentials	Explanation
B. Body Alignment	Proper posture is a key element of good running form. Positioning each joint correctly will help coordinate legs and arm motion, preventing wasted lateral energy.
A. Air-ground Awareness	Runners must know both how their bodies interact with the ground and how they reposition themselves in midair.
R. Reach Softly	The phrase "reach softly" is meant to conjure up an image of a hand reaching out to touch a soft object. Barefoot runners hyperextend (pull up) their toes before touching the ground, leave them extended on contact, and flex them just before leaving the surface. This sequence of events gives a runner the best possible feel for the ground.
E. Effortless Energy	The gentle foot plants, smooth arm swing, stable head position, and soft legs involved in a barefoot technique should make running more enjoyable and give you more stamina during workouts.
F. Foot Control	Recognizing the subtleties of how your foot moves during a run is a great step to improving form.
O. Optimize Rest	A major problem for runners is knowing when and why to let the body rest. Running for back-to-back days can be brutal, especially if these runs are performed at high intensity (intervals or speed work), with a new shoe, or on a new surface.
O. Organized Change	Change in technique takes time to master. The transition to proper barefoot running can frequently involve a sequence of "discoveries" of what it feels like to have run "softly" or with "bird steps."
T. Tune In	"Tuning in" ties all the other BAREFOOT Essentials together: recognizing body alignment, knowing how you interact with the air and ground, feeling the ball of your foot against the surface, noting the effortlessness of your stride, controlling foot movement, understanding when to rest, and allowing time for change.

In conclusion, while minimalist running may not be suitable for everyone, proper training and education may make this a plausible alternative to the traditional trainers, given that expectations and goals are realistic. Until there is more research to support minimalist running in the general population, coaches and trainers should continue to advise novice minimalist runners to transition with caution. Therefore, minimalist training should be implemented only after considering the potential benefits and risks

CHAPTER THREE: PROBLEM STATEMENT

A. Introduction

This chapter will begin by highlighting the potential gaps found in the literature, followed by a brief summary of outcome variables that have been studied on related topics. The chosen study population will be motivated, based on relevant comparisons in past research. Lastly, the aims of the present study will be presented.

B. Existing Literature and Motivation Research Outcomes

Running-related injuries (RRI's) have remained high regardless of several methods of attenuation (Terrier *et al.*, 2013). Fatigue can cause a reduction in the efficacy of the neuromuscular system, which likely adds to the already high injury risk seen in runners (Pendegrass *et al.,* 2003). Thereafter, injury may further impair neuromuscular control (NMC), resulting in a cycle of reduced NMC and injury re-occurrence. During long-distance running, apparent foot placement errors and miss-step injuries can often be noted. It would thus be important to determine the relationship between long distance running on NMC and postural control (PC).

Minimalist training has the potential to alter several kinematic variables found in running. Claimed benefits of minimalist training includes improved impact attenuation, improved proprioceptive ability, increased running economy, increased intrinsic musculature strength, and reduced injury rates. While widespread studies on the kinematic effects of minimalist shoe training have been conducted, little is known regarding the underlying mechanisms of NMC.

If minimalist shoe training can prove to bring about improved NMC, a scientific basis for the reduction in RRI rates can be synthesized. Improved NMC results in better foot placement, PC and muscular activation patterns. Research regarding the effect of minimalist shoe training is limited. Therefore studies to determine whether NMC is altered with minimalist shoes, is warranted. Further, most studies have been conducted on the advantages or disadvantages of minimalist training, but little is known in regards to the gender differences that possibly exist during both transition and minimalist running in general. These differences would most likely influence the ideal transition protocol recommended for each gender.

Previous biomechanical studies have set the foundation for minimalist training research, however, studies compared mostly acute adjustments to minimalist training and long-term studies are still lacking. The following studies investigated certain aspects of NMC but not all:

Divert and colleagues (2005) compared the difference in leg stiffness between running shoes and running barefoot. However, minimalist shoes were not used, and the study did not include an intervention period. Bishop and colleagues (2006) studied the effect of footwear on leg stiffness and running kinematics. While valuable discoveries were made regarding adaptations to running surfaces for improved shock attenuation, no further inquiry was made to the intrinsic cause of these stiffness adaptations.

Eslami and partners (2007) investigated the forefoot-rearfoot coupling patterns and tibial internal rotation during the stance phase of barefoot versus shod running. While this study may highlight potential coordinative variation between barefoot and minimalist shoes, limited information is given regarding overall NMC.

Squadrone and Galozzi (2009), De Wit and partners (2000[ab]) as well as Divert (2005[a]) conducted extensive studies regarding joint angle measurements and impact forces, while only Divert (2005[a]) included electromyographic (EMG) measurements. These articles provide important information on joint angles and the adaptations made to running kinematic parameters when in minimalist shoes, which could be related to measures of NMC. However, this was not the main aim of any of the studies.

Lieberman (2010) conducted a study on the collisional forces seen in habitual barefoot and shod runners, and discussed the possibility that parameters of NMC could be altered, although physical measurements were not taken. Therefore this study will include both direct (EMG) and indirect measures of NMC (balance and joint position sense), in order to gain a more comprehensive view of the overall control system.

Similar studies done on indirect measures of NMC in general have been conducted in the past. For instance, the effect of footwear on measures of balance in men, have been conducted extensively (Whitney & Wrisley, 2004; Robbins & Waked, 1997; Hosada *et al.,* 1997). These studies have been conducted to a large extent in the older population (Menz & Lord, 1999; Robbins *et al.,* 1994; Menant *et al.,* 2008; Brenton-Rule *et al.,* 2011). It is unlikely that findings in these studies can be generalized to the younger, active population. Therefore, research regarding the effects of footwear on indices of balance is warranted.

Studies have also been conducted on ankle JPS, which is also an important aspect of NMC. Squadrone and Galozzi (2011) investigated the effect of a minimalist shoe on static and dynamic ankle position sense in healthy amateur runners, by testing perceived direction and amplitude of a slope. However, the majority of studies including proprioceptive measurements are done on an injured population, which usually includes chronic ankle instability (CAI) (Willems *et al.,* 2002; Sefton *et al.,* 2009; Hertel, 2008; Fu & Hui-Chan, 2005). It might be practical to determine the degree of improvement in joint position sense seen when increasing the amount of sensory information to the plantar aspect of the foot, in relation to other measures of NMC, within a healthy population.

Studies have been conducted on the effect of other footwear types on NMC. For instance, Fong and Shamey (2013) studied the effect of Taekwondo footwear on postural stability in young adults, while Lobo Da Costa and partners (2013) investigated whether ballet slippers improves dynamic balance during dancing turns and poses.

Lastly, in a very similar study by Rose and colleagues (2011) the effect of minimalist footwear on dynamic balance was investigated. However, as balance is only a subcomponent of NMC, this study also did not answer the entire research question at hand. The effect of minimalist shoes on JPS and muscle activation patterns remains uncertain, and research in this area could be motivated.

Research relating to NMC and, more specifically balance, is more prevalent in the older population, as they are have a higher risk of falling (Brenton-Rule *et al.,* 2011; Jonsson *et al.,* 2004; Menz & Lord, 1999). Furthermore, children have become an increasingly popular choice as a study population especially during their developmental stages (Wilk & Garis, 2011; Wegener *et al.,* 2011). The effect of footwear on children's balance and gait is therefore becoming an increasingly important topic amongst researchers. Research has also been done extensively on the NMC of injured populations like CAI (Hertel, 2008; Gribble *et al.,* 2012; O'Driscoll & Delahunt, 2011), or populations with neuromuscular disorders (Wingert *et al.,* 2009; Busse *et al.,* 2005). However, not much research has been done on the healthy population and it remains uncertain whether minimalist shoes can provide additional NMC benefits over and above that seen in a healthy, recreational athlete. Elite athletes were not included as they have strict training schedules and cover higher mileages, increasing their initial risk of injury. Therefore, this study chose to include healthy, recreational athletes within the age of 21-35. The present study will make use of the definition described Buist and colleagues (2008) to classify recreational runners. A recreational runner can be defined as a person who has not been running regularly during the previous year (Buist *et al.,* 2008). The cut-off to define regularity was set at 20 km of total training volume per week. Therefore, runners who ran more than three times a week were excluded from the study, as well as persons running more than 20km per week.

To our knowledge, previous studies investigating the longer term effect of minimalist shoes on NMC in the younger, healthy population have not been conducted, and therefore research in this area is warranted.

F. Aim of the Study

The main aim of this study is to investigate whether training with minimalistic shoes will cause neuromuscular adaptations, which may lead to a reduction in RRI's over time.

The primary objectives of the study were to determine whether an 8-week minimalist training intervention affected:

1. Subjective ratings of muscle pain and lower limb comfort, as well as calf circumferences.
2. Muscle co-activation, pre-activation and total activation patterns.
3. Isokinetic ankle joint strength (i.e. dorsiflexion, plantar-flexion, eversion, inversion).
4. Changes in postural stability (i.e. acute and after eight weeks).
5. Joint position sense (i.e. passive).
6. Runners' ability to successfully adapt to a minimalist training program, by adjusting their running kinematics (knee angle at contact and footstrike pattern).

As a secondary objective the study were to determine whether:

1. Gender differences existed in any of the previously mentioned variables.

G. Independent Variables

Minimalistic Shoes
Conventional Cushioned Shoes
8-week Distance Training Program

H. Dependant Variables

Postural sway

- Overall Sway
- Anterior-Posterior (A/P) Sway
- Medial-Lateral (M/L) Sway

Joint position sense (i.e. passive)
Isokinetic strength - peak torque to body mass
Muscle activation patterns (as a percentage of the gait cycle)

- Pre-activation of the gastrocnemius (LG and MG), tibialis anterior (TA), and peroneus muscles (PER).

- Co-activation between combinations of TA, PER, lateral (LG) and medial (MG) gastrocnemius, biceps femoris (BF) and gluteus medius (GLUT).
- Total activation of TA, PER, LG, MG, BF, GLUT.

VO_{2max} ($ml.kg^{-1}.min^{-1}$)

I. Assumptions

It is assumed that participants will be honest when recording distance, total time run, and time run in barefoot shoes. They had to answer all questionnaires truthfully, without omission of any details. Further, the control group were expected to train in their usual trainers, only, with minimal barefoot exposure. Also, it is assumed that participants did not partake in any activity outside the training program that would adversely affect their training, or improve their balance and proprioception. This includes excessive intake of alcohol or caffeine 24 hours prior to their pre and post-tests.

CHAPTER FOUR: METHODOLOGY

A. Introduction

The practical aspect of the study will be considered in the following section. Firstly, a broad picture of the study overview will be given, followed by a more detailed description of materials and testing procedures. The intervention period will be explained, as well as statistical and ethical considerations.

B. Study Design

This study makes use of a pretest-posttest randomized-groups design. Following pretesting, participants from the control and experimental groups underwent similar intervention programs consisting of three running sessions a week. The same battery of tests was then repeated upon completion of the intervention program. Due to the fact that the participants are both chosen randomly and divided into groups randomly, one can assume that the groups are similar prior to the start of the study. Threats to internal validity are controlled maximally in this way, ensuring that the intervention treatment is the only factor attributable to different inter-group results (Thomas *et al.,* 2001). Threats to internal validity include history, maturity, testing, instrumentation, statistical regression, selection biases, experimental mortality, selection-maturation interaction, and expectancy. As factors outside of the study intervention cannot be accounted for or controlled, the threat of history effect is the only limiting factor. However, participants are given various questionnaires regarding overall wellbeing throughout the intervention period, in order to acknowledge and take into account possible interference effects. This study aims to investigate the effect that minimalist shoe training has on the neuromuscular control (NMC) of athletes. When looking at the objectives required to fully answering the research question at hand, the chosen study design would be the best-suited method.

C. Participants

A total of 23 runners (11 experimental, 12 control) were included in the study. Participation was completely voluntary throughout the duration of the study. The group consisted of 12 women and 11 men, with an average age of 24.25 (±3.2) years. The experimental (EXP) and control (CON) group will be considered both as a whole and with each gender separately. All participants ran habitually prior the study, and were capable of running 10 kilometres at the time of signing up. However, they all considered themselves to be recreational runners, who had not previously participated in half marathons. The mean height of participants was 175.3 (± 9.14) centimetres, while the average mass was 68.95 (± 12.68) kilograms.

1. Recruitment

Participants were recruited from in and around Stellenbosch, using several modes of advertisement. This included the placement of pamphlets on the University campus, advertisement on the University's intranet (www.sun.ac.za), as well as advertisement at local running clubs and gatherings. Examples of advertisement material are attached in Appendix A.

A total of 58 volunteers responded over a period of one month, mostly via email. In response to their enquiry and before invitation to the first visit, they were asked three basic questions via email:

1. Have you recently suffered from any running-related injury?
2. Are you participating in any big running events during the next three months?
3. Do you participate in any other sport?

Amongst the inclusion and exclusion criteria, the above questions were found to be most problematic, when trying to assign participants to the study. If a participant answered yes to any of the above questions, they were excluded from the study. If they answered no to all the above, they were sent a consent form explaining and describing all testing and training procedures, as well as a more detailed list of inclusion and exclusion criteria. Upon completion and signature of the consent form, they were invited to the first visit.

A total of 34 volunteer participants were invited to the first visit and interview. After obtaining all relevant information regarding the study, four of the volunteers decided against participation, due to travel plans during the study period or re-evaluation of their schedule, revealing inadequate time for participation. Figure 4.1 below provides a schematic representation of participation throughout:

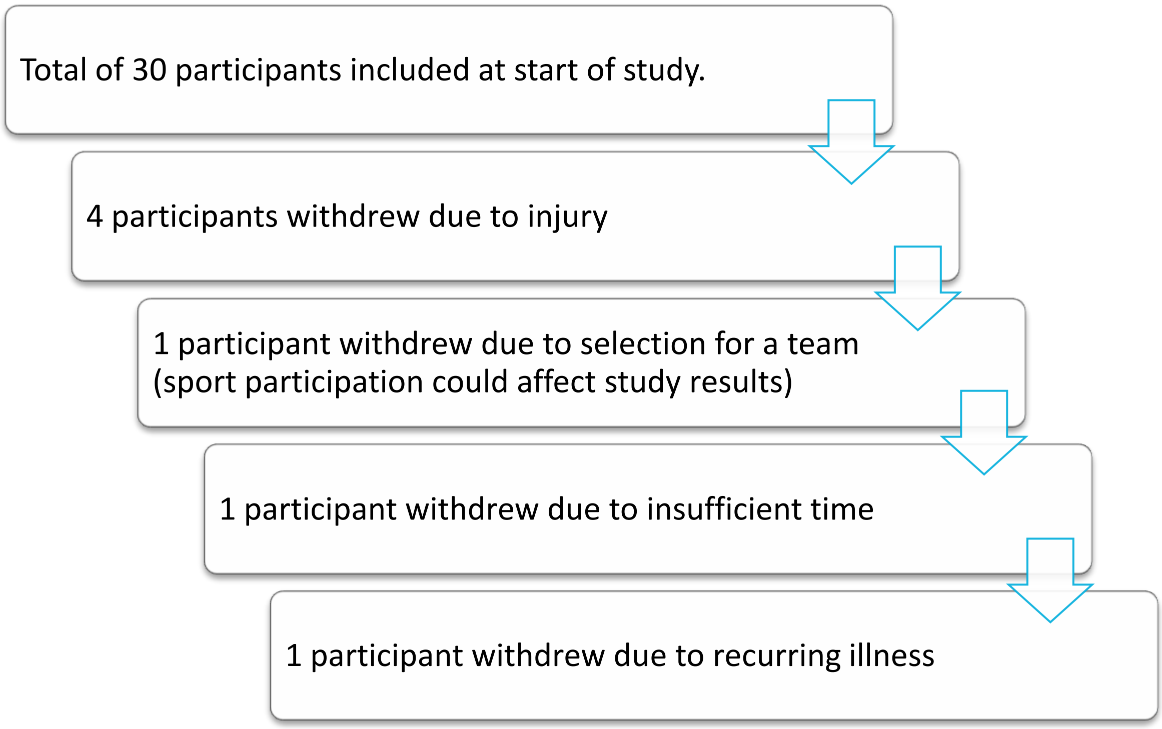


Figure 4.1. A schematic representation of participation throughout the intervention period, including reasons for termination of the study.

2. Inclusion and Exclusion Criteria

Healthy men and women between the ages of 21 and 35 years (Nigg *et al.,* 2012), with no history of lower limb injuries in the previous three months prior to the start of the study were included. Nigg and partners (2012) conducted a study on the effect that age has on lower extremity kinematics, and found that age influences the more dominant components of running. Nigg and colleagues (2012) further classified the participants into groups with most similar running kinematics, which resulted in four groups of ages 16-20, 21-35, 36-60 and 61-75. As the youngest group generally has a high level of outside sport participation, recruitment into the present study would be made difficult. Further, older runners (ages 36-60 and 61-75) are usually more experienced and would not consider themselves to be recreational runners, making inclusion into the present study equally challenging. Age also has a negative effect on performance and recovery. Although marked declines are usually only noted at the age of 60-65, most research states that a decline in performance starts roughly around the age of 35 (Bortz & Bortz, 1996). As minimalists shoes places high eccentric loads on the triceps surea, and requires fast recovery, the younger population was thought to be a good starting place for research.

Therefore, the age group 21-35 was deemed to be most fit for the proposed study (Fell and Williams, 2008).

Participants were excluded if they had any balance or cognitive defects, as well as any cardiovascular or neurological disorders, as these conditions were believed to interfere with either training participation or components of postural control (PC). This study was initiated to determine, firstly, whether minimalist shoes holds any added benefits to NMC and proprioception, to runners who are healthy and injury free, with the focus on injury prevention. Therefore future research could be aimed at specific injuries. Participants were considered for participation only if they ran at least one 10-kilometre race or fun run within the previous 12 months, for inclusion. Their 10 km finish time was used as an indication of their fitness level, and allowed the researcher to determine whether they were definitely capable of running 10 km. However, they were excluded if they had run more than one 21km within the previous 12 months. Also, as recreational runners, they should only have been training in conventional-cushioned footwear only and any experience in barefoot or minimal training required that they be excluded from the study. More experienced runners were not considered for the study, as runners who are accustomed to high weekly mileages seldom voluntarily reduce their mileages. Maintenance of high mileages during transition to minimalist shoes have been correlated with an increased injury rate. They had to have sufficient time available for training, as well as the means to get to Coetzenburg stadium at least three times a week. Participants were excluded if they had any other sporting commitments (hockey, soccer, rugby netball etc) during the study period, or regularly participated in pilates or yoga, which is believed to improve balance and proprioception measures independent of fitness level. Pilates and yoga may be viewed as alternative forms of balance training, as certain poses and positions require both static and dynamic balance. It is widely accepted that balance training improves static balance (Zech *et al.,* 2010). Lastly, they were excluded if they had a BMI of higher than 24. 8 kg.m^2, due to the fact that excess body mass places increased strain on foot structures (Faria *et al.,* 2010). This, in combination with barefoot or minimalist training might place them at an increased injury risk.

D. Study Outline

The purpose of the study outline is to provide a brief overview of the study in chronological order, to facilitate later navigation through more detailed sections. A brief description of events will be outlined, followed by a more detailed explanation of testing procedures for each visit.

1. Pre Testing - First Visit

The first visit constituted mainly interview type questioning, during which the participants were encouraged to discuss their current training habits, as well as goals for the near future. They were questioned about their running and sporting history, as well as medical health in the recent past. All aspects of the training and testing procedure were verbally communicated, and possible risks and benefits were also explained. Meeting times for running sessions were discussed; to ensure that participants could attend sessions and that there were no time constraints. The consent form was signed and handed in, where after the Lower Limb Comfort Index (LLCI) questionnaire was explained in detail. Participants were also shown how to complete these questionnaires for future use during the study. Participants were asked to complete the LLCI after every running session. Lastly, participants were asked to fill in a physical activity readiness questionnaire (PAR-Q), as well as a general health-screening questionnaire (Appendix B).

Following the administration section, basic anthropometric measurements were taken including height, body mass and body mass index (BMI). In order to determine leg dominance, participant were asked to kick a ball, whereby the chosen leg was recorded as the dominant leg. Lastly, the VO_{2max} test was perfomed by participants. Prior to the visit, participants were asked to refrain from consuming any caffeine (or substitutes) for at least four hours before testing (Momsen *et al.,* 2010), and not to eat anything for two to four hours before (to avoid digestive discomfort). Results from the VO_{2max} test were used to determine their anaerobic threshold, by which individual heart rate training zones were prescribed for training.

2. Subject Randomization

Following the first visit, participants were divided into either the control or experimental groups. Participants were divided by randomly assigning a numerical code to their names, where after the sort function in excel rearranged numbers into numerical order. Every second name was chosen from the rearranged list, and assigned to the experimental group.

3. Familiarization Period

To eliminate potential initial discomfort and novelty bias when running in new shoes for the first time, the inclusion of a familiarisation period is deemed necessary by most researchers. Uncomfortable shoes can alter plantar pressure distribution, muscle activation patterns and running kinematics in general (Chen *et al.,* 1995; Pradels *et al.,* 2011; Wakeling *et al.,* 2002; Bishop *et al.*, 2006; Bonacci *et al.,* 2013). Current literature remains somewhat ellusive when dealing with familiarization time frames and control during this period (Fron Yan, 2013), however a time frame of 7 to 14 days is generally considered to be acceptable (Bonacci *et al.*, 2013; Boyer and Andriacchi, 2009). Participants assigned to the experimental group were given a pair of minimalist shoes each, and instructed to familiarize themselves with the shoes over a period of one week prior to pretesting (Schutte and Venter, 2012). This included walking, sitting or standing in the shoes during daily tasks and activities, for approximately two to three hours. They were also given a few daily exercises to do to increase foot musculature, in preparation for minimalist running. Exercises included calf raises, toe taps, towel scrunching with toes, and picking up marbles with toes. The shortest acceptable time for familiarisation was chosen, so as to ensure that the experimental group remained as similar to the control group as possible, while still attempting to prevent transition injuries. The intervention period was further set to start at an extremely low weekly distance in minimalist shoes, so as to further allow adequate aclimatisation to the minimalist runnign shoes. As baseline testing needed to be done when the participants ran in their minimalist shoes for the first time, no running, jumping or jogging was allowed in the minimalist shoes during the familiarisation period. Participants were warned that they would be excluded from the study, should they not adhere to this regulation. Participants were, however, encouraged to maintain their average weekly running mileage of in their usual running trainers.

Figure 4.2. An example of the shoes used during the intervention period. Shoes were manufactured from the original Vibram® soles.

4. Pre Testing - Second Visit

The second visit consisted of data collection from the Biodex Balance testing, biomechanical measurement, electromyographical (EMG) measurement, proprioceptive testing, and isokinetic strength testing. These tests will be discussed thoroughly in section G (Measurements and Tests). In some cases, participants requested to split the testing procedures into two parts, as testing took up to two hours to complete. Thus, some participants opted for a third visit, during which the proprioceptive testing and isokinetic testing were done. Participants were also given their training programs that were obtained from the $VO_{2\,max}$ test completed at the previous visit. The results from the VO_{2max} report were explained thoroughly.

Table 4.1. Overview of the experimental procedure.

Recruitment	Advertisement, Personal Correspondence, Screening
First Visit	Administration, Biodex Balance, Anthropometric Measures, VO_{2max}
Familiarization	Walking , Exercises
Second Visit	Proprioceptive Testing, Isokinetic Strength Testing, Biomechanical Measurement, Electromyographic Measurement
Third Visit	Isokinetic Strength Testing, Proprioceptive Testing
Intervention	Running
Post Testing	Proprioceptive Testing, Isokinetic Strength Testing, Biomechanical Measurement, Electromyographic Measurement, Proprioceptive Testing

5. Intervention

The prescribed program consisted of three running sessions per week, for a period of eight weeks. During this period, the total running volume increased gradually, up to a goal distance of 21km at week eight. It was specifically communicated that runners were expected to try to adhere to the running program as closely as possible. However, as recreational runners were included in the study, many of whom had outside responsibilities, the study parameters allowed for a small proportion of sessions to be missed. Runners had to have an adherence rate of more than 80%, and missed sessions were not allowed to be consecutive. Further, a total of 5 running sessions were hosted weekly by the researcher, giving runners 2 sessions in which they could catch up with sessions missed. However, should a runner miss a session during a week, they had to catch up that session on another day within the same week. Therefore, runners were not allowed to run more that 3 sessions per week. Runners who did not succeed in maintaining an adherence rate of greater than 80% were excluded from the study. Further, runners who demonstrated extreme LLCI scores (explained in section F Running Performance) were not allowed to increase their running distance in minimalist shoes during the next running session.

In summary, each week consisted roughly of one short fast run, one medium distance and pace run, and one long slow run. During some sessions hills and strides were also included in training, and training surfaces were varied (described in section F and Appendix G). To aid in transitioning and reduce injury risk, at the start of the study participants in the EXP group ran for a small percentage of the distance in minimalist shoes, where after they completed the distance in their regular training shoes. During week one, participants in the experimental group ran for 20% of the total distance in minimalist shoes. Thereafter, percentages of distances run in minimalist shoes increased weekly by approximately 10%, to ensure that the total distance will be run in minimal shoes by the end of week eight. Figure 4.3. describes the aimed transition protocol of the EXP group used during the intervention period.

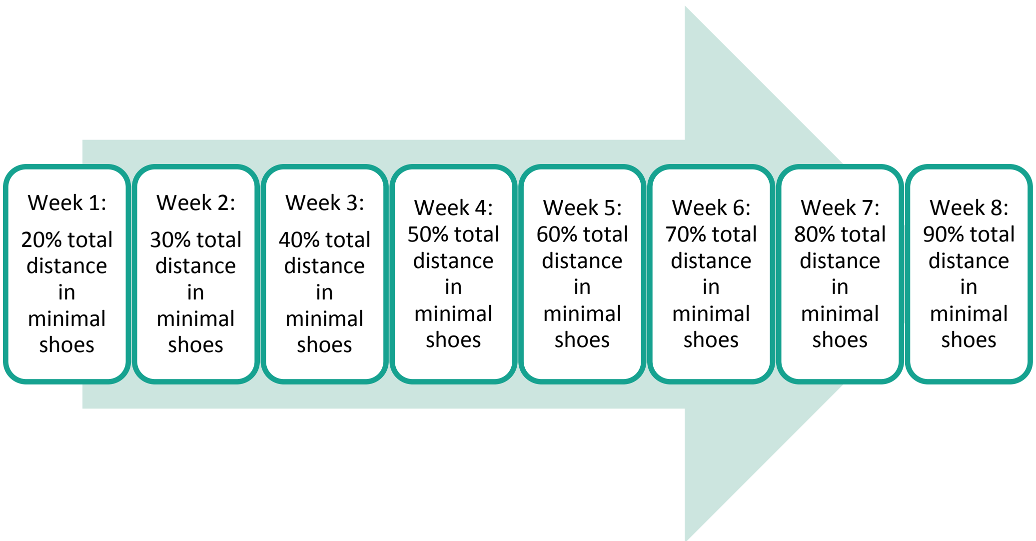


Figure 4.3. Overview of EXP group progression into minimalist shoes,throughout the intervention period.

6. Post Testing

To determine whether there was improvement in any of the variables and parameters, all baseline tests were exactly repeated, during post-testing, except for the VO_{2max}.

E. Ethical Aspects

All sessions and procedures were carried out in accordance with ethical regulations, as set out by the Ethics Committee of Stellenbosch University. Participants were duly informed of all testing procedures, both verbally and written, and were given opportunity to ask questions and raise any concerns before the start of the study. All participants were to sign a consent form, as well as general health screening forms, prior to inclusion to the study. Participants were advised that participation was voluntarily, and withdrawal from the study is allowed at any time, without penalty or consequence. All information obtained from the study was handled with utmost confidentiality and the researcher did not disclose any information to outside sources. Data was stored on a password-protected computer, to which only the researcher and study leaders had access. Names were given only to the study leaders, in the event that the circumstances absolutely required it to be so. All data collected was locked in a safe storage room at the Department of Sport Science, and will be kept for a period of 5 years. Thereafter, all documentation will be shredded and data will be erased.

F. Training Performance

1. Training Characteristics

All participants were given an eight-week training program, which acted as a guideline for distances and running speeds throughout the study. Participants wore Polar F2 heart rate monitors (Polar, Finland) during each session, which was utilized as a method of monitoring their intensity during each session, as well as a method for recording sessions completed. All sessions started from Coetzenburg stadium, and consisted of two loops. The first loop was done in minimalist shoes, whereas the second loop was run in conventional-cushioned shoes. Training started with an easy six-kilometre run, and increased gradually over the eight-week period (program attached).

By making use of google maps, a route was mapped out prior to each training session, and emailed to participants. The route was also explained prior to start of the run. Although participants started each session together, their individual heart rate zones frequently did not allow them to run at the same pace and some runners finished earlier than others.

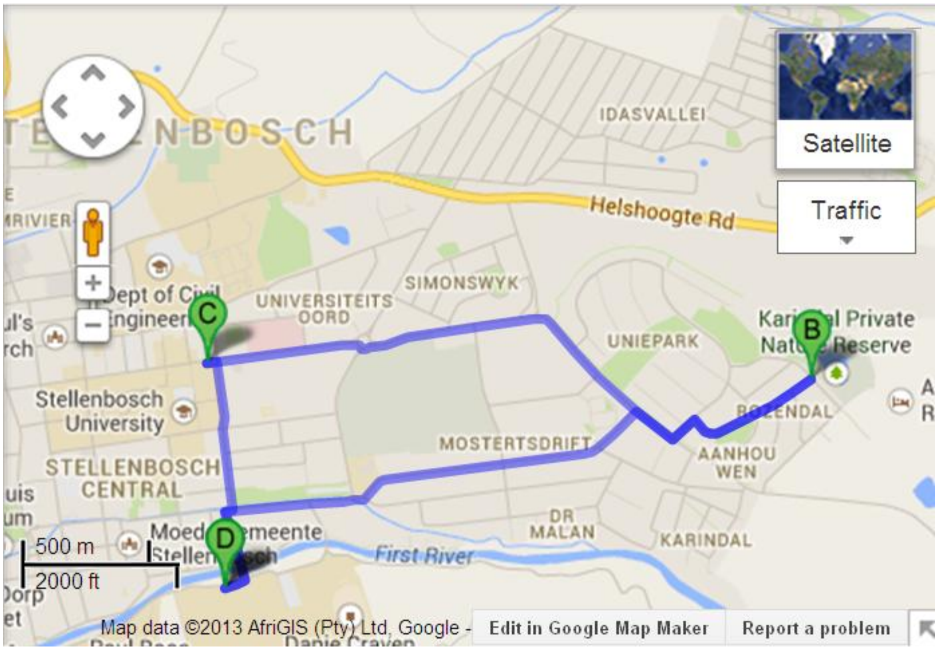


Figure 4.4. Example of a running route around Stellenbosch, sent to participants prior to a training session. Picture taken from Google Maps®.

Following each session cool down, participants were asked to complete the logbook, which was kept to record actual sessions run, and to fill out the LLCI. They were instructed to record the total distance run, the distance run in minimal shoes, average heart rate, as well as maximal heart rate. They were also given the opportunity to log any complaints, discomfort or general comments.

2. Program Prescription

Literature points to the use of large volumes of low-intensity training (long slow), combined with small amounts of high-intensity interval training as the most effective method for increasing fitness in distance athletes (Seiler & Tønnessen, 2009). Using results from the VO_{2max} test, each participant was prescribed individual heart rate zones, which they had to maintain during training sessions. Using the heart rate reference point at which their anaerobic threshold occurred, participants were instructed to train just below the reference value during long slow training, in order to make maximal use of the aerobic system (Powers & Howley, 2007; Marti *et al.,* 1987). This ensured proper base training, during which the aerobic system adapted favourably to training. Later in the program, some sessions included higher heart rate zones, which resulted in lactate threshold training (Daniels, 2005). Each participant was allocated specific HR training zones, which fell into three categories: blue for long slow training (ave HR

122 ± 7 to 145 ± 8), green from medium pace runs (ave HR 148 ± 9 to 168 ± 7), and yellow for fast runs (ave HR 170 ± 7 to 189 ± 6).

The exact program prescription is given in the following table:

Table 5.1. Overview of the 8-week training program prescribed during the intervention period.

	Day 1	**Day 3**	**Day 5-7**	**Total km per week**	**%minimal**	**Distance minimal**
Week 1	6km Blue	3km Blue	8km Blue	17km	20%	3.4km
Week 2	6km Blue	5km Green	8km Blue	19km	30%	5.7km
Week 3	7km Blue	5km Green	10km Blue	22km	40%	8.8km
Week 4	10km Blue + 4X100m sprints Yellow	6km Green	12km Blue	27km	50%	13.5km
Week 5	8km Blue + 6X100m sprints Yellow	5km Blue	14km Blue	27km	60%	16.2km
Week 6	8km Blue + 6X100m sprints	6km Green	16km	30km	70%	21km
Week 7	10km Blue + 8X100m sprints	2 X 4km Yellow	18km Blue	18km Blue	80%	25.6km
Week 8	8km Blue	10km Blue + 8X100m sprints	15km Blue	33km	90%	29.7km
Total distance	208km					123.9km

3. Lower Limb Comfort Index

The Lower Limb Comfort Index (LLCI) provides a method for the quantification of lower extremity discomfort. The LLCI was designed by Kinchington and partners (2010) to examine the relation between lower limb comfort scores and injury, and to monitor the changes in lower limb comfort that occurred over time, in response to intervention methods.

The LLCI monitors six anatomical areas, namely the foot, ankle, calf-Achilles, shin, knee and shoe. During each session participants were asked to score each anatomical area between zero and six, with zero indicating extreme discomfort (unable to run or jump) and six indicating extreme comfort (Kinchinton *et al.,* 2010; 2012). Following a session, the total score for lower limb comfort was calculated, and used to monitor overall levels of discomfort. In the event that participants scored below a four, the distance run in minimalist shoes was not increased for the next running session. This was done to ensure that the ankle and calf musculature had sufficient time to adapt and recover. To stay within the parameters of the study, the total distance was, however, still increased weekly. Control groups ran the same route as the experimental group, in conventional cushioned footwear only and distances were increased on a weekly basis.

4. Surface Selection

Surface characteristics can affect the demand placed on PC and NMC systems during running. Runners will, however, adjust their leg stiffness on different surfaces, to ensure relatively similar vertical impact forces throughout (De Wit *et al.,* 2000[a]). While hard surfaces can potentially create more impact forces, and thus increase the risk of injury, a soft surface places more stress the muscular system and increases the risk of muscle strain (Lohman *et al.,* 2011). This is due to changes in joint angles and joint reaction forces during running. The effect of different surface characteristics on running variables has been studied increasingly in recent years; however, the ideal surface for transition has not been agreed upon.

As minimalist shoes can often be perceived as hard and uncomfortable, participants were initially started on a soft grass surface in the minimalist shoes, as little as 20% of the starting distance. This was followed by road running in their usual trainers, to which participants were already accustomed. In week three, some road running was allowed in the minimal shoes, followed by running in trainers. In week four, road running was firstly done in minimal shoes. Thereafter easy trail routes were introduced for runs with trainers, followed by sprints on the grass. Week six and seven consisted of some road and easy trail running in both minimal shoes and trainers, as well as some sprints on the grass.

Hill running was introduced in week four, which started with long easy slopes, and gradually increased into steeper trail climbs in week six. Appendix G outlines the specific surfaces and conditions selected during each running session.

5. Gait Retraining

Participants were advised of the running technique most beneficial to minimalist running. They were instructed to keep their bodies upright and to make sure that the foot never extends past the knee (Goble *et al.*, 2013). However, the main emphasis was placed on avoiding a heelstrike. During weeks one to four participants were coached and observed to ensure suggested running form throughout.

Figure 4.5. Differences in running body form observed between forefoot/midfoot (right) and rearfoot strikers (left) (Photographs by Sulé Dreyer).

G. Measurements and Tests

By dividing the neuromuscular system into its different components, more accurate assumptions can be made regarding specific control mechanisms (Lephart, 1997). These different components including proprioception, static postural control, EMG, kinetics-kinematics and dynamic stability, have been studied extensively to better understand how balance is maintained in various situations (Wikstrom *et al.,* 2006).

During the first visit basic anthropometric measurements were taken, including height, mass and body mass index. Height was measured using a standard stadiometer (Seca, GMBH, Germany), with the participants' being asked to stand upright, feet together and heads in the Frankfurt plane. The height was recorded to the nearest 0.1 cm, while the participant took a deep breath in. Mass was measured using a calibrated scale (Seca, GMBH, Germany, 0.1 kg increments). Participants were asked to stand in the middle of the scale, looking straight forward, while wearing minimal clothing. The BMI was calculated from the mass and height using the following formula:

BMI= mass (kg) / height (m) ^{2}

1. Maximal Oxygen Uptake Testing

Measurement of VO_{2max} provides researchers with a direct means of quantifying the aerobic fitness of an individual, by calculating the maximal amount of oxygen which can be utilized by the system within a given period of time, per kilogram of body mass (Powers and Howley, 2007). Participants' VO_{2max} was tested using a standard treadmill (Saturn, HP-Cosmos, Nussdorf, Germany). All equipment was calibrated prior to the start of testing. The testing and safety procedures were thoroughly explained to each participant, followed by a 5 minute warm up period on the treadmill. The warm up speed was set at 6 km.h^{-1} for a fast walk during the first minute, whereafter they could increase the speed to a comfortable slow jog (self-selected). Following the warm up, a heart rate monitor (COSMO M2, Amer Sports Corporation, U. S. A.) was fastened, as well as a face piece for the measurement of inspired and expired air. As an added precaution, each participant was also asked to wear a safety harness. When a pulling force of more than 5 kg is applied to the harness, an emergency stop is activated by the treadmill. This prevents participants from falling off the back of the treadmill, should they fall or trip.

Participants were then asked to start running at 8 $km.h^{-1}$, at which point the test was started. The speed was increased by 1 $km.h^{-1}$, every 5 minutes, up to 13 $km.h^{-1}$. From 13 $km.h^{-1}$, both the speed was increased by 1 $km.h^{-1}$as well as the incline by 1 percent (6 degrees). Participants were encouraged to continue for as long as possible, until exhaustion. The test was considered to be complete, should any 2 of the following endpoints be reached:

- A plateau in the increase in oxygen uptake.
- The attainment of maximal heart rate (214- (0.8 x age) for men, and 209- (0.9 x age) for women)
- The attainment of a respiratory ratio (RER) of greater than or equal to 1.15.
- Volitional exhaustion.

After termination of the test, the immediate recovery heart rate was also measured for the duration of 1 minute. This protocol has previously been described by Guidetti and partners (2005).

Figure 4.6. VO_{2max} testing conducted by a participant, in the Physiology Laboratory of the Sport Science Department, Stellenbosch University.

2. Biodex Balance Assessment

The measurement of NMC includes measurement of cortical, spinal reflex, and brainstem pathways. By assessing dynamic PC researchers can objectively quantifying the efficiency by which the CNS integrates various neuromuscular afferent input signals, and produces an appropriate response. Assessment can act as a tool for determining the stability and NMC in healthy as well as injured individuals, by ascertaining whether proper motor responses are generated in order for the centre of gravity to stay within limits of the base of support (Hosseini *et al.,* 2012).

The Biodex Balance System (Biodex Medical Systems, Inc., New York, U.S.A.) has been accepted as a reliable means of measuring both static and dynamic balance (Cachupe *et al.,* 2001). It objectively quantifies the participant's ability to control their centre of pressures (COP) on a circular platform, which can sway in an anterior-posterior (A/P) direction as well as in the medial-lateral (M/L) direction simultaneously. Values obtained can then be compared against age and height predicted norms. The Biodex Balance System has a high reliability, with measures across 8 trails of R = 0.94 (overall stability), R = 0.95 (A/P sway index), R = 0.93 (M/L sway index). Participants were tested on both the dominant and non-dominant legs using both the Athletic Single Leg (ASL) protocol, and the modified Clinical Sensory Integration of Balance (mCTSIB) protocol. The ASL test measures dynamic postural stability on a single leg, while the mCTSIB test measures the efficiency of intergration of various proprioceptive inputs, using both legs.

For the ASL test, participants stood with their dominant foot in the middle of the circle on the platform. After noting heel placement, they were given the opportunity to feel the degree of platform looseness. The goal of the test was to maintain their COP as close to the middle of the circle as possible, for the duration of the trial. Visual feedback was given on the screen in the form of a cursor, indicating their current COP in relation to the centre starting point. The test consisted of three 20-second trails, separated by ten-second rest periods. The test was then repeated on the other (non-dominant) leg. The average of the three trials were taken, with the software automatically separating M/L sway components from A/P sway components. Thus, measurements noted were overall sway index, A/P sway and M/L sway, along with the standard deviation of each.

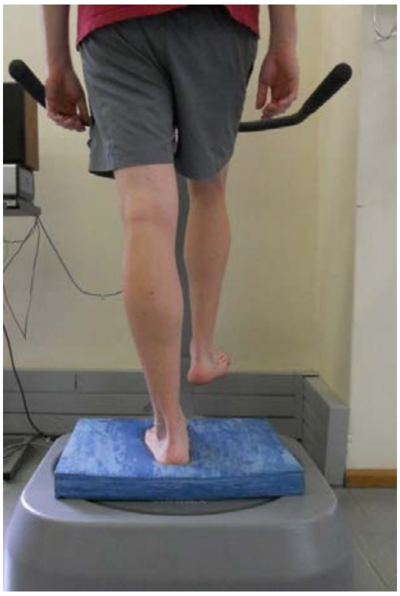


Figure 4.7. Athletic single leg test performed on the Biodex Balance, while barefoot by a participant.

The CSIB test procedure was performed on two feet and consisted of the following conditions:

- Eyes open on a firm surface
- Eyes closed on a firm surface
- Eyes open on a foam surface
- Eyes closed on a foam surface

Participants were placed with feet in a standard position, as marked on the Balance Biodex, with feet in approximately 10° abduction. Each trial lasted for 20 seconds with 10-second rest periods, and no visual feedback was given on screen.

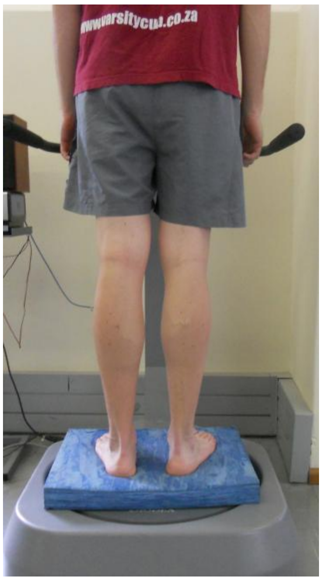


Figure 4.8. The Modified Clinical Test of Sensory Integration test conducted by a participant (condition 3/4), at the Biokinetics Centre, Stellenbosch University.

To determine whether differences in baseline sway index levels existed between the barefoot and shod condition, the experimental group was also tested using the exact same protocol wearing minimalist shoes. The order of the shoe condition was randomly selected for each participant. The control group was tested only in the barefoot condition.

3. Electromyographical Analysis

Electromyography is the preferred method used to analyze the amplitude, sequence and activation patterns of muscles during movements, for comparison between different conditions (Reaz *et al.,* 2006). Electromyography signaling is an indicator of electrical currents generated within the muscle during contraction, corresponding to neuromuscular activity. While the signal is generated by the nervous system, it is still completely dependant on the correct anatomical placement and physiological properties of the muscle, making it relatively complex to interpret. However, many advances have been made in recent EMG technology.

The Wave Wireless Electromyography device (12 lead wireless, Cometa; Italy) was used to measure the neuromuscular activity of the tibialis anterior, peroneus longus, lateral gastrocnemius, medial gastrocnemius, biceps femoris, and gluteus medius during slow, comfortable running on a standard treadmill (Johnson Jet 6000). The EMG activity of both the dominant and non-dominant legs were measured, to determine whether differences existed between left and right. Prior to placement of electrodes, participants were given the opportunity to warm up on the treadmill, at a self-selected speed. The warm up period consisted of five minutes of comfortable running. Preceding placement of electrodes, the area of skin under each electrode was shaved, lightly abraded and properly cleaned using etyl alcohol wipes.

The electrodes (Ambu, Blue Sensor ECG, Denmark) were then carefully placed onto the skin, parallel to the muscle fibers, approximately 2 cm apart. A similar preparatory procedure was also described by Stoggle and colleagues (2010). Wireless units were then attached to the skin, using a thin, double-sided film sticker (Lea Medizintechnik, Germany), to avoid excessive noise caused by swinging of the transmitting unit. Thereafter, force sensors were placed under the ball and heel of each foot, inside the shoe. As the force sensors required slightly more robust fixation due to the mechanical stress placed on them, they were affixed lightly with double-sided film as before, followed by overall attachment using stronger elastic tape. Data from the force sensors were synchronized with EMG data, to determine the exact moment of foot-strike. Equipment was then calibrated with the participant laying on a table. The sampling frequency of data collection was 2000 Hz.

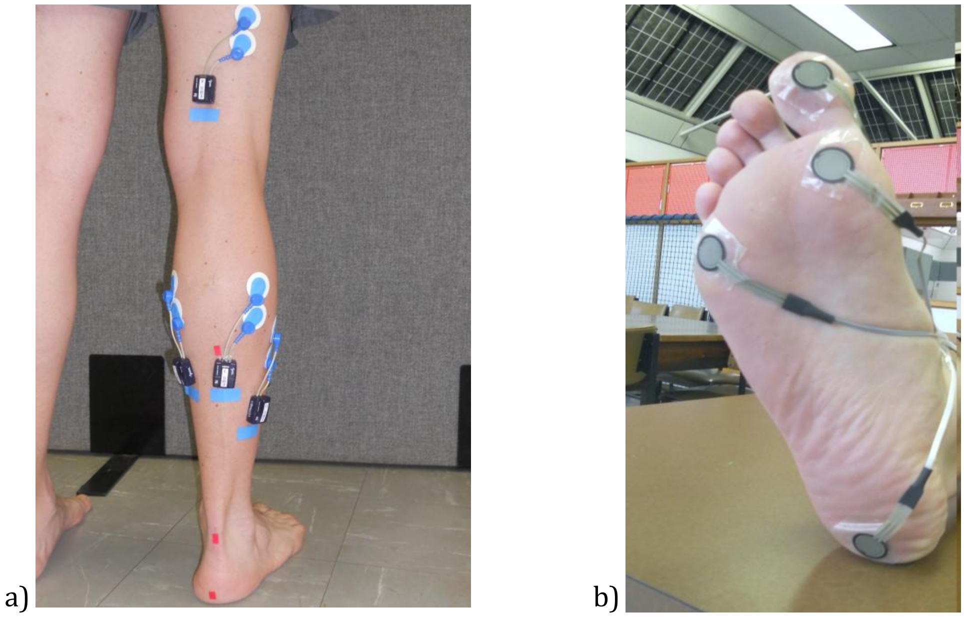


Figure 4.9. Electrode placement (a) during EMG data collection, and footswitch placement (b) for foot contact determination.

Participants were then instructed to start with a slow walk on the treadmill, to allow them to become accustomed to the sensors. Thereafter, they were instructed to start running at a steady pace of 8 km.h^{-1} for about four minutes, after which recording started. One particular research focus was to determine whether minimalistic training affects the NMC of recreational runners (over time), and therefore fatiguing protocols were not included. This approach was considered to be the first step in research, by determining whether differences exist between minimalist shoes and trainers in an unfatigued state. Future research is recommended to detemine whether fatigue amplifies or alters these differences in any way. Neuromuscular activity was recorded for approximately 60 to 80 seconds at a standard running speed of 9 km.h^{-1}. The control group wore standard trainers while the experimental group wore minimalist shoes during EMG data collection. Specific parameters that were investigated included the degree of pre-activation of specific muscles in the lower extremity prior to the moment of initial footstrike, the degree of co-activation between antagonistic muscles throughout the gait cycle, as well as total activation of each specific muscular group throughout the entire gait cycle. EMG-amplitudes were calculated in the gait-cycle phases published by Winter (1991), namely Pre-Activation, Acceptance and Push-Off. The raw signal was firstly full wave rectified and smoothed using a moving average at every 10 ms. A 60 Hz low pass zero phase Butterworth filter was applied, to preserve timing while smoothing out.

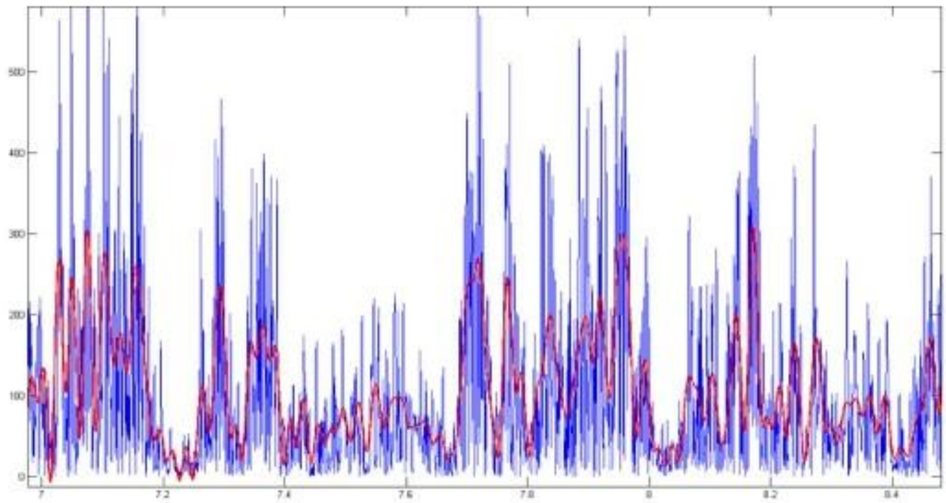


Figure 4.10. Example of the 60 Hz low pass zero phase Butterworth filtering applied to raw EMG data.

Post-processing further included the calculation of one average stride cycle out of ten consecutive stride cycles, which was to be used for data analysis. Representation of quantities of activation were calculated according to a time-normalized gait cycle, relative to earliest ground contact. Start and end of muscle activation was used to depict an on/off pattern. “On” was defined as a value higher than two standard deviations of the resting value. To find the baseline value and standard deviation the period with the lowest mean in the ten strides was used. This period length is fixed at 20% of average stride period. (i. e. if the average stride was 1 second then the researcher found the best 0.2 second period amongst the 10 strides). The footswitch was cleaned by defining a minimum period of 0.1 seconds. If the footswitch turned off for less than this specified time, it was artificial made to switch on again. This means that noisy up and downs, near the start and end of stances default to "on" until the foot switch presents with a more definite “off”. Pre-activation was then calculated as the percentage of time in a gait cycle phase that muscles were activated, prior to footstrike. Co-activation was calculated as the percentage of time in gait cycle phase that antagonistic muscles were activated at the same time.

The on/off pattern was investigated in this study, rather than the amount of activation (% maximal voluntary contraction), as previous studies have noted that eccentric muscle activation results in a smaller change in EMG amplitude, when compared to concentric activity (O’Connor *et al.,* 2004). As the muscles that are under investigation are both small and responsible for several eccentric contractions throughout the gait cycle (while the control group were expected to demonstrate more concentric contractions), the on/off pattern of analysis was deemed a better suited method for answering the research question at hand. A similar method of EMG analysis has also been described by Baur and colleagues (2011).

4. Analysis of Running Kinematics

Sagittal plane markers were placed on the greater trochanter, and on the lateral side of the knee, in the center and 2 cm above the tibial plateau. A third marker was placed at the ankle joint on the lateral malleolus, 0.05 cm anterior to its tip (De Wit *et al.,* 2000[a]).

A Canon HD (Legria HFG10) camera was mounted on a tripod and set up laterally to the treadmill. The cameras were focused onto the lower extremity of the participant, who was instructed to start running at 8 $km.h^{-1}$ on the treadmill. Participants were given 5 to 7 minutes to warm up, to ensure that adaptations made to kinematic parameters during the first four minutes to account for different shoe properties, were completed (Divert *et al.,* 2005). Both groups completed the kinematic analysis twice. The EXP group ran in minimalist shoes and barefoot, while the CON group ran in standard cushioned footwear and barefoot. Video recordings were done at 50 frames per second. After recording started, participants were encouraged to run as naturally as possible at 8 $km.h^{-1}$. After 45 seconds of recording, the speed was increased to 10 $km.h^{-1}$, and again increased to 12 $km.h^{-1}$ following the next 45 seconds. Speed flashcards were held in front of the camera (for about 3 seconds) during periods of increasing speed, to help with later identification of specific speed.

The exact protocol was then repeated in the seconds condition, and participants were again given several minutes to become accustomed to the new condition. Participants were randomly given either the barefoot or shoe condition first.

Lateral viewpoints were used to determine the angle of plantar-flexion/dorsiflexion at the moment of contact, as well as knee flexion at initial contact. Video data was uploaded onto a computer and analyzed using Dartfish software (Dartfish, U.S.A).

Figure 4.11 Photograph of Dartfish analysis done while participants ran on a treadmill, for lateral view with trainers. Participants ran at 8 $km.h^{-1}$, 10 $km.h^{-1}$ and 12 $km.h^{-1}$.

5. Joint Position Sense Testing

Kinesthesia, or joint motion sense (JMS), is evaluated by means of determining the threshold to detection of passive motion, whereas, joint position sense (JPS) is assessed by measuring accuracy of passive and active joint reproduction. Detection is processed in the somatosensory cortex, which is the highest level of cognitive functioning, and by performing these tests passively at a slow angular velocity, Ruffini, or Golgi-type joint receptors are stimulated selectively, whereas active joint reproduction stimulates both joint receptors and muscle spindle receptors (Lephart *et al.,* 1997; Ergen & Ulkar, 2008; Willems *et al.,* 2002).

Ankle joint position sense testing was performed on a Biodex Isokinetic Dynamometer (Biodex Medical Systems Inc, Shirley, New York) in both inversion/eversion mode, as well as plantar-flexion/dorsiflexion mode. The participant was seated and the dominant foot was placed and strapped onto the footplate, with the Biodex III setup in the standard inversion-eversion position. The testing protocol was thoroughly explained to the participant and three trial repetitions were given for familiarization. Once comfortable, they were blindfolded and handed the signal button.

The JPS test started in the maximal eversion position (approximately 45˚), after which the foot was passivley taken to a specific position (eg. 10˚ inversion) and held for 5 seconds. The participant was instructed to remember this position. The foot was then taken back to the starting position of 45˚ eversion (maximal eversion). Thereafter, the foot was once again slowly taken throughout the range of motion towards maximal inversion, and the participant was asked to signal with the button when they thought they reached the prior position which they had to remember. The actual angle was then recorded, and the foot taken back to the starting position. Each position had three trail repetitions, which included one movement by the Biodex to the position to be held and remembered, and one movement where the participant was asked to signal the previous position. Three positions were tested, namely 10˚ inversion, 25˚ inversion and 15˚ eversion, each with three repetitions.

a)  b) 

Figure 4.12. a) Proprioceptive testing conducted in the inversion/eversion mode. Figure 4.12b shows the hand held button used to signal target position.

Three types of errors in the subjects' ability to reach reference angles can be noted: absolute, exact, and variable errors. The absolute error measures the difference between the actual angle and the angle chosen by the participant. The exact angle determines whether the participant generally overshoot or undershoot (positive or negative). The variable error is calculated as the standard deviation of the exact angle. The same protocol was used by Willems and partners (2002).

The ankle position awareness test was also repeated in plantar-flexion/dorsiflexion mode, including three different positions (-15°, 15°, and 25°plantar-flexion, respectively), with three trail repetitions each.

2. Isokinetic Strength Testing

Isokinetic dynamometers provide a steady velocity, with variable resistance throughout the muscle range of motion. It has become a popular method for measuring dynamic muscle function, with variables obtained including torque, power and endurance (Drouin *et al.,* 2004). Using the same Biodex III Isokinetic Dynamometer (Biodex Medical Systems Inc, Shirley, NY) setup as for the proprioception testing, participants' dominant foot was strapped into the footplate. Participants were tested using the standard two-speed (30 and 60 deg.sec^{-1}) protocol for both the inversion-eversion mode, as well as the plantar-flexion/dorsiflexion mode. Prior to the start of testing the protocol was explained in detail and three to four practice repetitions were given to ensure that the participant knew exactly what to expect. Each test consisted of five repetitions at 30 deg.sec^{-1}, followed by five repetitions of 60 deg.sec^{-1}. Tests were separated by a 10 second rest period. Participants were instructed to try to improve with each repetition, and visual feedback was given on the computer screen. Peak torque, relative peak torque (peak torque divided by body mass) and antagonistic muscle strength ratios were recorded for each speed trail.

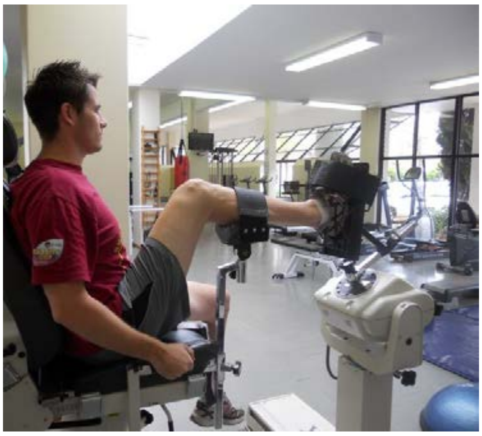


Figure 4.13. Isokinetic strength testing conducted in the inversion/eversion mode. Tests were conducted at 30 deg.sec^{-1}and 60 deg.sec^{-1}.

H. Outcome Variables

- Lower limb comfort index
- Neuromuscular control (muscle activation patterns)
- Postural control
- Joint position sense
- Isokinetic ankle joint strength
- Kinematic changes

I. Statistical Analysis

As data was spread normally parametric tests were used for statistical analysis. The level of significance was set at 95% ($p \leq 0.05$). Variables were first separated into either dependant or independat. Independent t-tests were used for training characteristics and anthropometric measurements. A four-by-two multifactorial ANOVA was done consisting of two time points (pre and post), and four groups (EXP, CON, MEN, WOMEN) for each vaiable. Thereafter LSD post-hoc tests were used to compare minimalist shoes against traditional trainers. Cohen's effect sizes were used to determine practical significance where necessary and were defined according to the criteria set out in Table 4.3.

Table 4.3 Effect size intervals according to strength of practical significance and associated qualitative outcomes.

Effect size (ES) interval	**Qualitative outcome**
≥ 0 – 0.15	Negligible (N)
≥ 0.15 – 0.40	Small (S)
≥ 0.40 – 0.75	Medium (M)
≥ 0.75 – 1.10	Large (L)
≥ 1.10 – 1.45	Very large (VL)
≥ 1.45	Huge (H)

Many of the outcome variables measured could not be directly compared between individuals, as either age-specific norms were not available (eg. isokinetic strength), or because data was not normalised (eg. EMG). Therefore, the improvement (or deterioration) of each individual from their own baseline values were rather compared between groups. Improvement was compared both in absolute format, and in percentage growth. This ensured that each individual acted as his/her own control. However, when either set of data (pre or post test) was missing or was corrupted, both data sets had to be discarded, as improvement over time could not be determined.

CHAPTER FIVE: RESULTS

A. Introduction

Following the presentation of the methodological procedures used in Chapter Four, applicable findings will be reported in the following chapter. A total of 23 participants (11 experimental; 12 control) were included for analysis of results. Findings will also be separated into men and women, for more accurate description.

B. Descriptive Characteristics

1. Participants

Basic anthropometric measurements were spread normally throughout the group, with no significant differences ($p < 0.05$) being recorded between the experimental (EXP) and control (CON) groups, with regard to their age, height, body mass, Body Mass Index (BMI), or size of their shoes. However, the age of the CON group was slightly lower than the EXP group, with a practical significance (ES = 0. 56^{M}; p = 0.21). The height of the EXP group was approximately three centimetres taller, with a large effect size of 0.94. Table 5.1 outlines the anthropometric findings.

Table 5.1. Descriptive data of EXP and CON groups for both men and women (±SD).

Variables	EXP (n=11)	CON(n=12)	P-value	Effect size
Age (years)	24 ± 3	25 ± 4	0.21	0.56^{M}
Height (cm)	178. 01 ± 8. 73	175.23 ± 10.64	0.73	0.94^{L}
Body Mass (kg)	70.74 ± 12. 14	69.13 ± 14.24	0.78	0.07^{N}
BMI(kg.m^{2})	22.63 ± 3. 12	22.43 ± 3.13	0.86	0.08^{N}
Shoe size (UK)	8 ± 2	7 ± 3	0.54	0.27^{S}

^{N} Neglible effect size , ^{S} Small effect size, ^{M} Medium effect size. ^{L} Large effect size.

*Men in the EXP and CON group were found to be taller (EXP p = 0.01; CON p = 0.02) and heavier (EXP p = 0.02; CON p = 0.03) when compared to women of the same group. Also, there was a significant difference between genders (EXP p = 0.04; CON p = 0.03) in shoe size, with men wearing larger shoes than women. Although not statistically significant (p>0.05), practically significant differences for BMI were observed between men and women in the CON and EXP groups (EXP ES = 0.99; CON ES = 0.85).

2. Baseline Performance Variables

No statistically significant ($p<0.05$) differences were noted between the EXP and CON groups, for HR rate at anaerobic threshold (HR_{AT}), maximum heart rate (HR_{max}), maximal oxygen capacity (VO_{2max}), oxygen capacity at anaerobic threshold (VO_{2AT}) or minute ventilation at anaerobic threshold (VE_{AT}). However, practically significant differences were noted between groups for HR_{AT} (ES = 0.67) and $HR_{max.}$ (ES = 0.57). Results from VO_{2max} testing prior to the intervention are presented in Table 5.2.

Table 5.2. Results from VO_{2max} testing prior to intervention (±SD)

Variables	EXP(n=11)	CON(n=12)	P-value	Effect Size
HR_{AT}	175.72 ± 6.42	170.24 ± 10.21	0.15	0.67^{M}
HR_{max}	192.23 ± 5.45	188.24 ± 8.93	0.22	0.57^{M}
VO_{2max} (ml/min/kg)	43.63± 5.06	43.86 ± 4.47	0.59	0.25^{S}
VO_{2AT}	37.63 ± 4.66	37.95 ± 4.26	0.86	0.01^{N}
VE_{AT} (L/min)	107.23 ± 20.36	114.25 ± 21.23	0.43	0.35^{S}

^{N} Negligible effect size^{S} Small effect size. ^{M} Medium effect size.

*Men and women in the EXP group did not differ significantly for any of the Baseline Performance Values, nor did the CON group.

3. Training History Variables

Table 5. 3 briefly describe the CON and EXP group training histories. There was no significant difference ($p<0.05$) between EXP and CON group running experience, weekly training, number of sessions per week, or shoe heel cushioning. A moderate practically significant difference was observed for running experience (ES = 0.48^{M}) between participants of the two groups, with the EXP group demonstrating slightly more running experience.

Table 5.3. Summary of training history variables, including running experience, weekly training, sessions per week and average shoe heel height.

Variables	EXP(n=11)	CON(n=12)	P-value	Effect Size
Shod running experience(yrs)	3 ± 1	2 ± 1	0.26	0.48^{M}
Weekly Training(km)	16.71 ± 5.32	18.13 ± 6.35	0.58	0.23^{S}
Number of Sessions per Week	3.12 ± 0.43	2.95. ± 0.50.	0.41	0.37^{S}
Shoe Heel Cushioning (mm)	26.90 ± 3.03	27.34 ± 2.92	0.79	0.21^{S}
10km time(min)	51.34 ± 16.72	57.22 ± 7.83	0.21	0.48^{M}

^{S} Small effect size ^{M} Medium effect size.*No significant differences existed between genders for either the EXP or CON group.

C. Training Performance

1. Total Performance Variables

Following the overview on pre-intervention training status and running history, the 8-week training data will now be portrayed in Table 5.4. Details pertaining to program adherence will also be highlighted, by describing training qualities. While not statistically significant ($p<0.05$), EXP group runners tended to run further on average, when compared to CON runners ($p=0.06$; ES = 0.98[L]). As the total time run (hours) did not differ significantly ($p = 0.05$) between groups, the EXP group ran slower.

Table 5.4. Total distance (km) and total time (min) run throughout the intervention period for both EXP and CON groups (x ± SD)

Variables	EXP (n=11)	CON (n=12)	P-Value	Effect Size
Distance (Km)	181.41 ± 10.52[#]	171.64 ± 10.86	0.06	0.98[L]
Time (Hrs)	19.73 ± 1.96	18.62 ± 3.50	0.39	0.39[S]

[S] Small effect size; [L] Large effect size.

*No differences existed between genders in either the EXP or CON group.

2. Session Performances

Figure 5.1 a, b and c, illustrates the average distance (a), duration (b) and heart rate(c) during each session, for CON and EXP groups, separately. The EXP group ran for a significantly longer distance during session six ($p = 0.04$; ES = 1.21[VL]), while the CON group ran significantly longer during session nine ($p= 0.01$; ES = 1.32[VL]). The heart rate of the EXP group was also significantly lower during sessions four ($p = 0.01$), five ($p = 0.04$), seven ($p = 0.01$), twelve ($p = 0.01$) and fourteen ($p < 0.01$). No significant differences were noted between groups for session durations.

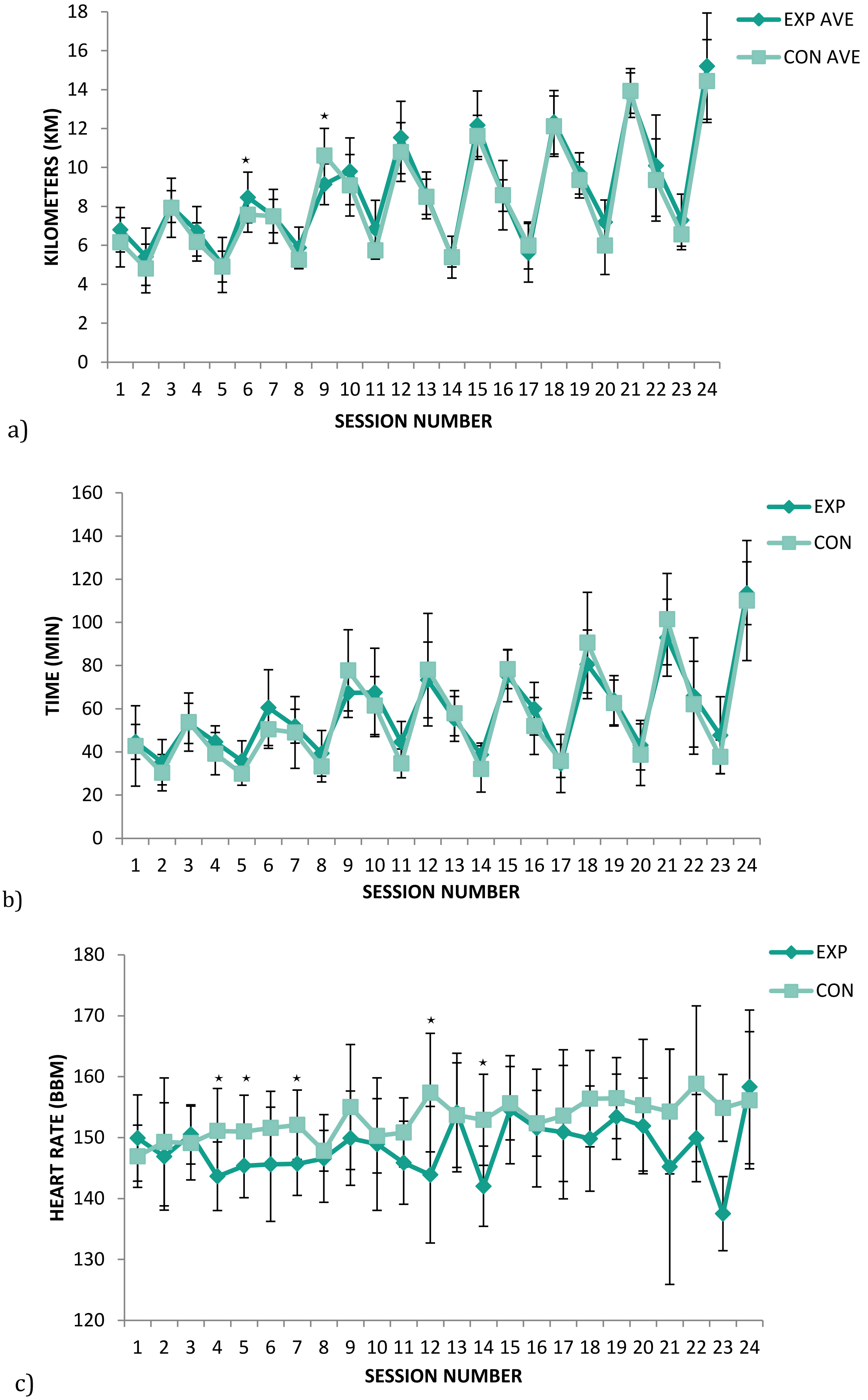


Figure 5.1. The average (a) distance (km), (b) average duration (min) and average heart rates (bpm) during each session, for CON and EXP groups (± SEM). *$p < 0.05$

3. Experimental Group Progression Into Minimalist

The EXP group transition from trainers to minimalist shoes will next be considered. Participants ran in minimalist shoes for approximately 16% of the total distance of the first session at the start of the program, and aimed at increasing the distance in minimalist shoes by approximately 10% weekly. At the end of the program the maximal percentage of distance run in minimalist shoes by the EXP group was 79%, indicating a weekly increase of 6%. An overview of the total distances ran in minimalist shoes, as an absolute value as well as a percentage of the total distance, throughout the entire 8-week period is provided in Table 5.6.

Table 5.5. EXP group progression into minimalist shoes (x ± SD).

Session Number	Ave Total Distance (Exp Group)	Sd	Ave Dist Minimalist	Sd2	Ave % Of Total In Minimalist	Sd3
1	6.81	1.14	1.09	1.38	16.02	18.51
2	5.42	1.47	1.11	1.17	20.49	20.25
3	8.00	0.82	2.21	1.31	27.63	16.70
4	6.73	1.27	2.60	0.87	38.65	7.53
5	5.00	1.41	1.69	0.65	33.75	26.85
6	8.47	1.30	3.40	0.95	40.15	14.30
7	7.51	0.86	2.96	0.56	39.41	5.68
8	5.89	1.05	2.39	1.05	40.57	10.13
9	9.14	1.05	3.16	0.45	34.57	8.52
10	9.81	1.71	4.87	1.47	49.68	18.60
11	6.86	1.46	3.57	0.98	52.08	9.76
12	11.54	1.86	4.78	1.56	41.39	10.01
13	8.57	1.20	5.03	1.79	58.64	20.36
14	5.39	0.50	2.57	1.27	47.67	24.78
15	12.18	1.76	6.90	2.69	56.66	12.99
16	8.56	0.81	5.53	1.62	64.58	20.14
17	5.63	1.51	4.81	2.17	85.56	23.40
18	12.33	1.63	7.35	2.01	59.59	18.07
18	9.70	1.06	5.65	3.11	58.25	34.47
20	7.20	1.14	5.50	2.22	76.39	21.99
21	13.72	1.14	8.70	2.45	63.41	17.53
22	10.10	2.60	7.90	2.77	78.22	19.90
23	7.30	1.34	5.75	2.04	78.77	24.31
24	16.01	2.73	8.10	4.20	50.59	28.43

Table 5.6. Total distances run by EXP group, in minimalist, total minimalist and trainers combined, as well as the percentage of total distance run in minimalist shoes.

Variable	Distance Minimalist (km)	Total Distance (Minimalist & Trainer) (km)	% Total Distance
EXP Group	95.14 ± 13.12	181.44 ± 12.22	52.30 ± 5.81

4. Lower Limb Comfort Index

Figure 5.2 illustrates the level of comfort or discomfort experienced during each session, as an average of the scores between the EXP and CON group. Values are given as a score out of 36, which is the highest possible value obtainable (indicating greatest possible comfort).

Comfort scores decreased considerably with sessions of increasing distance. This trend was observed in both the CON and EXP groups, where increases in distance affected comfort scores notably (increased distance resulted in decreased LLCI score). When comparing LLCI scores throughout the intervention, the EXP group averages were considerably lower than CON scores. Experimental group LLCI scores were found to be significantly lower in sessions seven ($p < 0.01$), fifteen ($p < 0.01$), eighteen ($p = 0.01$), twenty ($p = 0.02$) and twenty-two ($p = 0.02$).

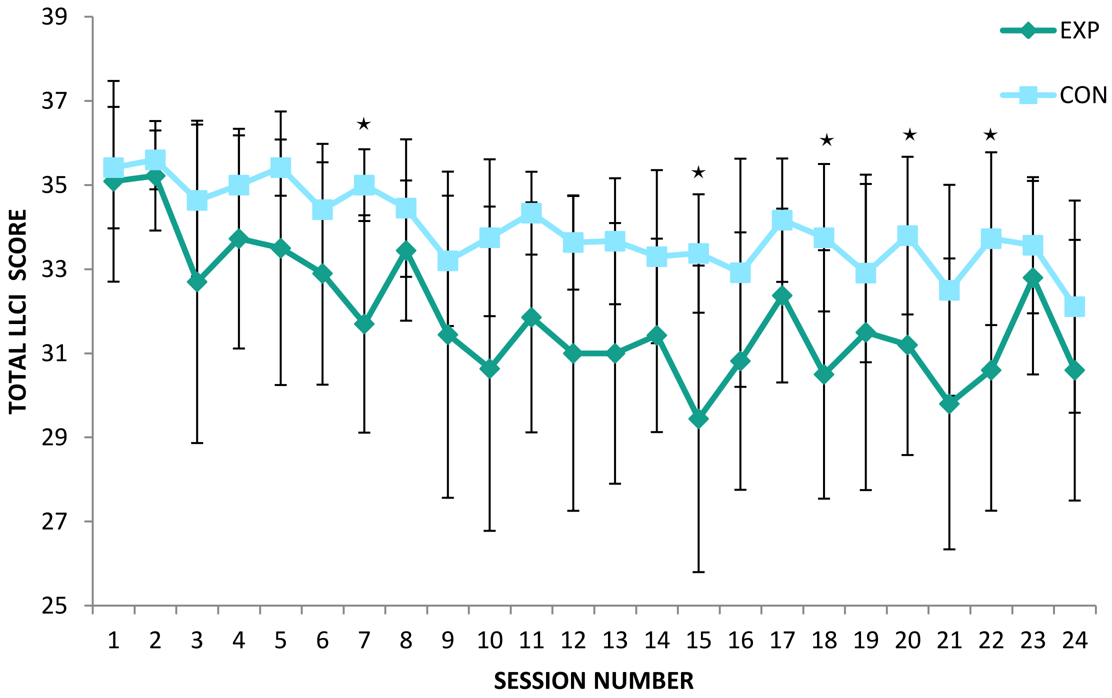


Figure 5.2. Average total LLCI Scores for each session for both EXP and CON groups (± SEM). *$p < 0.05$.

When considering the average of each anatomical area across groups, throughout the duration of the intervention period, the EXP group demonstrated significantly more discomfort in the calf ($p < 0.01$), Achilles ($p < 0.01$), foot ($p = 0.01$) and ankle ($p < 0.01$) areas. The CON group had more discomfort in the knee area ($p < 0.01$) when compared to EXP. Average scores for each anatomical area are presented in Figure 5.3. for EXP and CON groups.

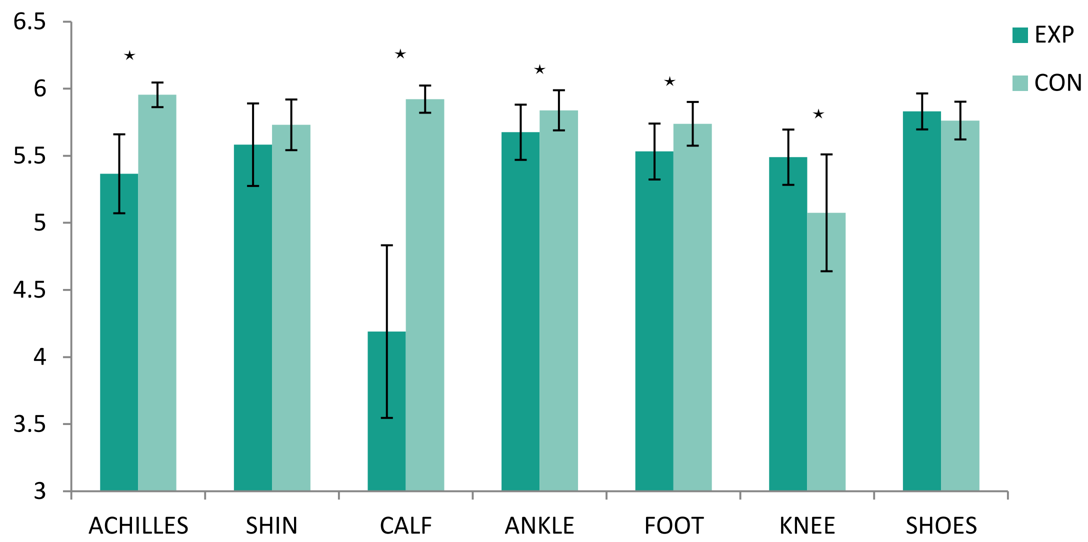
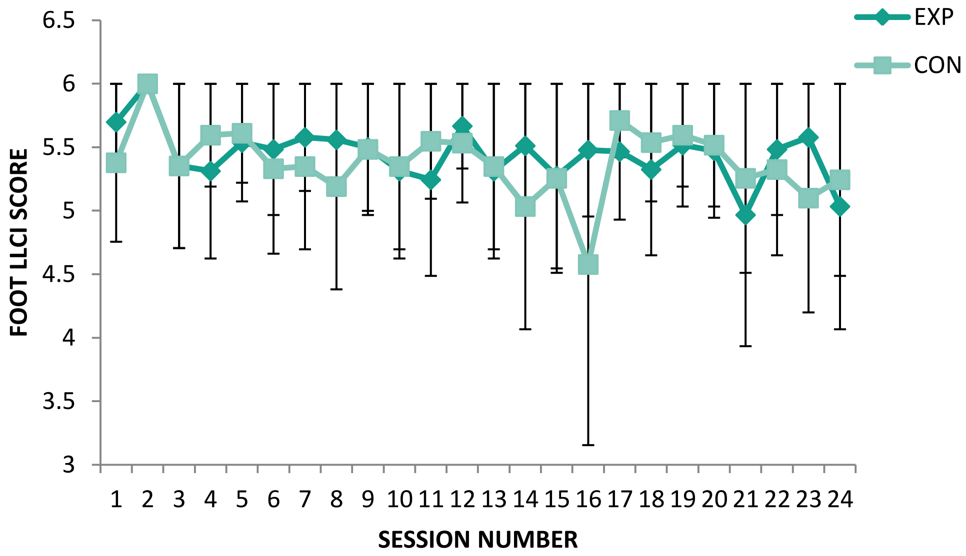


Figure 5.3. Average LLCI scores for each anatomical area over the duration of the intervention period for EXP and CON groups (± SEM). * $p < 0.05$.

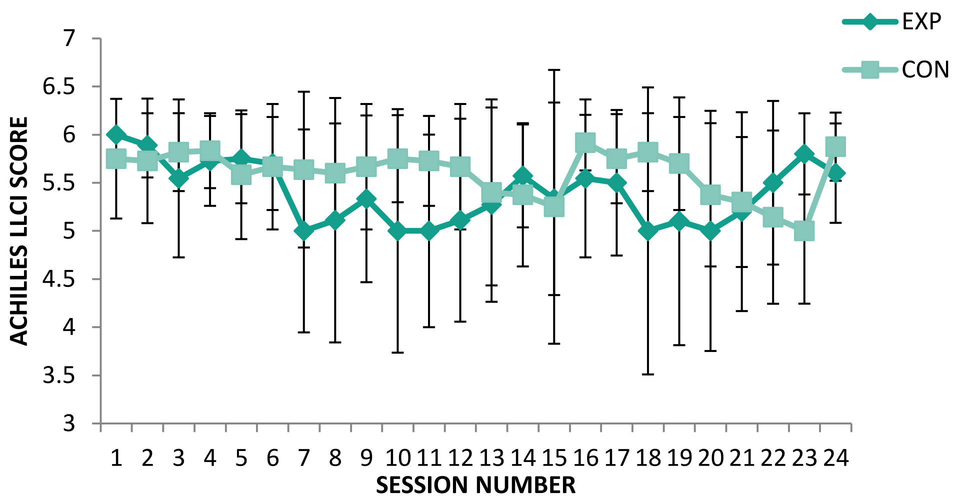
In Figures 5.4 (a-g) LLCI scores compare specific anatomical areas of EXP and CON groups, for each running session. No statistically significant differences were observed between groups in the foot or Achilles, for specific running sessions. This was due to large variability in foot and Achilles LLCI scores. In the calf, however, the EXP group demonstrated significantly more discomfort for sessions five ($p = 0.05$), six ($p < 0.01$), nine ($p = 0.04$) and sessions ten to twenty-four ($p < 0.01$).

LLCI scores were significantly lower in the calf for the EXP group, from session three onwards (p=0. 04) up to session 22 (p=0. 01), when compared to the CON group. On the other hand, CON group experienced significantly more knee discomfort during sessions eleven (p=0. 05) and twelve (p=0. 02), when compared to the EXP group. No significant differences existed between groups for the shin, shoe or ankle areas ($p > 0.05$). While tendencies were noted for sessions eight ($p = 0.08$) and twenty-three ($p = 0.07$), significantly lower knee LLCI scores were only noted for the CON group, in session twenty-four ($p = 0.04$).



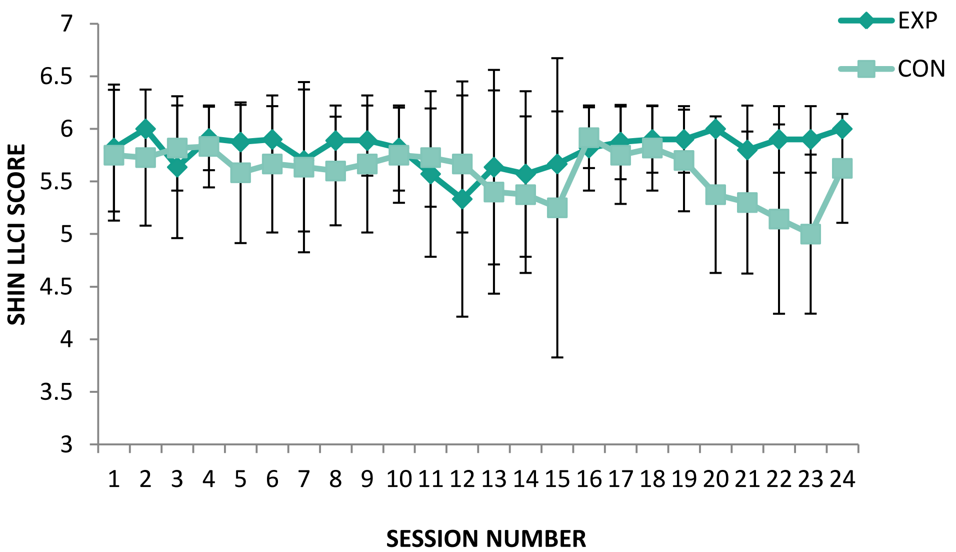
EXP
CON
FOOT LLCI SCORE
6.5
6
5.5
5
4.5
4
3.5
3
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
SESSION NUMBER

a)



EXP
CON
ACHILLES LLCI SCORE
7
6.5
6
5.5
5
4.5
4
3.5
3
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
SESSION NUMBER

b)



EXP
CON
SHIN LLCI SCORE
7
6.5
6
5.5
5
4.5
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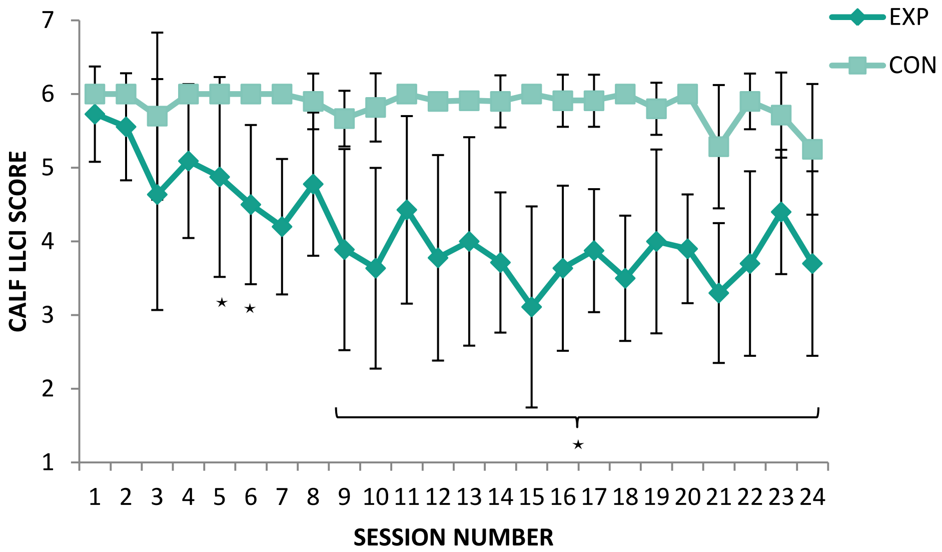
3.5
3
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
SESSION NUMBER

c)


EXP
CON
CALF LLCI SCORE
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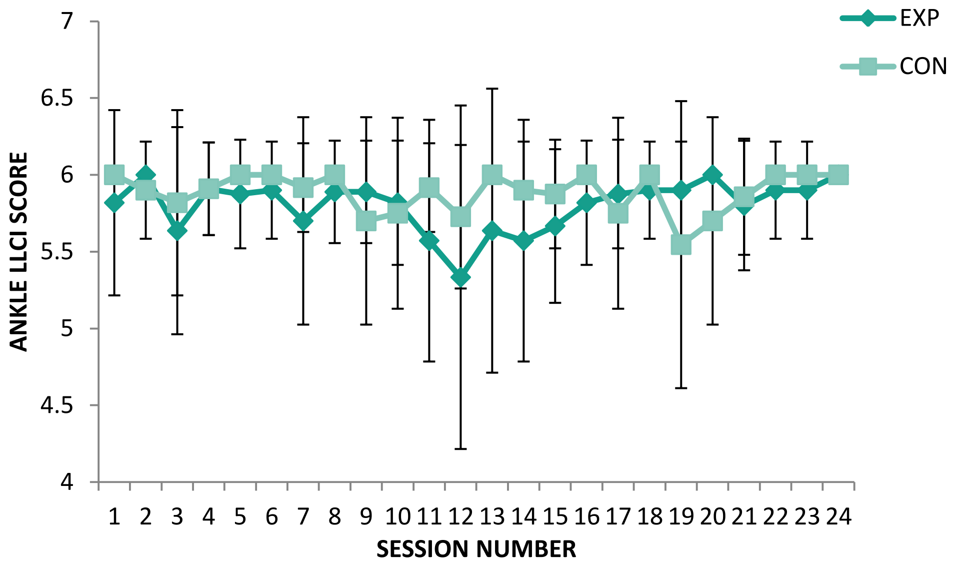
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
SESSION NUMBER

d)


EXP
CON
ANKLE LLCI SCORE
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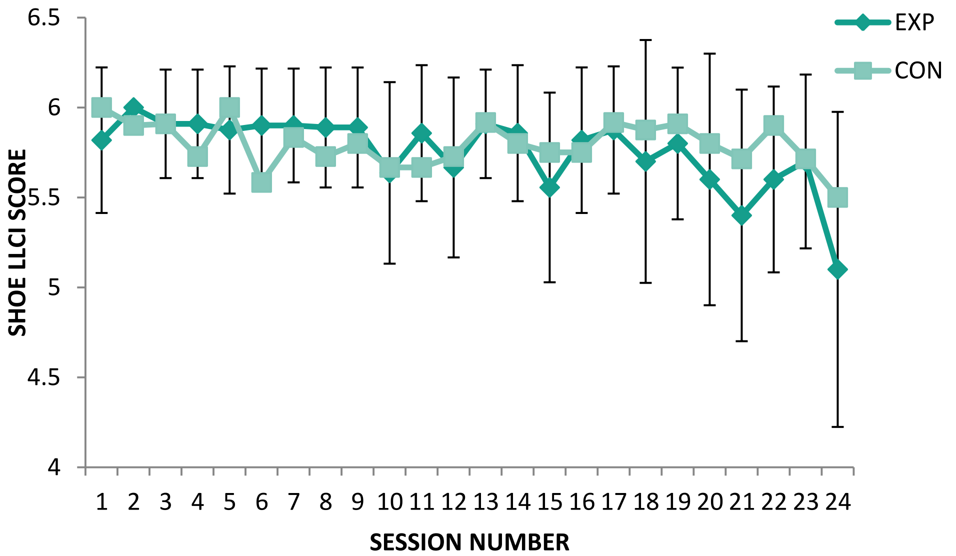
SESSION NUMBER

e)


EXP
CON
SHOE LLCI SCORE
6.5
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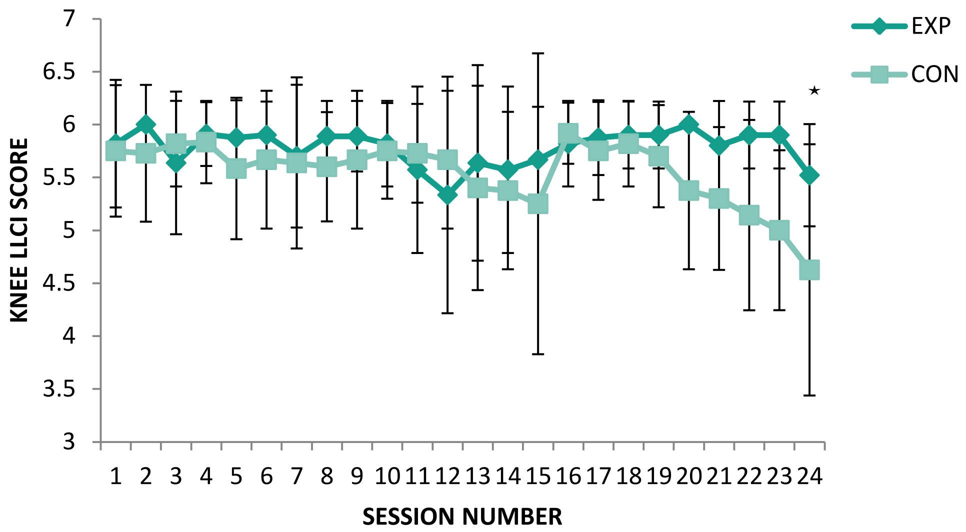
4
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
SESSION NUMBER

f)



g)

Figure 5.4. LLCI scores for each anatomical area, given for EXP and CON groups, across each session. The session number is plotted on the x-axis. The anatomical areas are as follows a) foot, b) Achilles, c) shin, d) calf, e) ankle, f) shoe, g) knee (± SEM). *p < 0.05

5. Adverse Reactions

The most prominent cause for discomfort was excessive tightness of lower calves and Achilles tendon, which was experienced by most runners in minimalist shoes at some point in time during the study. Calf tightness was also experienced with increasing intensity following longer distance runs. Further, most participants experienced blistering of feet, especially around the underside of the toes. This was due to increasing training volume, as both EXP and CON groups struggled with blistering. Four EXP participants developed slight Medial Tibial Stress Syndrome (MTSS) during session eleven to fifteen, which caused some discomfort but did subside somewhat thereafter. The participants were constantly evaluated to determine whether deterioration occurred, but severity of the MTSS did not increase. In some cases, these participants took an extra rest day following long runs (but then decreased rest days between short runs to remain within the parameters of the study). A total of seven cases of patellofemoral pain were reported, five of which occurred in the CON group (three women, 2 men). In general the knee pain experienced in the CON group was more severe than the EXP group. However, one of the participants in the EXP group chose to withdraw from the study due to severe knee discomfort. The other EXP group participant with knee pain presented with pain slightly more superior on the patella, indicating that a possible Pattellar Tendinopathy was present. Symptoms of Plantar Fasciitis were observed in four runners, however, none of these cases deteriorated to the point of missing running sessions, and neither did any participants seek any form of medical attention. Lastly, it must be noted that one of the female EXP participants withdrew due to an inversion sprain, causing a grade 2 tear of the tibiocalcaneal ligament. This injury was obtained during a trial running event, which she chose to participate in outside of the study.

D. Calf Circumferences

Both the EXP and CON groups demonstrated statistically significant changes in the dominant (EXP $p < 0.01$; CON $p < 0.01$) and non-dominant legs (EXP $p < 0.01$; CON $p < 0.01$) over time. However, at post testing there were no statistically significant differences between groups ($p = 0.99$). Figure 5.30 illustrates the differences in EXP and CON in calf circumferences at post testing compared to pretesting. Medium practically significant differences were noted between groups for both the dominant (ES = 0.68[M]) and non-dominant legs (ES = 0.65[M]). Average change in calf circumferences can be seen in Figure 5.5 for EXP and CON groups. No significant differences were observed between men and women for either leg ($p > 0.05$).

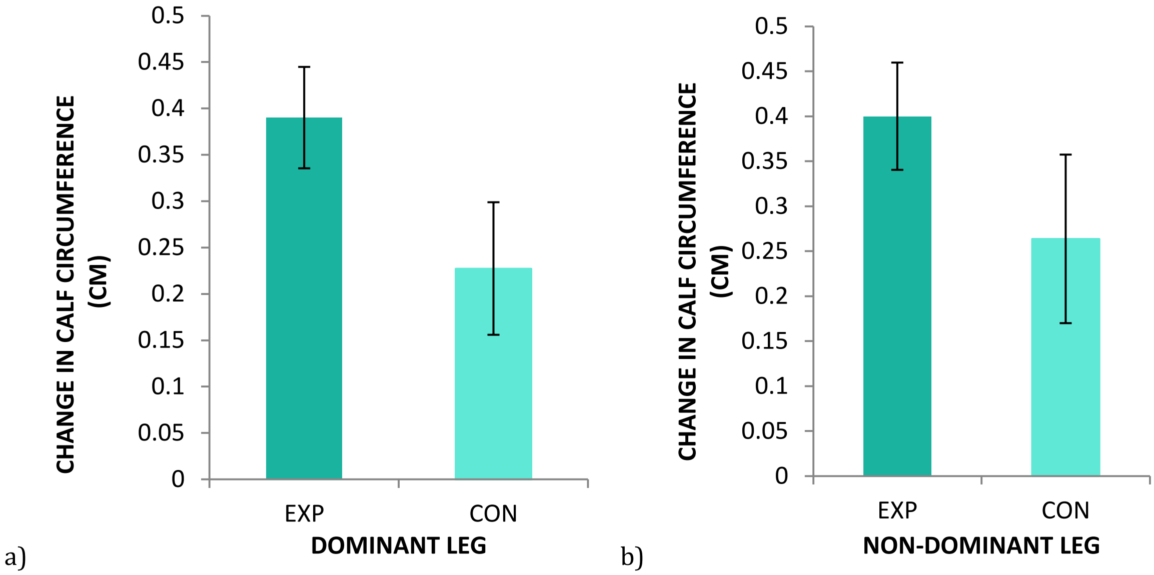


Figure 5.5. Average change in calf circumference as measured prior to and after the intervention period, for the CON and EXP groups in a) dominant leg and b) non-dominant leg (± SEM).

E. Outcome Variables

1. Electromyographical (EMG) Measures

i. Tibialis Anterior Pre-activation

Strong tendancies for significant time effects occurred for the tibialis anterior in the dominant leg (p = 0.06) but not the non-dominant (p = 0.90). Likewise an interaction tendancy was noted in the dominant (p = 0.09) but not in the non-dominant (p = 0.34). Dominant leg Tibialis Anterior (TA) pre-activation occurred considerably closer to initial foot contact in the CON group (0.17% of the entire gait cycle) (p = 0.14), whereas the change in pre-activation time for the EXP group (Figure 5.6) was relatively small (p = 0.28) (-0.02%). A large practically significant difference was noted between groups for the dominant leg, (p = 0.12; ES = 0.79[L]), with the CON group demonstrating later pre-activation. However, the non-dominant leg showed little change in pre-activation for both groups (EXP p = 0.81; CON p = 0.82), and was not statistically or practically significant (p = 0.40; ES = 0.08[N]) between groups.

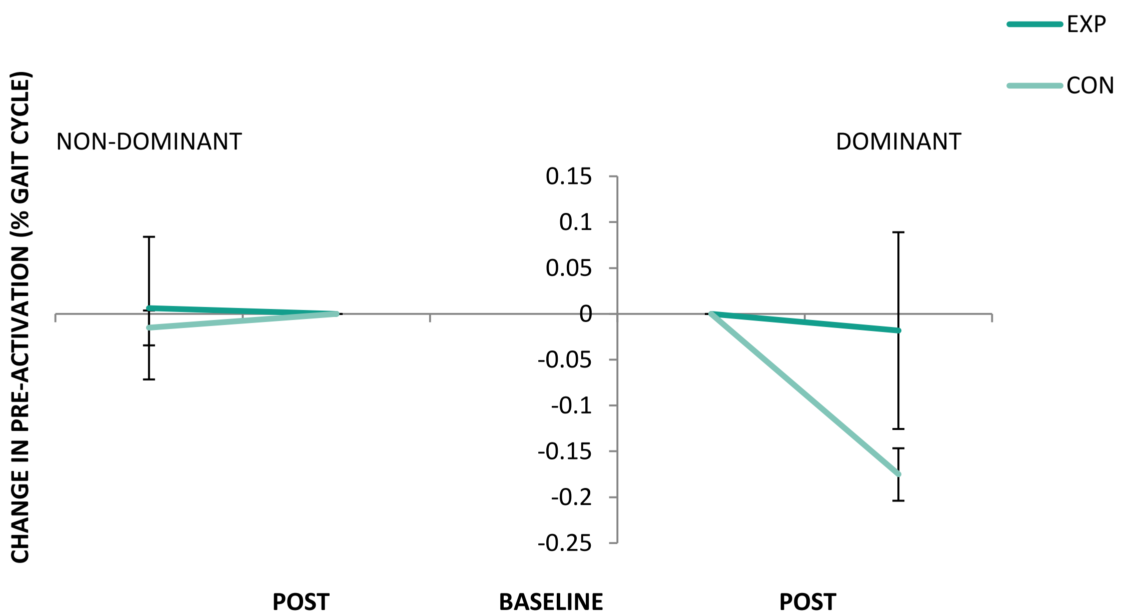


Figure. 5.6 Change in TA pre-activation, as the percentage of the gait cycle, from baseline to post-testing in the dominant and non-dominant legs for EXP and CON groups (± SEM).

ii. Peroneus Pre-Activation

Significant time effects were observed for the dominant leg (p = 0.01) but not for the non-dominant (p = 0.62). Interaction effects were noted in the dominant (p= 0.08) but not for the non-dominant (p = 0.25). Overall Peroneus (PER) pre-activation decreased by 0.17% in CON group's dominant leg (p = 0.05), whereas the EXP group demonstrated only a slight decrease in pre-activation (-0.04%) (p = 0.09). No statistically significant differences were observed between groups, however a practically significant difference was noted between groups (p = 0.09; ES = 1.36[VL]) indicating a decrease in pre-activation time for the dominant leg of the CON group. Pre-activation in the non-dominant leg did not change significantly for either group (EXP p = 0.95; CON p = 0.59), and the differences were not statistically or practically significant (p = 0.28; ES = 0.15[N]).

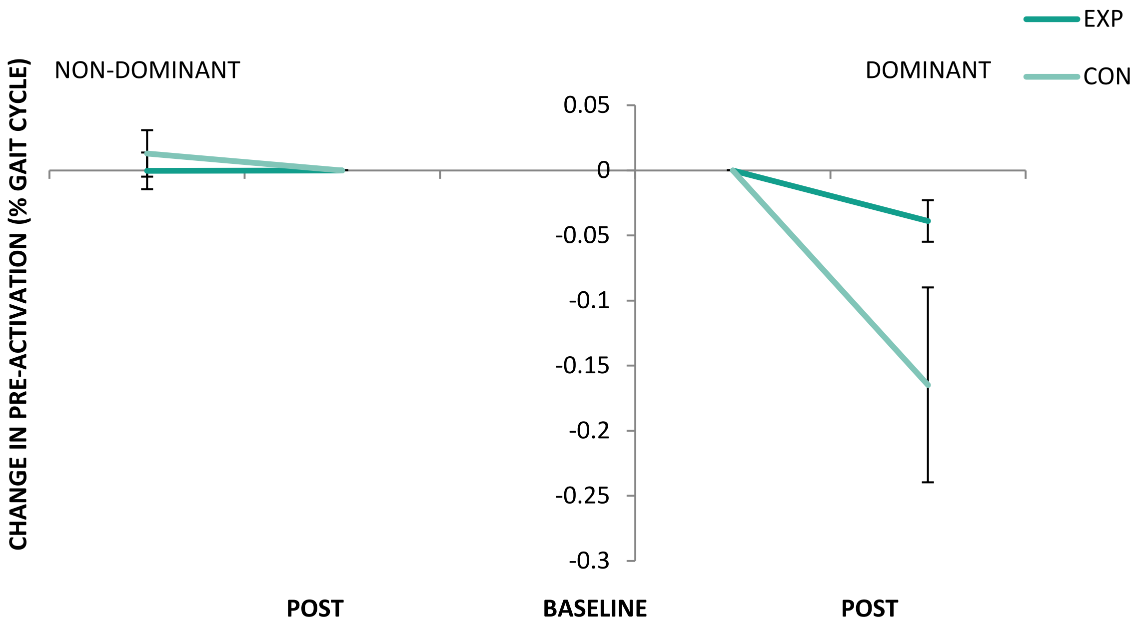


Figure. 5.7 Change in PER pre-activation, as a percentage of the gait cycle, from baseline to post testing in non-dominant and dominant legs of EXP and CON groups (± SEM).

iii. Lateral Gastrocnemius Pre-activation

Significant time effects were not observed for either leg (non-dominant p = 0.32; dominant p = 0.68). Pre-activation in the dominant leg increased by 0.01% for the EXP group (p = 0.52), while the CON group decreased by 0.03% over time (p = 0.22). Therefore the EXP group demonstrated practically significant earlier pre-activation in the dominant leg (p = 0.11; ES = 0.88[L]). In the non-dominant leg the EXP group increased pre-activation by 0.03% (p = 0.19), while the CON group showed almost no change (p = 0.93). This resulted in the medium practically significance only (p = 0.21; ES = 0.54[M]).

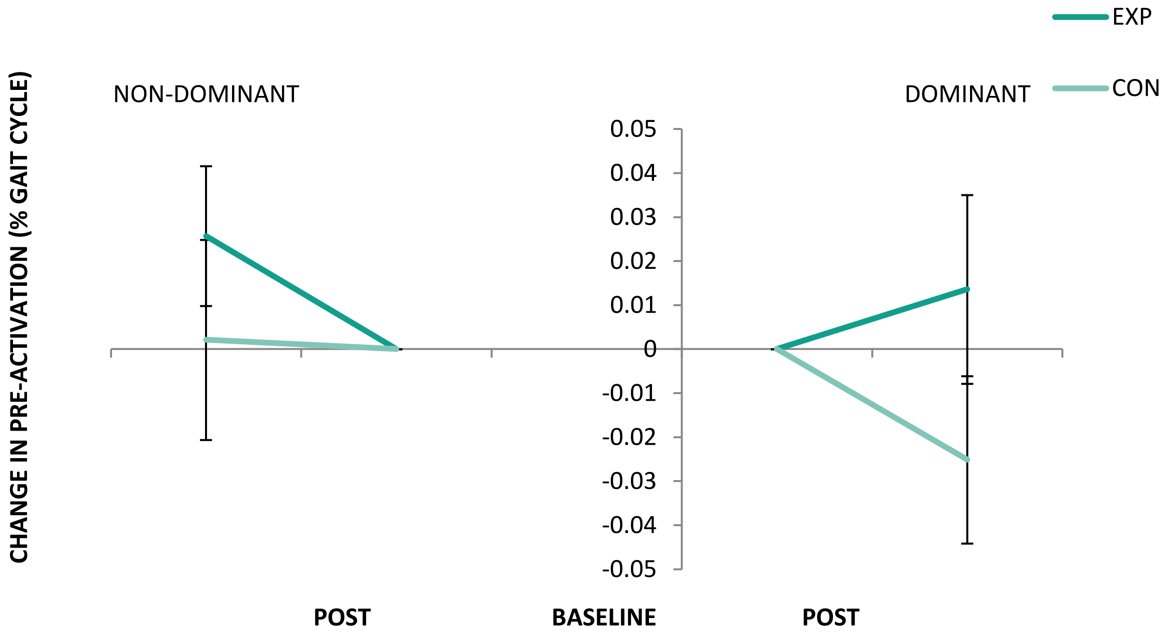


Figure. 5.8 Change in LG pre-activation, as a percentage of the gait cycle, from baseline to post testing in non-dominant and dominant legs of EXP and CON groups (± SEM).

iv. Medial Gastrocnemius Pre-Activation

Significant time effects were observed for the dominant leg pre-activation (p = 0.02), but not the non-dominant (p = 0.68). As can be seen in Figure 5.9, dominant leg medial gastrocnemuis (MG) pre-activation time decreased in both the EXP (0.03%) (p = 0.20) and CON groups (0.12%) (p = 0.06). The non-dominant leg demonstrated no change for the EXP group, while a very small increase of 0.01% was noted for the CON group. Statistically significant differences were not observed for either leg (dominant p = 0.14; non-dominant p = 0.42), however, practically significant differences were noted between groups for the dominant leg (ES = 0.71[L]), but not for the non-dominant (ES = 0.24[S]).

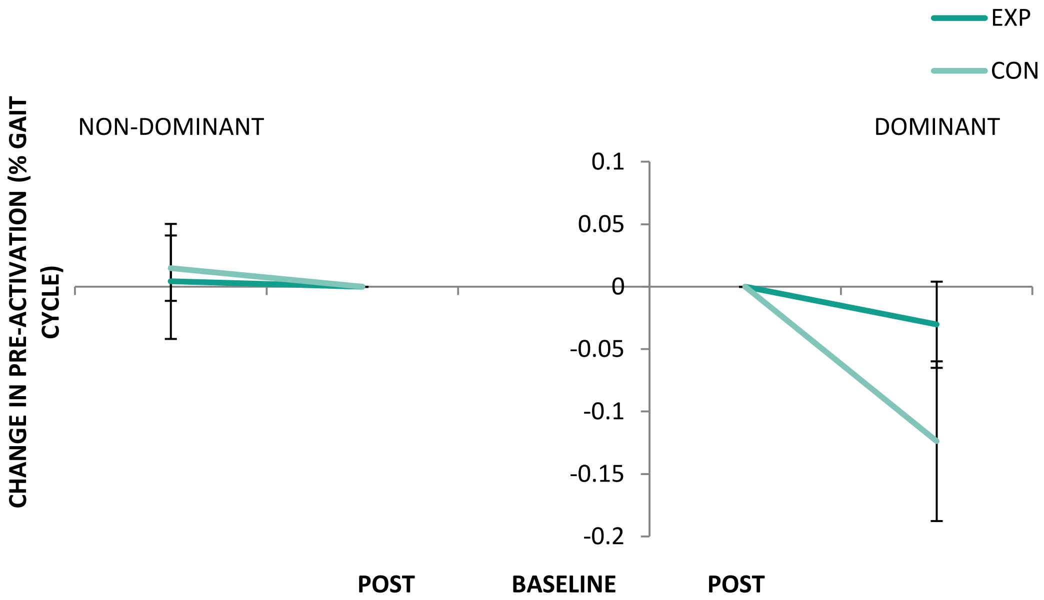


Figure. 5.9. Change in MG pre-activation, as a percentage of the gait cycle, from baseline to post testing in non-dominant and dominant legs of EXP and CON groups (± SEM).

v. Gender Differences

When considering TA pre-activation in women only, the CON group demonstrated later pre-activation in the dominant leg (-0.03%; p = 0.13), while the EXP group demonstrated smaller decreases (-0.03%; p = 0.34). Strong tendencies and practically significant differences were found for the dominant leg (p=0.06; ES = 1.18[L]), indicating that CON women showed later pre-activation compared to EXP women. In the non-dominant leg, the CON group decreased pre-activation by -0.04% (p = 0.53) and the EXP group decreased by -0.01% (p = 0.82). Therefore, very large practically significant differences were noted for the non-dominant (ES=1.1[L]) leg, with CON group showing later pre-activation. Men in the CON group decreased pre-activation in the dominant leg slightly (p = 0.5), while the non-dominant leg demonstrated little change and large variability (p = 0.99). The EXP group demonstrated smaller decreases in pre-activation for the dominant leg (p = 0.30), resulting in medium practically significant differences between groups. While the non-dominant leg of CON group did not change significantly over time, the EXP group increased pre-activation slightly (p = 0.75). Practically significant differences were observed between men of the CON and EXP groups non-dominant leg (p = 0.11; ES = 0.86[L]) as well (Figure 5.11b).

When considering PER pre-activation in women separately, the CON group (Figure 5.10a and 11a) showed a decreased activation time of 0.22% in the dominant leg, but a slightly increased pre-activation time of 0.04% in the non-dominant leg. Similarly, the EXP group also decreased in dominant leg pre-activation time by 0.01%, while an increased pre-activation time was noted in the non-dominant (0.01%). Statistically significant differences were noted between groups for the dominant leg (p = 0.04) only, with an analogous practical significance of 1.3 (ES^{VL}). Pre-activation between female groups did not differed significantly for the non-dominant leg (p < 0.01; ES = 0.98^{L}). Men in the CON group (Figure 5.10b and 5.11b) demonstrated decreases in pre-activation of 0.12% in the dominant, but no change in the non-dominant. The men in the EXP group also demonstrated very little change in the non-dominant leg, while the dominant leg decreased by 0.05%. As the CON group showed greater decreases in pre-activation practically significant differences were noted in the dominant leg between groups (p = 0.25; ES = 0.51^{M}), but not for the non-dominant leg (p = 0.12; ES = 0.13^{N}).

Women in the CON group decreased LG pre-activation time by 0.01% in the dominant leg (p = 0.17) and 0.01% in the non-dominant leg (p = 0.67), while EXP group women increased in pre-activation time by 0.05% in both the non-dominant (p = 0.18) and dominant legs (p = 0.37) (Figure 5.10a and 5.11a). Statistically significant differences were observed between women of the CON and EXP groups, in the non-dominant (p < 0.01; ES = 4.65^{H}), while very large practically significant differences were noted between groups for the demonstrated (p = 0.10; ES = 1.15^{VL}). Men in the CON group decreased in pre-activation time in the dominant leg by 0.57% (p = 0.39), but increased by 0.01% (p = 0.79) in the non-dominant leg. Men in the EXP group also decreased in pre-activation by 0.01% (p = 0.66) in the dominant leg, while increasing by 0.02% (p = 0.45) in the non-dominant (Figure 5.10b and 5.11b). As men in the EXP group demonstrated less decreases in dominant leg pre-activation than the CON group men, practically significant differences were observed between groups in the dominant leg (p = 0.22; ES = 0.61^{M}), but not in the non-dominant leg (p = 0.44; ES = 0.11^{S}).

By further analysing MG pre-activation findings according to genders, it was found that women (Figure 5.10a and 5.11a) in the CON group demonstrated large decreases in pre-activation time (0.13%) (p = 0.18) in the dominant leg, with smaller increases in the non-dominant leg (0.06%) (p = 0.48). Experimental women, however, increased pre-activation time in both the non-dominant (0.05%) (p = 0.40) and dominant legs (0.04%) (p = 0.72). This resulted in statistically significant differences between groups (dominant p = 0.04; non-dominant p < 0.01). Practically significant differences were also noted between CON and EXP groups in the dominant leg (ES = 1.33^{VL}) and non-dominant (ES = 0.67^{M}) leg. Men did not demonstrate statistically or practically significant differences in either leg (dominant p = 0.31; non-dominant p = 0.23) (Figure 5.10b and 5.11b), with groups demonstrating similar change in both the dominant leg (EXP p = 0.19; CON p = 0.33) and non-dominant leg (EXP p = 0.71; CON p = 0.81) over time.

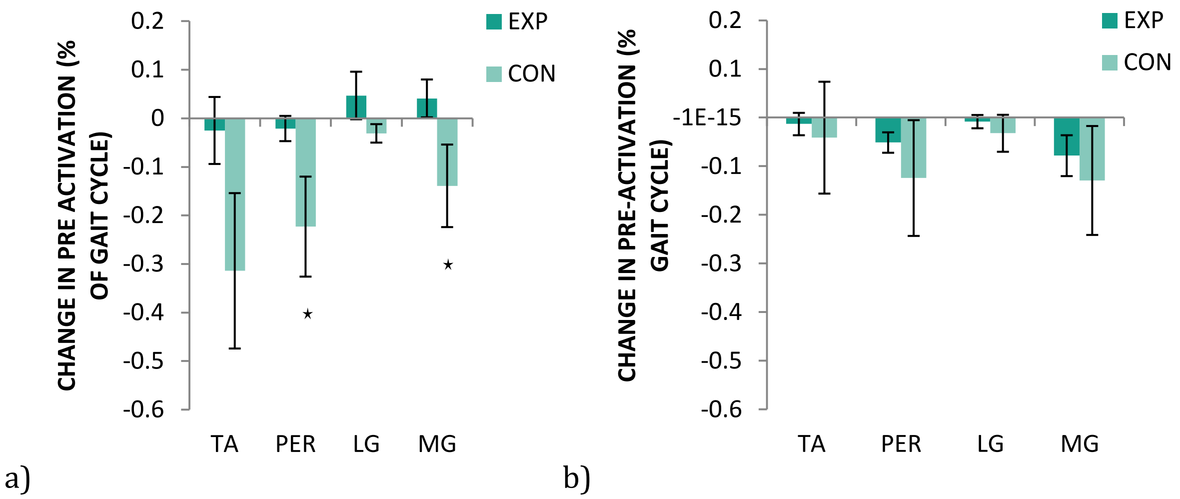


Figure 5. 10. Change in pre-activation, as a percentage of the gait cycle, from baseline to post-testing for the dominant leg of a)women, b) men of both the EXP and CON groups.

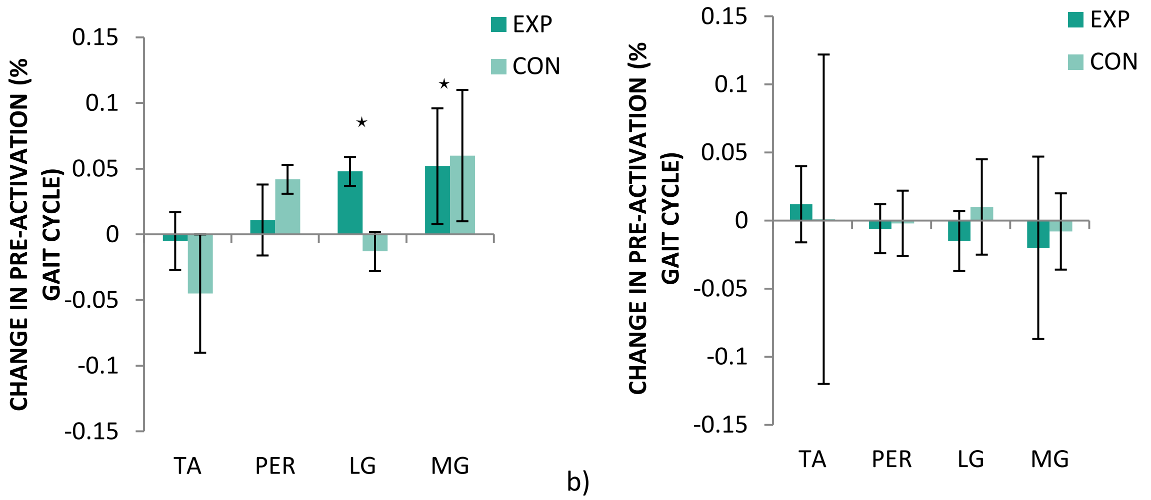


Figure 5. 11. Change in pre-activation, as a percentage of the gait cycle, from baseline to post-testing for the non-dominant leg of a)women, b) men of both the EXP and CON groups.

vi. Tibialis Anterior-Medial Gastrocnemius (TA-MG) Co-Activation

Significant time effects were not observed for either leg (dominant p = 0.56; non-dominant p = 0.38). As can be seen in Figure 5.12 the CON group presented with a 0.15% increase in co-activation (p = 0.31) in the dominant leg at post testing, while the EXP group did not change notably (0.02%) (p = 0.97). This resulted in a practically significant difference (ES = 0.59^{M}; p = 0.18) between groups at post testing. Non-dominant leg co-activation decreased slightly in both the EXP (-0.08%) (p = 0.47) and CON groups (-0.02%) (p = 0.68), although differences were not significant (p = 0.33; ES = 0.26^{S}).

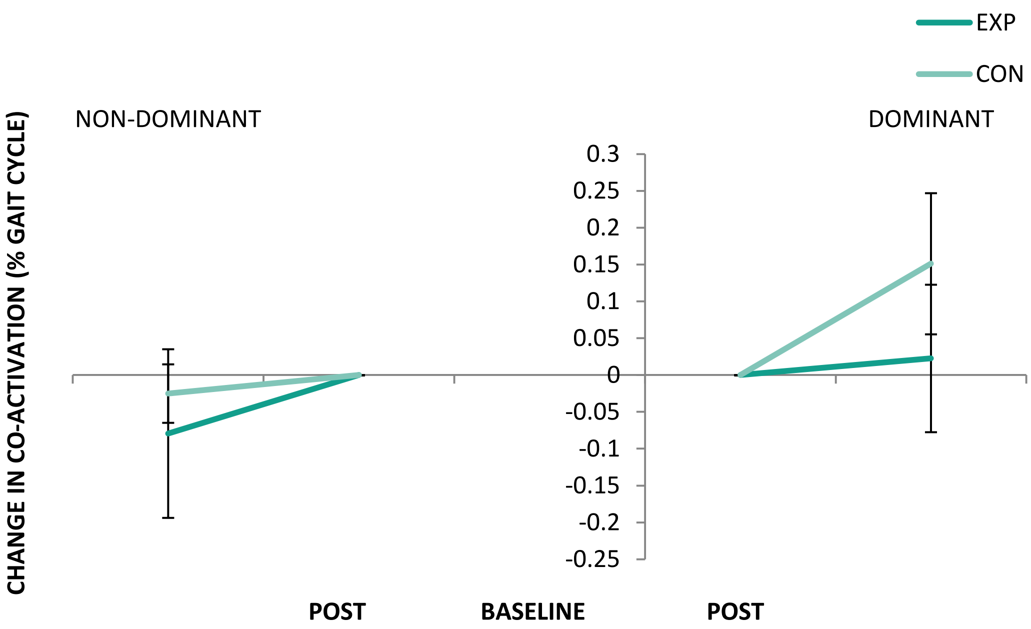


Figure. 5.12 EXP and CON group co-activation between MG and TA, in both dominant and non-dominant legs (± SEM).

vii. Medial Gastrocnemius Peroneus (MG-P) Co-Activation

Significant time effects were not observed for either the non-dominant (p = 0.43) or dominant legs (p = 0.68). Co-activation between the MG and PER increased in the dominant leg of the CON group by 0.13% (p = 0.5), while the EXP group showed almost no change (0.02%) (p = 0.97) resulting in practically significant differences (p = 0.21; ES = 0.52^{M}) between groups (Figure 5.13). Differences in the non-dominant leg were not practically or statistically significant (p = 0.38; ES = 0.27^{S}). This was due to the fact that neither group changed pre-activation levels over time (EXP p = 0.53; CON p = 0.68).

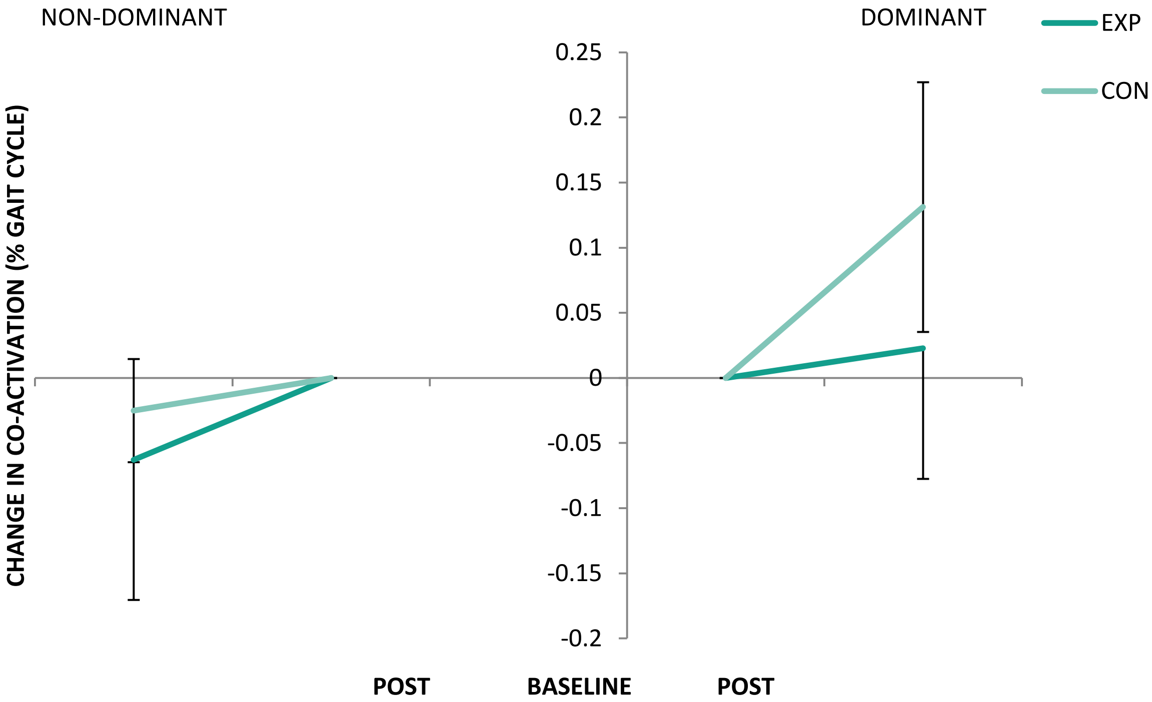


Fig. 5.13 EXP and CON group co-activation between MG and PER, for both dominant and non-dominant legs (± SEM).

viii. Lateral Gastrocnemius and Biceps Femoris (LG-BF) Co-Activation

Significant time effects were not observed for either the dominant (p = 0.93) or the non-dominant (p = 0.45). However, small interaction effects were noted in the dominant (p = 0.09) and non-dominant (p = 0.08). Dominant leg co-activation between the LG and BF increased in the CON group by 0.12% (p = 0.24), while decreasing in the EXP group by 0.05% (p = 0.58), resulting in practically significant differences (p = 0.12; ES = 0.77^{L}) between groups. Likewise, co-activation increased in the non-dominant leg of the CON group by 0.05% (p = 0.35) and decreased in the EXP group by 0.12% (p = 0.13), resulting in significant differences (p = 0.02; ES = 1.43^{VL}) between groups. Lateral Gastrocnemius-Biceps Femoris co-activation is graphically presented in Figures 5.14.

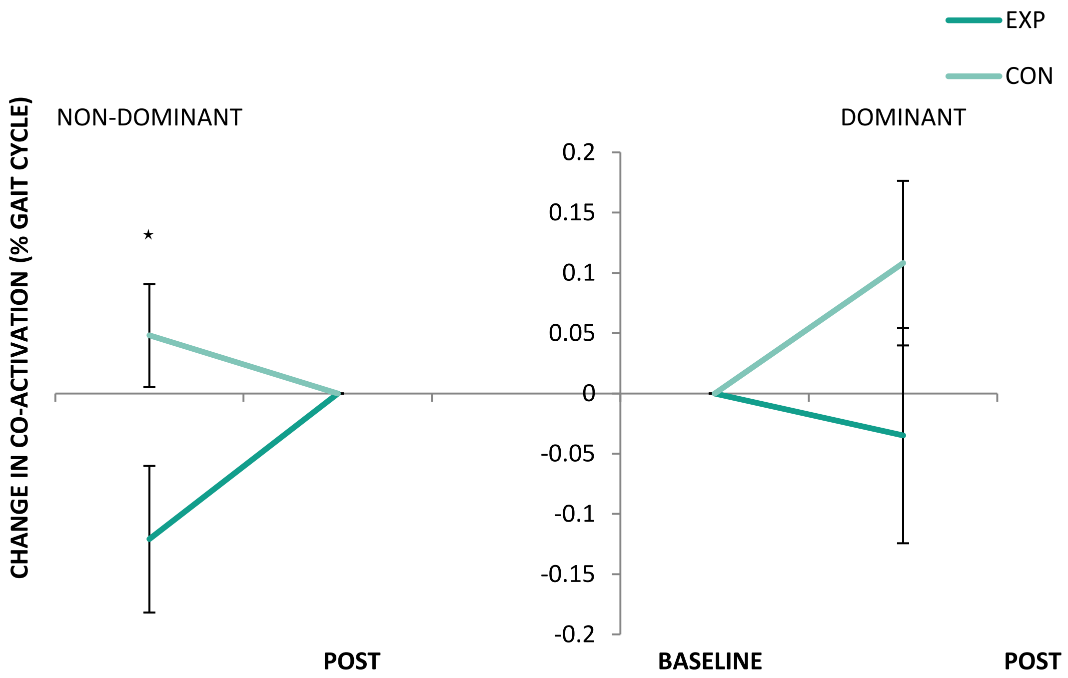


Fig. 5.14. Co-activation between LG and BF for both EXP and CON group dominant and non-dominant legs (± SEM).

ix. Biceps Femoris and Gluteus Medius (BF-GLUT) Co-Activation

Significant time effects were not observed over time for BF-GLUT co-activation (dominant p = 0.5; non-dominant p = 0.99). Co-activation of BF-GLUT increased in the dominant leg of the CON group by 0.14% (p = 0.18), while the EXP group showed no change (p = 0.89). Likewise, co-activation in the non-dominant leg of the CON group increased by 0.07% (p = 0.18), while the EXP group demonstrated a small decrease of 0.07% (p = 0.29). Practically significant differences were noted between groups for both legs (dominant p = 0.12; ES = 0.76[L]; non-dominant p = 0.05; ES = 1.15 [VL]).

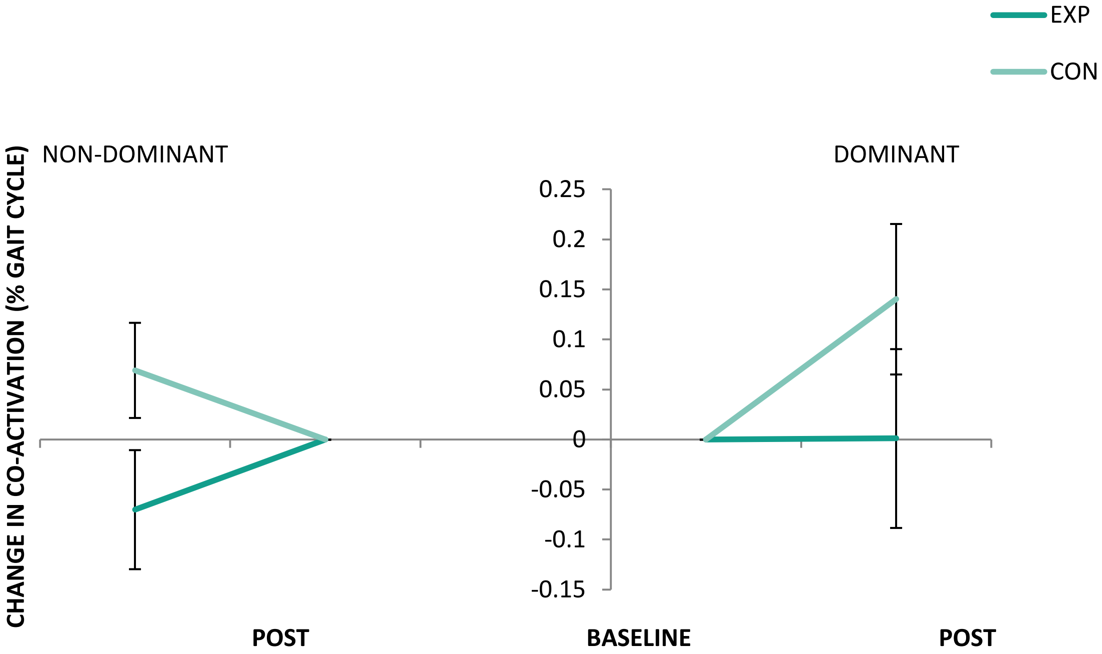


Fig. 5.15. EXP and CON group co-activation between BF and GLUT, in both dominant and non-dominant legs (± SEM).

x. Gender Differences

When considering TA-MG co-activation in women only, it was found that co-activation in the dominant leg of women did not change significantly over time (EXP p = 0.21; CON p = 0.88), nor did co-activation differ significantly (p = 0.34, ES = 0. 22^{S}) between groups. The non-dominant leg did, however, demonstrate practically significant differences between groups (ES = 0.51^{M}), with the EXP group increasing co-activation by 0.06% (p = 0.69), and the CON group decreasing by 0.01% (p = 0.94). When considering men only, the CON group increased dominant leg co-activation by 0.02%, while the EXP group increased co-activation to a lesser extent (0.10%). This resulted in a statistically significant difference between groups (p = 0.04) as well as a practically significant difference (ES = 1.25^{VL}). Co-activation in the non-dominant leg decreased more in the EXP group (0.15%) compared the CON group (0.03%), resulting in a practically significant difference of 0.57 (ES) (p = 0.21).

When looking at MG-PER co-activation in women only, it was found that both EXP (0.16%) and CON (0.09%) women (Figure 5.16a) increased co-activation in the dominant leg (EXP p = 0.21; CON p = 0.75). However, in the non-dominant leg, the CON group decreased co-activation by 0.01%, while the EXP group women increased co-activation by 0.05% (EXP p = 0.69; CON p = 0.94). Practically significant differences were observed between groups for the non-dominant leg (p = 0.27; ES = 0.51^{M}), but not the dominant (p = 0.34; ES = 0.28^{S}). When considering men (Figure 5.16b) only, the EXP group decreased co-activation in the dominant leg by 0.1%, while the CON group increased co-activation markedly by 1.0% (EXP p = 0.47; CON p = 0.19), with statistically significant differences noted between groups (p = 0.04; ES = 1.04^{L}) at post testing. In the non-dominant leg, a practically significant difference was noted between groups (p = 0.25; ES = 0.47^{M}), with both EXP and CON groups decreasing co-activation, by 0.12% (p = 0.4) and 0.03% (p = 0.41), respectively.

When considering LG-BF co-activation in women only, dominant leg co-activation increased slightly in both groups (EXP p = 0.44; CON p = 0.89) and did not demonstrate significant differences between groups (p = 0.4; ES = 0.21^{S}). The non-dominant leg demonstrated 0.01% decreases in CON (p = 0.89) and 0.06% decreases in EXP groups (p = 0.59), resulting in a practical significant difference (p = 0.25; ES = 0.57$^{M)}$. When considering men only statistically significant differences were noted for both the non-dominant (p = 0.01; ES = 1.21^{L}) and dominant (p = 0.01; ES = 1.34^{VL}) legs, with CON men increasing co-activation (dominant p = 0.06; non-dominant p = 0.25), while EXP men decreased co-activation (dominant p = 0.29; non-dominant p = 0.20).

When looking at BF-GLUT co-activation in women only, results in both the dominant (p = 0.43; ES = 0.14^{N}) and non-dominant (p = 0.47; ES = 0.08^{N}) legs did not produce significant differences. This was due to the fact that the EXP (dominant p = 0.23; non-dominant p = 0.69) and CON (dominant p = 0.67; non-dominant p = 0.84) groups demonstrated similar increases in co-activation over time. Control men, however, increased co-activation in both the non-dominant (0.09%) and dominant legs (1.0%), while EXP men reduced co-activation in both the non-dominant (0.12%) and dominant legs (0.09%). Statistically (dominant p = 0.01; non-dominant p = 0.01) and practically significant (dominant ES = 1.11^{VL}; non-dominant ES = 1.71^{VL}) differences were noted in both legs. Co-activation in men and women is shown in Figure 5.16 and 6.17 for both groups.

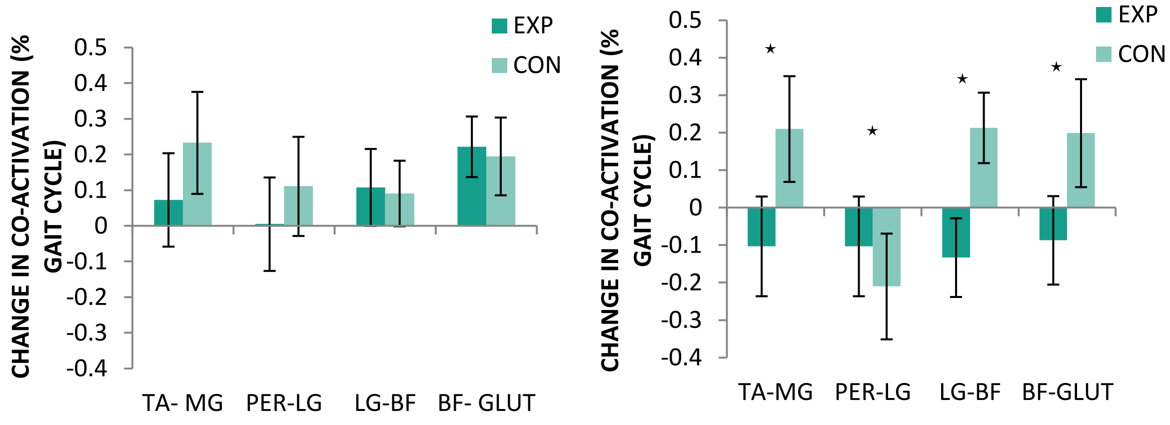


Figure 5.16 Change in co-activation, as a percentage of the gait cycle, from baseline to post-testing for the dominant leg of a) women, b) men of both the EXP and CON groups.

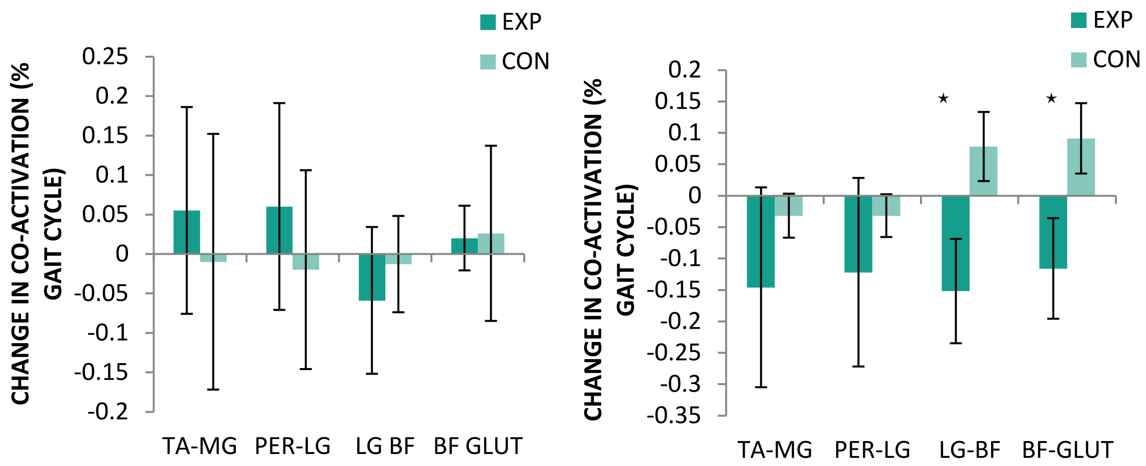


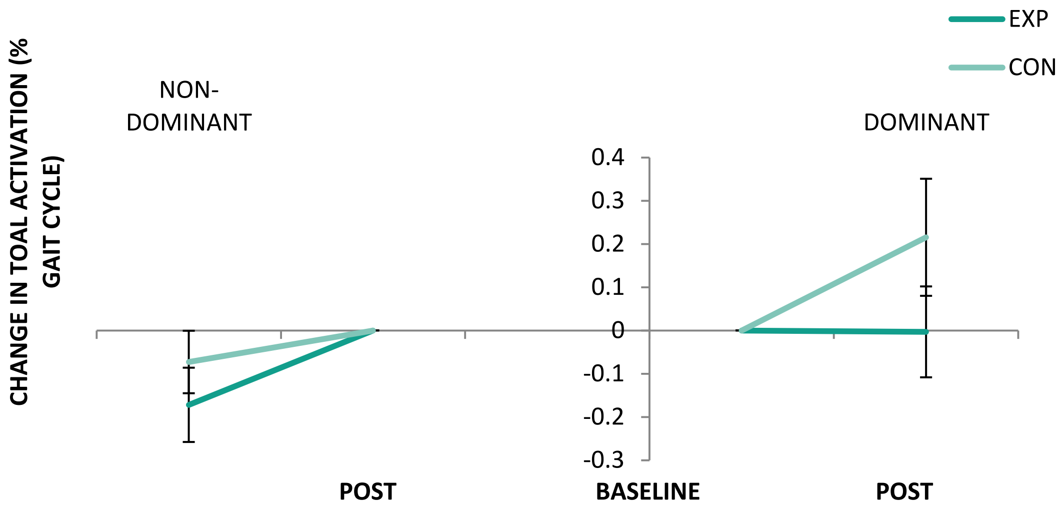
Figure 5.17 Change in co-activation, as a percentage of the gait cycle, from baseline to post-testing for the non-dominant leg of a) women, b) men of both the EXP and CON groups.

i. Total Activation

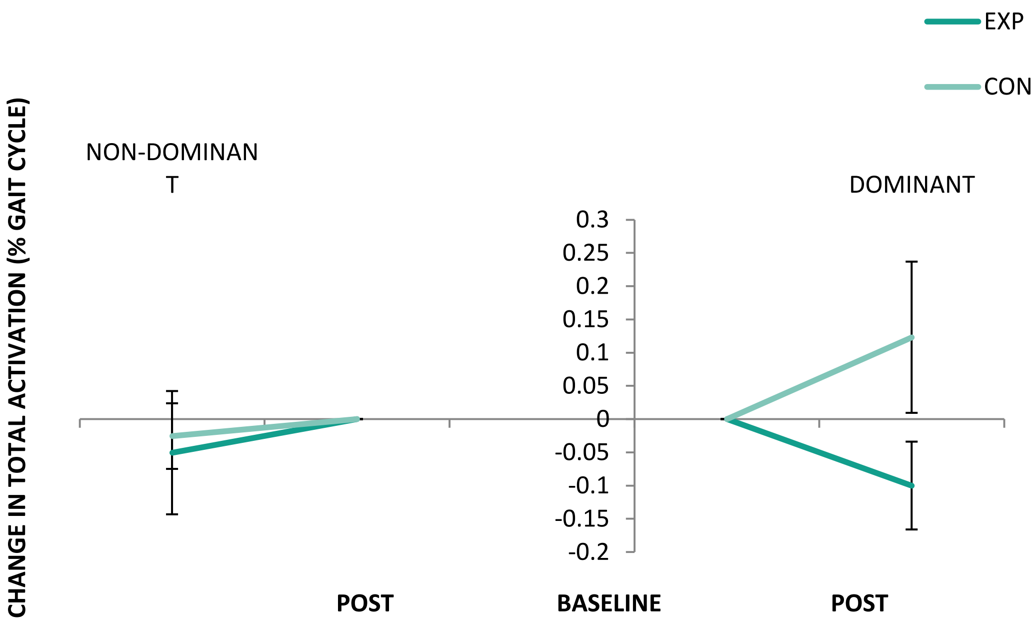
Significant time effects were not observed for TA total activation in the non-dominant leg (p = 0.36) but strong tendencies were noted in the dominant leg (p = 0.06). Tibialis Anterior dominant leg total activation increased by 0.22% (p = 0.64) of the entire gait cycle in the EXP group, while the CON group did not change notably (p = 0.93). Practically significant differences were noted between groups (p = 0.14; ES = 0.71[L]). In contrast, non-dominant leg total activation declined by 0.17% in the EXP (p = 0.14) and by 0.07% in the CON (p = 0.38) groups, with practically significant differences noted (p = 0.20; ES = 0.56[M]).

Time effects were not observed for PER activation (dominant p = 0.14; non-dominant p = 0.49). Total activation increased by 0.12% in the dominant leg of the CON group (p = 0.41), while the EXP group decreased by 0.01% (p = 0.22). In the non-dominant leg, the EXP group decreased by 0.05% (p = 0.59) and CON groups decreased by 0.03% (p = 0.70). Practically significant differences was noted for the dominant leg (p = 0.08; ES = 0.94[L]), but not the non-dominant (p = 0.41; ES = 0.25[S]).

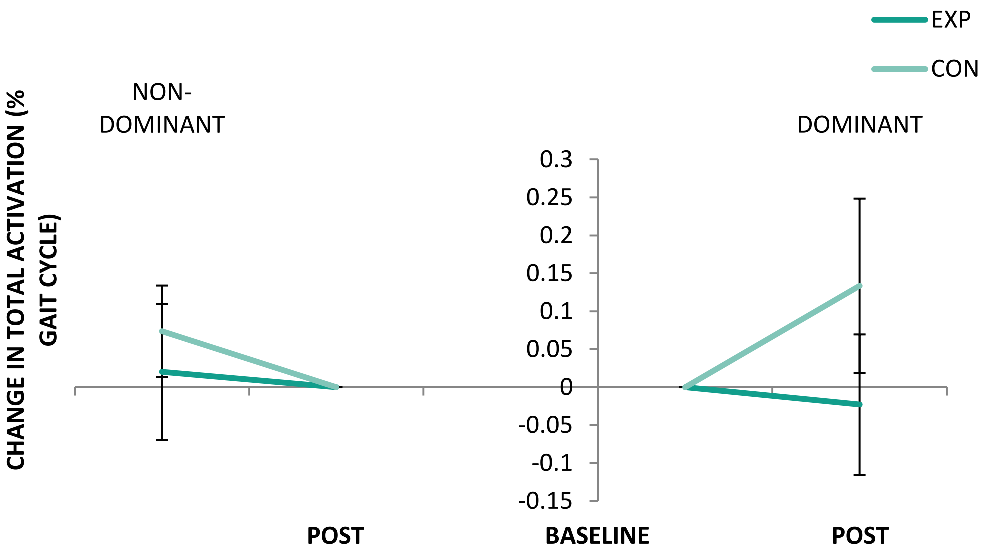
Significant time effects were not observed for LG in either leg (dominant p = 0.85; non-dominant p = 0.42). Dominant leg LG total activation increased by 0.13% in the CON group (p = 0.98), while a decrease of 0.02% was noted in the EXP group (p = 0.78), with practically significant differences noted (p = 0.17; ES = 0.61[M]) between groups. No differences were noted between groups for the non-dominant leg (p = 0.32; ES = 0. 43[M]). The percentage of total activation relative to the entire gait cycle is graphically displayed below in figure 5.18 for a) TA, b) PER, and c) LG .



a)



b)



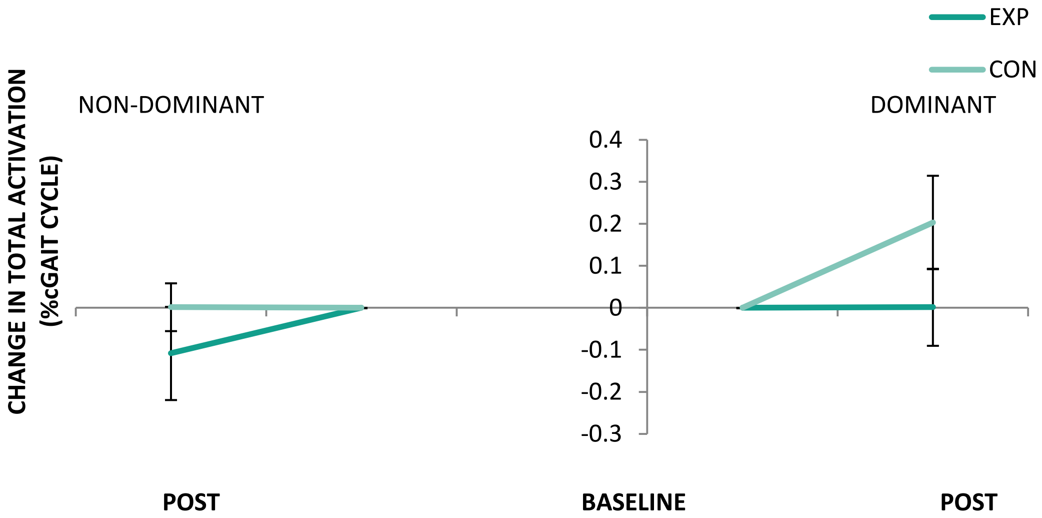
c)

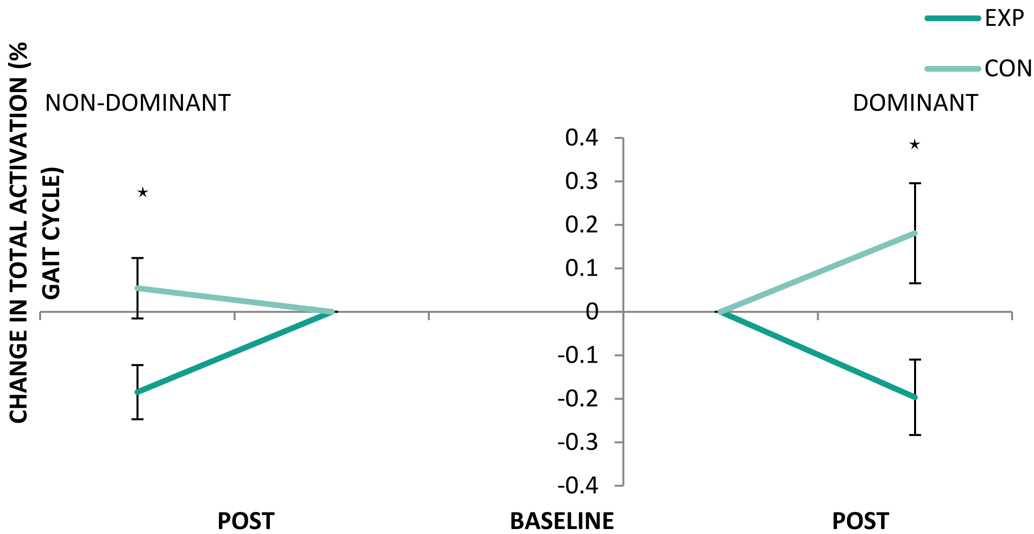
Fig. 5.18 (a, b, c). Change in dominant and non-dominant leg total activation time, given as a percentage of the gait cycle, from baseline to post testing for the a) TA, b) PER, and c) LG (± SEM).

Time effects were also not observed for either leg (dominant p = 0.75; non-dominant p = 0.37) in regards to MG total activation. Dominant leg total MG activation increased by 0.2% (p = 0.53) in the CON group, but did not change in the EXP group (p = 0.98). In the non-dominant leg, no change was noted in the CON group (p = 0.97), while the EXP group decreased by 0.11% (p = 0.32). Practically significant differences were noted between CON and EXP groups for both the non-dominant (p = 0.12; ES = 0.56[M]) and dominant legs (p = 0.20; ES = 0.79[L]).

Significant time effects were observed for BF total activation in the dominant (p = 0.08) but not the non-dominant (p = 0.36). Interaction effects were also noted for both legs (dominant p = 0.05; non-dominant p = 0.05). Total BF activation increased in the dominant leg by 0.18% (p = 0.52) and in the non-dominant leg by 0.05% (p = 0.59) for the CON group. In contrast, the EXP group demonstrated a decrease of 0.02% (p = 0.02) in total BF activation in the dominant leg, and 0.18% (p = 0.09) in the non-dominant leg. Statistically significant differences were noted between groups for both the non-dominant (p = 0.01; ES = 1.62[VL]) and dominant (p = 0.02; ES = 1.51[VL]) legs.

Significant time effects were not observed for GLUT activation (dominant p = 0.81; non-dominant p = 0.79), while tendencies for interaction effects were noted (dominant p = 0.09; non-dominant p = 0.08). Total GLUT activity increased in the CON group by 0.22% (p = 0.02) for the dominant leg, with little change in the non-dominant leg (p = 0.64). The EXP group demonstrated a 0.21% (p = 0.09) increase in the non-dominant leg, but no change in the dominant leg (p = 0.91). Practically significant differences were noted between groups, for both the non-dominant (p < 0.01; ES = 2.33[H]) and dominant legs (p = 0.13; ES = 0.90[L]), while only the non-dominant side was statistically significant.





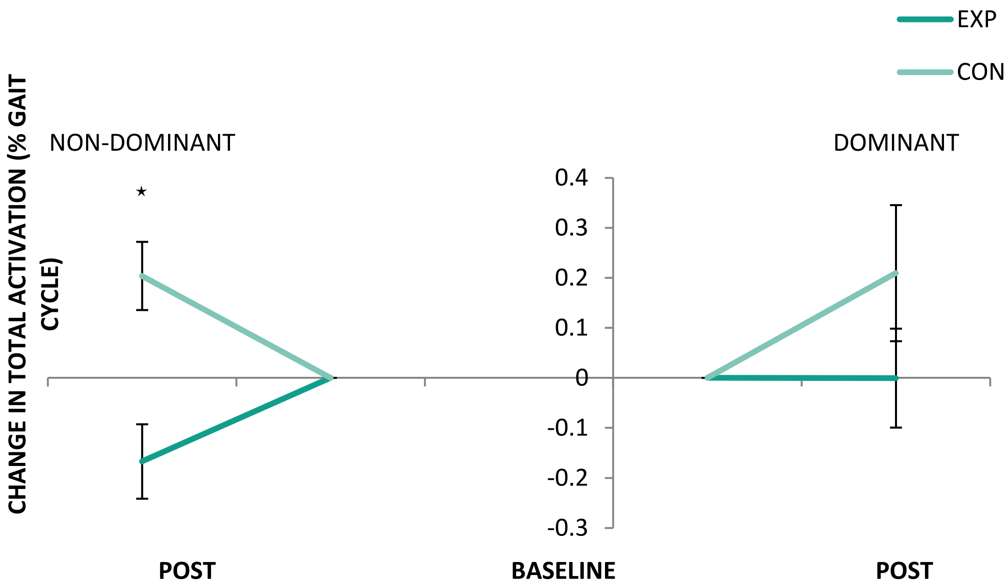


Fig. 5.19 (a, b, c). Dominant and non-dominant leg total activation time, given as a percentage of the gait cycle for a) MG, b)BF, and c) GLUT for both groups (± SEM).

xi. Gender Differences in Total Activation

Further statistical analysis divided results between men and women. Tibialis anterior total activation decreased in CON women by -0.13% in the non-dominant leg (p = 0.38), while the dominant leg increased total activation by 0.23% (p = 0.39). Experimental women showed similar decreases in the non-dominant leg (0.08%) (p = 0.14), and increases in the dominant leg (0.23%) (p = 0.64). Practically significant differences were noted for both the dominant (p = 0.25; ES = 0.46[M]) and non-dominant legs (p = 0.25; ES = 0.84[L]). Control men also demonstrated a 0.04% decrease in total activation in the non-dominant leg (p = 0.66), and a 0.98% increase in total activation in the dominant leg (p = 0.13), while the EXP men decreased TA activity by 0.22% in the non-dominant leg (p = 0.24) and by 0.06% in the dominant legs (p = 0.86). Practically significant differences were noted between groups for both the non-dominant (p = 0.11; ES = 0.86[L]) and dominant legs (p = 0.09; ES = 0.95[L]). The percentage of total activation, relative to the entire gait cycle, is given below in figures 5.20 and 5.21.

Total PER activation in women increased similarly for both groups in the dominant leg (EXP p = 0.95; CON p = 0.20), with only practically significant differences noted between groups (p = 0.27; ES = 0.4[M]). In the non-dominant leg, the CON group showed reduced total activation by 0.08% (p = 0.66), while the EXP group increased total activation by 0.2% (p = 0.17), resulting in statistically significant differences (p < 0.01; ES = 26.95[H]). Men in the CON group increased activation by 0.19% in the dominant leg (p = 0.27), while EXP men decreased peroneus total activation by 0.17% (p=0.17), resulting in statistically significant differences (p = 0.02; ES = 1.48[VL]). In the non-dominant leg, EXP men decreased activation by 0.18% (p = 0.14), while the CON group also decreased co-activation by 0.08% (p = 0.33). Practically significant differences were, however, noted between groups (p = 0.12; ES = 0.84[L]). The percentage of total activation, relative to the entire gait cycle, is given below in figures 5.20 and 5.21.

Total LG activation increased by 0.11% in the dominant leg of EXP women (p = 0.28) and by 0.09% in CON women (p = 0.55). Significant differences were not observed (p = 0.46; ES = 0.08[N]) between groups. In the non-dominant leg, CON women decreased total activation by 0.06% (p = 0.73), while the EXP women increased activation by 0.22% (p = 0.14). Statistically (p = 0.01; ES = 2.45[H]) significant differences were observed for the non-dominant leg. Men in the CON group increased total LG activation by 1.01% in the dominant leg (p = 0.31), and by 0.14% in the non-dominant leg (p = 0.66), while EXP men decreased total activation in both the dominant (0.17%) (p = 0.27) and non-dominant legs (0.18%) (p = 0.43). Practically significant differences between groups were recorded for both the non-dominant (ES = 1.7[VL]) and dominant legs (ES = 1.08[L]), while only the non-dominant was statistically significant (p=0.02).

Total MG activation increased 0.16% in the dominant leg of CON women ($p = 0.65$), and decreased by 0.22% for EXP women ($p = 0.01$). However, differences between groups were not statistically or practically significant ($p = 0.43$; ES = 0.09^{N}) due to the large individual variation seen. In the non-dominant leg, the EXP group decreased in total activation by 0.05% ($p = 0.53$), while the CON group increased total activation by 0.07% ($p = 0.43$), resulting in statistically significant differences ($p = 0.03$; ES = 1.74^{VL}). When considering men only, the non-dominant leg demonstrated 0.03% decreased activity in the CON group ($p=0.66$) and 0.14% in the EXP group ($p = 0.43$), resulting in practically significant ($p = 0.26$; ES = 0.46^{M}) differences between groups. The dominant leg demonstrated a 0.15% increase in total MG activity in the EXP group ($p = 0.27$), while the CON group decreased total MG activity by 1.02% ($p = 0.02$), resulting in statistically significant differences ($p = 0.02$; ES = 1.59^{VL}).

Total BF activation increased in the female CON group by 0.17% ($p = 0.46$) for the dominant leg and 0.12% for the non-dominant leg ($p = 0.93$), while total BF activity decreased in the EXP group by 0.08% in the dominant leg ($p = 0.56$), and 0.12% in the non-dominant leg ($p = 0.31$). Therefore, practically significant differences were noted for both the dominant ($p = 0.11$; ES = 0.83^{L}) and non-dominant legs ($p = 0.02$; ES = 2.04^{H}), while only the non-dominant leg was statistically significant. Similarly, BF activity in the male EXP group decreased by 0.28% in the dominant leg ($p = 0.02$) and 0.22% in the non-dominant leg ($p = 0.21$), while total BF activity in the men of the CON group increased by 1.02% in the dominant leg ($p = 0.02$) and 0.07% in the non-dominant leg ($p = 0.58$). Therefore, statistically significant differences were noted in both the non-dominant ($p < 0.01$; ES = 1.72^{VL}) and dominant legs ($p = 0.01$; ES = 2.36^{H}).

Total GLUT activation increased in the women of the CON group by 0.22% in the dominant leg ($p = 0.37$) and 0.30% in the non-dominant leg ($p = 0.43$). Experimental women, however, demonstrated increased GLUT activity in the dominant leg by 0.22% ($p = 0.47$), but decreased GLUT activity in the non-dominant leg by 0.03% ($p = 0.88$). Statistically significant differences were found between CON and EXP GLUT total activation for the non-dominant leg ($p = 0.03$; ES = 2.01^{H}) and practically significant differences in the dominant ($p = 0.27$; ES = 0.40^{M}). Men in the CON group increased total GLUT activity by 1.04% in the dominant leg ($p = 0.20$), and by 0.16% in the non-dominant leg ($p = 0.02$), while EXP men decreased total GLUT activity in the dominant leg by 0.07% ($p = 0.08$) and in the non-dominant leg by 0.24% ($p = 0.64$). Statistically significant differences were observed in the non-dominant leg ($p < 0.01$; ES = 1.56^{VL}), but not the dominant leg ($p = 0.07$; ES = 1.07^{L}). The percentage of total activation for TA, PER, LG, MG, BF and GLUT, relative to the entire gait cycle, is given below in figures 5.20 and 5.21.

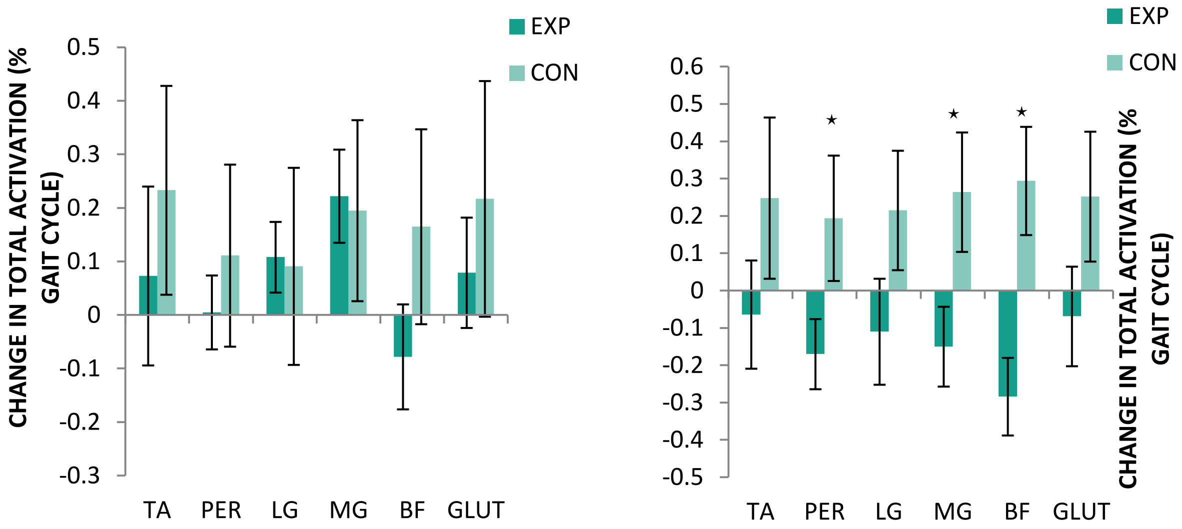


Figure 5.20 Change in total activation, as a percentage of the gait cycle, from baseline to post-testing for the dominant leg of a) women, b) men of both the EXP and CON groups.

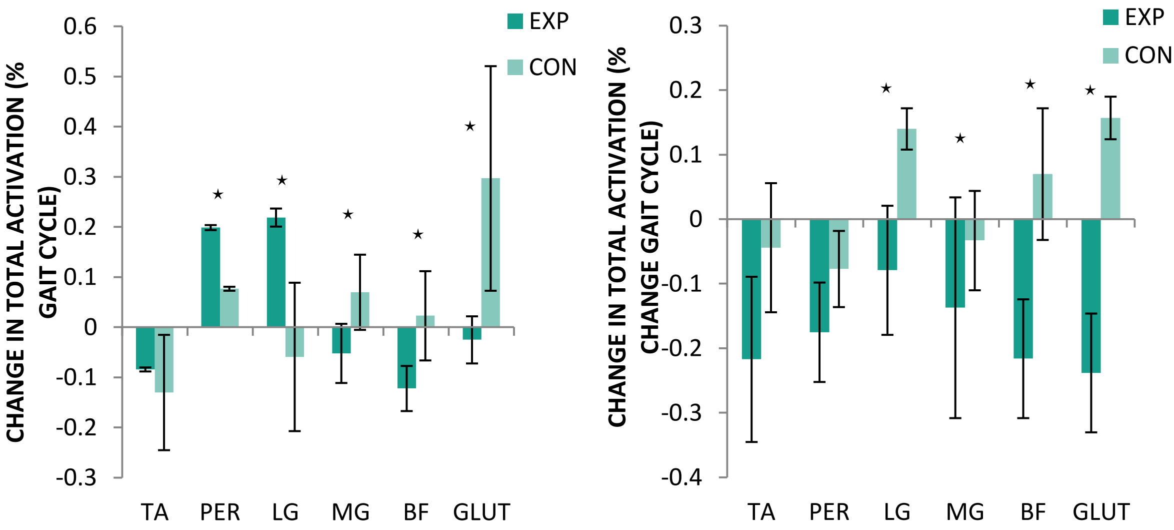


Figure 5.21 Change in total activation, as a percentage of the gait cycle, from baseline to post-testing for the non-dominant leg of a) women, b) men of both the EXP and CON groups.

F. Isokinetic Ankle Joint Strength

1. Dorsiflexion (Peak Torque To Body Mass)

Significant change over time occurred for both speeds (30°.sec^{-1} $p = 0.02$; 60°.sec^{-1} $p = 0.02$). The change in relative dorsiflexion strength for CON and EXP groups is given below in Figure 5.22 for 30°.sec^{-1}, and 60°.sec^{-1}. The CON group improved significantly with an increase of 38% and 24%, for 30°.sec^{-1} ($p < 0.01$) and 60°.sec^{-1}, ($p = 0.04$), respectively. The EXP group improved by 11% in the slower speed and 13%, which was significant in the slower speed only (30°.sec^{-1} $p = 0.04$ vs. 60°.sec^{-1} $p = 0.1$). However, there were no significant differences between groups agt post testing for either speed (30°.sec^{-1} $p = 0.93$; 60°.sec^{-1} $p = 0.86$). However large practically significant differences were noted in the slow speed (ES = 1.24[VL]), and medium practically significant differences in the faster speed (ES = 0.63[M]).

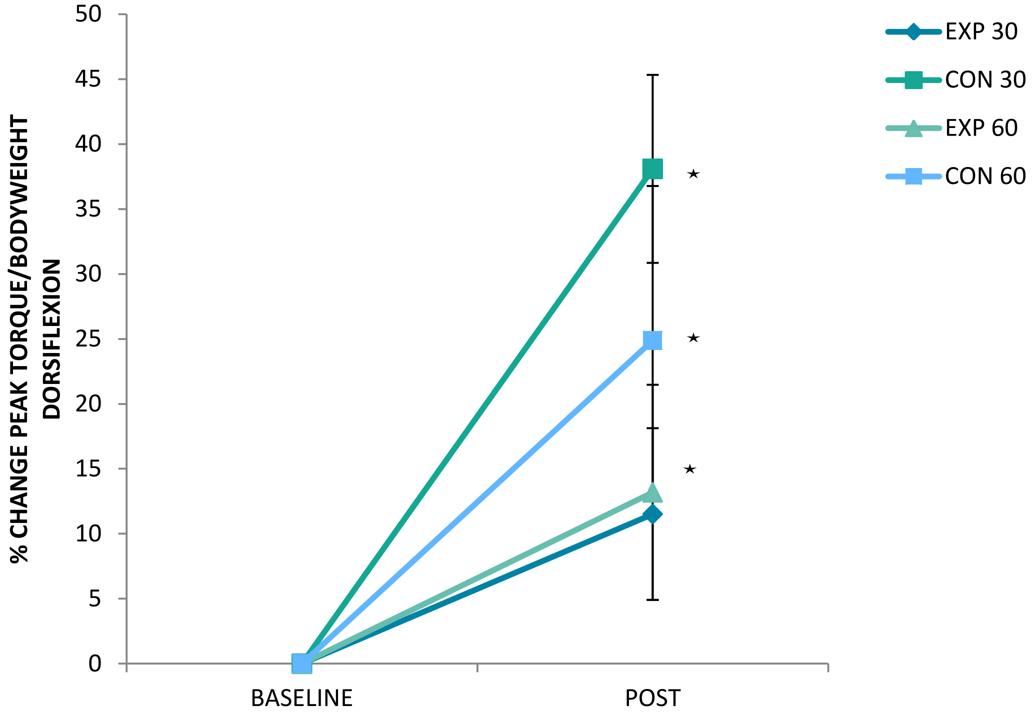
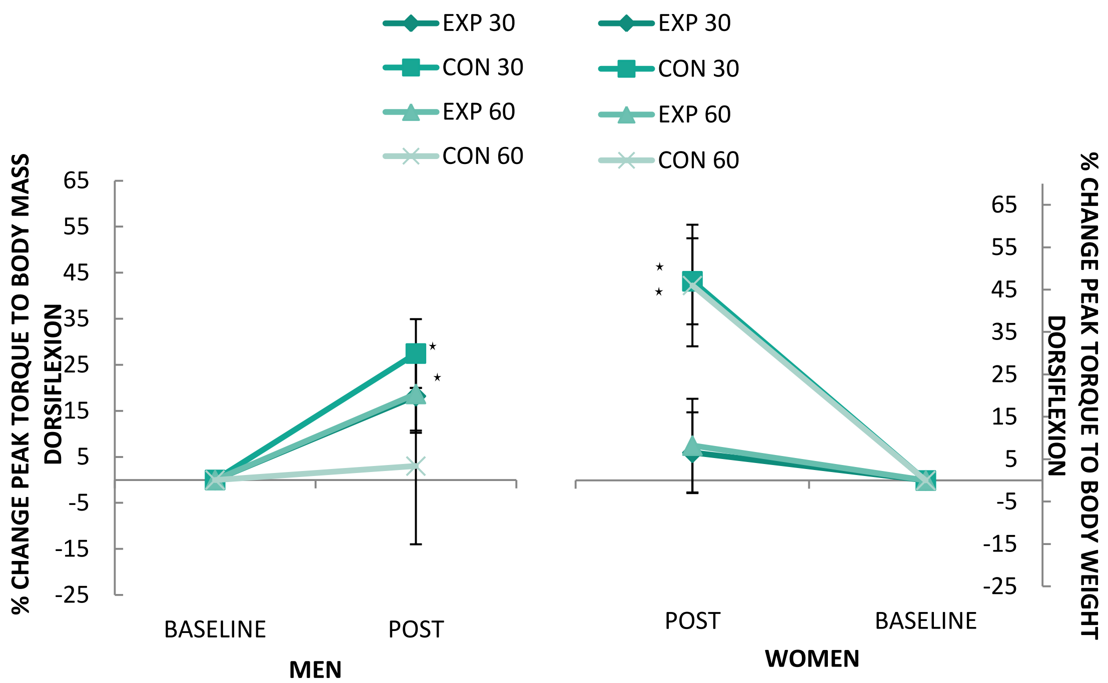


Figure 5.22. Percentage change in dorsiflexion peak torque to body mass, for CON and EXP groups, at 30˚.sec^{-1} and 60°.sec^{-1}(± SEM). *$p < 0.05$

i. Gender Differences

Further statistical analysis separated results between men and women (Figure 5.23). The CON group women improved significantly in both speeds (30°.sec^{-1} $p < 0.01$; 60°.sec^{-1} $p < 0.01$) with a relative change of 47% and 46%, respectively. Experimental women, however, did not improve significantly in either speed (30°.sec^{-1} $p = 0.36$; 60°.sec^{-1} $p = 0.55$) with only a 7% and 8% strength increase. Practically significant differences were observed between the groups in both the slower (ES = 1.81[L]) and faster speeds (ES = 1.38[L]). Control group men improved significantly in 30°.sec^{-1} ($p = 0.01$) with an increase of 27%, however, the 60°.sec^{-1} speed did not improve significantly ($p = 0.82$), with a small increase of 3%. Similarly, EXP men also improved by 19% in the slower speed, which was statistically significant in 30°.sec^{-1} ($p = 0.04$). But an increase of 18% in the 60 °.sec^{-1} condition ($p = 0.20$) was not significant. A medium practically significant difference was noted between the group improvements for the slower speed only (ES = 0.56[M]), while the faster speed yielded small differences (ES = 0.3[M]).



Figure

Figure 5.23 Percentage change for men and women separately, in dorsiflexion peak torque to body mass for CON and EXP groups, at 30°.sec^{-1} and 60°.sec^{-1} (± SEM).

2. Plantar-flexion (Peak Torque To Body Mass)

A significant effect over time was observed in both speeds for plantar flexion peak torque to bodyweight (30°.sec^{-1} $p < 0.01$; 60°.sec^{-1} $p = 0.02$). The CON group demonstrated significant improvements over time (30°.sec^{-1} $p < 0.01$; 60°.sec^{-1} $p = 0.03$) whereas the EXP group did not improve significantly (30°.sec^{-1} $p = 0.22$; 60°.sec^{-1} $p = 0.22$). Average percentage change over the intervention period can be seen below in Figure 5.24. The CON group improved 21% more than the EXP group for the 30°.sec^{-1} speed, and 6% more for the 60°.sec^{-1} speed. A medium practically significant difference was found for the slower speed (ES = 0.53^{M}), while the faster speed demonstrated very small differences in improvement (ES = 0.18^{S}).

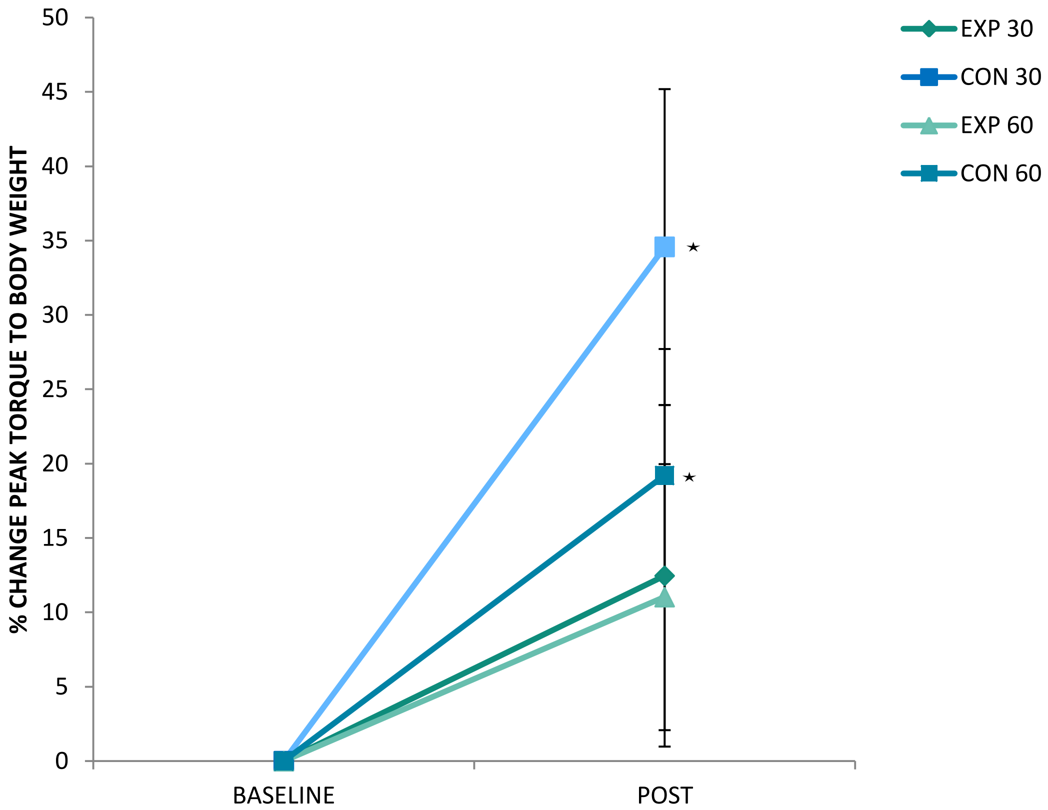


Figure 5.24. Percentage change in plantar-flexion peak torque to body mass, for CON and EXP groups, at 30°.sec^{-1} and 60°.sec^{-1} (± SEM).

i. Gender Differences

When analysing men and women separately, men in the CON group improved significantly for the slower speed (30°.sec^{-1} $p = 0.09$), but not in the faster speed (60°.sec^{-1} $p = 0.14$). Men in the EXP group improved by 43% and 39% for the slower and faster speeds, respectively, which was statistically significant in both cases (30°.sec^{-1} $p = 0.02$, ES = 0.6^{M}; 60°.sec^{-1} $p = 0.02$, ES = 1.33^{VL}). Women in the CON group demonstrated significant improvements of 46% ($p < 0.01$), for the slower speed and 22% for the faster speed, which was not statistically significant ($p = 0.06$). Women in the EXP group did not change significantly over time for either speed (30°.sec^{-1} $p = 0.51$; 60°.sec^{-1} $p = 0.45$) with small decreases of 7% (30°.sec^{-1}) and 8% (60°.sec^{-1}) in plantar-flexor strength throughout the intervention period. Therefore, a huge practically significant difference was noted between group improvements in the slower speed (ES = 1.46^{H}), and a large difference was noted in the faster speed (ES = 0.98^{L}). Relative change in plantar-flexion for men and women is graphically displayed in Figure 5.25a and b.

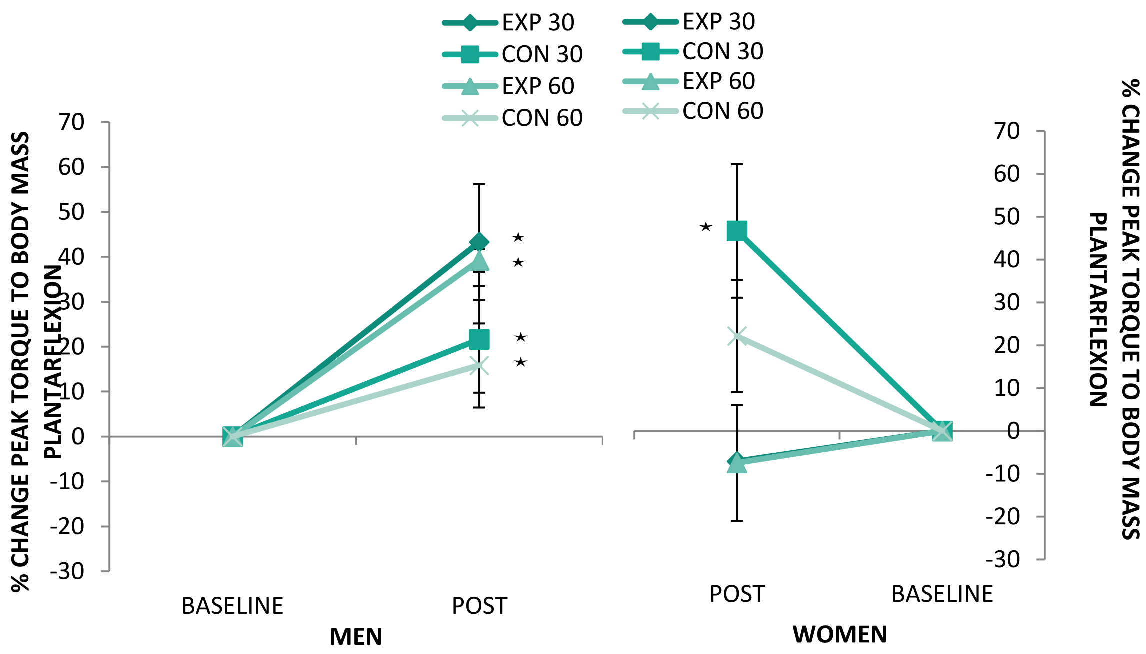


Figure 5.25. Percentage change for men and women separately, in plantar-flexion peak torque to body mass for CON and EXP groups, at 30°.sec^{-1}and 60°.sec^{-1} (± SEM). *p < 0.05

3. Inversion Strength (Peak Torque To Body Mass)

A significant time effect was observed for inversion in both the slower (30°.sec^{-1} p = 0.03) and the faster speeds (60°.sec^{-1} p = 0.01). The CON group strengthened significantly for the slower speed (p = 0.04) with an improvement of 37%, while a smaller, non-significant change was noted in the faster speed (p = 0.11) with an improvement of 16%. The EXP group improved by 15% for the slower speed (p = 0.22), and by 18% for the faster speed, (p = 0.02). Therefore a medium practically significant difference was noted between group improvements for the slower speed (ES = 0.49^{M}), while no difference was noted in the faster speed (ES = 0.08^{N}). The improvement for CON and EXP groups are depicted in Figure 5.26.

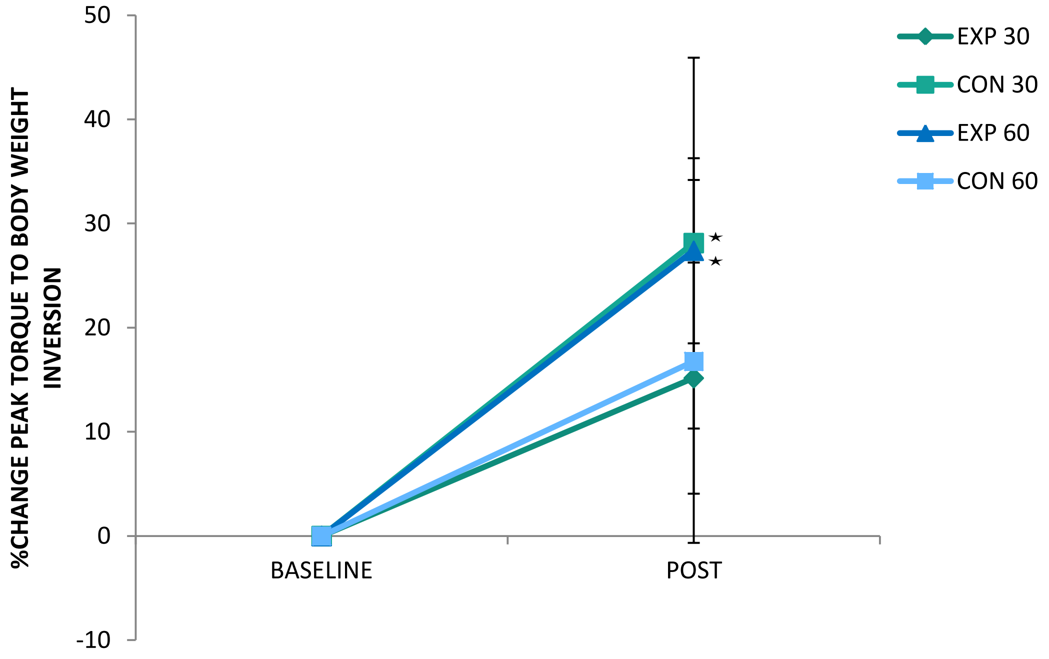


Figure 5.26. Percentage change in inversion peak torque to body mass, for CON and EXP groups, at 30°.sec^{-1}and 60°.sec^{-1}(± SEM). *p < 0.05.

i. Gender Differences

Women in both EXP and CON groups did not demonstrate significant changes over time for either the faster speed (EXP p = 0.16; CON p = 0.39) or the slower speed (EXP p = 0.39; CON p = 0.09). Nevertheless, CON group women improved by 33% in the slower speed (30°.sec^{-1}) and 14% in the faster speed (60°.sec^{-1}), whereas EXP group women improved by 15% (30°.sec^{-1}) and 24% (60°.sec^{-1}). Therefore the CON group women improved 18% more than the EXP group, for the slower speed, while the EXP group improved 10% more than the CON group in the faster speed. A medium practically significant difference was noted between group improvements for the slower speed (ES = 0.55^{M}), while the faster speed yielded negligible differences (ES = 0.03^{N}).

The CON group men also did not demonstrate significant (p < 0.05) changes in strength over time in either speed (30°.sec^{-1} p = 0.21; 60°.sec^{-1} p = 0.17). However, EXP men showed a significant strength increase in the faster speed (p = 0.04), but not in the slower speed (p = 0.37). Control group men improved by 22% for the slower speed and 19% in the faster speed, whereas EXP group men improved by 15% in the slower speed and 29% in the faster speed. Differences between group improvements were not statistically or practically significant for either speed. The group improvements across the intervention period can be viewed in Figure 5.27a and b.

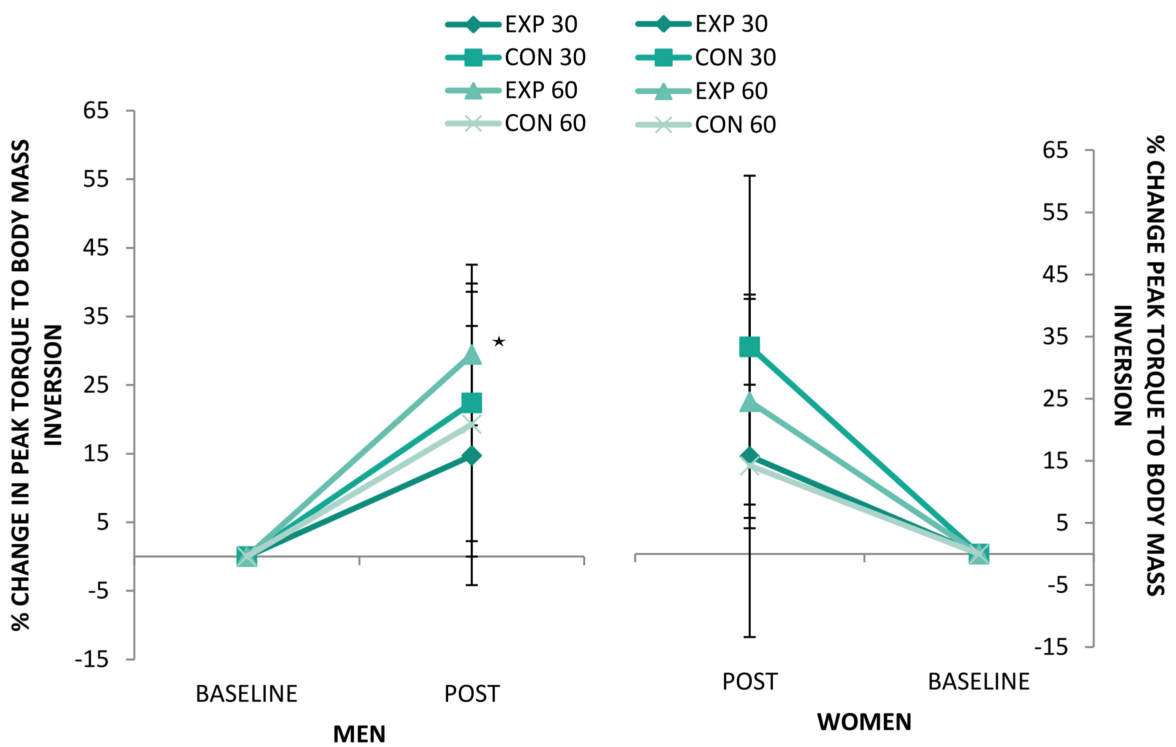


Figure 5.27 Percentage change for men and women separately, in inversion peak torque to body mass for CON and EXP groups, at 30°.sec^{-1}and 60°.sec^{-1}(± SEM). *p < 0.05.

4. Eversion Strength (Peak Torque To Body Mass)

A significant time effect was observed for eversion peak torque to body mass in both speeds (30°.sec^{-1} p = 0.02; 60°.sec^{-1} p = 0.01). The CON group improved by 25% in the slower speed and by 19% in the faster speed which proved to be statistically significant in both cases (30°.sec^{-1} p = 0.03; 60°.sec^{-1} p = 0.04). The EXP group improved by 4% and 20% for the slower and faster speeds, respectively, while only the faster speed proved to be statistically significant (30°.sec^{-1} p = 0.26; 60°.sec^{-1} p = 0.03. The CON group improved 21% more than the EXP group for the slower speed, which proved to be a practically significant (ES = 0.46^{M}). However, when comparing group averages for the faster speed, practically significant difference were not noted (ES=0.2^{S}). Figure 5.28 illustrates the group improvements in eversion for both the slower and faster speeds, in CON and EXP groups.

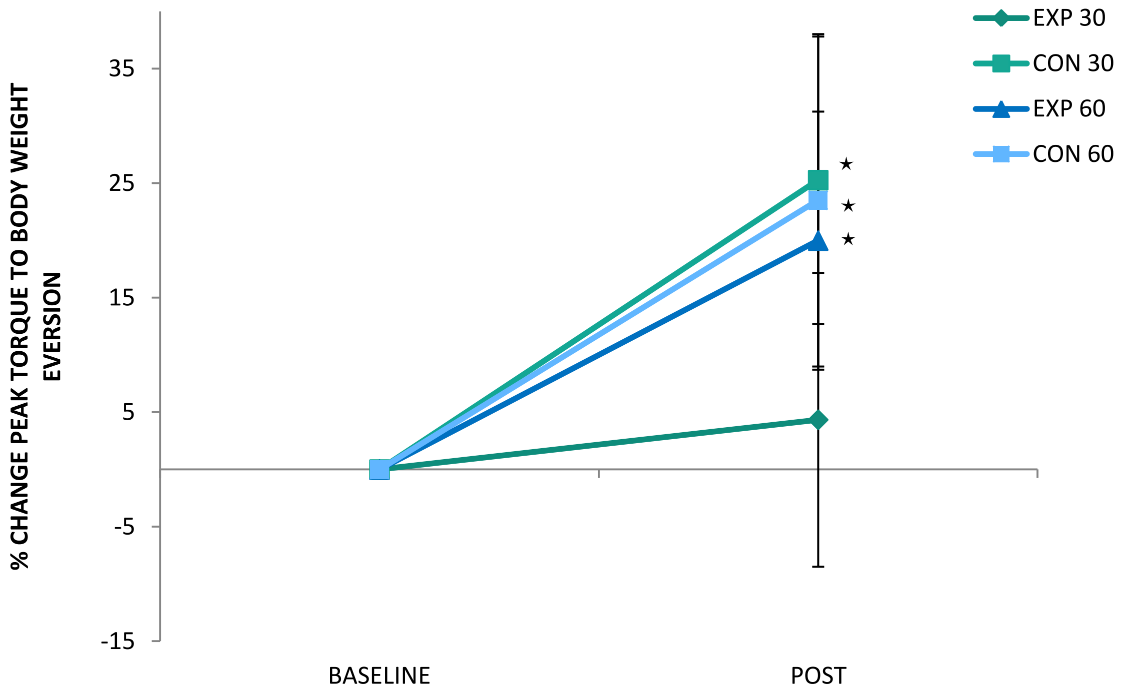


Figure 5.28. Percentage change in eversion peak torque to body mass, for CON and EXP groups, at 30°.sec^{-1} and 60°.sec^{-1} (± SEM). *p < 0.05.

i. Gender Differences

When considering women only, the EXP group improved by 28% for the slower speed (p = 0.29) and 41% for the faster speed (p = 0.02). Control group women improved by 22% for the slower speed (p = 0.12) and 27% for the faster speed (p = 0.09). Differences in group improvements were not practically significant in either speed (ES = 0.2^{M}).

Control group men improved by 30% in the slower speed (p = 0.02), but decreased by 9% in the faster speed (p = 0.69). Experimental group men decreased by 4% in the slower speed (p = 0.69) and 17% in the faster speed (p = 0.06). Therefore, the CON group improved 34% more than the EXP group for the slower speed, and decreased 8% less than the EXP group for the faster speed. Practically significant differences were noted between group improvements for both speeds (30°.sec^{-1} ES = 1.26^{VL}; 60°.sec-1 ES = 0.68^{M}). Figure 5.29 a and b graphically display the percentage of eversion strength improvement, following the intervention period, for both EXP and CON groups.

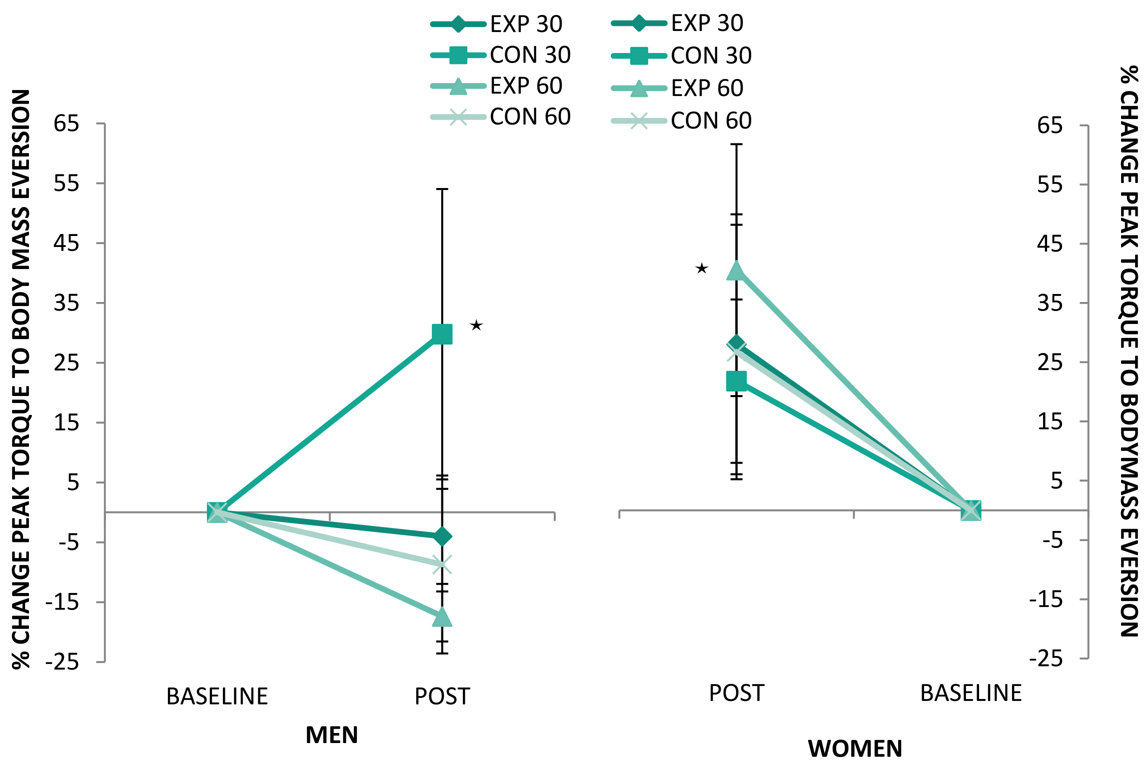


Figure 5.29. Percentage change for men and women separately, in eversion peak torque to body mass for CON and EXP groups, at 30°.sec^{-1} and 60°.sec^{-1} (± SEM). *p < 0.05.

G. Postural Stability

1. Athletic Single Leg (ASL) Test (Non-Dominant Leg)

A significant time effect was observed for the medial lateral (M/L) sway index ($p < 0.01$), but not for overall sway ($p = 0.06$) or anterior posterior (A/P) sway ($p = 0.68$). The overall sway for both groups did not differ between groups on average ($p = 0.77$) or over time (EXP $p = 0.14$; CON $p = 0.24$). However, an improvement in M/L sway over time was observed in the CON group ($p < 0.01$), while the EXP group did not change significantly ($p = 0.12$). No changes were observed in A/P sway for any of the groups, either across time (EXP $p = 0.34$; CON $p = 0.68$) or in comparison ($p = 0.71$). The average sway index values for M/L, A/P and overall sway is presented in Figure 5.30, for both EXP and CON groups prior to and following the intervention. When considering the percentage change in sway index across the intervention period for overall sway, the EXP group improved by 25%, while the CON group improved by 6%, resulting in a medium practically significant difference between group improvements (ES = 0.72^{L}). Similarly, the EXP group improved by 13% in the A/P plane, while the CON group deteriorated by 6%, resulting in a practically significant difference (ES = 0.47^{M}). However, in the M/L plane, the CON group improved by 27%, while the EXP group improved by only 13%, with a similar medium practically significant difference (ES = 0.46[M]) between groups.

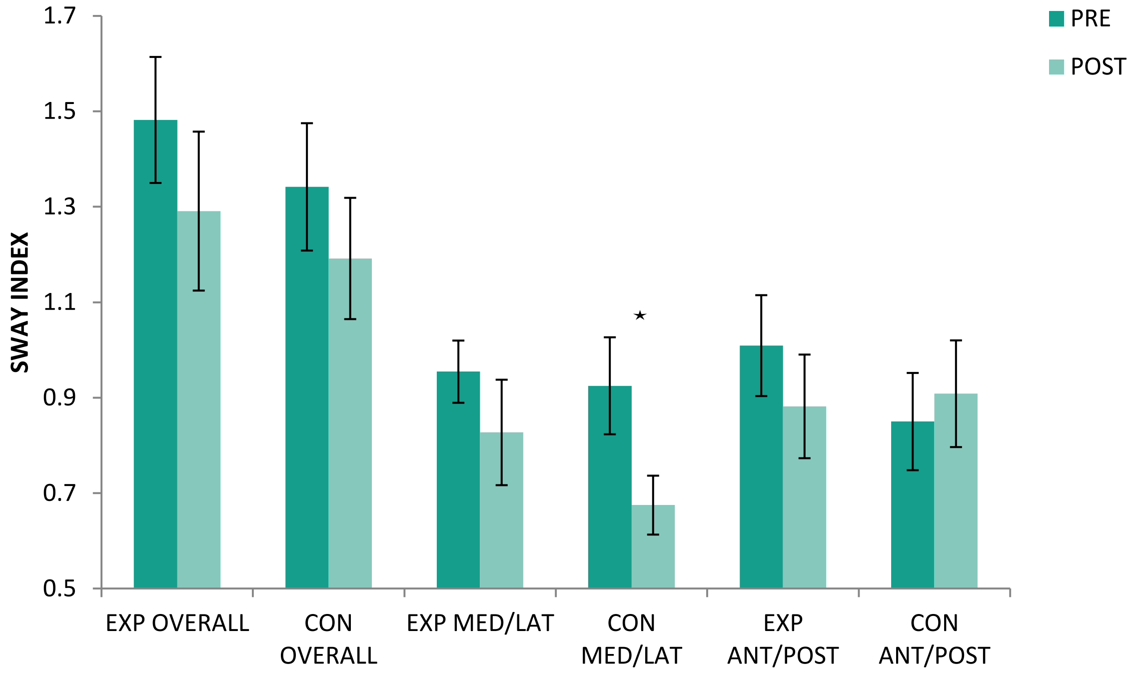


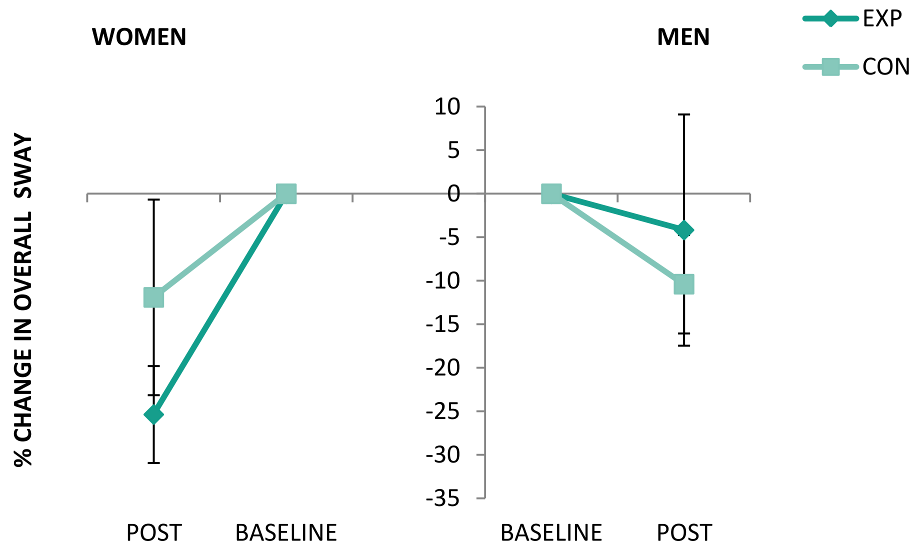
Figure. 5.30. Non-dominant leg overall, M/L, and A/P sway for CON and EXP groups at baseline and post testing (± SEM). *p < 0.05.

i. Gender Differences

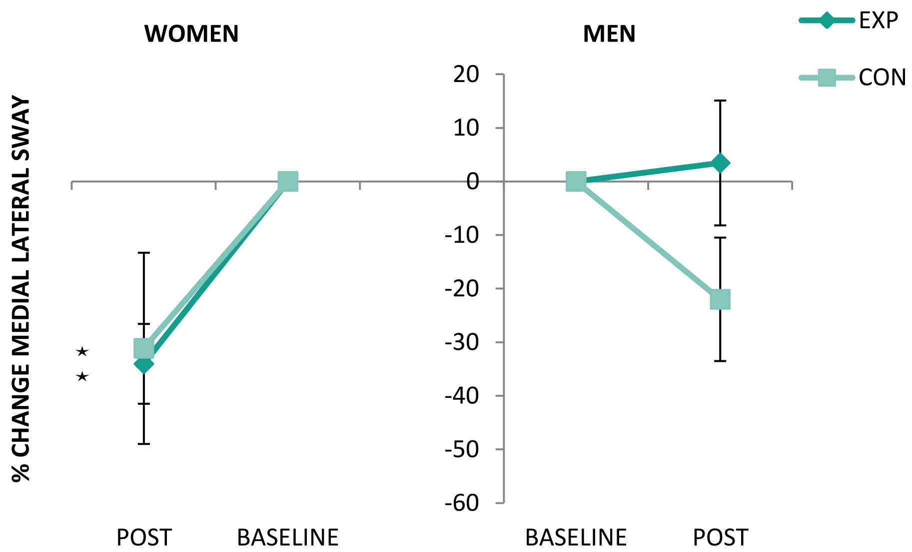
When considering the postural sway among women, M/L sway improved significantly for both groups over time (EXP p = 0.02; CON p = 0.01). However, no significant changes over time were seen for either group in overall sway (EXP p = 0.09; CON p = 0.39) and A/P sway (EXP p = 0.19; CON p = 0.60). EXP group women improved by 25% in overall sway, while CON women improved by 12%. This produced practically significant differences in group improvements (p = 0.83; ES = 0.58[M]). No differences were seen between groups for M/L plane (p = 0.90; ES = 0.24[S]). EXP group women improved by 16% in the A/P plane, while the CON group women deteriorated by 12%, bringing about a practically significant difference in group improvements (p = 0.73; EXP = 0.61[M]).

When considering men, no significant changes over time were seen for either group in M/L sway (CON p = 0.09; EXP p = 0.08) overall sway (EXP p = 0.71; CON p = 0.42) and A/P sway (EXP p = 0.51, CON p = 0.19). For overall sway, EXP group men improved by 4%, while CON group men improved by 10%. This brought about small practical difference between group improvements (p = 0.58; ES = 0.26[S]). In the M/L plane, EXP group men deteriorated by 3%, while CON group men improved by 22%. This resulted in large practically significant differences between groups (p = 0.19; ES = 1.03[L]). Anterior posterior sway improved by 10% for the EXP group men, while CON group men deteriorated slightly by 2%, resulting in very small group improvement differences (p = 0.85; ES =0.13[N]).

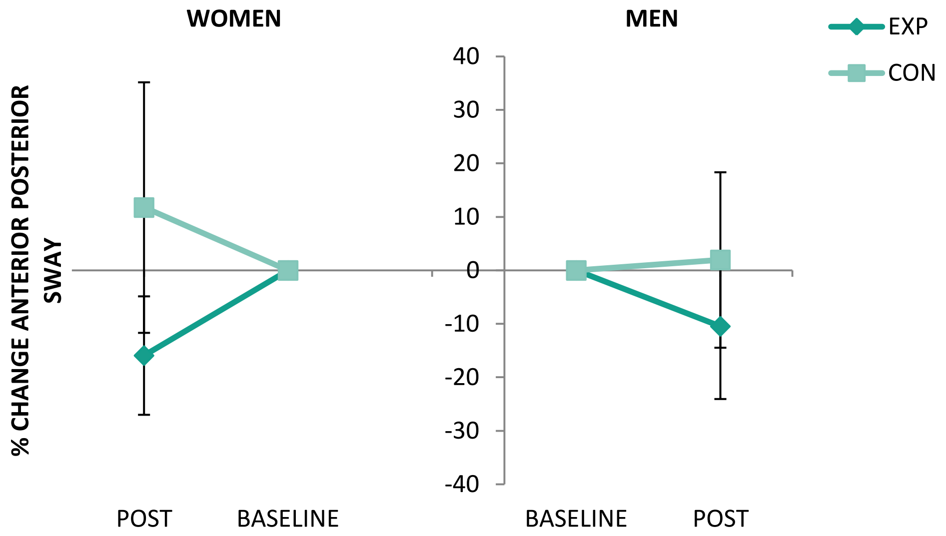
In summary, women improved to a greater extent in overall sway and M/L sway. However, in the A/P plane, the EXP group improved to a greater extent than the CON group. Percentage change in ASL sway scores between men and women over time are depicted in Figures 5.31(a, b & c).



a)



b)



c)

Figure 5.31 (a, b and c). Percentage change in non-dominant leg between men and women in a) overall sway, b) M/L sway, c) A/P sway for both EXP and CON groups (± SEM). *p < 0.05.

2. Athletic Single Leg (ASL) Test (Dominant Leg)

The ASL test showed significant effects over time for overall sway index (p = 0.04) and M/L sway index (p = 0.01), however, the A/P sway index was not significantly different over time (p = 0.14).

No significant differences were found across time for the EXP group, in overall sway (p = 0.36), M/L sway (p = 0.11) or for A/P sway (p = 0.67). Significant improvements were noted for CON group overall sway (p = 0.04) and for the CON group M/L sway (p = 0.05), indicating improvements in postural sway following the intervention period. An improvement of 26% was noted for the CON group, while the EXP group improved by 10% for overall sway. This resulted in a practically significant difference in group improvements (p = 0.34; ES = 0.44^{M}). The CON group improved by 33% in the M/L plane, while the EXP group improved by 18%, bringing about a practically significant difference in group improvements (p = 0.96; ES = 0.45^{M}) as well. The CON groups' A/P sway showed a weak tendency but did not change significantly over time (p = 0.09). A 21% reduction in sway was noted in A/P sway for the CON group while the EXP group presented with almost no change (2% decrease in sway). Group improvements did not differ either practically or statistically (p = 0.14; ES = 0.38). Figure 5.32 depicts EXP and CON ASL sway scores, for both baseline and post testing

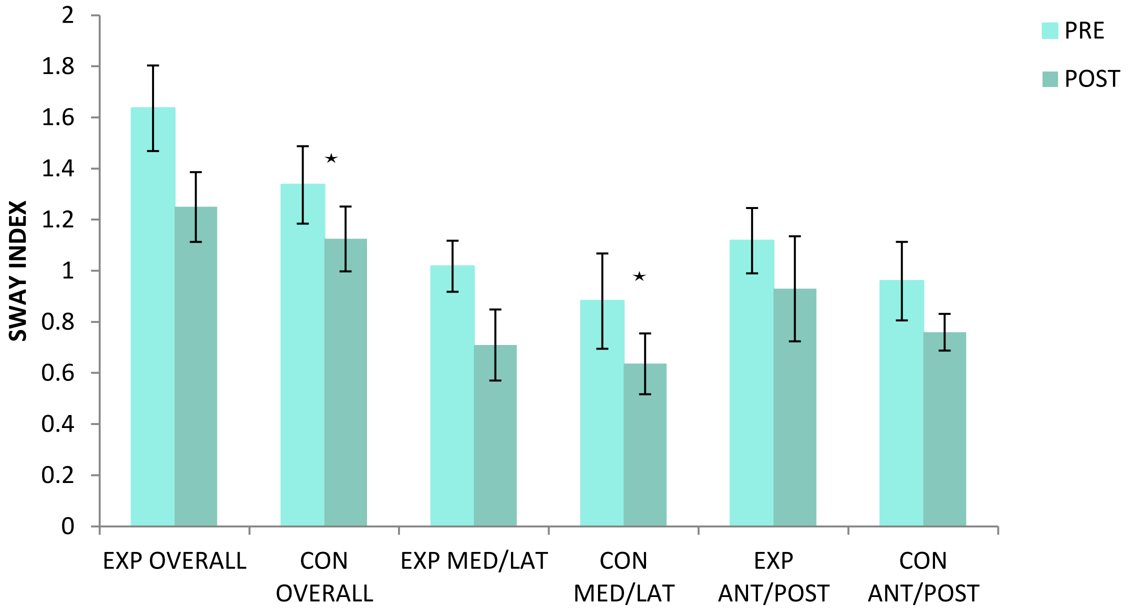


Figure 5.32. Dominant leg ASL sway scores in both the EXP groups, for overall, M/L and A/P sway scores (± SEM). *p < 0.05.

i. Gender Differences

Control group women demonstrated a significant decrease in M/L sway (p = 0.01), but not overall (p = 0.39) or A/P sway (p = 0.60). Experimental group women demonstrated significant improvements in overall sway (p = 0.04), and M/L sway (p = 0.02) over time, but not in A/P sway (p = 0.47). When comparing groups, overall sway improved by 28% in the EXP group, and by 13% in the CON group. However, overall sway group improvements did not differ with statistical or practical significance (p = 0.75; ES = 0.12^{S}). Experimental group women improved by 42% in M/L sway, while CON group women improved by 29%, with a medium practically significant difference between group improvements (p = 0.75; ES = 0.50^{M}). Anterior posterior sway decreased in EXP women by 34%, with a large practically significant difference over time (p = 0.47; ES = 1.28^{VL}), while sway decreased by 21% in the CON group (p = 0.63; ES = 0.27^{S}). However, group improvements did not differ with practical (p = 0.73; ES = 0. 19^{S}) or statistical significance.

Men in the EXP group improved by 9%, for M/L sway, while men in the CON group deteriorated by 23%. A large practically significant difference was noted between group improvements (p = 0.19; ES = 1.04^{L}) for M/L sway. Overall sway increased by 5% in the EXP group, while the CON group men improved by 15%. Once again, large practically significant differences were noted between groups (p = 0.58; ES = 0.79^{L}). Anterior posterior sway improved by 23% in the EXP group, and 25% in the CON group, with negligible differences between groups (p = 0.85; ES = 0.08^{N}). Figure 5.33(a, b and c) shows average percentage change in sway scores for men and women, when compared to baseline values.

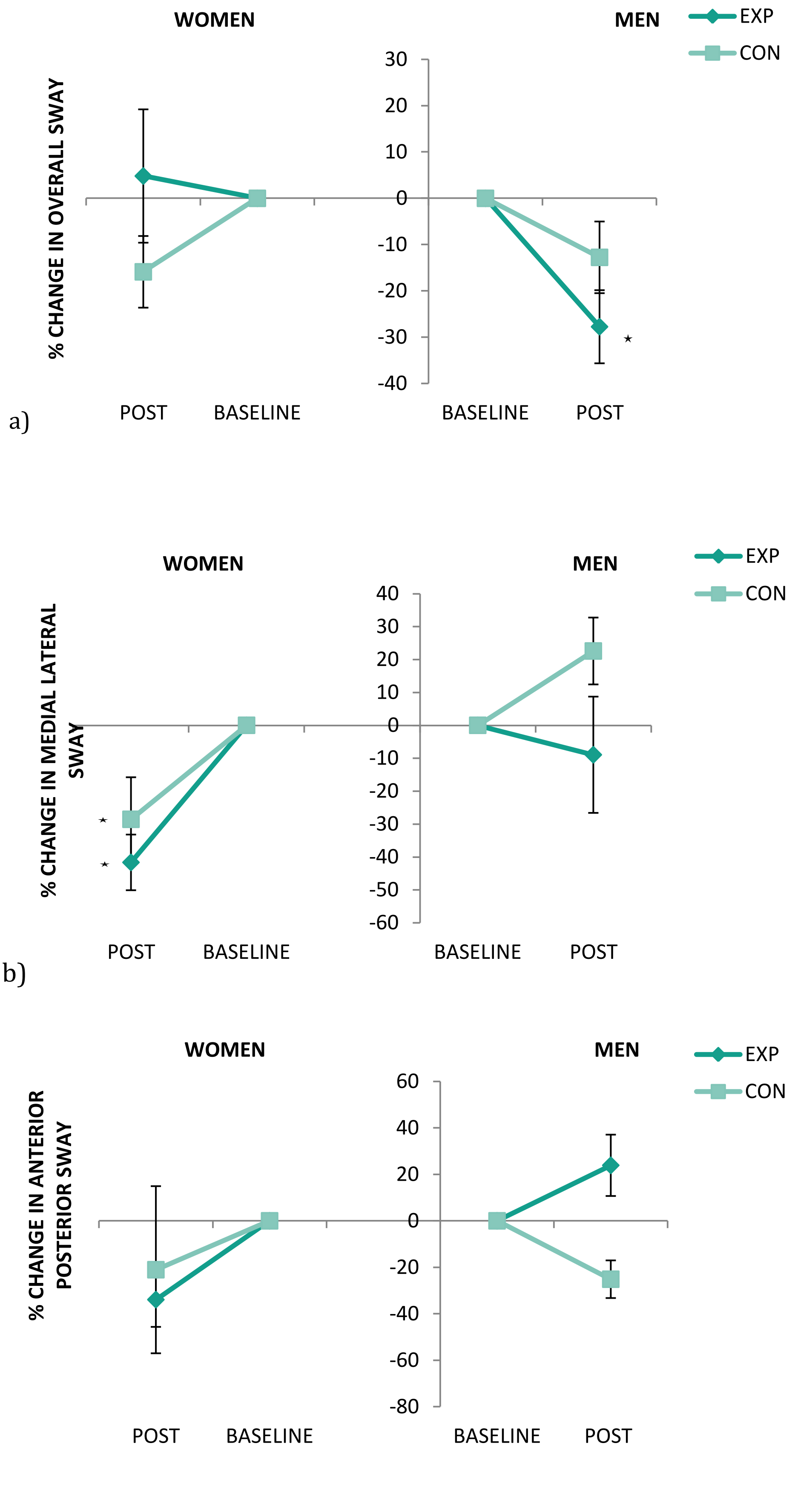


Figure 5.33. Dominant leg ASL percentage change between men and women in a) overall sway, b) M/L, c) A/P sway for both EXP and CON groups (± SEM). *$p < 0.05$.

3. Acute Postural Sway Changes

Comparison of changes in postural sway when wearing minimalist shoes to barefoot, yielded interesting differences. Figure 5.34 demonstrates the change from barefoot to minimalist shoes in the three ASL test planes for the EXP group, at both baseline testing and post-testing (both legs). The x-axis can be viewed as the normalised barefoot condition, with minimalist shoes plotted in relation to barefoot. Thus each data point shows how much the minimalist shoe trial differs from the barefoot trial in the specific condition. Dominant leg overall sway was significantly lower (p = 0.05) in minimalist shoes compared to barefoot, at baseline testing. Although most planes did not yield statistically significant results, practical tendencies were noted. At pretesting, overall (dominant p = 0.14; ES = 0.59^{M}; non-dominant p = 0.24; ES = 0.60^{M}), M/L (dominant p = 0.06; ES = 0.63^{M}; non-dominant p = 0.52; ES = 0.67^{M}) and A/P (dominant p = 0.05; ES = 0.50^{M}; non-dominant p = 0.18; ES = 0.54^{M}) sway were lower in minimalist shoes when compared to barefoot, for both legs.

However, at post testing A/P sway increased in minimalist shoes for both the dominant (p = 0.33; ES = 0.35) and non dominant legs (p = 0.32; ES = 0.44). Medial lateral sway was higher in minimalist shoes at post testing, when compared to barefoot (dominant p= 0.44, ES = 0.66^{M}; non-dominant p = 0.58, ES = 0.44^{M}). However, overall sway was insignificantly lower in the non-dominant leg at post testing in the minimalist shoes and practically significantly higher in the dominant leg in minimalist shoes (p = 0.76; ES = 0.14). Direct comparisons of sway in minimalist shoes at pre and post testing revealed medium and large effect sizes for M/L sway (dominant ES = 0.89^{L}, non-dominant ES = 0.79^{L}) and overall sway (dominant ES = 0.60^{M}, non-dominant ES = 0.48^{M}), but not in A/P sway.

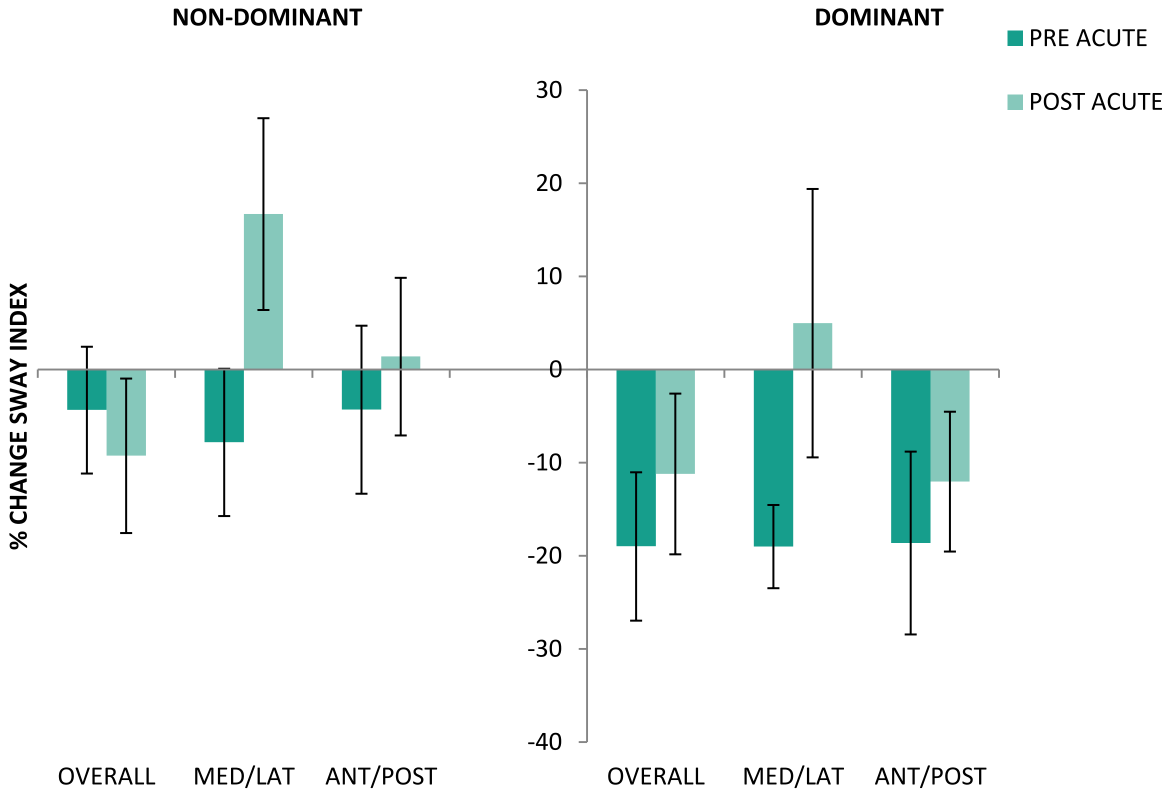


Figure 5.34. Acute changes in postural sway at both baseline and post testing, when wearing minimalist shoes as compared to barefoot for A/P, M/L plane, and overall sway, in both the dominant and non-dominant legs (± SEM) *p < 0.05. The barefoot value is normalized as the x-axis, with values in minimalist plotted on the y-axis for comparison.

4. Modified Clinical Test of Sensory Integration

A significant time effect was observed for condition one (p = 0.01), however no time effects were noted for conditions two (p = 0.47), three (p = 0.40) or four (p = 0.69). Conditions one (p = 0.12), three (p = 0.29) and four (p = 0.39) did not demonstrate significant interaction effects (time x shoes), while only condition two did (p = 0.02). The CON group demonstrated lower sway values than the EXP group at post testing, for condition two. The sway index scores for EXP and CON groups can be viewed in Figure 5.35, for both baseline and post testing. Please note that lower sway indices represent improved postural control (decreased sway).

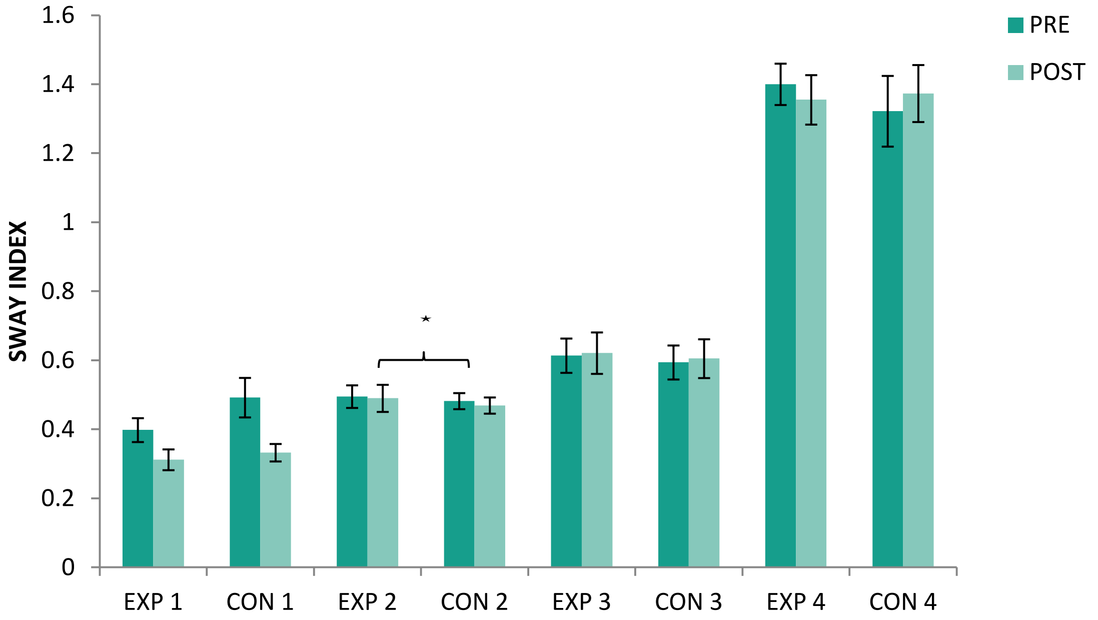


Figure 5.35. Average sway index values across groups for the four mCTSIB conditions, given both prior to and after the intervention period (± SEM).

i. Gender Differences

When separating results between different genders, EXP men demonstrated a slight improvement in sway index scores (p = 0.13) for condition one, whereas CON men showed a large improvement of approximately 43% (p < 0.01). Large practically significant differences were observed between EXP and CON groups for condition one (p = 0.36; ES = 0.85^{L}). For condition two, EXP men improved by 9% (p = 0.83) whereas CON men declined by 5% (p = 0.79), resulting in very large practically significant differences at post testing (p = 0.06; ES = 1.27^{VL}). For condition three, EXP men declined by 44% (p = 0.08), while CON men improved by 8% (p = 0.71). However, a large degree of variability (CV=21%) was seen in the EXP group, resulting in medium practically significant differences between groups at post testing only(p = 0.20; ES = 0.53^{M}). Condition four did not demonstrate any significant changes over time (EXP p = 0.75; CON p = 0.52) or between groups (p = 0.65; ES = 0.22^{S}). The relative change (%) in sway index scores is depicted in Figure 5.36.

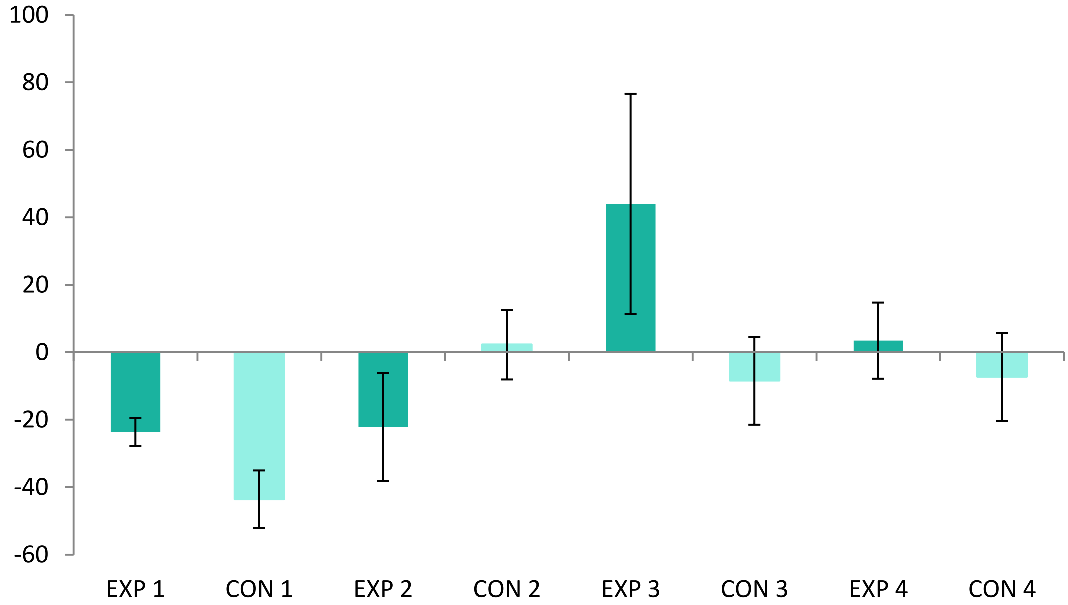


Figure 5.36. Percentage change in sway index scores for men of the CON and EXP groups, across four conditions of the mCTSIB test. The conditions are as follows: condition 1- eyes open, firm surface; condition 2 – eyes closed firm surface; condition 3 – eyes open, foam surface; condition 4 – eyes closed foam surface (± SEM).

When evaluating women separately, the CON group demonstrated more perceivable changes across time with improvements in the firm surface conditions one (14%; p = 0.40) and two (4%; p = 0.67), while showing a decline in foam surface conditions three (13%; p = 0.61) and four (17%; p = 0.26). A relatively large improvement was observed in condition one for the EXP group (36%; p = 0.20), which was 22% more than the CON group. Other conditions (two p = 0.75, three p = 0.61 and four p = 0.26) demonstrated negligible differences in the EXP groups, when comparing baseline to post testing. When comparing groups, a practically significant difference was observed for condition one (p = 0.68; ES = 0.77^{L}) and a statistically significant difference for condition two (p = 0.01; ES = 1.73^{VL}), respectively. Condition three (p = 0.70; ES = 0.28^{S}) and four (p = 0.84; ES = 0.18^{S}) did not produce significant differences between CON and EXP women. Percentage change is sway scores can be seen in Figure 5.37, for EXP and CON women.

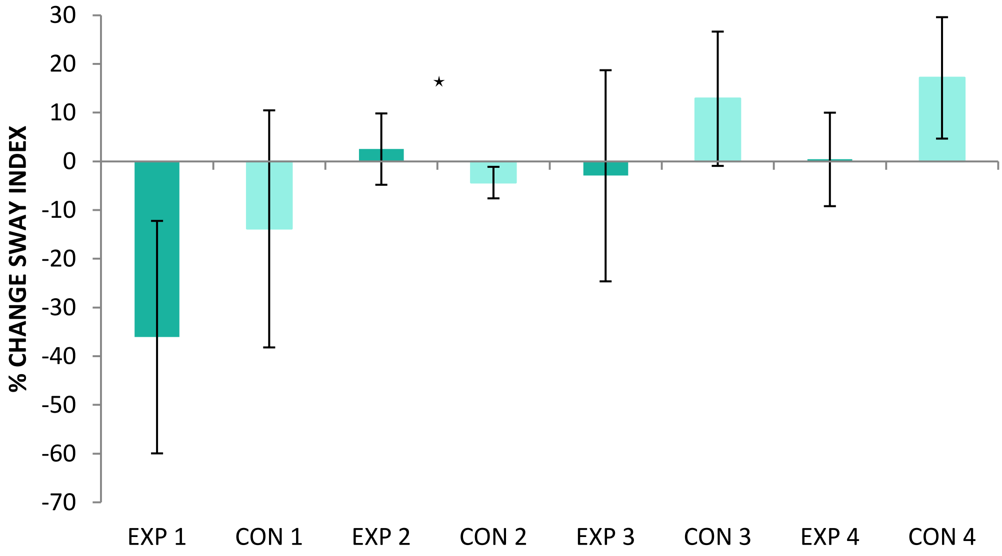


Figure 5.37. Percentage change in sway index scores for women of the CON and EXP groups, across four conditions of the mCTSIB test (± SEM). The conditions are as follows: condition 1- eyes open, firm surface; condition 2 – eyes closed firm surface; condition 3 – eyes open, foam surface; condition 4 – eyes closed foam surface.

1. Acute Change In Sway Index

When comparing the immediate effect of the minimalist shoes on indices of the mCTSIB test, interesting results were found for the EXP group. At pretesting the EXP group demonstrated reduced sway (16%) in the minimalist shoes for condition one, but little change for condition two (5%). Increased sway in the minimalist shoes were observed for the foam condition three (17%), with very little change in condition four (3%). However, post testing revealed marked increases for condition one (23%) and two (43%), with little change in condition three (-3%) and four (1%). Condition two revealed significantly higher sway scores in minimalist shoes at post testing ($p = 0.01$; ES = 1.18^{L}), with only small differences noted at pre testing ($p = 0.97$; ES = 0.26^{S}).

Practically significant differences were observed for conditions one (ES = 0.83^{L}), two (ES = 1.47^{VL}) and three (ES = 0.77^{L}), when comparing the difference between barefoot and minimalist at baseline testing and post testing. Figure 5.34 illustrated the acute changes in ASL sway scores during pre testing, compared to post testing. This graph may be interpreted in a similar way as Figure 5.34. The barefoot condition can be viewed as the normalised x-axis, with the minimalist condition plotted against, in comparison. Practically or statistically significant differences were not observed between men and women for either group.

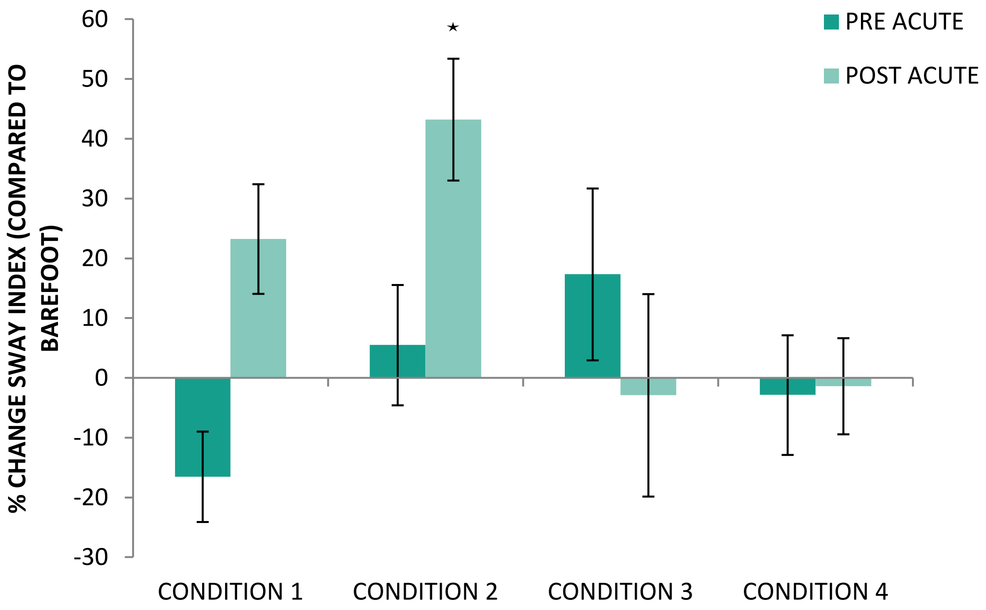


Figure 5.38. Acute change in percentage sway index scores for the four conditions of the mCTSIB test in minimalist shoes compared to barefoot, during baseline and post testing (± SEM). *$p < 0.05$.

When considering men separately (Figure 5.39) results were similar to whole group findings. Condition one demonstrated lower sway values in minimalist compared to barefoot during baseline testing ($p = 0.53$), but increased sway at post testing ($p = 0.45$). This resulted in practically significant differences between pre and post testing for condition one ($p = 0.45$; ES = 1.62^{H}). Condition two demonstrated little change during baseline testing ($p = 0.18$), but increased sway at post testing ($p = 0.01$), with practically significant differences in sway between baseline and post testing (ES = 1.48^{H}). Condition three, however, demonstrated increased sway in minimalist shoes compared to barefoot at baseline testing ($p = 0.58$), but reduced sway at post testing ($p = 0.23$), with medium practically significant differences recorded between baseline and post testing (ES = 0.51^{M}). Condition four demonstrated little change at baseline ($p = 0.90$) and post testing ($p = 0.83$) and practically significant differences between baseline and post testing (ES = 0.45^{M}).

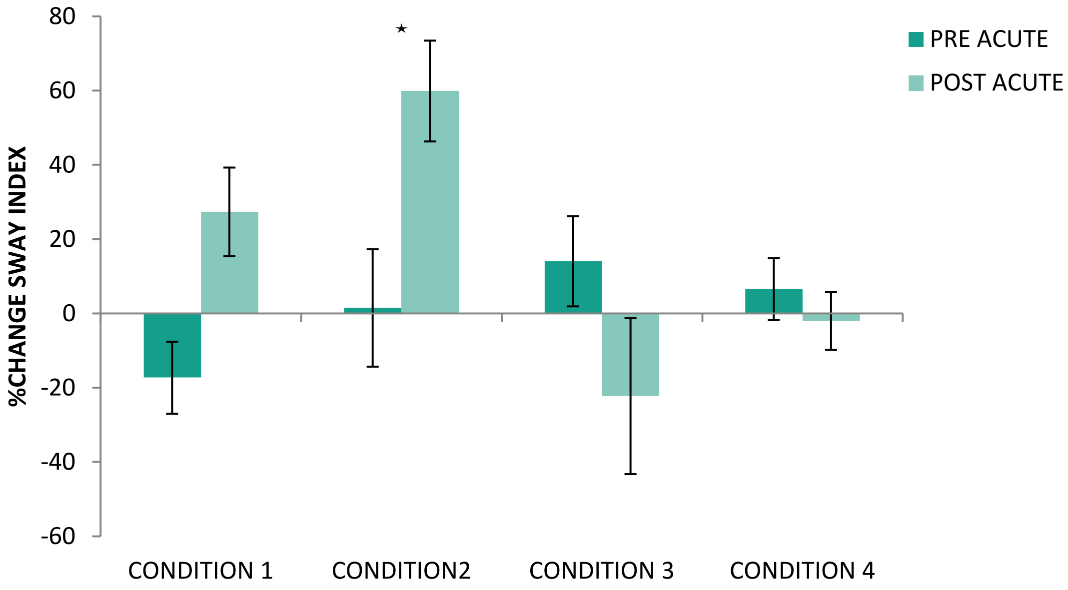


Figure 5.39. Percentage change in male sway index scores for the four conditions of the mCTSIB test in minimalist shoes compared to barefoot, during baseline and post testing (± SEM). *$p < 0.05$.

Women demonstrated a similar pattern as for the whole group, with improvements at baseline testing in minimalist compared to barefoot for condition one (p = 0.11) and no change in condition two (p = 0.88). Increased sway in minimalist shoes compared to barefoot for condition three (p = 0.41) occurred at baseline testing, while condition four (p = 0.48) demonstrated slightly lower values. Post testing revealed increased sway in minimalist compared to barefoot for condition one (p = 0.93), two (p = 0.07) and three (p = 0.70), with reduced sway in minimalist shoes compared to barefoot for condition four (p = 0.27). Very large (ES=1.19^{VL}) and huge (ES=2.24^{H}) practically significant differences were observed between baseline and post testing for conditions one and two, respectively. Condition three demonstrated an improvement in sway both prior to and after intervention in the minimalist shoes. However, the increase in sway was greater at pretesting, with a large practically significant difference occurring between pre and post testing (ES=0.85^{L}). Condition four demonstrated a greater reduction in sway in minimalist compared to barefoot at post testing, with a medium practically significant difference (ES = 0.47^{M}) occurring between baseline and post testing. Percentage change in sway scores can be seen in Figure 5.40 for EXP and CON women.

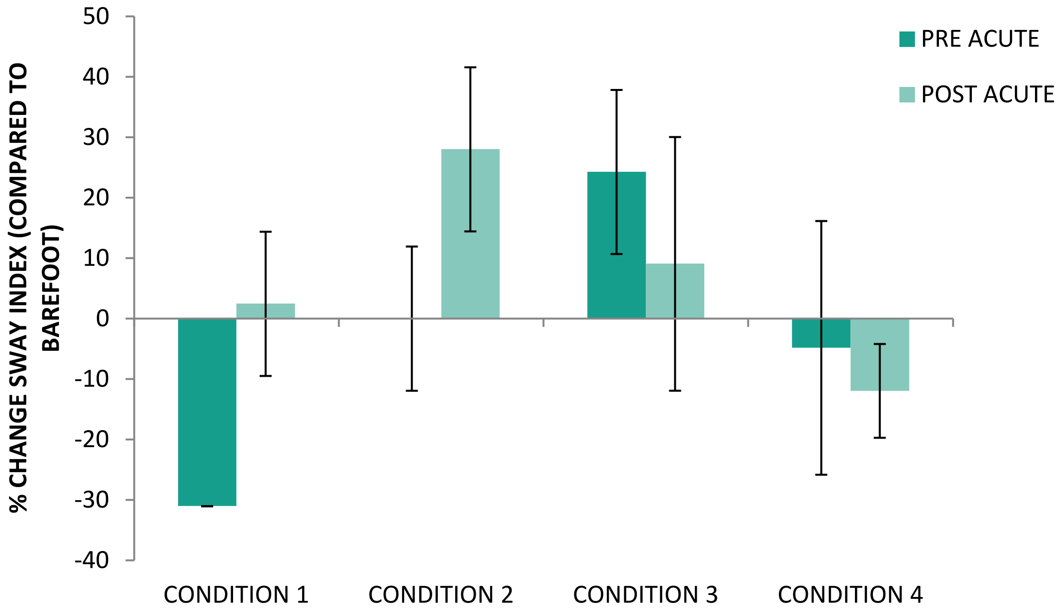


Figure 5.40. Percentage change in female sway index scores for the four conditions of the mCTSIB test in minimalist shoes compared to barefoot, during baseline and post testing (± SEM). *p < 0.05.

H. Joint Position Sense

1. Inversion - Eversion

There were no significant effects over time for any of the three foot position sense trials (Trial 1 p = 0.83; Trial 2 p = 0.16; Trial 3 p = 0.58). No interaction effects were noted for any of the trials (Trial 1 p = 0.99; Trial 2 p = 0.24; Trial 3 p = 0.93). Trial one did not demonstrate statistically significant differences between groups (p = 0.87). Similarly trial two showed no statistically significant differences between groups (p = 0.48), as well as no significant difference over time for either the EXP (p = 0.87) or CON (p = 0.07) groups. Lastly, no significant differences were recorded between groups (p = 0.28), or over time (EXP p = 0.75; CON p = 0.65) for trial three. However, a practically significant difference was observed in the CON group for trial two only (ES = 0.49^{M}), indicating an increase in foot position error. The results are summarized in Table 5.7.

Table 5.7. Average foot position sense errors (degrees error) for three passive inversion/eversion trials (-15 degrees, 15 degrees and 25 degrees inversion), prior to and after intervention, for both EXP and CON groups

		Baseline (Mean ±SD)	Post (Mean ±SD)	p-value	Effect Size
Trial 1	EXP	4.21 ± 2.03	4.78 ± 2.30	0.56	0.24^{S}
	CON	5.45 ± 4.04	5.26 ± 2.67	0.87	0.05^{N}
Trial 2	EXP	4.16 ± 2.02	4.25 ± 1.38	0.87	0.07^{N}
	CON	3.87 ± 2.64	5.13 ± 2.93	0.07	0.49^{M}
Trial 3	EXP	3.17 ± 1.48	3.41 ± 2.24	0.75	0.18^{S}
	CON	4.24 ± 2.56	4.53 ± 2.66	0.65	0.14^{N}

^{N}Negligable; ^{S}Small; ^{M}Medium

i. Gender Differences

Further statistical analysis was done to determine whether differences between genders existed, either prior to or after the intervention period. Men demonstrated no statistically significant difference between groups for any of the three trials (Trial 1 p = 0.39; Trial 2 p = 0.93; Trial 3 p = 0.13).

Practically significant differences over time were not observed for the EXP group (Trial 1 p = 0.55; ES = 0.29^{S}; Trial 2 p = 0.86; ES = 0.15^{S}; Trial 3 p = 0.82; ES = 0.27^{S}), while the CON group presented with practically significant results in trial one (p = 0.80; ES = 0.38^{S}), two (p = 0.27; ES = 0.94^{L}), and three (p = 0.50; ES = 0.38^{S}), indicating a decrease in foot position error for trial one (4.13 ± 1.42 to 3.70 ± 1.28) but an increase for trials two (2.75 ± 1.33 to 3.83 ± 1.22) and three (3.97 ± 3.36 to 4.96 ± 2.56) over time.

Further, practically significant differences were observed between groups for trial one (p = 0.38; ES = 0.7^{M}) and three (p = 0.13; ES = 1.11^{L}), where the CON group had lower foot position error scores in Trial one, but EXP had lower scores in Trial three. Trial two was not significantly different between groups (p = 0.93: ES = 0.22^{S}). The findings are quantified in Table 4.8.

Table 5.8. Mean foot position errors measured in men across three trials (15, 25 and -15 degrees inversion, respectively), for CON and EXP groups prior to and after intervention (x±SD).

		Pre (Mean ±SD)	Post (Mean ±SD)	p-value	Effect Size (d)
Trial 1	EXP	4.52 ± 3.54	5.42 ± 3.68	0.55	0.29[S]
	CON	4.13 ± 1.42	3.70 ± 1.28	0.80	0.38[S]
Trial 2	EXP	3.51 ± 1.45	3.70 ± 1.03	0.86	0.15[S]
	CON	2.75 ± 1.33	3.83 ± 1.22	0.30	0.94[L]
Trail 3	EXP	2.46 ± 0.78	2.76 ± 1.64	0.82	0.27[S]
	CON	3.97 ± 3.36	4.96 ± 2.56	0.50	0.38[S]

[S]Small effect size; [L]Large effect size

Women demonstrated similar results, with no statistically significant differences being noted between groups at post testing for any of the trials (Trial 1 p = 0.25; Trial 2 p = 0.35; Trial 3 p = 0.10). No improvement over time occurred for either the CON (Trial 1 p = 0.97; Trial 2 p = 0.10; Trial 3 p = 0.93) or EXP (Trial 1 p = 0.47; Trial 2 p = 0.95; Trial 3 p = 0.82) group.

Nevertheless, medium effect sizes were found across time for trial one (ES = 0.62[M]), in the EXP group indicating a decrease in foot position error (5.26 ± 2.13 to 4.15 ± 2.52). A medium effect size (ES = 0.47[M]) was noted in the CON group for trial two, indicating an increase in foot position error (4.66 ± 3.13 to 6.10 ± 3.54). Therefore the EXP group had slightly lower foot position error scores at post testing, with an average of 4.4 degrees error, where the CON women had average foot position error scores of 5.6 degrees. The results for the female foot position errors are summarized in Table 5.9.

Table 5.9. Mean foot position errors measured in women across three trials (15, 25 and -15 degrees inversion, respectively), for CON and EXP groups prior to and after intervention (x±SD).

		Pre (Mean ±SD)	Post (Mean ±SD)	p-value	Effect Size (d)
Trial 1	EXP	5.36 ± 2.13	4.15 ± 2.52	0.47	0.62 [M]
	CON	6.27 ± 5.04	6.35 ± 2.96	0.97	0.01[N]
Trail 2	EXP	4.75 ± 2.63	4.83 ± 1.46	0.95	0.03[N]
	CON	4.66 ± 3.13	6.10 ± 3.54	0.10	0.47[M]
Trail 3	EXP	3.94 ± 1.62	4.31 ± 2.74	0.82	0.17[S]
	CON	4.40 ± 2.13	4.33 ± 0.70	0.93	0.08[N]

[N] Negligible effect size S Small effect size [M] Medium effect size

2. Plantar-flexion - Dorsiflexion

Plantar dorsiflexion was measured across three trials (15 degrees, 25 degrees and -10 degrees plantar-flexion), with no statistically significant differences being evident. No time effects were observed in any of the trials for the entire group (Trial 1 p = 0.28; Trial 2 p = 0.28; Trial 3 p = 0.11), indicating that plantar dorsiflexion JPS did not change in any way following the intervention. When considering groups separately, no significant changes occurred over time for either the EXP or CON groups for trial one (EXP p = 0.22; CON p = 0.78), two (EXP p = 0.85; CON p = 0.09) or three (EXP p = 0.14; CON p = 0.41). However, the EXP group showed a medium effect size for trial one (ES = 0.51[M]) and a large effect size for trial three (ES = 0.82[L]) indicating a decrease in foot position error. On the contrary, a medium effect size was observed in the CON group for trial two (ES = 0.67[M]), also indicating a decrease in foot position error. The findings are summarized in Table 5.10.

Table 5.10. Mean plantar dorsi flexion foot position errors measured across three trials (15, 25 and -15 degrees inversion, respectively), for CON and EXP groups prior to and after intervention.

		Pre (Mean ±SD)	Post (Mean ±SD)	p-value	Effect Size (d)
Trial 1	EXP	3.91 ± 2.63	2.82 ± 1.90	0.22	0.51[M]
	CON	3.05 ± 1.74	2.93 ± 1.38	0.78	0.15[S]
Trial 2	EXP	3.02 ± 1.44	3.18 ± 1.96	0.85	0.07[N]
	CON	3.57 ± 2.06	2.47 ± 1.24	0.09	0.67[M]
Trial 3	EXP	3.33 ± 2.06	2.35 ± 0.97	0.14	0.82 [M]
	CON	2.79 ± 1.50	2.23 ± 1.91	0.41	0.33[S]

[N] Negligible effect size [S] Small effect size [M] Medium effect size.

i. Gender Differences

Further statistical analysis separated results between genders. When considering men, a statistically significant time effect was not observed for any of the trials (Trial 1 p = 0.28; Trial 2 p = 0.28; Trial 3 p = 0.11). Significant changes in foot position error occurred for the CON group in trial two (EXP p = 0.86; CON p = 0.05) but not for either group in trial one (EXP p = 0.23; CON p = 0.79) or trial three (EXP p = 0.19; CON p = 0.55). The CON group demonstrated a very large practical significance for trial two (ES = 1.23[VL]), demonstrating a substantial decrease in mean foot position error (4.76 ± 2.37 to 2.51 ± 1.59). A medium practically significant difference was noted in the EXP group for trial one (ES = 0.55[M]) and trial three (ES = 0.69[M]) indicating a moderate reduction in foot position error. Figure 5.45 illustrates the change in relative foot position errors for men in the EXP and CON groups, across three trials (15 degrees, 25 degrees and -10 degrees plantar-flexion, respectively).

Table 5.11. Mean plantar dorsi flexion foot position errors measured across three trials (15, 25 and -15 degrees inversion, respectively), for control and experimental women prior to and after intervention.

		Pre (Mean ±SD)	Post (Mean ±SD)	p-value	Effect Size (d)
Trial 1	EXP	4.33 ± 3.10	2.90 ± 2.50	0.23	0.55[M]
	CON	3.74 ± 2.36	3.40 ± 1.45	0.79	0.15[S]
Trial 2	EXP	3.33 ± 1.54	3.13 ± 1.77	0.86	0.07[N]
	CON	4.76 ± 2.37	2.51 ± 1.59	0.05	1.23[L]
Trial 3	EXP	3.81 ± 2.76	2.54 ± 1.02	0.19	0.69 [M]
	CON	1.92 ± 0.86	1.32 ± 1.11	0.55	0.33[S]

[N] Negligible effect size [S] Small effect sizeM Medium effect size. [L]Large effect size.

Further statistical analysis found that women did not show any statistically significant differences between groups (Trial 1 p = 0.88; Trial 2 p = 0.45; Trial 3 p = 0.39) or across time for trial one (EXP p = 0.56; CON p = 0.90) trial two (EXP p = 0.68; CON p = 0.75) or trial three (EXP p = 0.41; CON p = 0.41).

However, in the EXP group a medium (ES = 0.48[M]) and large (ES = 1.06[L]) practically significant difference was found in trial one and three, respectively, indicating a relative decrease in plantar dorsiflexion foot position error. The CON group demonstrated a medium (ES = 0.49[M]) practically significant difference between baseline and post testing, indicating a reduction in foot position error for trial three as well. The relative change in foot position error for both groups, are summarized in Table 5.12, indicating that there is an overall improvement in foot position error, with the exception of the EXP group in trial two.

Table 5.12. Mean plantar dorsi flexion foot position errors measured across three trials (15, 25 and -15 degrees inversion, respectively), for control and experimental women prior to and after intervention.

		Pre (Mean ±SD)	Post (Mean ±SD)	p-value	Effect Size
Trail 1	EXP	3.41 ± 2.17	2.72 ± 1.28	0.56	0.48[M]
	CON	2.63 ± 1.23	2.56 ± 1.27	0.90	0.15[S]
Trial 2	EXP	2.74 ± 1.54	3.16 ± 2.37	0.68	0.07[N]
	CON	2.75 ± 1.52	2.47 ± 1.15	0.75	1.23[L]
Trial 3	EXP	2.82 ± 0.32	1.97 ± 0.65	0.41	1,06[M]
	CON	3.32 ± 1.72	2.88 ± 2.34	0.41	0.49[M]

[N] Negligible effect size [S] Small effect sizeM Medium effect size. [L]Large effect size

I. Running Kinematics

1. Ankle Angle At Contact

Ankle angle at contact increased significantly within the EXP group across all speeds (8km.h^{-1} $p < 0.01$; 10km.h^{-1} $p < 0.01$; 12km.h^{-1} $p < 0.01$). This translates to a more plantar-flexed ankle at initial contact. Ankle angle increased further into plantar-flexion, with increasing speeds. The opposite was true for the CON group, where a decrease in ankle angle into more dorsiflexion was noted over time, although not statistically significant (8km.h^{-1} $p = 0.48$; 10km.h^{-1} $p = 0.47$; 12km.h^{-1} $p = 0.54$). The ankle angle also decreased further with increasing speeds. At post testing, ankle angle differed significantly between groups, for all speeds (8km.h^{-1} $p = 0.01$; 10km.h^{-1} $p = 0.01$; 12km.h^{-1} $p = 0.01$). Similar practically significant differences were found between groups for the 8km.h^{-1} (ES = 1.39^{VL}), 10km.h^{-1} (ES = 1.46^{VL}) and 12km.h^{-1} (ES = 1.73^{VL}) speeds. Average changes in plantar-flexion angles can be seen in Figure 5.41 for EXP and CON groups.

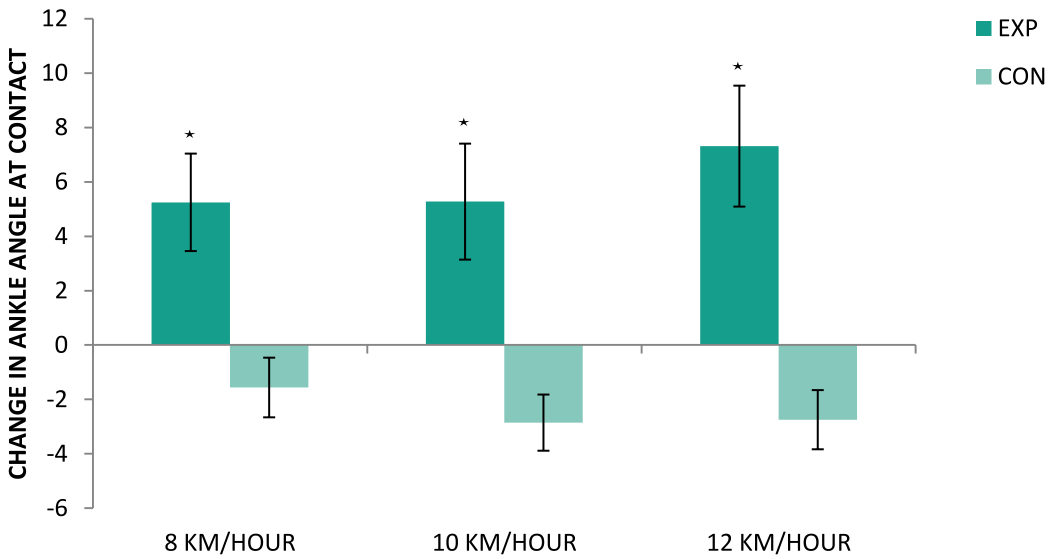


Figure 5.41. Average change in ankle angle from baseline testing to post-testing, for CON and EXP groups, across three speeds (8km.h^{-1}, 10km.h^{-1}, 12km.h^{-1}) (± SEM). *$p < 0.05$.

i. Gender Differences

Further statistical analysis was done to determine whether differences occurred between genders. Experimental women showed a statistically significant differences in ankle angle over time in all three speeds (8km.h^{-1} $p = 0.03$, ES = 1.34^{VL}; 10km.h^{-1} $p = 0.02$, ES = 1.22^{L}; 12km.h^{-1} $p =$

0.01, ES = 1.58[VL]), while men demonstrated strong tendencies in ankle angle over time for the faster speeds (10km.h^{-1} p = 0.06 and 12km.h^{-1} p = 0.06) and significant changes in the slower speed (8km.h^{-1} p = 0.05).

Both men (8 km^{-1} p = 0.87, ES = 0.12[S]; 10 km^{-1} p = 0.97, ES = 0.09[N]; 12 km^{-1} p = 0.67, ES = 0.28[S]) and women (8 km^{-1} p = 0.33; 10 km^{-1} p = 0.21; 12 km^{-1} p = 0.34) of the CON group did not demonstrate significant differences over time. As can be seen in Table 5.13, female EXP participants demonstrated greater relative change in ankle angle across time. Differences were noted between EXP and CON women for the 8 km^{-1} (p = 0.01), 10 km^{-1} (p = 0.02) and 12 km^{-1} (p = 0.03), whereas weak tendencies were noted between EXP and CON men for 8 km^{-1} (p = 0.11), 10 km^{-1} (p = 0.09) and 12 km^{-1} (p = 0.08) speeds.

Table 5.13. Summary of ankle angles at initial contact for men and women of the CON and EXP groups at baseline and post testing, across three speeds (8km.h^{-1}; 10km.h^{-1}; 12km.h^{-1}).

	8 km.h^{-1} Pre	8 km.h^{-1} Post	10 km.h^{-1} Pre	10 km.h^{-1} Post	12 km.h^{-1} Pre	12 km.h^{-1} Post
EXP Women	92.12 ± 8.24	102.34 ± 10.44*	89.63 ± 4.95	101.71 ± 12.62*	88.72 ± 5.05	101.74 ± 12.84*
CON Women	85.14 ± 3.86	88.23 ± 7.96	84.67 ± 3.85	88.54 ± 9.12	85.34 ± 3.68	88.16 ± 9.13
p-value	0.17	0.01	0.36	0.02	0.54	0.03
EXP Men	97.32 ± 11.54	104.65 ± 6.15	96.92 ± 12.24	105.05 ± 6.35	96.54 ± 12.86	105.06 ± 6.98
CON Men	95.77 ± 8.45	96.32 ± 7.64	95.17 ± 9.24	95.66 ± 8.06	94.55 ± 8.03	95.54 ± 9.836
p-value	0.77	0.11	0.73	0.09	0.71	0.08

*Significant change from baseline to post. [N] Neglible effect size , [S] Small effect size, [M] Medium effect size. [L]Large effect size.

2. Knee Angle at Contact

Average knee flexion increased in the EXP group across time for all speeds, although only significant at 12km.h^{-1} (8km.h^{-1} p = 0.38; 10km.h^{-1} p = 0.59; 12km.h^{-1} p = 0.05). However, practically significant differences were noted between groups for all speeds (8km.h^{-1} ES = 0.64[M]; 10km.h^{-1} ES = 0.49[M]; 12km.h^{-1} ES = 0.51[M]). This increase in knee flexion also increased with increasing speed in the EXP group. On the contrary, the CON group decreased their flexion at contact from baseline to post testing, resulting in a more extended knee at initial contact (8km.h^{-1} p = 0.03; 10km.h^{-1} p = 0.05; 12km.h^{-1} p = 0.82). A strong linear relationship between speed and knee angle was not as evident in the CON group, with statistically significant changes occurring only in the 8$km.h^{-1}$ speed and 10$km.h^{-1}$ speed. The largest change in knee angle from baseline to post testing occurred in the 10$km.h^{-1}$ speed where knee extension increased by an average of 0.57˚ ± 0.28˚ for the CON group.

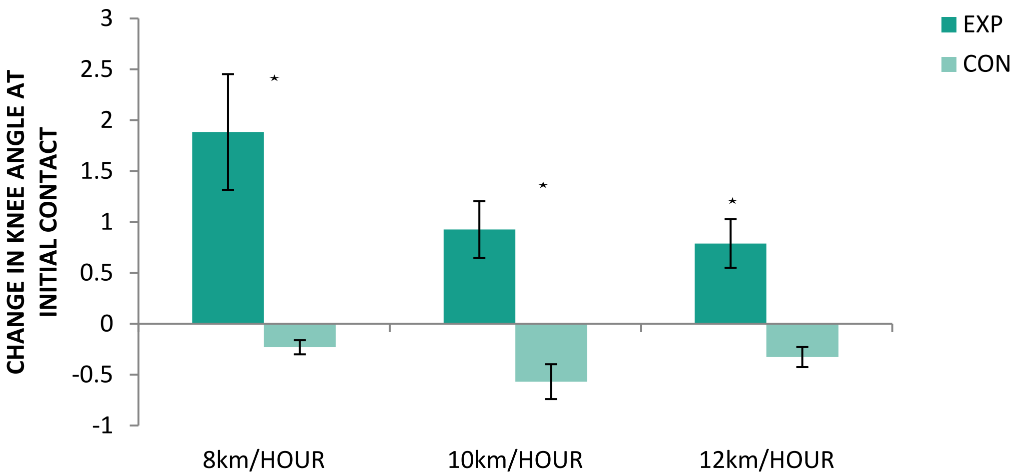


Figure 5.42. Average change in knee angle from baseline to post-testing, for CON and EXP groups, across three speeds (8$km.h^{-1}$; 10$km.h^{-1}$, 12$km.h^{-1}$) (± SEM) *$p < 0.05$.

i. Gender Differences

Table 5.14 summarizes the findings for average knee angles at contact for men and women of the EXP and CON groups. Women in the EXP group did not change their knee angles significantly over time for any of the speeds (8km^{-1} $p = 0.13$; ES = 0.29^{S}; 10km^{-1} $p = 0.19$; ES = 0.11^{N}; 12km^{-1} $p = 0.08$; ES = 0.42^{M}), however the 12km^{-1}speed demonstrated slightly increased knee extension. Men in the EXP group demonstrated slight increases in knee flexion for the 8 km^{-1} ($p = 0.27$; ES = 0.43^{M}) and 10 km^{-1} speed ($p = 0.74$; ES = 0.07^{N}), but slightly more knee extension for the 12 km^{-1} ($p = 0.43$; ES = 0.32^{S}). No differences occurred between EXP men and women (8 km^{-1} $p = 0.71$; 10 km^{-1} $p = 0.15$; 12 km^{-1} $p = 0.33$). Control women increased knee extension for all speeds (8 km^{-1} $p = 0.13$ ES = 0.34^{S}; 10 km^{-1} $p = 0.19$ ES = 0.22^{S}; 12 km^{-1} $p = 0.79$ ES = 0.99^{L}), and so did CON men (8 km^{-1} $p = 0.27$, 10 km^{-1} $p = 0.74$; 12 km^{-1} $p = 0.92$). No differences were observed between men and women of the CON group ($p = 0.30$; $p = 0.33$; $p = 0.89$). Lastly, no differences were observed between the EXP and CON men or EXP and CON women for any of the speeds.

Table 5.14. Summary of knee angles at initial contact for men and women of the CON and EXP groups at baseline and post testing, across three speeds (8km.h-1; 10km.h-1; 12km.h-1).

	8 km.h-1 Pre	8 km.h-1 Post	10 km.h-1 Pre	10 km.h-1 Post	12 km.h-1 Pre	12 km.h-1 Post
EXP Women	166.72 ± 5.85	166.32 ± 6.73	164.75 ± 5.47	165.43 ± 5.64	163.93 ± 5.23	166.54 ± 7.45*
CON Women	162.43 ± 7.26	164.65 ± 6.15	162.85 ± 5.77	164.55 ± 4.72	164.2 4± 4.565	167.66 ± 3.01
p-value	0.20	0.59	0.48	0.87	0.84	0.14
EXP Men	169.14 ± 1.96	167.63 ± 3.95	168.72 ± 2.22	168.33 ± 4.33	167.62 ± 3.03	166.56 ± 3.03
CON Men	165.35 ± 3.35	167.85 ± 3.57	164.94 ± 3.45	167.24 ± 2.52	164.75 ± 3.52	165.34 ± 2.73
p-value	0.23	0.93	0.18	0.68	0.75	0.73

*Significant change from pre to post. N Neglible effect size , S Small effect size, M Medium effect size. L Large effect size.

CHAPTER SIX: DISCUSSION

A. Introduction

The present study investigated the effect of minimalist shoes on the neuromuscular control (NMC) of recreational distance runners. The main focus of this study was to determine whether muscle activation patterns, joint position sense (JPS) and postural control (PC) could be improved following an eight-week intervention period in minimalist shoes. Subsequently, the isokinetic ankle joint strength and kinematic consequences of the possible NMC adaptations were also investigated. Following the presentation of data in chapter five, the pertinent findings will be addressed in relation to the research objectives set out prior to the study.

Training and intervention characteristics will first be discussed, providing a basis for presenting main findings of the dependant variables to follow. Thereafter, precise conclusions will be made pertaining to the research questions at hand. Possible limitations to the study will be explored, where after recommendations will be made in order to aid future studies.

B. Descriptive Characteristics

1. Participants

No statistically significant differences were found between the randomized control (CON) and experimental (EXP) groups for any of the anthropometric and descriptive measurements (Table 5.1; page 73). Participants were young and physically active, and small differences in age were not expected to have any effect on outcome variables. Although it is expected that balance and JPS does decline with age, significant decreases are usually only noted from the approximately age of 60 to 65 and older (Jonsson *et al.,* 2004; Bullock Saxton *et al.,* 2001). As all participants were in their twenties, small age differences were not expected to influence the data. It should be noted that a decline in recovery is noted with increasing age and that these declines can be detected from the age of 35 (Fell & Williams, 2008; Bortz & Bortz, 1996). Therefore results from the present study should not be generalized to older populations. Future research on the effect of minimalist shoes on NMC might be warranted in older study populations. Lastly, as mentioned on page four, being under the age of 34 places female runners at an increased risk of patellofemoral pain syndrome (PFPS), and men at an increased risk of ITB, Patellar

Tendinopathy and MTSS. Interestingly, two EXP women and three CON women experienced PFPS to a moderate degree (also, one EXP women that did not complete the study experienced moderate to severe PFPS). Three EXP men also experienced MTSS. Lastly, a possible Patellar Tendinopathy was noted in one EXP runner, although a formal diagnosis was not made by a medical doctor. These findings suggest that age is an important factor for certain injury types and that future research regarding injury prevention in these cases should be encouraged.

Due to exclusion criteria, both groups had a healthy BMI under 25 $kg.m^{-1}$ and did not differ significantly. It was, however interesting to note that one of the EXP women and four of the CON women had BMI's of below 21 $kg.m^{-1}$ which places them at an increased risk of developing Tibial Stress Fractures and spinal injuries (Taunton *et al.,* 2002). Fortunately, no stress fractures or spinal injuries were reported in any of the participants. This may be due to the fact that the study was conducted over a relatively short time period and exercise volumes were conservative. Future research over longer time periods and greater distances may be called upon, to determine the specific risk for minimalist runners.

A large difference in the height was noted (Table 5.1; page 73), with the EXP group being 2.83 cm taller than the CON group. While height may influence balance, the researcher was careful to only include studies that normalized for height (such as the Biodex Balance). Measurements taken after the intervention period were only compared to baseline tests of that same participant, thereby ensuring that each participant acted as his/her own control. However, height does affect running kinematics, which may incur slight differences between groups. Taller runners can take larger steps without over-reaching. As tests were conducted at standard running speeds, it could be possibly that a small degree of the differences noted between groups are due to height differences. Men are also generally taller than women, and kinematic differences could therefore possibly be expected at absolute running speeds. Schache and colleagues (2011) investigated the differences noted between genders at 4. 0 $m.s^{-1}$ and found that because women are shorter, they demonstrate significantly shorter stance time, swing time, stride time, stride lengths. However, when running at an absolute pace women were shown to compensate with higher stride rates, when compared to men. This results in similar relative stride lengths, stance times and swing times between men and women.

2. Baseline Performance Variables

During the first visit a VO_{2max} test was administered, in order to determine both maximal and steady state fitness values. No statistically significant differences existed between the CON and EXP groups, for any of the performance variables (Table 5.2; page 74). Both groups were relatively fit and performed close to their age-predicted VO_{2max} values. The EXP and CON group also had similar average VO_{2AT} values, which occurred at approximately 86% of the VO_{2max}. This indicates that both groups were aerobically fit prior to the start of the study. Likewise, similar results were obtained for minute ventilation, with the EXP group reaching 68% of their age predicted VE, and the CON group reaching 70%. These values were slightly lower than the expected 80% in healthy individuals. However, as participants did not have any respiratory illnesses or complaints they were still deemed fit to participate in the study.

Slight differences did exist between groups for HR_{max} and HR_{AT}. These differences were accounted for by prescribing HR training zones according to each individual's inherent heart rate. Also, participants ran at approximately 140 - 160 bpm which was much lower than any of the HR_{max} values. Moderate intensities were chosen to allow the plantar-flexor muscles time to adjust to the minimalist shoes. Therefore, although individual physiological differences were taken into account, maximal performance values should not affect outcome variables as training occurred at low submaximal percentages.

Interestingly, EXP women had lower HR_{max} (women 184.4 ± 7.2; men 191.3 ± 5.2); and HR_{AT} (women 165.0 ± 6.5 bpm; men 174.7±8.2) values than men, while CON women had similar HR values compared to CON men. EXP women performed at 101% of their age predicted VO_{2max} values, while EXP men performed at 98% of their age predicted VO_{2max}. When considering the CON group, women performed at 107% of their age predicted VO_{2max}, while CON men reached 101%. Given these observations, one could deduce that men and women did not differ significantly in the relative baseline performance variables.

3. Training History Variables

No statistically significant differences were noted between CON and EXP group training history variables (Table 5.3; page 74). However, the EXP group did have ten to twelve months more running experience than the CON group. It must be noted that subjects were simply questioned regarding their approximate running history, and answers obtained were somewhat subjective. Further, runners tended to train somewhat inconsistently prior to the study, as they were running for recreational reasons only and had no obligation to train. This may have made the estimation of training history variable more difficult. Taking all of the above into account, runners were deemed to be at the same fitness level and running experience and the moderate differences noted between groups for experience is not expected to influence outcome variables. This proposition is further supplemented by the fact that group 10 km running times did not differ significantly prior to the study (Table 5.3; page 74).

C. Intervention Characteristics

1. Total Performances Variables

Overall, no statistically significant difference was noted in any of the training variables (Table 5.4; page 75) throughout the duration of the study. Overall, both groups ran similar distances, but there was a 10km (6%) difference in total distance accumulated over the intervention period. This may be due to the fact that, on occasion, runners missed sessions. Reasons for missing sessions included headaches, colds, writing of tests and exams and occasionally travel. The study was designed to allow some flexibility in the program, for unexpected disruptions of the normal weekly routine. For instance, morning and afternoon sessions were held on the same day, to allow participants more opportunities to make sessions. This helped adherence tremendously. Runners were expected to have a minimum of 80% adherence rate. Therefore, they had to complete 20 out of the prescribed 24 sessions at the end of the eight-week period, or they were excluded from the study. It is possible that sessions missed by CON runners were of longer distances, than those missed by EXP runners, resulting in a slight distance discrepancy.

The slightly higher total distance covered by the EXP group could have several possible effects. Firstly, the increased discomfort experience by the EXP group could at least be partly explained by the 6% difference in running distance. Extrinsic risk factors increasing the risk of injury include shoes, surface characteristics and training variables (Daoud *et al.,* 2012), which could mean that EXP runners had an increased injury risk. EXP runners would then be expected to demonstrate slightly lower LLCI scores. Secondly, the increased distance covered by the EXP runners could mean that they had an improved endurance capacity, and could run more than the CON group. This could possibly be explained by the improved economy often noted in minimalist runners due to the reduced shoe mass (Perl *et al.,* 2012; Hanson *et al.,* 2010). Thirdly, as it is very difficult to produce a placebo effect with minimalist shoes, runners were not blind to the group they were in. Control runners may not have had the same level of motivation as EXP runners, due to the fact that they knew they were simply serving as controls. Future research may be advised to have separate sessions for EXP and CON runners, while still running the same route.

2. Session Performances

Figure 5.1 (page 76) describes the average session performances over the intervention period. The average distance increased gradually over the 8-week period, with proportional increases in time. Each micro cycle (week) consisted of one longer, one shorter, and one average length run. Similarly, duration time varied in direct proportion to the prescribed distance.

Heart rate (HR) varied considerably between individuals and sessions, depending on physiological differences, temperature and duration of run. Although individual HR training zones were prescribed for each participant according to their fitness level, it was noted that the CON group preferred to remain at the higher end of their prescribed heart rate zone, while the EXP group preferred to maintain their heart rate at the lower end of the training zone. Experimental group HR was 10% lower during sessions four, 9% lower during session five, 5% lower during session seven, 9% lower during session twelve and 7% lower during session fourteen. However variability in individual heart rate zone makes the significance of this finding less substantial. It may be possible that, while running distance was set, EXP participants who experienced lower extremity discomfort chose to run slower, in an attempt to reduce discomfort. It is widely accepted that following excessive eccentric work, muscle damage occurs, causing significant strength deficits (Fredsten *et al.,* 2008). Therefore, it is likely that running in minimalist shoes may cause an initial decrease in performance during the transitioning period, as can be seen by the slower speed (or lower HR) in the EXP group.

On the other hand, the reduced HR in minimalist runners could also be partly explained by the improved running economy noted in the literature. If there is less shoe mass and improved utilization of the elastic spring system in EXP runners, their HR might be lower due to a reduced aerobic demand. The HR was significantly lower during session four, five and six. Sessions four and five were early in the program, and could possibly be attributed to individual variations in HR. However, during session six, the EXP group ran a significantly longer distance, and therefore, lower average HR values were not expected. Possibly, as this was the second weekly long run, individual HR differences may have been amplified over a longer time. Interestingly, session twelve was the first long run over 10 km, and demonstrated significant differences in HR as well. Lastly, session fourteen was a shorter run, but included a relatively large hill, which may have influenced HR values markedly. Lastly, a larger proportion of the EXP group runners preferred to participate in morning sessions. As morning sessions were cooler, it could be expected that lower HR values were to be seen during these sessions.

The distance run during each session was similar between CON and EXP groups. There, was, however, a statistically significant difference during session 6 where the EXP group ran approximately 900 metres further. However, during session nine, the CON group ran significantly further, which compensated for differences seen during session six. These differences could be explained by the fact that in some cases, participants missed running sessions, but then made up for distances missed during later sessions.

Following the discussion of participants and performance variables, the specific research objectives will next be discussed.

A. RESEARCH OBJECTIVE ONE

To Determine Whether an Eight-Week Intervention Affects Subjective Ratings of Injury Risk.

1. Lower Limb Comfort Index

The Lower Limb Comfort Index was used to monitor participants with every running session (Figure 5.2; page 78). The first, most apparent observation that can be made is that the total LLCI score is closely associated with the distance run during that session. It was expected that as distance increased, total LLCI would decrease, indicating more discomfort. This was observed for both groups. Further, the EXP group experienced more discomfort, especially in the calves, while the CON group experienced slightly more knee pain. This finding is closely associated with the running kinematics exhibited by runners in each group. As EXP runners landed in more plantar-flexion, it was expected that they might experience more discomfort in the calves. Likewise the CON group demonstrated running kinematics believed to place more strain on the knee (increased dorsiflexion and knee extension), which was also portrayed by LLCI scores.

The EXP group demonstrated significantly more discomfort in the foot, ankle, Achilles, and calves, when taking the average score of each anatomical area over the intervention period. The EXP group was expected to show more discomfort firstly due to the reduction in cushioning, and secondly due to the increased recruitment of intrinsic musculature of the foot and ankle. As trainers can be confining, inflexible and tight, reduced recruitment of intrinsic musculature occurs, resulting in weakness and atrophy over time. Then, during the initial transitioning stages, these muscles are overloaded and might become fatigued prematurely, resulting in excessive discomfort.

Significantly lower LLCI scores were noted in the EXP group during session seven, which may be due to the introduction of road surfaces in minimalist shoes for the first time. The drop in LLCI was particularly noted in the Achilles, calf and ankle areas. As the CON group were already accustomed to road surfaces, no difference was noted in LLCI scores. An interesting finding was that LLCI scores were lower during sessions of longer distances for both groups, but that LLCI values in the EXP dropped more severely during long runs, resulting in statistically significant differences during sessions six, fifteen and eighteen. The Achilles, calf and shoe areas, in particular, dropped during these sessions. Occasionally, the EXP group LLCI scores remained slightly depressed following a long run, as can be seen in session twenty-two especially. Further, calf LLCI scores were significantly lower in the EXP group throughout. This may indicate that the eccentric actions produced in the calves of EXP runners resulted in prolonged muscle soreness. It is therefore essential that enough emphasis is placed on adequate recovery days in those wanting to transition in the future. Following session eight, LLCI scores were slightly more depressed than before. This may have been due to increases in total running distance from session nine onwards, which for the first time increased over 10 km. This increase in running volume is thought to be the reason for the drop in LLCI scores of both the EXP and CON groups.

Foot LLCI scores remained relatively similar throughout, with a sharp drop seen during session sixteen only for the CON group. Achilles LLCI scores remained slightly depressed in the EXP group, especially during sessions ten to twelve and sessions eighteen to twenty. This may have been linked to overall increases in total running distance, or the introduction of hill running. Control group shin LLCI scores dropped slightly from session nineteen onwards, with a sharp recovery during session twenty-four. Session twenty-four consisted of a very flat route, aimed at slowly easing participants out of the training program. Therefore, improved LLCI scores were expected, as no hills, sprints or hard running was involved. Ankle LLCI scores were particularly low in the EXP group during session twelve. This was possibly due to the introduction of hill running during this session. From session twelve onwards, EXP shoe scores were closely associated with distances run. Control group knee scores demonstrated noted declines from session nineteen onwards. Lastly, the increased knee discomfort experienced by the CON group when compared to the EXP group suggests that minimalist running might be advantageous to persons struggling with knee injuries, as most of the impact absorption is offloaded from the knees to the ankles (Bonacci *et al.*, 2013).

When comparing LLCI values to those obtained in previous studies (Schutte & Venter, 2013), the present study reflected considerably less discomfort in general. The reason for these lower values might be that the intervention periods differed slightly. Previously, a linear progression program was followed, with weekly incremental increases, which was possibly adjusted when extreme discomfort was experienced. This study made use of a step progression program, consisting of microcycles within the program, as described by Bompa (1999). Thus, while overall volume still increased weekly, each week included one long slow run, one medium distance run and one shorter distance run. The result was that a shorter run always followed a longer run, allowing participants some degree of active recovery. This finding may be of practical value to future research, and to runners wishing to transition into minimalist shoes.

2. Injuries Related to Running Techniques

Minimalist shoes are believed to have an effect on injury trends. While a marked decrease in knee and hip joint loading has been observed in the past (Bonacci *et al.,* 2013), remarkably more stress is placed on the plantar-flexor muscles, increasing the risk of Achilles tendinopathies (Hamill *et al.,* 2011). Moen and partners (2009) proposed that increased plantar-flexion at the moment of contact increased tension in the soleus, tibialis posterior and flexor hallucis longus muscles, inducing more strain on the tibial fascia and in turn the periosteum. As plantar-flexion is greater in minimalist runners, an increased risk of shin splints may be expected (Giandolini *et al.,* 2013). Although not statistically significant, the EXP group did demonstrate isolated accounts of shin splints (Please refer to Chapter 5- Adverse Reactions). However, as only a small proportion of EXP runners experienced mild MTSS, this finding did not reflect in over all EXP group scores.

Additionally, as runners become fatigued load shifting occurs from under the toes to the metatarsal heads, overloading osseous structures and increasing the risk of metatarsal stress fractures (Nagel *et al.*, 2008). The second and third metatarsals are particularly susceptible as they are longer and thinner than the other metatarsal bones, and they incur a great amount of pressure (Griffin & Richmond, 2005). Novice runners are particularly vulnerable to this type of injury, as the toe flexors are not accustomed to the impact and duration of forefoot strike running, resulting in earlier fatigue than trained barefoot runners. Early fatigue in the toe flexors converts to pressure being placed under the metatarsal heads prematurely, resulting in increased overall mechanical load of metatarsals with increased risk of injuries such as sesamoiditis or metatarsalgia (Goble *et al.,* 2013). Therefore, runners experiencing pain or discomfort in the metatarsals, should not hesitate in seeking medical attention, in order to rule out metatarsal stress fractures.

In summary, those opposing barefoot running claim that it simply serves to alter the injury type, rather than its occurrence (Rixe *et al.,* 2013). However, the high impact transients observed when running in trainers have been linked with a variety of running injuries, including PFPS, tibial stress fractures, meniscal injuries, ITB etc. (Altman & Davis, 2012). Further, in a retrospective study conducted by Daoud and colleagues (2012), hip, knee and low back pain was found to be 2.7 times more likely in rearfoot strikers.

Taken the above into consideration, it might be prudent to consider the runner's specific strengths and weaknesses, when considering transition to minimalist running. Further, injury history should be viewed as one of the largest contributory factors to this decision.

B. RESEARCH OBJECTIVE TWO

To Determine Whether an Eight-Week Minimalist Training Intervention Affects Muscle Co-Activation, Pre-Activation and Total Activation Patterns

1. Pre-Activation

As certain kinematic adaptations occurred during the minimalist training program, concurrent changes in muscle activation patterns were expected. These changes should include differences in pre-activation, co-activation and total activation between EXP and CON participants. The kinematic adaptations most frequently observed in minimalist runners include a reduction in stride length and contact time. Also, the change from a rearfoot strike to a forefoot strike is expected to alter muscle activation patterns considerably. Pre-activation refers to the activation of a muscle immediately prior to initial contact (i.e. 200 ms prior to footstrike) which is measured as a percentage of the gait cycle. Similarly, co-activation between muscle combinations and total activation of each specific muscle was measured as a percentage of the entire gait cycle.

Tibialis Anterior pre-activation did not differ significantly between groups (Figure 5.6, page 84). However, marked gender differences were noted. In CON women, pre-activation in TA occurred much later in the dominant leg, as can be seen in Figure 5.10 (page 89), when compared to the rest of the group. However, TA strength increases were considerably greater amongst CON women (Figure 5.23; page 103). The findings of these two variables together could possibly be expained by the running kinematics exhibited by these participants, who ran in 10° more dorsiflexion, when compared to both the men of the CON group and the EXP group (Table 5.13; page 128). It may be possible that the TA of CON women was more active throughout large parts of the swing phase as the foot needed to be held in an exaggerated dorsiflexed position throughout the entire gait cycle. The TA would also have to eccentrically contract at higher amplitude during the first part of weight acceptance, in order to avoid uncontrolled at heel strike (Von Tscharner *et al.*, 2003). Von Tscharner and colleagues (2003) found that pre-activation of the TA is not affected by shoe conditions, but the TA intensity is considerably higher in trainers, when compared to minimalist. This could explain strength differences noted between groups.

While strength gains are generally considered to be a benefit, increases in TA strength could be detrimental to runners either at risk or with a history of anterior compartment syndrome. As the TA cross-sectional area will increase, more pressure is place on the surrounding structures, aggravating anterior compartment syndrome symptoms. Other participants did not demonstrate significant changes in TA pre-activation (Figure 5.10 and 5.11, page 89). Baur and colleagues (2011) found that increased running distance (> 45km) a week caused a reduction in TA and MG pre-activation. Although Baur and friends' study (2011) did not make use of minimalist shoes, and participants ran further than the present study, it may be possible that the large increase in running volume compared to previous training produced the same effect in the CON group.

Lastly, differences were noted between the dominant and non-dominant legs for almost all muscles. According to Gavilanes-Miranda (2012) differences in legs are to be expected since the type of muscle activity in the one leg is adapted to the activity in the other leg.

Peroneus pre-activation did not change notably in the EXP group, but decreased by 0. 17% in the CON group dominant leg (Figure 5.7; page 85). This finding was not entirely consistent with literature, as increases in peroneus pre-activation were expected in the CON group. Peroneus pre-activation has been shown to increase in cushioned shoes, in order to combat the increases in lever arm length (Kerr *et al.,* 2009). The thick cushioning of trainers, increases the distance between the foot and ground and increases lever arm length between the ground reaction force and subtalar joint axis. This decreases ankle coordination and magnifies supination forces and stresses on lateral ankle ligaments when running in trainers (Stacoff *et al.,* 1996). Therefore, decreases noted in the present study in pre-activation in the dominant leg of the CON group might be considered to place the runners at an increased risk of inversion injury. When considering the small changes noted in the non-dominant leg of the CON group, and both legs of the EXP group, the present study corresponds with those of Divert and colleagues (2005) who found no difference in TA and PER activity between minimalist shoes and trainers. However, Divert and partners (2005) made use of a cross-sectional study, whereas the present study investigated the long term effects of minimalist shoes. This might suggest that while there are no immediate PER pre-activation changes noted between minimalist shoes and trainers, a long-term adaptation may also not be present.

Lastly, when considering the EXP group in isolation, the foot is placed in a more plantar-flexed and slightly inverted position immediately prior to contact when running in minimalist shoes. In this case, PER pre-activation may be equally important in minimalist runners, as the ankle is placed in a more vulnerable position, which increases the risk of inversion sprains (O'Driscoll & Delahunt, 2011). Due to the fact that the PER muscle does not activate sooner in minimalist shoes (Kerr *et al.,* 2009) it may not be advisable for persons with CAI to transition to minimalist running (Goble, 2013). The present study also did not find increases in PER pre-activation when running in minimalist shoes. Pre-activation is essential in the ankle so as to ensure dynamic joint stability upon landing. Therefore, persons with CAI who have mechanically unstable ankles and possible sensorimotor deficits, might be placed at an increased risks of re-injury in minimalist shoes.

Lateral gastrocnemius activity increased to a large extent in the EXP group for both dominant and non-dominant legs (Figure 5.8; page 86). This was expected and is consistent with literature, where the immediate effects of minimalist shoes are compared to trainers (Giandolini, 2013; Divert, 2005). However, Giandolini and colleagues (2013) suggested that further studies are needed to determine the long-term effect of these neuromuscular adaptations. The present study confirms that pre-activation in the LG is maintained over time when running with a midfoot strike. Pre-activation is an important adaptation, especially taking into account the specific gait cycle phases. During the stance phase somatosensory feedback is available from the plantar aspect of the foot, aiding the regulation of movement. However, during the swing phase the runner must utilize feedforward control mechanisms to alter muscle activity and prepare the system for impact. Pre-activation can be seen as the initialization of feedforward control mechanisms.

An additional benefit of improved pre-activation is that, when the triceps surea are pre-activated the ankle is better controlled into eccentric dorsiflexion, whereby more energy is translated into rotational energy within the ankle joint, resulting in less impact force being transmitted upwards along the kinetic chain (Lieberman *et al.,* 2010). Therefore, pre-activation increases ankle stiffness, but reduces total leg stiffness slightly, resulting better control over COP displacement, or sudden downward deceleration. Pre-activation could thus be beneficial in that the more proximal joints are deloaded (Bonacci *et al.,* 2013). It must be noted, however, that pre-activation increased more significantly in the EXP women, and in fact, pre-activation did not increase in the dominant leg of the men at all (Figure 5.10 and 5.11 a & b, page 89).

Demont and Lephart (2013) conducted a study in which gender differences in pre-activation were specifically investigated. While no differences were noted in the gastrocnemius muscles, significant pre-activation differences were noted in the semimembranosis. These findings support the notion that noteworthy differences exist in NMC between genders. However, Demont and Lephart (2013) investigated the NMC of the knee, and therefore included downhill running as their testing procedure. As downhill running encourages a shift to a rearfoot striking pattern, it may be the reason why pre-activation in the gastrocnemius did not demonstrate significant change. Nevertheless, major differences certainly exist in NMC and future research is warranted in this area, especially in relation to the long term benefits of improved pre-activation and injury rates.

Similarly, pre-activation in the medial gastocnemius increased significantly in both legs of EXP women, while the EXP men decreased in pre-activation (Figure 5.10 and 5.11 a & b, page 89). This could alternatively be related to the differences observed in running kinematics presented in Table 5.13 (page 128), depicting that EXP female runners demonstrated a larger increase in plantar-flexion angle from baseline to post testing. It may be that pre-activation only increases with larger changes in ankle contact angle. Increased pre-activation as seen in women should further result in improved ankle joint stability upon landing. Joint stability provides a dynamic restraint during the landing phase which is very important for injury prevention. These dynamic restraint mechanisms need to activate prior to landing in a feedforward manner. Thereafter co-activation between antagonistic or synergistic muscles can be adjusted via sensory feedback. By combining these feedforward and feedback mechanisms total joint stability could be achieved throughout the entire gait cycle.

2. Co-Activation

Co-activation is helpful in improving joint and dynamic stability during daily tasks, and is needed to provided protection against unexpected perturbations. Therefore, co-activation can be viewed as a benefit during daily activities. However, overly increased co-activation may be inefficient and is generally used only when there is uncertainty in the execution of a task or during the learning of a new-skill (Busse *et al.,* 2005). This theory is reinforced by the fact that co-activation is markedly increased in persons with neuromuscular disorders (Aria *et al.,* 2012). Co-activation between the TA and MG (TA-MG) increased in EXP group women, but decreased in EXP group men (Figure 5.16 and 5.17 a & b, page 95). This possibly suggests an improvement in dynamic NMC in the men of the EXP group, with a more effective transition between antagonistic movements and better movement coordination. This might also reduce the amount of energy wasted when muscles contract against each other, possibly contributing to improvements noted in running economy in the literature (Hanson *et al.,* 2010; Divert *et al.,* 2008). Due to improved timing and regulation of movements, this faster transition between antagonistic movements could result in more excursion through joint range of motion, with better utilization of the spring system (Lieberman, 2010) due to improved timing and regulation of movements. By demonstrating increased co-activation, it would appear that women in the EXP group demonstrated greater joint stability, whereas men possibly demonstrated improved dynamic NMC. This pattern of co-activation between men and women remained similar in all combinations of muscles tested (Figure 5.16 and 5.17 a & b, page 95). The only exception was MG-BF co-activation for the non-dominant leg of EXP women, which decreased by 0.06% (practically significant).

When considering PER-MG co-activation, in Figure 5.16 and 5.17 (page 95), the EXP women had slightly higher co-activation than the CON group, in both legs. An increase in PER–MG co-activation might be a benefit, ultimately resulting in a more stable ankle when perturbed in a lateral direction. Motorneuron pool excitability, as measured by EMG, of the peroneus has been found to be one of the most influential measurements used when classifying CAI, and may be more important than joint kinaesthesia and dynamic balance. For this reason improvements in co-activation may be indicative of a more stable ankle (Sefton *et al.,* 2009). It may also serve an important function in ensuring a stable base for adequate push-off. However, co-activation may also serve to increase ankle stiffness, which may alter the way in which shock is attenuated through the kinetic chain. Gavilanes-Miranda and partners (2012) also suggested that cushioning and stability are conflicting terms and that more cushioning brings about less stability. It would seem that there is a constant exchange in the neuromuscular system between co-activation, or stability, and ankle stiffness (or cushioning). It could also be possible that the levels of co-activation and ankle stiffness are optimal at different levels, for different runners, due to anatomical and kinematic differences.

Interestingly, LG-BF and BF-GLUT co-activation increased in the CON group (Figure 5.14 and 5.15, page 92 and 93), but decreased in the EXP group (with the exception of the non-dominant leg MG BF co-activation in women). This may simply be due to the fact that the overall work done by the ankles is increased during barefoot running, causing a moderate decline in the work done at the knee and hip (Bonacci *et al.,* 2013). Biceps Femoris and GLUT total activation time (throughout the entire stance phase) was also significantly reduced in both the dominant and non-dominant leg of the EXP group (Figure 5.19 b & c, page 98) This may be beneficial to runners struggling with hip or hamstring injuries, whereby minimalist running may serve to deload the hip musculature.

The function of the BF during running includes eccentric actions during the final part of the swing phase to decelerate the tibia and absorb impact during weight acceptance. Therefore, as minimalist runners take smaller steps and land with more flexion in the knee, it could be possible that reduced braking forces are required by the BF. These forces are reduced due to the lower loading rate observed in minimalist runners, and because the gastrocnemius muscles take over a part of the eccentric deceleration function. It would therefore be expected that BF activation would decrease, with concomitant decreases in BF co-activation combinations. Similarly, Divert and partners (2005a) found increased braking and pushing impulses in minimalist runners.

Co-activation between the CON groups' TA-MG, PER-MG, as well as the LG-BF demonstrated large dominant-to-non-dominant leg differences. The dominant leg demonstrated increased co-activation where the non-dominant leg reduced co-activation. This phenomenon could possibly be explained by the concept proposed by Clifford and Holder-Powell (2010) who demonstrated that motor control strategies are often separated into a mobilizing function for one leg, and a stabilizing function for the other. Therefore, the dominant leg increased co-activation to serve a more stabilizing function, whereas the non-dominant leg reduced co-activation to serve a mobilizing function. However, Clifford and Holder-Powell (2010) proposed that the non-dominant leg serves a more stabilizing function whereas the dominant leg serves a mobilizing function.

3. Total Activation

Total activation refers to the amount of time that a specific muscle was active for, throughout the entire gait cycle. It provides an idea of the amount of work done by the muscle during each stride. Total activation times are expected to differ between EXP and CON groups as different running techniques are used.

Total TA activation was lower in the EXP group for both legs when compared to the CON group (Figure 5.18; page 97). This may be due to the reduced dorsiflexion angles noted in the EXP group (Figure 5.13, page 130). In the EXP group the TA did not have to activate with the same high intensities to maintain the dorsiflexion angles noted in the CON group. The fact that shoe mass was also less in the EXP group means that the TA had a reduced load during the swing phase, which could possibly reduce the total activation time. Lastly, as CON runners were shorter than EXP runners, they were more likely to over-reach during a stride. This, combined with an inherent rearfoot strike should lead to increased TA activation during the pre-activation phase and weight acceptance phase.

It should be noted in Figure 5.20 and 5.21 (page101) that significant differences were observed for TA activation between genders, with women demonstrating an increase in TA total activation and men demonstrating a decrease in TA total activation. These differences were noted in both the EXP and CON groups, but were more noticeable in the EXP group. However, as can be seen in Table 5.13 (page 128), women in both groups demonstrated increased dorsiflexion at contact both prior to and following the intervention period. It would thus be expected that the TA in women would be active for a greater proportion of the gait cycle.

Further, differences were observed between dominant and non-dominant legs. Karamanidis and colleagues (2003) found small differences between angular displacement parameters and contact time between dominant and non-dominant legs, while even larger differences were found in angular velocity, displacement and flight times. The differences noted by Karamanidis and partners (2003) should more than likely also be reflected by EMG. However, it must be noted that considerable variation occurred between subjects, making comparison difficult.

Peroneus longus total activation increased in both legs of the EXP women, while decreasing in both legs of the EXP men. This may once again be related to the specific running kinematics displayed by each gender. As the PER serves an accessory plantar-flexory function (women demonstrated greater plantar-flexion angles), it may be expected that women increased PER activation throughout.

Experimental group women had lower total PER activation in the dominant leg, when compared to CON women, but significantly higher total PER activation in the non-dominant leg. Experimental men, on the other hand, demonstrated lower PER total activation for both legs, when compared to CON runner, while only the non-dominant leg was significant. Baur and colleagues (2010) investigated whether gender specific differences existed in PER muscle activation. Similar to the present study the authors noted improved pre-activation in women, which is believed to result in better shock attenuation. The authors argued, however, that an increased activation during weight acceptance and push off may result in a higher contribution of the PER muscle to plantar flexion, which could lead to a more efficient running style (Baur *et al.,* 2010). Therefore, there are advantages to both an increase in PER pre-activation and an increase in total activation.

When looking at LG activation throughout the entire gait cycle (Figure 5.21 and 5.22; page 101) , large differences were observed between groups for the non-dominant leg in both men and women, while practically significant differences were noted for the dominant leg of men. Women in the EXP group demonstrated lower total LG activation, whereas men in the EXP group demonstrated greater total LG activation, when compared to the CON group. It may be possible that poorer pre-activation leads to a less prepared spring system (Lieberman *et al.*, 2010), which ultimately results in the gastrocnemius muscles having to activate more and work harder during the latter part of the stance phase. Therefore, improved pre-activation could result in slight reductions in total activation, whereas reduced pre-activation is more likely to correlate with increases in total activation. This suggestion was also made by Baur and colleagues (2010) albeit for the PER. Baur and partners (2010) suggested that increased work during the push-off phase is not necessarily a disadvantage. It seems that pre-activation might be helpful for shock attenuation and long-term injury prevention, while reduced pre-activation leads to increased activation during the weight acceptance and push-off phases (total activation), resulting in improved propulsion.

The opposite point of view could also be argued, as, according to Divert and colleagues (2005) pre-activation allows better storage and restitution of elastic energy, which means that decreased pre-activation diminishes the elastic properties of the plantar flexors, resulting in an increased demand for concentric contraction to promote propulsion. Therefore, the CON group may have adapted by increasing LG activity. Future research is warranted in this area, to determine whether the long-term consequences of improved pre-activation are truly beneficial and, if so, to running economy, injury prevention, or both.

Total MG activation also increased in both legs of the CON group, while a decrease was noted in the dominant leg of the EXP group, but not the non-dominant leg. Similar patterns were observed between men and women, with statistically significant differences noted between groups in the dominant leg for men, and in the non-dominant leg for women, and practically significant differences noted in the other leg of both genders. Once again, women demonstrated more asymmetry between legs, possibly indicating that the neural adaptation has not been completed, and that motor commands have not been finalized in learning the new skill, or running style (Busse *et al.*, 2005).

Biceps femoris total activation (Figure 5.21 and 5.22; page 101) decreased markedly in both legs EXP men and women compared to the CON group. As with BF-GLUT co-activation and BF-MG co-activation, the decrease noted in the EXP group could possibly be due to the load shift toward the plantar flexor muscles, resulting in a decreased demand placed on the BF. When considering the running kinematics, minimalist runners generally demonstrate reduced stride length, which should then translate to a reduced propulsion action during weight acceptance and push-off. Additionally, as the ankles are translating impact energy into translational energy (due to the forefoot striking pattern) less impact is experienced by the BF during impact and weight acceptance.

Gluteus medius total activation decreased in both legs of the EXP men, while CON men demonstrated an increase. Similar changes occurred for CON women; however, the EXP women also increased GLUT total activation in the dominant leg slightly. The practical application of this would be that the demand placed on hip musculature is reduced in minimalist running. This might be of importance to runners who struggle with hip injuries or who have a history of hip surgery. Hip labral tear incidences are showing marked increases and have become a growing concern to health care practitioners (Dolan *et al.,* 2011). Future research is merited in determining whether minimalist shoes aid in the prevention of labral tears.

C. RESEARCH OBJECTIVE THREE

To Determine Whether an Eight-Week Minimalist Training Intervention Affects Isokinetic Ankle Joint Strength.

Dorsiflexor strength increased by 38% and 25% in the CON group (Figure 5.23; page 103). This could be linked to the muscle activation patterns observed during EMG analysis, where increased TA activation was noted throughout the entire stance phase. An interesting finding is that CON women improved to a much greater extent than did men. A possible explanation could be found in Table 5.13 (page 128), where one can see that CON women demonstrated greater dorsiflexion angles both prior to and following the intervention. TA strength might then increase firstly, due to the additional demand placed on the TA to maintain the ankle in this dorsiflexed position during the swing phase, and secondly due to an increase in eccentric activity during heelstrike, where the TA is responsible for avoiding uncontrolled plantar-flexion (Von Tscahrner *et al.,* 2003). Therefore, while TA pre-activation reduced in CON women and an increase in total activation was noted in both legs of the EXP women. This is in line with the suggestion made by Baur (2010) on page 145, in regards to pre-activation and work done during push-off.

Plantar-flexion increased by 40% in the CON group, for the slower speed (30deg.sec^{-1}) and by approximately 20% for the faster speed (60 deg.sec^{-1}), while the EXP group improved by only 12% for both speeds (Figure 5.24, page 104) This finding was not expected as running on the forefoot or midfoot increases recruitment of plantar-flexor muscles, which should lead to PF strength increases over time. A possible reason may be due to the muscular action involved in testing. While running, the majority of work done by the gastrocnemius in the CON group was concentric, whereas the gastrocnemius of the EXP group functioned mainly eccentrically during forefoot landing. As isokinetic strength testing was administered only concentrically, the eccentric gastrocnemius strength value may not have been accurately represented. Future research should be advised to apply the concept of specificity when testing, by including both concentric and eccentric actions.

However, when analyzing genders separately (Figure 5.25; page 105), larger increases in plantar flexor strength was recorded for the EXP men, when compared to CON group men. In contrast, EXP women deteriorated in plantar flexor strength, bringing the overall value of the EXP group down considerably. The reason for this unexpected result in female plantar-flexor strength may be linked to differences in muscle damage and repair. Much research has been focused on the protective effect that estrogen has on skeletal muscle damage, following the finding that estrogen diminishes indices of damage in cardiac muscles following ischemia-reperfusion injury (Korzick & Lancaster, 2013). Estrogen has been linked to gender differences in muscle damage and recovery, and is believed to have a protective function immediately following exercise (Enns & Tiidus, 2010). While eloquent studies have been done to show acute reductions in swelling and inflammation in women, there is some degree of disagreement on this subject. Stupka (2001) compared muscle damage and inflammation markers following two bouts of exercise, and found that women had increased neutrophil counts for longer following the second bout. Therefore it is possible that estrogen alters the inflammation process, causing slight differences in recovery for men and women

In another study comparing men and women using a step protocol where one leg worked concentrically and the other eccentrically, women showed a significantly larger strength decrease in the eccentric leg than the men on the post exercise day (Fredsten, 2008). As minimalist running involves mainly eccentric work by the gastrocnemius muscles, and it may be possible that the timing of the training program resulted in different responses in women, due to the fact that their inflammatory timeline differs from men. Therefore, it might be plausible to incorporate gender specific training programs in future research. Fredsten (2008) also suggested gender specific training programs to avoid excessive muscle damage. As a prudent approach, women might be given more recovery days following running sessions.

The EXP group calf circumference (Figure 5.5; page 83) increased to a greater extent when compared with the CON group. However, strength increases did not occur in women. This finding may suggest that increase calf circumferences are possibly attributed to oedema, caused by muscle damage and not hypertrophy. As compared to baseline, the women's plantar flexion angle at contact (Table 5.13; page 128) changed to a greater extent in women throughout the intervention period, when compared to men. Increased plantar-flexion may induce greater muscle damage, due to the increased eccentric muscle action placed on the gastrocnemius .This increased muscle damage could be largely responsible for differences noted between genders in many of the variables. This may be linked to the improved pre-activation noted in women. Pre-activation and forefoot landing may be beneficial to whole-body running biomechanics, but the gastrocnemius is then largely responsible for initial impact attenuation. This means that increased strain is placed on the plantar-flexor muscles, which induces muscle damage during initial transition.

While minimalist running results in positive adaptations such as pre-activation, improved shock attenuation and running economy, muscle damage may also have detrimental effects. It is therefore imperative that a safe transition program is followed, to avoid excessive muscle damage. Safe transitioning is discussed in research objective six.

In Figure 5.26 (page 109) inversion strength improved to a greater extent in the CON group for the slower speed (30 $deg.sec^{-1}$). Eversion strength improved notably in the CON group for both speeds (30 $deg.sec^{-1}$and 60 $deg.sec^{-1}$), and in the EXP group for the faster speed (60 $deg.sec^{-1}$), but not for the slower speed (30 deg.sec^{-1}) (Figure 5.28. page 108). While running involves mostly sagittal plane movements, it is difficult to determine the exact cause of these improvements in strength. It may be possible that the peroneus muscles increased in strength simply due to the differences noted in running surfaces. Small inclines or slopes could encourage increased invertor or evertor muscle activation depending on the direction of inclination. This could, over time, lead to small improvements in invertor and evertor muscle strengths. Furthermore, some of the invertor and evertor muscles have accessory plantar flexion functions. Therefore it might be possible that these muscles were recruited more to assist the gastrocnemius with the increased training demand. The invertor and evertor muscles were then expected to improve slightly during the intervention period.

It was noted that improvements in strength occurred generally to a greater extent in the slower speed for the CON group, while the EXP group showed improvements in the faster speed. This may be due to the type of action utilized during landing. It is widely accepted that minimalist running results in a reduction in stride length and contact time (De Wit *et al.,* 2000[b]), therefore a faster muscular action at the ankle is required in minimalist running during landing, which coincides with the improvements seen in the faster speed of the EXP group. As mentioned earlier, the foot is placed in a more plantar-flexed and inverted position prior to contact. This finding, combined with the faster muscular actions required, places a much greater demand on the muscles surrounding the ankle and requires precise NMC during landing. Therefore minimalist running could provide a training tool to athletes wishing to improve their intrinsic and extrinsic musculature strength and ankle NMC. However, persons with CIA, peroneus weakness or other sensorimotor deficits might be placed at an increased risk of injury.

D. RESEARCH OBJECTIVE FOUR

To Determine Whether an Eight-Week Minimalist Training Intervention Affects Postural Stability.

1. Athletic Single Leg Balance Test

In the non-dominant leg (Figure 5.30; page 110), only the CON group improved from baseline to post intervention in the M/L plane. However, all runners showed moderate reductions in postural sway, except for the CON group in A/P sway. It is possible that the small sample size could have influenced results. Future research should be encouraged to include larger sample sizes, so that clearer conclusions can be drawn from the findings. Additionally, the moderate reductions noted in most of the runners at post testing could possibly be attributed to a learning effect. Although runners were given time to become accustomed to the Biodex Balance at baseline testing, most had never performed and ASL test before the study. It is possible that they had a better idea of what was to be expected at post testing and that they may have been slightly better prepared.

Women in both the CON and EXP group improved in all directions (Figure 5.31 a, b and c; page 111-112), except for A/P sway in the CON group. Medium practically significant differences were found between women groups for overall sway and A/P sway, with EXP women showing greater improvements over time. Men of the CON group improved mostly in the M/L sway, whereas men of the EXP group improved in the A/P direction. Large practically significant differences were observed for M/L sway only, with the CON men demonstrating greater improvements over time.

Two main observations can be made from these results for the non-dominant leg. The first is that postural sway generally improved more in women. The second is that the CON group showed greater improvement in M/L planes, whereas the EXP group showed improvements in A/P sway (similar changes over time noted for overall sway). This was interesting as Menant and colleagues (2008) found impairments in M/L sway in softer shoes, compared to harder soled shoes. However, this study by Menant and partners (2008) was of cross-sectional design and did not follow up on the long-term effects of walking in different shoes. Therefore, it is possible that different results in sway were obtained over time.

In the dominant leg (Figure 5.32; page 114), the ASL test revealed greater improvements in M/L and overall sway for the CON group. Experimental men improved in the M/L plane and overall sway, whereas CON men improved in the A/P plane and overall sway. Women in both groups improved in all planes (except EXP women in overall sway), with EXP women demonstrating practically significant changes over time in M/L (Figure 5.33; page 114). This was not expected, as EXP women demonstrated plantar-flexion strength deficits, and muscle soreness possibly due to muscle damage. It would be expected then that women would demonstrated increased postural sway due to reduced accuracy of plantar-flexor muscle spindle information, possibly caused by muscle damage and soreness. A possible explanation for the improvements in ASL in EXP women could be that, as postural sway is an indirect method of measuring proprioception, women may have incorporated other proprioceptive input types more effectively. It would have been interesting to determine whether women demonstrated the same improvements in altered sensory and visual conditions as with the modified clinical test of sensory integration and balance (mCTSIB). It must be noted that CON women also decreased in all planes, with the same improvements in proprioceptive integration being possible.

For the dominant leg, men in the EXP group demonstrated reductions in overall and M/L sway, with large practically significant differences between groups (Figure 5.32; page 114). However, increases in A/P sway were noted. Although EXP women improved in M/L and A/P sway, larger differences were seen between CON and EXP men. This may indicate that EXP group men had an enhanced ability to use proprioceptive information from the plantar aspect of the foot, and it may also be possible that men adapted to utilize the benefits of minimalist shoes more effectively, when compared to CON.

While no differences should exist in PC and proprioception between men and women, it is possible that NMC differences were emphasized during the intervention period, strengthening different muscles in different genders. Similar gender differences have also been observed in past studies. Escovier and colleagues (2011) used pattern classification during running to distinguish between genders, and found that mean hip abduction was the only characteristic needed to make the discrimination. Schache and partners (2011) found greater peak-to-peak oscillations in most angular rotations, in women. These oscillations could also produce more muscle damage. Wunderlich and partners (2008) suggested that anatomical differences like higher arches, shorter outside foot length and smaller instep circumferences observed in women might be a large contributing factor to the biomechanical and kinematic differences often demonstrated which could then possibly lead to the increased injury rates recorded in women. Wunderlich and partners (2008) also found that women had greater peak pressures under the first metatarsal. These kinematic and NMC differences may also transfer to PC strategies, as mentioned by Wojcik and partners (2011) who suggested that differences exist in the organization of PC strategies between men and women.

Secondly, a left-to-right cross over effect was noted in many cases, with improvements in M/L sway occurring in one leg, while improvements in A/P sway occurred in the other leg. Motor control strategies are often separated into a mobilizing function for one leg, and a stabilizing function for the other. This correlates well with the differences observed between left and right (or dominant and non-dominant) legs in muscle activation measured by EMG, as mentioned on page 140 and 143. Commissural Interneurons (CINs) are responsible for coordinating left-to-right movements. It was suggested by Butt and colleagues (2002) that these CINs play a more important role in maintaining reciprocal inhibition between bilateral motorneuron pools, and subsequently allows a great integration of information from ipsilateral and contralateral afferent inputs, resulting in a much greater degree of flexibility in the system. It is for this reason that greater left- to-right differences are noted in humans.

It must be noted that continuous postural sway is important in providing updated sensory information to the CNS (Gatev *et al.,* 1999) and, as more sway typically occurs in the A/P plane small changes are more difficult to determine. Therefore, changes in M/L sway are generally noted before changes in A/P sway. As greater improvements are required in A/P sway to bring about significant differences, any improvements noted could thus be emphasized.

An alternative hypothesis may be that co-activation of synergistic muscles generally increased in women, which then caused larger improvements in balance, when compared to men. Tse and colleagues (2013) found that recruitment of hip and ankle musculature increased with tasks of increasing postural demand, in order to bring about greater stability. It could be that women increased muscle recruitment, bringing about improvements in joint stability, which is then transferred to the ASL test. This increase in co-activation may also have occurred as compensation to the strength deficits noted in the gastrocnemius. Increasing co-activation in response to fatigue or weakness have been documented in the literature, as demonstrated by Vie and partners (2013) who found that reduced myotatic reflex in fatigued invertor muscles facilitates the action of evertor muscles. Interestingly, increased co-activation between antagonistic muscles is associated with increased postural sway (Laughton *et al.,* 2003). Therefore, these theories may be speculative and should be considered with caution.

2. Modified Clinical Test Of Sensory Integration And Balance

The EXP and CON groups improved in mCTSIB sway scores (Figure 5.35; page 117) in condition one during the intervention. Conditions two, three and four showed almost no change either across time or between groups, suggesting no change in proprioceptive integration or PC. This might have been expected as the same results were observed by Whittney and Wrisley (2004) who found no significant difference in mCTSIB scores between the barefoot condition and with shoes.

Condition one provides information regarding the integration of proprioceptive information and can be viewed as the baseline condition where all proprioceptive input types are available. Figure 5.35 (page 117) shows that postural sway increased as sensory systems were removed or disrupted. This is a normal response and was expected.

Although significant changes over time did not occur for either group in condition two of the mCTSIB test, significant interaction effects were noted between groups, indicating that the CON group improved slightly more than the EXP group. It can be deduced that the CON group demonstrated better integration and utilization of visual sensory input during the intervention period and that the CON group was not reliant on visual information in order to maintain PC. This can be drawn from the fact that condition two occurs on a firm surface in the absence of visual input. If removal of visual input causes excessive increases in postural sway one can infer that the participant is reliant on visual information to maintain PC. No change in postural sway over time was expected, as running either in minimalist shoes or trainers should not have a significant effect on the visual system.

An absence of change in condition three (distortion of sensory information) indicates that no significant alterations occurred in the use of plantar sensory proprioceptive input (and muscle and joint proprioceptive input) during the intervention, in either the EXP or CON groups. Therefore, we can conclude that in order for the neuromuscular system to improve in the utilization of sensory information, specificity in training is required. While running in minimalist shoes may improve cardiovascular fitness similar to regular running, as well as improve plantar-flexor strength, shock attenuation and intrinsic musculature strength (Jenkins & Cauthon, 2011), it does not necessarily act as a form of neuromuscular training.

One of the most basic concepts upholded by exercise physiologists and physical therapists is that a given training effect is *specific* to the muscles involved, the fibre types recruited, the principle energy system utilized and the type of muscle action required (Powers & Howley, 2007). Likewise, for significant improvements in NMC and PC to occur, one should make use of neuromuscular and balance training. Page 164 provides a brief overview for recommendation on types, duration and intensities of neuromuscular and balance training. In a previous study conducted by Du Plessis and Venter (2011), a minimalist shoe intervention period consisted of not only distance running, but included speed drills, agility drills, plyometrics and muscle endurance tasks. This study found significantly greater improvements in the EXP group for agility and PC outcomes, with a practically significant increase in 10 m speed (Du Plessis & Venter, 2011). We could therefore deduce that minimalist shoes might supplement neuromuscular adaptations, provided specific training modalities are included.

Lastly, condition four demonstrated little change between EXP and CON groups, indicating negligible differences in the utilization of the vestibular apparatus (in absence of visual input and distortion of sensory input by foam). This outcome was expected as distance running should not interfere with the function of the vestibular apparatus in the long term.

When considering men and women separately (Figure 5.36, page 118; Figure 5.37, page 119), small decreases in sway were observed for condition one and two in EXP men during post testing. Condition three demonstrated an increase in postural sway for EXP men. This suggests that EXP men performed slightly better on the firm surface conditions at post testing. Men in the EXP group could then possibly have adapted to become more reliant on sensory information for balance, over time. This is further supported by the fact that postural sway increased in condition three, where sensory information was distorted. This finding relates well to those of the ASL test where decreases in sway were observed for EXP men in overall and M/L sway for the dominant leg and overall sway and A/P sway in the non-dominant leg. Control men demonstrated reduced sway for condition one, with almost no change in the other conditions.

Therefore, a possible improvement in the integration of proprioceptive input can be suggested for the CON men.

Women in the EXP group showed moderate reductions in postural sway for condition one only, indicating improved integration of proprioceptive information when all inputs are available. This supplements the findings of the ASL test on page 150, where it was suggested that women utilize proprioceptive input other than sensory information, better. Women in the CON group demonstrated increased sway in condition four demonstrating that balance deteriorated when visual input was removed and sensory input was disrupted. An increase in sway under these conditions is normal, although it may have been slightly emphasized at post testing. This may relate well with the findings of condition one, which indicates that EXP women integrate proprioceptive information better, but it may also mean that they are reliant on all forms of proprioceptive information in order to maintain PC accurately.

In conclusion, while modest differences were observed between groups for selected trials, the effect of minimalist shoes on PC was small. It must be noted that postural sway, at best, remains to be an indirect measure of proprioception and NMC, with many additional factors contributing to sway. Therefore, PC provides an overall indication of the efficiency of proprioceptive information, and any increases or decreases in sway cannot be directly related to a single proprioceptive input. Therefore measures of postural sway should only be used to supplement other results regarding NMC. Significant differences were seen between genders, where women tended to demonstrate greater proprioceptive integratory ability, whereas men utilized sensory information (from the plantar aspect of the foot) better.

3. Acute Differences

In comparing acute changes in ASL scores when wearing minimalist shoes compared to barefoot, differences were noted between baseline and post testing (Figure 5.34; page 116) . At pretesting lower sway values were observed in minimalist shoes, when compared to barefoot for both the dominant and non-dominant legs. Post testing revealed higher sway indices for M/L and overall sway plane in minimalist shoes, compared to barefoot. This may suggest that the immediate effect of the shoes aid in improving balance. However, long-term use of minimalist shoes may not have the same effect. A possible explanation could be that muscle damage occurring during the transition period may decrease proprioception (Torres *et al.,* 2010), by causing muscle spindle information to become less accurate.

Further, while the sole of the minimalist shoe is thinner compared to regular trainers, it is not exactly the same as being barefoot and may still mask information received by the cutaneous receptors regarding surface characteristics. This might cause the CNS to rely more on muscle and joint proprioceptive information. With muscular damage occurring throughout the intervention period, muscle spindle information becomes increasingly unreliable, causing small changes in postural sway.

When considering acute changes in postural sway for the mCTSIB between barefoot and minimalist shoes (Figure 5.38; page 120), the comparison between baseline and post testing proved similar to what was found in the ASL test. At pretesting, postural sway improved in minimalist shoes compared to barefoot for conditions one and two, but conditions three and four deteriorated in minimalist compared to barefoot. The opposite was true for post testing. Conditions one and two demonstrated increased sway in minimalist shoes compared to barefoot, whereas condition three and four produced increased sway compared to barefoot. This suggests that the immediate effect of shoes improves balance. However, long-term use of minimalist shoes may not have the same effect. As increased sway was observed at post testing in the firm surface conditions one and two, it may be possible that participants were reliant on sensory information from the foot. The same results were found in the Athletic Single Leg test, where M/L sway increased in minimalist shoes at post testing.

Figure 5.39 (page 121) and Figure 5.40 (page 122) considers the differences in acute changes in postural sway for men and women. Men demonstrated marked increases in sway for condition two at post testing, while women demonstrated much smaller differences in sway at post testing. These findings again suggest that women utilized different proprioceptive inputs more effectively, and that these adaptations were maintained over the intervention period.

While minimalist shoes may be beneficial in improving immediate sway scores on firm conditions the long term adaptation observed suggest that minimalist shoes shift the sensory reweighing balance away from plantar sensory input. According to Sozzi and partners (2012) sensory reweighing can occur within one to three seconds, when information is withdrawn. This suggests that the type of surface participants train on has an effect on the integration process of proprioceptive information. Rose and colleagues (2011) found that dynamic balance assessed during a single-leg jump landing protocol was better barefoot, than in either minimalist shoes or in trainers. Although a measurement was taken only at a single point in time, the researchers made use of runners who were habitual wearers of Vibram® Five-Finger minimalist shoes, therefore still incorporating the long term effect of minimalist shoes on dynamic balance. These findings suggest that although minimalist shoes improve proprioceptive input from the plantar aspect of the feet when compared to trainers, the golden standard for optimal proprioceptive input remains to be in bare feet. The shift away from the utilization of sensory information may be detrimental to JPS, PC and NMC.

In the present study, this masking effect could be increased due to the fact that the specific minimalist shoes used in the intervention did not have the individual toe compartments that Vibram Five Fingers have. These compartments allow the toes to spread out and "feel" the ground, increasing the ability to differentiate between surface variables. The specific shoes used incorporated the original Vibram® sole into a minimalist shoe, but without the toe compartments.

The pain response may also play an important role in the changes observed in sensory reweighing in the EXP group. It has been shown that sensory changes or pain induced in the plantar aspect of the foot causes load shifting away from sensitive areas (Pradels *et al.,* 2011; Nurse & Nigg, 2001) Likewise, experimental muscle pain also induces changes in PC (Hirate *et al.,* 2010). Experimental runners were not accustomed to the hard shoe, and complained of blisters often during the intervention period. While these studies investigated only the immediate effect of the pain response on PC, it may be reasonable to argue that these pain responses also infer long-term effects such as sensory reweighing away from cutaneous input, especially when the pain stimuli occurred repeatedly within a small amount of time.

E. RESEARCH OBJECTIVE FIVE

To Determine Whether an Eight-Week Minimalist Intervention Affects Ankle Joint Position Sense.

1. Inversion Eversion

For inversion/eversion joint reproduction testing, moderate overall increases were found in the CON group for foot position error following the intervention period (Table 5.7; page 123). Control participants deteriorated by an average of 25%, while EXP participants deteriorated by an average 9%. It might be inferred from these findings that foot position error was very slightly reduced following minimalist training, when compared to regular trainers. This is consistent with findings in the literature regarding minimalist shoes and foot positions sense. Squadrone and Galozzi (2011) found that minimalist shoes allow a more accurate estimation of foot position sense when compared to barefoot, and that cushioned trainers significantly impair foot position sense. Men in the EXP and CON groups demonstrated very similar results (Table 5.8; page 124), thus the main differences between groups were brought about by women (Table 5.9; page 124). Control women increased foot position error by 45% whereas EXP women increased foot position error by only 21%. Passive joint reproductive testing isolates ligamentous and joint mechanoreceptors, while active joint reproductive testing evaluates muscle and tendon mechanoreceptors. If excessive muscle damage occurred during the intervention period it may be possible that EXP women adapted to preferentially make use of joint and ligament mechanoreceptors to a greater extent, as muscle spindle information may have become less reliable. By testing these mechanoreceptors in isolation afterwards (with passive joint reproduction testing), improvements in joint position sense (JPS) were more pronounced in EXP women. The findings from the joint reproduction tests correspond well to the previous findings in the ASL and mCTSIB tests, where women demonstrated improved sensory input integration capabilities. It may be that the neuromuscular system was challenged to a greater extent in women, due to the fact that muscle damage made muscle spindle proprioceptive information less reliable. This could have caused the women to use other proprioceptive input more effectively, resulting in better integration of proprioceptive inputs following the intervention.

The significance of sensory reweighing (from muscle to joint mechanoreceptors) can be seen in the experimental protocol by Villa Cha and colleagues (2011), where experimentally induced muscle damage in the knee brought about by eccentric exercise caused significant decreases in knee proprioception, but only in the non-weight bearing condition. This suggests that during weight bearing conditions, the CNS prioritizes other sensory inputs, to improve proprioception.

Further, the decline in foot position error found in the CON group is also in accordance with literature. While certain sporting types may induce positive effects on ankle JPS (such as ballet, tai chi, or ice hockey) runners generally do not have superior proprioceptive abilities, and are generally similar to sedentary individuals (Xian Li *et al.*, 2009). It may be possible that repetitive impacts accumulated during long distance running serves to desensitize lower extremity mechanoreceptors and particularly cutaneous mechanoreceptors, resulting in reduced proprioception. However, research regarding this subject is severely limited. Alfuth and Rosenbaum (2011) did not find any acute effects on plantar sensitivity, plantar pressure distribution or peak forces following a 10 km run, while Willems and colleaugues (2012) found deviations in plantar pressure distribution following a 20 km run, suggesting modified proprioceptive input. However, the long-term effects of running on proprioception have not been directly established.

2. Plantar Dorsi Flexion

Both EXP and CON groups demonstrated improvements in foot position error (Table 5.10, page 125), of approximately 20% in the PF/ DF movement. However, these improvements were consistent across both groups and genders. Therefore, these small improvements could possibly be attributed to a learning effect of the testing method. These results were not expected as an increase PF/DF range of motion in minimalist running, combined with the reduced sole thickness was thought to improve PF/ DF proprioception. However, calf soreness could have affected PF/DF JPS, resulting in increased foot position error scores.

F. RESEARCH QUESTION SIX

To Deermine Whether Recreational Runners Can Successfully Adapt to a Minimalist Training Program by Adjusting Their Running Kinematics.

1. Transition into Minimalist Shoes

Progression into minimalist running has been a problematic topic in the past, with the majority of runners experiencing moderate to severe discomfort. Therefore, transition took place very cautiously and gradually, with increments of less than ten percent. It is important to remember that the NMC noted in runners is directly related to the running kinematics noted. Increases in ankle plantar-flexion angle and knee flexion at contact were noted in the EXP group, consistent with a change to forefoot striking pattern. In contrast, the CON group showed slight increases in ankle dorsiflexion and knee flexion at contact during the intervention. These kinematic adjustments to minimalist running have been noted repeatedly in the past and are consistent with literature (Lieberman, 2010; Squadrone & Gallozi, 2009; Bishop *et al.,* 2006; Divert *et al.,* 2005[a]). Further, as speed increased the EXP group increases in plantar-flexion angle and knee flexion occurred in an almost linear fashion. The CON group also increased ankle dorsiflexion and knee extension almost linearly. This joint excursion differences are also similar to differences found by Bishop and colleagues (2006). The greatest knee flexion was observed at the 10 $km.h^{-1}$ speed in the CON group, suggesting that this is the speed at which knee joint loading is greatest.

Therefore, given the kinematic changes noted in the EXP group, one may be inclined to conclude that the participants did transition successfully. However, as participants did experience discomfort, and EXP women still demonstrated strength deficits, more time may be needed to fully transition to minimalist shoes. Therefore, kinematic adaptations may precede those of the neuromuscular system.

When addressing the issue of successful transitioning, the topic of gait retraining needs to be discussed. Previous studies have chosen to include runners already habitually running barefoot or shod, or have chosen to include novice runners with the aim of recording the natural transition from heelstrike to forefoot strike. However, the natural transition to a forefoot strike may not always occur in minimalist shoes, which will have detrimental consequences as the impact transient is markedly increased in runners who maintain their rearfoot strike while in minimalist shoes (Lieberman *et al.*, 2010). As much of the benefits associated with minimalist running is related to running with a forefoot strike, and the fact that habitually shod runners may be at an increased risk of injury when they run in minimalist while maintaining a heelstriking pattern (Shih *et al.,* 2013), this study chose to include gait retraining during the transition period. According to Shiang and colleagues (2013), the footstrike pattern is more important than the shoe condition in running, and forefoot strikers can gain more shock absorption and lower extremity compliance, regardless of shoe condition. However, this fact is conflicted in the study by Giandolini (2013), who found greater reductions in loading rate in minimalist running compared to gait retraining with real-time feedback. Nevertheless, regardless of the more correct answer to this question, the differences in NMC would be compared more appropriately, when runners ran with a forefoot strike as is intended by minimalist running.

Considering that kinematic adaptations occurred, reduced discomfort was noted compared to previous studies, and improvements were seen in muscle activation patterns, it can be deduced that a relatively safe transition to minimalist shoes took place. The gradual increase in distance run in minimalist shoes, combined with a step training program allowed for better transitioning results. It must be noted however, that at the end of the 8-week intervention, the average distance run in minimalist shoes by the EXP group was 79% of the total distance during session number 23 (Table 5.5; page 77), and not a 100% as planned. The increase in percentage of total distance ran, became slower towards the end of the study, suggesting that 5% weekly increases might be more appropriate from week 6 onward, when working towards longer distances. Future research might also be advised to allow for a longer time to transition.

As mentioned previously, women demonstrated a larger change in degree of plantar-flexion resulting in excessive muscle soreness. Therefore, we could conclude that women participants possibly did not transition as successfully as men did. Whether these kinematic differences are due to gender-specific NMC strategies remains uncertain, however, considerable differences were noted in all outcomes measured, making it impossible to generalize findings across genders. Therefore, it might be suggested that women may require a longer transitioning period.

Ridge and partners (2013) investigated the effect of a minimalist shoe transition program on foot bone marrow oedema, and found that of the 11 runners who had excessive bone oedema (indicative of increased stress fracture risk), 8 were women. Ridge and colleagues (2013) also suggested a longer transition time for women. Interestingly, however, women demonstrated improved JPS and PC strategies than men did, indicating that they did compensate to a certain degree.

Taking aside gender differences, a further practical application is that, while gait retraining occurs, some runners may tend to overemphasize the forefoot strike, or transition too quickly from extreme dorsiflexion running. This may be severely detrimental, especially at the start of the program when the plantar-flexory muscles are at their weakest, resulting in an increased recovery time between runs. Strength deficits caused by eccentric overloading can be significant up to 96 hours following an eccentric fatiguing protocol, with return to baseline values only after seven days (Stupka, 2001). Future research might be advised to rather emphasize a midfoot strike, or a transitional program consisting of a gradual increase in plantar-flexion (Altman & Davis, 2012; Lieberman *et al.*, 2010; Divert *et al.,* 2005; Robbins & Hannah, 1987).

CHAPTER SEVEN: CONCLUSION

A. Summary of Findings

Running in minimalist shoes produces biomechanical changes resulting from a change in ankle and knee kinematics. This in turn, leads to the belief that minimalist shoes may have an affect on NMC strategies, as measured by EMG muscle activation patterns, postural sway, joint position sense and strength characteristics. Given that these adaptations in NMC could hold benefits to minimalist runners, the association between running style and injury rates or types could be argued. Therefore, the findings of this study could shed light on injury prevention strategies by way of correcting NMC mechanisms. Improvements in pre- and or co-activation could be the cause of attenuated injury rates seen over time in minimalist runners. Modest improvements in foot position error could further contribute to the efficiency of minimalist runners, and possible injury reductions. In contrast, minimalist running is associated with other injury types, especially during the transition period.

Safe transitioning protocols into minimalist shoes is essential, as increased initial injury risk might outweigh the benefits of possible long-term injury reduction for some. The present study contributed to the literature by making recommendations, based on findings, regarding transitioning into minimalist shoes. These recommendations include very gradual transition into minimalist shoes, using step progression programs, with the use of appropriate monitoring tools. It was noted that participants running with increased dorsiflexion angles at baseline, and who were required to make a larger changes in ankle angle over the intervention, also required more time to transition successfully (this generally occurred in women). Therefore the individual running characteristics should be considered prior to the design of a transitioning program.

The main findings of this study were that considerable differences occurred between genders during the transition period, resulting in marked differences in outcomes measured. Men demonstrated larger improvements in strength and muscle co-activation strategies, whereas women improved to a greater extent in muscle pre-activation, PC and possibly foot position error. More research regarding the differences in NMC between genders is warranted, in order to provide accurate transitioning advice. It is therefore imperative that future research takes these gender differences into consideration prior to the design of studies. Similarly, the prescription of gender specific shoes could be a reasonable option in the future. Interestingly, women improved in the two of the outcome variables most closely associated with reductions in injury risk. Improvements in pre-activation is thought to result in attenuated impact forces, whereas improvements in JPS results in better foot placement and a possible reduction in injuries over time.

Lastly, it appears that there are often immediate and long-term adaptations to minimalist shoes. However, these acute adaptations are not always reflected over time. Researchers should thus be cautious when generalizing findings from cross-sectional studies to be the long term effect as well.

B. Limitations And Future Directions

Firstly, when considering the intervention period, certain limitations were experienced. For example, some difficulties with the LLCI were experienced, as anatomical areas were described too vaguely according to participants. The main concerns were that participants were not sure whether to mark blistering under the “shoe” or “foot” boxes, and that pain was often experienced at the intersection between the calf and Achilles, where participants were uncertain whether to tick “calf” or “Achilles”. Lastly, pain experienced by a tight and inflamed tibialis posterior occurred postero-medially to the shin, and some confusion was experienced as to whether this was classified as “calf” or “shin” discomfort. It may be advised to make use of a questionnaire that includes smaller, more specific anatomical areas. Recently the Lower Limb Functional Index (LLFI) was developed by Gabel and partners (2012). While this questionnaire was designed for a slightly more clinical setting (patients following surgery or for patients with lower extremity conditions), it provides a more comprehensive description of the functional status of the lower extremity and includes the knee and thigh. Further, it also distinguishes between left and right legs, which is an additional limitation of the LLCI. An adapted version of the LLFI might be recommended for future studies. Alternatively, the LLCI could be utilized, with additional boxes for anatomical areas.

In regards to the training period, it may have been beneficial to allow enough time for participants to reach the full 100% of the total distance in their minimalist shoes. However, in this case, the timing of the intervention period as a whole did not allow for longer training. On a more subjective level, participants were struggling toward the end of the study, as many of them were students entering the mid-year exam period. Academic pressure outside of the sporting environment may have caused performance declines toward the end of the study. Therefore, the study did not last for longer than the time period stipulated.

Further, one of the main limitations is the differences in intervention and outcome measures found in the literature. Proprioception is difficult to measure and often requires several indirect outcome measures. This makes findings very hard to compare. There are some inconsistencies in the literature regarding whether weight-bearing and non-weight bearing measurements are preferred. A further challenge is the fact that real-life dynamic situations are difficult to mimic in a laboratory setting. Also, inter-individual differences are often large, further decreasing the power of the study.

Neuromuscular control shows relatively large inter-subject variability. Therefore, it was essential that each participant return for the post-test, in order to compare values. Electromyographic values cannot be directly compared between participants, only the relative change over time. Additionally, while training time, distance, surface and footwear are controlled as much as possible, there are certain external factors that might have had an effect on NMC. This includes adequate sleep (Gomez *et al.,* 2008), adequate liquid intake (Derave *et al*., 2012), and limited intake of caffeine and/or alcohol prior to the test. It is assumed that participants were well rested and hydrated at both baseline and post testing.

Unfortunately, due to technical complexities, the researcher was not able to capture the same number of EMG observations for the non-dominant leg, as with the dominant leg. Therefore, compared to 11 EXP and 9 CON measurements in the dominant leg, only 7 EXP and 6 CON measurements were taken in the non-dominant leg, reducing the power of the findings considerably. In some cases, wireless units did not transmit accurately, or sometimes force sensors defaulted. In these cases the researcher prioritized the dominant leg.

Further, as the time parameters of muscle activation were only studied, it might have been useful to include muscle activation amplitudes by making use of normalized maximal voluntary contraction measurements prior to measurement. This would have lent insight not only to the timing of activation, but the intensities as well.

Considerable left-to-right (or dominant-to-non-dominant) differences were noted in many of the outcomes measured. While one strength of this study is that bilateral EMG measurements were taken, it may be a limitation that strength, running mechanics and proprioception was only measured in the dominant leg. This made the cause of the differences between left and right difficult to analyze. Future research should be encouraged to measure both sides. However, it must be noted that including both sides often increases testing time substantially, which might limit the amount of tests which can be done in a session.

In retrospect, the addition of skeletal muscle damage markers may have been a useful inclusion to the test battery. As skeletal muscle damage affects proprioception, it may have been helpful to quantify the amount of muscle damage present in each participant. Testing could then possibly have been arranged following adequate recovery. Muscle damage markers may also have been practical during the intervention, to determine whether participants have recovered sufficiently from the previous running session, and whether ensuing sessions might cause excessive overload.

As mentioned previously, it may have been prudent to include isokinetic strength testing in the eccentric mode as well as concentric modes, to better differentiate between specific strength increases between groups. Active joint reproductive testing should possibly also have been included, to differentiate between joint and muscle mechanoreceptors. However, although these tests may have added to the study, it should be mentioned that many of the proprioceptive and PC tests require a great deal of concentration by the participants. As participants were already coming in twice for pre testing the researcher chose to prioritize the chosen tests, rather than to lose participants' concentration and reduce the accuracy of all the tests.

It must be noted that participants underwent post testing within three days following their last running session and that it may be reasonable to assume that muscle damage may still have been present in some runners. This could possibly have affected their NMC and proprioceptive abilities. Future research may be advised to include a retention test following a two week rest period (from minimalist shoes) to ensure that complete muscle recovery and regeneration occurred. Women in particular, would be expected to perform considerably better in the retention test. By including a retention test, the muscle damage time parameters could potentially also be investigated, leading to more appropriate advice being given to runners in the future, regarding training and timing of races with minimalist shoes.

With regards to the issue of specificity mentioned in Section E (mCTSIB) recommendations for NMC training will now be given, taken from findings in literature. Neuromuscular control training has been used extensively in rehabilitative settings; however its value in the healthy, non-injured population has also been discovered recently, with possible benefits of improved performance and injury prevention (Zech *et al.,* 2010). Neuromuscular control training involves not only balance and stabilization exercises, but some researchers include a multi-intervention combination of balance, strength, plyometric, agility and sport-specific exercises (Coughlan & Caulfield, 2007)

It must be mentioned that few scientific guidelines exist for prescribing balance exercises (Granacher *et al.,* 2011). However, the general guidelines for balance training is to include static and dynamic exercises on stable or unstable surfaces, with eyes open or eyes closed, while in bipedal or monopedal stance (Granacher *et al.,* 2010). In a study comparing postural sway and EMG analysis of hip and ankle muscles, it was concluded that balance tasks can be progressed according to the rank of the task's difficulty by increasing the number of sensory factors altered in a balance task (Tse *et al.,* 2013). The average recommendation for balance training is between two to seven times a week for between 5 and 90 minutes per session (Heitkamp *et al.,* 2001;

Emery *et al.,* 2005; Soderman *et al.,* 2000). Further, studies with significant training effects generally lasted for six weeks or longer (Emery *et al.,* 2005; Oliveira *et al.,* 2013; Gioftsidou *et al.,* 2006; Kovacks, 2004; Zech *et al.,* 2010).

Page (2004) prescribed guidelines for NMC training that flows from static balance tasks to more dynamic balance exercises, and finally into more functional movements. Within each stage, patients progress through exercises in different postures, bases of support and challenges to centres of gravity.

Future research may be directed at balance training in minimalist shoes, compared with regular trainers to determine whether differences exist between outcome variables. In a related study comparing the effect of taekwondo footwear (with thin soles and minimal support) to the barefoot condition, on single leg balance parameters, no statistically significant difference was noted (Fong & Ng, 2013). While no specific intervention period was included, the study made use of regular wearers of taekwondo shoes, who also regularly participate in balance training (as it is an inherent part of the Taekwondo sport).

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APPENDIX A: ADVERTISEMENT MATERIAL

APPENDIX B:

GENERAL SCREENING & HEALTH ASSESSMENT

Name: ____

Date of Birth: ____

Height:____

Weight: ____

Male/Female: ____

Address:____

Shoe size: ____

Thickness of Shoe soles:____________________________________

Waist circumference: _______________________________________

PAR-Q

Please read the questions carefully and answer each one honestly: check YES or NO.

yes _____no_____1. Has your doctor ever said that you have a heart condition and that you should do physical activity recommended by a doctor?

yes _____no_____2. Do you feel pain in your chest when you do physical activity?

yes _____no_____3. In the past month, have you had chest pain when you were not doing physical activity?

yes _____no_____4. Do you lose your balance because of dizziness or do you ever lose consciousness?

yes _____no_____5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?

yes _____no_____6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?

yes _____no_____7. Do you know of any other reason why you should not do physical activity?

If you answered yes to any of the above questions, please first consult a medical practitioner before becoming much more active.

Type of shoes you normally run in: ____

Average weekly distance run: ____

Number of weekly running sessions:____

For how long have you participated in running:_______________________________

Have you suffered any running related injuries in the past 12 months? Yes_______ No__________

If yes, please indicate type of injury and treatment used:

____

____

____

Have you used any other type of shoes in the past 24 months? Yes__________ No_________

If yes, please specify which type of shoe and the approximate distances covered:

____

____

____

Have you participated in any races in the last 6 months? ____________________________________

If yes, please indicate date and distance:

____

____

____

Do you participate in any other physical activity, besides running? Yes_____________ No___________

If yes, please specify:

____

____

____

Do you do regular balance/proprioceptive training? Yes___________ No____________

If yes, please explain type and amount:

____

____

____

How many cups of coffee do you drink daily (or any caffeine substitute)? ____________

How many cups of water do you drink daily? ___________

How much water do you drink during an average 1 hour training session? _____________

How many hours do you sleep most week nights? _______________

Weekend nights? _______________

Occupation____

What time in the day do you normally train? ____

Will you be able to attend training sessions at Coetzenburg Stadium three times a week? _________________

If yes, which times do you prefer? ____

Do you have any visual defects? ____

Do you wear glasses/contact lenses? ____

Do you wear glasses/contact lenses during running? ____

BYLAAG B

ALGEMENE GESONDHEIDSASSESSERINGS VRAELYS

Naam:____

Geboortedatum:____

Lengte:____

Gewig: ____

Manlik/Vroulik: ____

Adres: ____

____

Skoengrote: ____

Skoensool dikte: ____

Middelomtrek:____

Fisiese Aktiviteit - Gereedheids Vraelys

Lees asb die onderstaande vraelys en antwoord JA of NEE langs elke vraag eerlik.

Ja____ nee____ 1. Het U dokter U al vantevore gediagnoseer met 'n hartstoestand EN gese dat U fisiese aktiwiteit gemonitor moet word deur 'n dokter?

Ja____ nee____2. Voel U ooit borspyn gedurende 'n oefensessie?

Ja____ nee____3. In die vorige maand, het U enigsens borspyn ervaar terwyl U nie oefen nie?

Ja____ nee____4. Verloor U ooit U balans as gevolg van duisligheid, of verloor U ooit bewustheid?

Ja____ nee____5. Het U 'n been of gewrigsprobleem (byvoorbeeld rug, knieg of heup) wat vererger kan word deur 'n verandering in fisiese aktiviteit?

Ja___ nee____6. Skryf U dokter tans enige medikasie vir U bloeddruk of hartstoestand voor?

Ja____nee____7. Is U bewus van enige ander rede waarom U nie aan fisiese aktiwiteit mkan deelneem nie?

Indien U op enige van die bogenoemde vrae JA geantwoord het, raadpleeg asb eers U mediese praktisyn voor U meer aktief word.

Wat is die maak en tipe skoene waarin U gewoonlik

hardloop?____

____

Gemiddelde afstand wat U gewoonlik hardloop in 'n week?

____

Hoeveel maal per week draf U?____

Het U enige hardloop verwante besering opgedoen in die afgelope 12 maande? Ja_____ Nee_____

Indien ja, beskryf asb volledig, en noem ook hoe die besering behandel

was:____

____

____

Het U in enige ander tipe skoene geoefen in die afgelope 24 maande? Ja________ Nee_________

Indien ja, beskryf asb die maak en afstand in hulle gehardloop tot dusver.:

____

____

Het U deelgeneem in enige wedlope die afgelope 6 maande? Ja________ Nee________________

Indien ja, beskryf asb volledig:

____

____

____

Neem U deel in enige ander vorm van fisiese aktiwiteit, buiten langafstand hardloop? Ja_____ Nee_____

Indien ja, beskryf asb volledig:

____

____

____

Doen U gereelde balans/proprioseptiewe oefening? Ja__________ Nee_________

Indien ja, beskryf asb tipe en hoeveelheid:

____

Hoeveel koppies koffie (of soortgelyke kaffiene inhoud) drink U gemiddeld per dag? ________________________________

Hoeveel water drink U gemiddeld per dag? ____________________________________

Hoeveel water drink U gemiddeld gedurende 'n een uur oefensessie? ____

Hoeveel ure slaap U gemiideld per weeksaand? _________________________________

Naweek aande? ____

Wat is U beroep? ____

Hoe laat oefen U gewoonlik? ____

Sal U beskikbaar wees om oefen sessies by Coetzenburg stadion by te woon, drie keer 'n week? ____

Indien wel, hoe laat sal U verkies om oefensessies by te woon? ____________________

Het U enige probleme met U sig? ____

Dra U kontaklense/ brille? ____

Dra U kontaklense/brille terwyl U oefen? _______________________________________

APPENDIX C: CONSENT FORM

STELLENBOSCH UNIVERSITY
CONSENT TO PARTICIPATE IN RESEARCH

THE EFFECT OF MINIMALIST SHOE TRAINING ON NEUROMUSCULAR CONTROL OF RECREATIONAL DISTANCE RUNNERS.

You are asked to participate in a research study conducted by Sulè Dreyer (BSc Honours Biokinetics) from the Department of Sport Science at Stellenbosch University. The results obtained in this study will contribute towards a thesis, in order to meet the requirements of a Masters Degree in Sport Science, and will be published in a scientific journal. You were selected as a possible participant in this study because you meet the inclusion criteria of the study, and enjoy recreational distance running.

1. PURPOSE OF THE STUDY

The purpose of the study is to determine whether training in minimalistic shoes holds any added benefits, namely improved proprioception and dynamic balance.

2. PROCEDURES

If you volunteer to participate in this study, you will be asked to take part in a battery of tests, including the following:

- Basic anthropometric measurements – height, weight, BMI and calf circumferences.
- A VO_2max test – a treadmill run to measure maximal oxygen uptake.
- Biomechanical analysis – a video will be taken while you run on a treadmill to determine your specific gait pattern.
- Balance assessment – a single leg balance test on the Biodex balance board.
- Balance assessment – a single leg stance on the floor with two small sway (tri-axial accelerometers) detectors taped to your lower back.
- Isokinetic strength test – measurement of ankle muscle strength in saggital and frontal planes, using a Biodex Isokinetic machine.
- Ankle foot position awareness – a simple blindfolded test to measure your judgement of degrees of inversion/eversion of your ankle (also in the Biodex Isokinetic Machine).
- EMG analysis of specific foot muscle activation during a slow treadmill run.
- Questionnaires regarding your thoughts and feelings during and after training, the amount of comfort/discomfort you felt in your ankles during the run, as well as your general level of stress (this will include questions about other aspects of your life as well). Specifically, this will include the Recovery and Stress Questionnaire, Lower Limb Comfort Index, Attentional Focus Questionnaire, and the Motivation of Marathoners Scale.

Following the test battery, you will be randomly assigned into a control and experimental group. The intervention period will last for 8 weeks, in which you will be asked to join three (3) running sessions a week, at Coetzenburg stadium. The control group will run in normal, cushioned running shoes and the experimental group will run in minimalistic shoes. The running distance will slowly increase over the intervention period. You will be given heart rate monitors to run with, which should help you to train in the correct heart rate zones. You will also be asked to fill in regular questionnaires throughout the duration of the study, pertaining to your level of comfort throughout the run, and psychological effects of the run. The test battery will be repeated following the intervention period, to determine if there are any improvements.

3. POTENTIAL RISKS AND DISCOMFORTS

The study could bring about some risks and discomforts including light-headedness, dizziness, fainting, shortness of breath, wheezing, nausea, cramps or muscle aches, and prolonged fatigue following a training session. However, you will be carefully monitored by a registered Biokineticist (Sulè Dreyer), and will be advised on how to manage symptoms. A medical doctor will also be on call throughout the duration of the study.

As you are not accustomed to minimalist shoes, which have little cushioning and arch support, you can expect some muscle tenderness in your ankles following a run. This discomfort should subside within a day or two. The soles of your feet may also become sensitive; however, this should not last long into the study.

4. POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

The study could hold promising benefits for the participant, including improved cardiovascular fitness, body composition, psychological wellbeing and overall health. The participant will also be taught how to train efficiently using a heart rate monitor to stay within optimal heart rate zones. Lastly, the participant will be monitored closely and training volumes will be increased gradually, allowing them to run their first half marathon at the end of the study, with minimal risks of overuse injury. Participants will be made aware of any discoveries obtained throughout the study, so that they will also benefit from the new information.

The study will benefit society in that more will be learnt about the benefits of minimalistic shoes, especially regarding balance and proprioception. This will aid footwear prescription in the future.

5. PAYMENT FOR PARTICIPATION

Participants will receive no payment for participation. Participation will also not cost the participant anything.

6. CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. Confidentiality will be maintained by means of assigning codes randomly to names. These codes will be used throughout the duration of the study, keeping names anonymous. Names will only be accessible to the researcher and study supervisor, and will be kept on a password protected computer.

Participants will be allowed full rights to their test results, and will also be allowed to review their biomechanical assessment. Video data will be stored electronically on the same password protected computer. All video data will be erased after publication of the study.

The study will be published in a scientific journal, using only statistical numbers and codes. No names will be disclosed in the article.

7. PARTICIPATION AND WITHDRAWAL

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you don't want to answer and still remain in the study. The investigator may withdraw you from this research if circumstances arise which warrant doing so. Should you partake in any other sporting events which could affect your test results during the study, your participation may be terminated, without regard to consent.

8. IDENTIFICATION OF INVESTIGATORS

If you have any questions or concerns about the research, please feel free to contact the researcher, Sulè Dreyer at 082 814 1066 (suledreyer@gmail.com), or the Supervisors Dr R Venter, at 021 808 4915 (rev@sun.ac.za), and Dr K Welman at 021 808 4733 (welman@sun.ac.za)

9. RIGHTS OF RESEARCH SUBJECTS

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, contact Ms Maléne Fouché [mfouche@sun.ac.za; 021 808 4622] at the Division for Research Development.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

The information above was described to me, ________________ by Sulè Dreyer in both English and Afrikaans and I am in command of these languages or it was satisfactorily translated to me. I was given the opportunity to ask questions and these questions were answered to my satisfaction.

I hereby consent voluntarily to participate in this study. I have been given a copy of this form.

____

NAME OF SUBJECT/PARTICIPANT

____

Name of Legal Representative (if applicable)

__________________________________ ____________

SIGNATURE OF SUBJECT/PARTICIPANT OR LEGAL REPRESENTATIVE DATE

SIGNATURE OF INVESTIGATOR

I declare that I explained the information given in this document to _______________ [*name of the subject/participant]* and/or [his/her] representative _________________ [*name of the* *representative].* He/she was encouraged and given ample time to ask me any questions. This conversation was conducted in [Afrikaans/English] and no translator was used.

__________________________________ ____________

SIGNATURE OF INVESTIGATOR DATE

UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
jou kennisvennoot • your knowledge partner

UNIVERSITEIT STELLENBOSCH

INWILLIGING OM DEEL TE NEEM AAN NAVORSING

DIE EFFEK VAN OEFENING MET MINIMALISTIESE SKOENE OP DIE NEUROMUSKULÊRE BEHEER IN DIE ENKEL VAN REKREASIE LANGAFSTANDATLETE.

U word gevra om deel te neem aan 'n navorsingstudie uitgevoer te word deur Sulè Dreyer (BSc Honneurs Biokinetika), van die Departement Sportwetenskap aan die Universiteit Stellenbosch. Die resultate verkry in hierdie studie sal deel maak van 'n tesis, om sodoende te voldoen aan die vereistes vir 'n Meestersgraad in Sportwetenskap, en sal gepubliseer word in 'n wetenskaplike joernaal. U is as moontlike deelnemer aan die studie gekies omdat U voldoen aan die insluitingskriteria van die studie, en dit geniet om gereeld langafstande te hardloop.

10. DOEL VAN DIE STUDIE

Die doel van die studie is om te bepaal of oefening met minimalistiese skoene enige addisionele voordele inhou, naamlik verbeterde enkel posisie bewustheid (propriosepsie) en dinamiese balans.

11. PROSEDURES

Indien u inwillig om aan die studie deel te neem, sal van U gevra word om deel te neem aan die volgende battery toetse:

- Basiese antropometriese afmetings – hoogte, gewig, middellyf- en kuit omtrekke.
- 'n VO_2maks toets – 'n hardloop sessie op 'n trapmeul om sodoende u maksimale suurstof opname te bepaal.
- Biomeganiese Analise – 'n videoanalise sal gedoen word tydens n gemaklike draf sessie op 'n trapmeul, om U spesifieke loopgang patrone te bepaal.
- Balans asessering – die Biodex balans bord sal gebruik word vir 'n enkelbeen balans toets.
- Balans assesering – 'n tweede enkelbeen balans toets, wat op die vloer gedoen sal word, met twee klein "detectors" wat op U laerug geplak sal word.
- Isokinetiese Krag toets – Bepaling van enkel spierkrag, met behulp van 'n Biodex Isokinetiese Dinamometer.
- Enkel Posisie bewustheid – deelnamers sal gevra word om die graad van inversie/eversie te skat gedurende 'n geblindoekte toets (ook op die Biodex Isokinetiese Dinamometer)
- Elekromiografiese analise sal gedoen word van spesifieke spieraktiverings patrone gedurende 'n stadige draf op 'n trapmeul.
- Vraelyste aangaande U gedagtes en gevoelens tydens en na 'n oefensessie, die hoeveelheid gemak/ongemak wat U gevoel het gedurende die hardloopsessie, asook die

algemene vlak van stres wat U tans ervaar (hierdie vraelys sal ook vrae insluit oor ander aspekte van U lewe). Om spesifiek te wees sal die Herstel en Stres Vraelys, Onderste Ledemate Gemaklikheids Indeks, Plasing van Aandag Vraelys en die Skaal van Motivering vir Maratoners gebruik word.

Na die battery toetse, sal U op ʼn lukrake wyse in óf die eksperimentele, of kontole groep ingedeel word. Die intervensie periode sal vir 8 weke duur, waartydens U 3 oefensessies ʼn week sal moet bywoon, by Coetzenburg stadion. Die kontrolegroep sal oefen in konvensionele, sagter hardloop skoene, terwyl die eksperimentele groep minimalistiese skoene sal dra tydens oefensessies. Die hardloop afstande sal gelydelik toeneem gedurende die intervensie periode. Hart tempo monitors sal verskaf word, waarmee U gevra sal word om mee te oefen, om sodoende te verseker dat U in die korrekte hart tempo zones oefen.

12. MOONTLIKE RISIKO'S EN ONGEMAKLIKHEID

Hierdie studie kan moontlike risoko's inhou, naamlik duisligheid, lighoofdigheid, floute, 'n gevoel van kort asem, naarheid, maag- of spierkrampe, en langdurige moegheid na 'n oefensessie. U sal, alhoewel, deeglik gemonitor word deur 'n geregistreerde Biokinetikus (Sulè Dreyer), wat jou sal raadpleeg oor metodes om bogenoemde simptome te verhoed. Daar sal ook deur die loop van die studie 'n mediese dokter beskikbaar wees.

Aangesien U enkels nie gewoond is aan minimalistiese skoene, met beperkte beskerming en voetbrug ondersteuning nie, kan daar verwag word dat van U enkel en voetspiere effens teer is na n hardloopsessie. Hierdie ongemaklikheid behoort binne ʼn dag of twee op te klaar. Die onderkant van U voete mag ook teer wees, aangesien wrywing effens verhoog word tedyns oefening in minimalistiese skoene.

13. MOONTLIKE VOORDELE VIR PROEFPERSONE EN/OF VIR DIE SAMELEWING

Hierdie studie kan positiewe effekte he op die deelnamer, naamlik verbeterde kardiovaskulere fiksheid, liggaamsaamestelling, algehele geesteswelstand, en gesondheid. Die deelnamers sal ook geleer word hoe om effektief met ʼn harttempomonitor te oefen, en sodoende in die korrekte hert tempo zones te bly. Laastens, sal die deelnamer ook deeglik gemonitor word, terwyl hulle oefen volume geleidelik sal toeneem tot hul doelafstand van 21km. Dit sal verseker dat hul minimale risiko het om enige beserings op te doen. Deelnamers sal op hoogte gehou word van enige ontdekkings wat gemaak is gedurende die studie, sodat hulle ook sal baat by enige nuwe informasie.

Die studie sal die samelewing baat, in dat meer geleer sal word van die voordele van minimalistiese skoene, veral rondom die effek wat dit het op balans en propriosepsie. Dit sal toekomstelike skoenvoorskrif meer akkuraat maak.

VERGOEDING VIR DEELNAME

Proefpersone sal nie enige vergoeding ontvang nie. Hulle sal ook nie gevra word om vir enige deel van die studie te betaal nie.

14. VERTROULIKHEID

Enige inligting wat deur middel van die navorsing verkry word en wat met u in verband gebring kan word, sal vertroulik bly en slegs met u toestemming bekend gemaak word of soos deur die wet vereis. Vertroulikheid sal gehandhaaf word deur middel van kodes wat lukraak toegewys word aan name. Net die navorser en studie leier sal toegang hê tot name, wat gestoor word op n wagwoord beskermde rekenaar.

Deelnemers sal ten alle tye volle toegang hê tot hul toets resultate, en sal ook hulle biomeganiese analise kan hersien. Video data sal elektronies gestoor word, ook op n wagwoord beskermde rekenaar, en sal uitgevee word sodra die studie gepubliseer is.

Die studie sal gepubliseer word in n wetenskaplike joernaal, waarin slegs statistiese kodes gebruik sal word. Dus, sal geen name geopenbaar word nie.

15. DEELNAME EN ONTTREKKING

U kan self besluit of u aan die studie wil deelneem of nie. Indien u inwillig om aan die studie deel te neem, kan u te enige tyd u daaraan onttrek sonder enige nadelige gevolge. U kan ook weier om op bepaalde vrae te antwoord, maar steeds aan die studie deelneem. Die ondersoeker kan u aan die studie onttrek indien omstandighede dit noodsaaklik maak. Indien U gedurende die studie deelneem in enige ander sport geleenthede, wat moontlik jou toets resultate kan affekteer, sal deelname in die studie onmiddelik geindig word, sonder betrekking tot toestemming.

16. IDENTIFIKASIE VAN ONDERSOEKERS

Indien u enige vrae of besorgdheid omtrent die navorsing het, staan dit u vry om in verbinding te tree met die navorser, Sule Dreyer by 082 814 1066 (suledreyer@gmail.com), of die studieleiers Dr R Venter by 021 808 4915 (rev@sun.ac.za), en Dr K Welman by 021 808 4733 (welman@sun.ac.za).

17. REGTE VAN PROEFPERSONE

U kan te enige tyd u inwilliging terugtrek en u deelname beëindig, sonder enige nadelige gevolge vir u. Deur deel te neem aan die navorsing doen u geensins afstand van enige wetlike regte, eise of regsmiddel nie. Indien u vrae het oor u regte as proefpersoon by navorsing, skakel met Me Maléne Fouché [mfouche@sun.ac.za; 021 808 4622] van die Afdeling Navorsingsontwikkeling.

VERKLARING DEUR PROEFPERSOON OF SY/HAAR REGSVERTEENWOORDIGER

Die bostaande inligting is aan my, ______________________, gegee en verduidelik deur Sulè Dreyer in Afrikaans en Engels en ek is dié tale magtig of dit is bevredigend vir my vertaal. Ek is die geleentheid gebied om vrae te stel en my vrae is tot my bevrediging beantwoord.

Ek willig hiermee vrywillig in om deel te neem aan die studie.'n Afskrif van hierdie vorm is aan my gegee.

____

NAAM VAN PROEFPERSOON/DEELNEMER

____

Naam van regsverteenwoordiger (indien van toepassing)

_____________________________________ ___________________

HANDTEKENING VAN PROEFPERSOON/DEELNEMER OF REGSVERTEENWOORDIGER DATUM

VERKLARING DEUR ONDERSOEKER

Ek verklaar dat ek die inligting in hierdie dokument vervat verduidelik het aan______________________ en/of sy/haar regsverteenwoordiger ________________________[*naam van die regsverteenwoordiger*]. Hy/sy is aangemoedig en oorgenoeg tyd gegee om vrae aan my te stel. Dié gesprek is in Engels en Afrikaans gevoer en geen vertaler is gebruik nie.

_____________________________________ _____________

HANDTEKENING VAN ONDERSOEKER DATUM

Goedgekeur Subkomitee A 25 Oktober 2004

APPENDIX D: ETHICAL CLEARANCE

UNIVERSITEIT·STELLENBOSCH·UNIVERSITY
jou kennisvennoot • your knowledge partner

Approved with Stipulations

Response to Modifications- (New Application)

04-Apr-2013
DREYER, Sule

Protocol #: HS893/2013
Title: Effect of minimalist shoe training on neuromuscular control of recreational runners

Dear Miss Sule DREYER,

The **Response to Modifications** - ***(New Application)*** received on **02-Apr-2013**, was reviewed by Research Ethics Committee: Human Research (Humanities) via Committee Review procedures on **04-Apr-2013**.

Please note the following information about your approved research protocol:

Protocol Approval Period: **04-Apr-2013 -03-Apr-2014**

Present Committee Members:

The Stipulations of your ethics approval are as follows:
1. The researcher is requested to add a statement in the Informed Consent Form, advising participants that they will be responsible for their own travel costs.

Standard provisions
1. The researcher will remain within the procedures and protocols indicated in the proposal, particularly in terms of any undertakings made in terms of the confidentiality of the information gathered.
2. The research will again be submitted for ethical clearance if there is any substantial departure from the existing proposal.
3. The researcher will remain within the parameters of any applicable national legislation, institutional guidelines and scientific standards relevant to the specific field of research.
4. The researcher will consider and implement the foregoing suggestions to lower the ethical risk associated with the research.

You may commence with your research with strict adherence to the abovementioned provisions and stipulations.

Please remember to use your **protocol number** (**HS893/2013**) on any documents or correspondence with the REC concerning your research protocol.

Please note that the REC has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.

After Ethical Review:
Please note that a progress report should be submitted to the Committee before the approval period has expired if a continuation is required.
The Committee will then consider the continuation of the project for a further year (if necessary). Annually a number of projects may be selected randomly for an external audit.

National Health Research Ethics Committee (NHREC) number REC-050411-032.

This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes 2004 (Department of Health).

Provincial and City of Cape Town Approval

Please note that for research at a primary or secondary healthcare facility permission must be obtained from the relevant authorities (Western Cape Department of Health and/or City Health) to conduct the research as stated in the protocol. Contact persons are Ms Claudette Abrahams at Western Cape Department of Health (healthres@pgwc.gov.za Tel: +27 21 483 9907) and Dr Helene Visser at City Health (Helene.Visser@capetown.gov.za Tel: +27 21 400 3981). Research that will be conducted at any tertiary academic institution requires approval from the relevant parties. For approvals from the Western Cape Education Department, contact Dr AT Wyngaard (awyngaar@pgwc.gov.za, Tel: 0214769272, Fax: 0865902282, http://wced.wcape.gov.za).

Institutional permission from academic institutions for students, staff & alumni. This institutional permission should be obtained before submitting an application for ethics clearance to the REC.

APPENDIX E: LOWER LIMB COMFORT INDEX

Name:	**Foot**	**Ankle**	**Calf**	**Achilles**	**Shin**	**Knee**	**Footwear**	**Total**
Comfort Index: Place a score of 0-6 in each box								/36

COMFORT DESCRIPTORS

0

extremely uncomfortable (unable to run or jump);

1

2

3

neither uncomfortable or comfortable (more or less uncomfortable / comfortable)

4

5

6

zero discomfort (extremely comfortable; best ever feel)

Table 1. Lower Limb Comfort Index shows a numeric rating scale with fixed anchor points at key positions on the scale. Visual descriptive explanations provide further interpretation of the anchors relevant to physical requirements participating in long distance running.

ONDERSTE LEDEMATE SKAAL VAN GEMAKLIKHEID

Naam:	**Voet**	**Enkel**	**Kuit**	**Achilles**	**“Shin”**	**Knie g**	**Skoene**	**Totaal**
Skaal van Gemaklikheid: Merk ‘n telling van 0-6 in elke boks								**/36**

BESKRYWING VAN GEMAKLIKHEID

0

verskriklik ongemaklik (kan nie harloop of spring nie);

1

2

3

nie gemaklik of ongemaklik nie (min of meer gemaklik/ ongemaklik)

4

5

6

geen ongemak (verskriklik gemaklik; beste gevoel ooit)

Tabel 1. Die onderste ledemaat Skaal van Gemaklikheid dui ‘n noemerise skaal aan, met verduidelikings by belandrike punte. Visuele beskrywings maak die interpretasie van die belangrike punte nog makliker om te verstaan, om sodoende dit relevant te maak tot die fisiese vereistes van deelname in langafstand hardloop.

APPENDIX F: RUNNING LOG

Date: ______________________________ Time run: ____

Distance: ____________________________ Distance in minimalist shoes: ___________________________

Type of surface: _____________________ Temperature: ____

Average HR: __________________________ HR max ____

Comments: ____

____

BYLAE F: OEFENJOERNAAL

Datum: _____________________________ Totale tyd gehardloop: _________________________________

Afstand: ____________________________ Afstand in minimalistiese skoene: ________________________

Tipe oppervlak: _______________________ Temperatuur: _______________________________________

Gemiddelde HR: _______________________ HR maks: ____

Addisionele notas:

____

____

APPENDIX G: SESSION PERFOMANCES

Week number	Medium Distance Run	Long Distance Run	Short Distance Run
ONE **Description**	Flat Route Minimalist Grass Trainers Road	Flat Route Minimalist Grass Trainers Road	Flat Route Minimalist Grass Trainers Road
Distance(km)	6.41	7.91	5.12
LLCI (Total)	35.3	33.67	35.41
TWO **Description**	Flat Route Minimalist Grass Trainers Road	Flat Route Minimalist Grass Trainers Road	Flat Route Minimalist Grass Trainers Road
Distance	6.43	8.05	5.03
LLCI(Total)	34.36	33.66	34.46
THREE **Description**	Flat Route Minimalist Grass Trainers Road	Flat Route Minimalist Grass Trainers Road	Flat Route Minimalist Grass Trainers Road
Distance	7.53	9.90	5.60
LLCI (Total)	33.00	32.00	33.95
FOUR **Description**	Easy Hill Route Minimalist Road Trainer Road	Flat Route Minimalist Road Trainer Road	Hill Route Minimalist Road Trainer Road (Sprints at End))
Distance	9.43	11.24	6.33
LLCI (Total)	32.19	32	33
FIVE **Description**	Easy Hill Route Minimalist Road Trainer Road	Hill Route Minimalist Road Trainer Road	Minimalist Road Trainer Road Sprints at End (Grass)
Distance	8.53	11.94	5.40
LLCI (Total)	32.3	31	32.36
SIX **Description**	Intermediate Hill Route Minimalist Road Trainer Easy Trail	Flat Route Minimalist Road Trainer Road	Hill Route Minimalist Road Trainer Easy Trail Sprints at End
Distance	8.66	12.24	5.82
LLCI (Total)	31.87	32	33.27
SEVEN **Description**	Minimalist Easy Trail Trainer Trail Route Incl. Intermediate Hill	Minimalist Easy Trail Trainer Road	Minimalist Easy Trail Trainer Trail Sprints at End
Distance	9.54	13.82	6.61
LLCI (Total)	32	31	33
EIGHT **Description**	Road Only (Easy Hill)	Road only (Flat)	Road only (Flat)
Distance	9.74	15.23	6.91
LLCI (Total)	32.16	31.35	33.00

APPENDIX H: LETTER OF SPONSORSHIP

MERRELL

21 January 2013

To whom it may concern,

This letter serves to confirm that Merrell has consented to sponsor minimalist shoes (Merrell Trial Gloves) to be used in a research study conducted at the University of Stellenbosch, by Sulé Dreyer.

This study is in partial fulfillment of her MSc degree in Sport Science. The shoes are donated purely for the benefit of research, and Merrell expect nothing in return. Thus, there is no conflict of interest.

Should there be any further enquiries, kindly contact the office at marketing@medicus.co.za.

Regards,

Liezel Jooste
Marketing Manager: MERRELL SA
Tel: +27414841645

Medicus Shoes (Pty) Ltd, 79 Grahamstown Road, North End, Port Elizabeth,6001
Tel: (041) 48481645, marketing@medicus.co.za

APPENDIX I: LETTER OF PERMISSION FROM STELLENBOSCH UNIVERSITY

UNIVERSITEIT • STELLENBOSCH • UNIVERSITY
jou kennisvennoot • your knowledge partner

20 March 2013

Ms Sulè Deyer
Department of Sport Science
Stellenbosch University

Dear Ms Dreyer

Concerning research project: *Effect of Minimalist Shoe Training on Neuromuscular Control of Recreational Distance Runners*

The researcher has institutional permission to solicit the participation of Stellenbosch University students and staff in this project as stipulated in the research proposal.

This permission is subject to the following conditions:

- the researcher obtains ethical clearance from the Stellenbosch University Research Ethics Committee,
- the researcher obtains the participants' full informed consent for all facets of their participation in this study,
- participation is voluntary,
- participants may withdraw at any time,
- data that is collected may only be used for the purpose of this study,
- individuals may not be identified in the dissemination of the results of the study.

The researcher will act in accordance with Stellenbosch University's principles of research ethics and scientific integrity as stipulated in the *Framework Policy for the Assurance and Promotion of Ethically Accountable Research at Stellenbosch University.*

Best wishes,

Jan Botha
Senior Director: Institutional Research and Planning

Afdeling Institusionele Navorsing en Beplanning • Institutional Research and Planning Division
Privaatsak/Private Bag X1 • Stellenbosch • 7602 • Suid-Afrika/South Africa
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