

# TOWARDS AN IMPROVED UNDERSTANDING OF THE BIOMECHANICAL IMPLICATIONS AND RISK OF INJURY OF BAREFOOT RUNNING

by

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### a) ARTICLES IN INTERNATIONAL PEER-REVIEWED JOURNALS:

1. **Tam, N.**, Astephen Wilson, J.L., Noakes, T.D., Tucker, R. (2014) Barefoot running: an evaluation of current hypothesis, future research and clinical applications. **British Journal of Sports Medicine** 48(3): 349-355.
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## LIST OF ABBREVIATIONS

<b>ANOVA</b>	:	Analysis of variance
<b>apGRF</b>	:	Anterior-posterior ground reaction force
<b>BF</b>	:	<i>Biceps femoris</i>
<b>BMI</b>	:	Body mass index
<b>BW</b>	:	Body weight
<b>CO<sub>2</sub></b>	:	Carbon dioxide
<b>CV</b>	:	Co-efficient of variation
<b>ES</b>	:	Effect size
<b>EVA</b>	:	Ethylene-vinyl acetate
<b>EMG</b>	:	Electromyography
<b>GM</b>	:	<i>Gluteus medius</i>
<b>LED</b>	:	Light-emitting diode
<b>LG</b>	:	<i>Gastrocnemius lateralis</i>
<b>MG</b>	:	<i>Gastrocnemius medialis</i>
<b>mIGRF</b>	:	Medio-lateral ground reaction force
<b>O<sub>2</sub></b>	:	Oxygen
<b>PL</b>	:	<i>Peroneus longus</i>
<b>RF</b>	:	<i>Rectus femoris</i>
<b>SENIAM</b>	:	Surface electromyography for non-invasive assessment of muscles
<b>SD</b>	:	Standard deviation
<b>TA</b>	:	<i>Tibialis anterior</i>
<b>VO<sub>2</sub></b>	:	Oxygen uptake
<b>vGRF</b>	:	Vertical ground reaction force



## ABSTRACT

Barefoot running is a subject of significant interest, both in scientific publications and in the lay media as a result of its alleged benefits for runners. These benefits include the potential to reduce injury risk, more economical running and broadly speaking, a better understanding of running biomechanics. Although there are numerous scientific publications describing differences between barefoot and shod running, there is a dearth in understanding whether all runners are able to adapt to the proposed benefits and how this may affect long-term injury risk.

Thus, we sought to investigate the biomechanical, neuromuscular and metabolic changes associated with habitually shod runners during the transition to pure barefoot running over an 8-week progressive training programme. This thesis begins with a critical review of the literature, which evaluates the theories and evidence for barefoot running, as well as describing the necessary future research to confirm or refute the barefoot running hypotheses.

Our first study aimed to describe acute changes occurring in habitually shod runners when first exposed to barefoot running. We were particularly interested in the variability in response, and whether we could identify factors that predicted potentially favourable changes in kinematic and kinetic outcomes. Fifty-one runners were recruited and assessed using a 3-D motion capture system and integrated force platforms using conventional methods. We found that loading rate was significantly greater in the barefoot condition, but that high individual variability existed, particularly in the barefoot trials. We found that an increase in ankle dorsiflexion is associated with an increase in initial loading rate when in the barefoot condition, supporting previous findings in this regard.

We then performed a supervised, pure barefoot running training programme, over 8 weeks, to determine whether the biomechanics of barefoot running would adapt gradually to habituation. Twenty-three runners were recruited for participation, and performed comprehensive biomechanical and neuromuscular assessments before and after the 8-week programme. The first finding was runners do not adapt similarly to barefoot training, and that biomechanics do not change significantly over the 8-week period. High variability in ankle kinematics and loading rate

were found, with three sub-groups identified, namely positive responders (reduced loading rate after training), non-responders (no change in loading rate) and negative responders (increase in loading rate after training).

We found significant associations between initial loading rate the changes in ankle flexion angle at initial ground contact, presumably as a result of its influence on footstrike. This finding suggests that conscious instruction might be necessary in order to achieve reductions in collision forces during barefoot running.

With respect to neuromuscular variables, a persistently higher gastrocnemii muscle pre-activation was found in the barefoot condition before and after the training intervention. Increased gastrocnemius pre-activation was associated with lower initial loading rate. An increase in gluteus medius and peroneus longus and a decrease in tibialis anterior pre-activation were also associated with a reduction in initial loading rate after barefoot training. This finding suggests a refined neuromuscular activation strategy prior to ground contact in the barefoot condition to stabilize the hip and centre of mass.

Lastly, oxygen cost of transport was found to improve as a result of the barefoot training programme in the male runners and this improvement was found to be associated with a decrease in ground contact time and increase in stride frequency, but no a change in ankle flexion angle at initial ground contact.

The outcomes from this thesis elucidate the highly variable response of individuals to barefoot running. This advises individuals choosing to transition to barefoot running to do so with caution. With this in mind, we suggest certain characteristics that may be used as screening mechanisms to indicate individual suitability to barefoot running based on the “collision force theory”. Further, benefits associated with barefoot running other than varied responses in initial loading rate such as improvements in oxygen cost of running are pre-dominantly hypothesised to be a result of musculo-tendinous adaptations, neuromuscular strength and motor control.

# **CHAPTER 1**

## Preamble and Scope of the Thesis

## 1.1 Preamble

### *i.) Origins of the research questions in this thesis*

Barefoot running has gained enormous scientific popularity in the last five years. This is observed in the scientific literature as a five-fold increase in barefoot running related research papers in PUBMED. The scientific interest in barefoot running owes considerable credit to the success of the book “Born to Run” by Christopher McDougall(1). In this book, McDougall relates the story of the Tarahumara Indians of Mexico, who he describes as a tribe of “super athletes”, who run long distances in primitive sandals called huaraches, purportedly without any injuries. McDougall develops a thesis that the modern running shoe, which was introduced in the early 1970s, has done little to reduce the prevalence of running injuries(2–4).

Further, McDougall weaves a narrative of the Tarahumara with descriptions of scientific studies and interviews with evolutionary biologists and argues that modern running shoes are in fact part of the cause of running injuries(1). A seminal article by Bramble and Lieberman (2004) in the journal *Nature* is a pillar of this argument, for it argued that endurance running was instrumental in the evolution of the human body form(5).

From this, as is occasionally the case, public interest, industry’s response and the widespread enthusiasm for an idea preceded the scientific evidence supporting (or refuting) it. An example of this occurred recently in the field of talent and skill acquisition, where popular books such as *Outliers*(6), *Bounce*(7) and *The Talent Code*(8) expounded theories that expert performance, including elite sporting performance, was the result of the accumulation of 10 000 hours of deliberate practice. The scientific evidence, which existed prior to the publication of these books, was in effect drowned out by the volume and reach of more populist media, and only later did studies begin to directly refute this oversimplification of expertise, by explaining the complex interaction between genes, environment and practice on performance(9).

Similarly, it is our view that barefoot running, and its uptake by the running community and the running shoe industry, was in large part driven by the hype surrounding the book “Born to Run”(1), and that scientific evidence evaluating the claims that were given momentum by sometimes inaccurate media portrayal has come only later(10–16). That evidence, provided three to five years later, provides pause for consideration, and is as yet incomplete.

This thesis is our contribution to that body of scientific evidence. It is our endeavour at providing a balanced, evidence-based view of the potential benefits and risks associated with barefoot running, and a critical evaluation of theories that were proposed to support barefoot running in the immediate aftermath of Born to Run’s success(1,17–20).

At the time that this thesis began, the seminal paper in the field had just been published in *Nature* by Lieberman et al. (2010)(17). This study, described in more detail later in this thesis (Chapters 2, 3 and 4), explored differences in running biomechanics in habitually barefoot *versus* shod runners. It revealed that habitually barefoot runners often landed on the mid- or forefoot, whereas habitually shod runners were heel-strikers as a result of the cushioning provided by the running shoe(17).

Further, the collision forces, most notably the initial loading rate (the rate of force development of the foot at initial ground contact), were significantly lower in this habitually barefoot group who landed on the mid- or forefoot. This was attributed to more ankle plantarflexion allowing a more compliant ankle during impact, and possible protection against injury(17).

*ii.) Inappropriate dissemination and prescription of barefoot running*

Because of its timing and profile in *Nature*, this study became central in the barefoot debate, and was widely reported in the popular media. The populist translation of the science has not always been accurate, and Harvard University took the unusual step of creating a website that attempted to more fully control the discussion by explaining the science to interested runners(21). Nevertheless, despite the existence of previous scientific literature, it

was this study that provides much of the foundation for subsequent questions and controversy related to barefoot running(17,22,23). That controversy has two primary sources:

First, the link between initial loading rate and general running related injury is tenuous. Certainly, initial loading rate is one of many factors associated with running related injury, and we describe these factors in Chapter 2. It is clear that running related injury is multi-factorial and complex, and so any advocacy or dismissal based exclusively on initial loading rate is an oversimplification, which we wish to acknowledge.

Secondly, Lieberman et al. (2010) suggested that the majority of runners, who by nature are habitually shod, do not display the supposedly favourable kinematic adjustments to barefoot running, and as a consequence do not reduce initial loading rate, but rather increase it(17). Even taking into account the debate around initial loading rate and injury risk, it seemed to us that this argument, which had become central to the advocacy of barefoot running (by the media, not scientists, it must be noted), was worthy of further scrutiny. That individual variation in response, and the question as to whether a habitually shod runner would be able to acquire the supposedly favourable kinematics and kinetics (as per the findings of Lieberman et al. (2010)) was of particular interest(17).

Thus, in this thesis, we emphasise the complexity of running injury aetiology, but have chosen to focus our own results and detailed analyses on the initial loading rate because a) it was clearly of wider interest to the barefoot running debate as a result of the *Nature* paper published by Lieberman et al. (2010)(17), which created the context for the debate both outside and inside scientific circles, and we felt that interrogating it would be relevant and of value beyond pure research; and b) in the course of our research, this variable was consistently different between footwear conditions and with training, and we discovered numerous potentially intriguing associations between it and barefoot running.

We do not wish to position our research findings as an endorsement of the initial loading rate as a possible benefit or risk of injury associated with barefoot running. However, it

represents a starting point in our quest to identify the factors that may one day predict the success or failure of runners who make the transition to barefoot running.

This will, ultimately, only be possible with prospective, long-term studies. We have initiated such a study in this thesis (Chapter 4, 5 and 6), and attempted to introduce pure barefoot running in a group of trained runners in order to identify whether there are adaptations in a learned response, or whether biomechanics do not change with habituation.

In the future, such prospective studies will expand their focus, and may identify more accurately who responds positively and negatively to barefoot or minimalist running. However, even these studies will have to call upon data like that which we propose in this thesis to characterise the individual responses to barefoot running. That is, if prospective studies one day demonstrate that certain individuals succeed when barefoot while others fail, then a mechanism must be sought. It is our hope that the theories offered in this thesis, based on our studies of acute and training related differences and individual variation, will inform the quest for those mechanisms.

## 1.2 The structure of this thesis

This thesis comprises seven chapters and focuses on the popularly claimed benefits associated with barefoot running. It aims to address the purported biomechanical, neuromuscular and metabolic changes that may occur in the typical individual who would have interests in adopting barefoot running.

Chapter two is titled: “Barefoot running: an evaluation of current hypothesis, future research and clinical applications”, and has been published in a modified form in the *British Journal of Sports Medicine* (2014) 48(5):349-355. This chapter investigates the scientific literature and critically analyses whether the numerous benefits associated barefoot running are evidence based. More specifically it reveals that long-term prospective studies have yet to be conducted and that the link between barefoot running and injury or performance remains equivocal. It also addresses that barefoot running may not be as instinctive as some propose and may be a skill that is acquired.

Chapter three is titled “Loading rate increases during barefoot running in habitually shod runners: evidence for individual variability” and an edited version of this was one of three finalists for the *Nike Award for Footwear Research 2013* at the *11<sup>th</sup> Biennial Footwear Biomechanics Symposium in Natal, Brazil*. This manuscript examined a group of 51 trained habitually shod runners and their acute biomechanical and neuromuscular responses when running barefoot. We were able to describe the acute response in the barefoot condition on initial loading rate and relate changes in initial loading rate to kinematics that changed favourably in certain individuals only.

As the acquisition of advantageous barefoot running biomechanics is proposed as a skill, the following three chapters form part of a prospective study investigating the influence of an 8-week progressive barefoot running training programme on biomechanical, neuromuscular and metabolic factors during barefoot running.

Thus, Chapter four, titled “An 8-week progressive barefoot running training programme and its relationship to initial loading rate: a case of individual variability” presents the kinematic and kinetic results from our 8-week pure barefoot training intervention. We scrutinised the skill acquisition of barefoot running with regards to initial loading rate and kinematic changes of the ankle and knee joint. Here we were able to establish the individual responses to this training intervention and their relationships associated with the initial loading rate.

Subsequently, “The association of initial loading rate and lower limb pre-activation after an 8-week barefoot running training programme” (Chapter 5), explored the neuromuscular response to barefoot running training. In this chapter we identified variation in neuromuscular control strategies associated with initial loading rate both before and after the training intervention. This chapter also analysed differences in neuromuscular activity in the resultant groups of responders described in Chapter four.

The last of the experimental chapters, titled “Investigating the effect of 8-weeks of barefoot running training on oxygen cost of transport” (Chapter 6), explored the changes in oxygen cost of transport after the 8-week barefoot running training programme in a subset of male runners. The novelty of this study was that oxygen cost of running tests were performed on an indoor running track that allowed for overground running at a set-pace, providing an ecologically valid setting to measure oxygen cost of transport.

The final chapter of this thesis (Chapter 7) represents a synthesis of the studies and novel findings added to the body of literature on the performance and risk of injury associated with barefoot running. Further, we discuss practical advice and future directions in this ongoing challenge of prescribing evidence-based advice for barefoot running with the aid of improving athlete performance whilst avoiding running injury.



## CHAPTER 2

Review of the literature

### **BAREFOOT RUNNING:**

AN EVALUATION OF CURRENT HYPOTHESIS, FUTURE  
RESEARCH AND CLINICAL APPLICATIONS

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## 2.1 Abstract

Barefoot running has become a popular research topic, driven by the increasing prescription of barefoot running as a means of reducing injury risk. Proponents of barefoot running cite evolutionary theories that long-distance running ability was crucial for human survival, and proof of the benefits of natural running. Subsequently, runners have been advised to run barefoot as a treatment mode for injuries, strength and conditioning. The body of literature examining the mechanical, structural, clinical and performance implications of barefoot running is still in its infancy. Recent research has found significant differences associated with barefoot running relative to shod running, and these differences have been associated with factors that are thought to contribute to injury and performance. Crucially, long-term prospective studies have yet to be conducted and the link between barefoot running and injury or performance remains tenuous and speculative. The injury prevention potential of barefoot running is further complicated by the complexity of injury aetiology, with no single factor having been identified as causative for the most common running injuries. The aim of the present review was to critically evaluate the theory and evidence for barefoot running, drawing on both collected evidence as well as literature that have been used to argue in favour of barefoot running. We describe the factors driving the prescription of barefoot running, examine which of these factors may have merit, what the collected evidence suggests about the suitability of barefoot running for its purported uses and describe the necessary future research to confirm or refute the barefoot running hypotheses.

## 2.2 Introduction

Barefoot running has recently gained significant attention, both in scientific publications and in the lay media as a result of its alleged benefits for runners of all levels. These benefits include the potential for reduced injury risk, more economical running and broadly speaking, a better understanding of running biomechanics. The translation of scientific theories into popular lay publications such as “Born to Run”(1) has transformed barefoot running into a topic of interest not only to scientists and clinicians, but all runners.

Recently, Lieberman (2012) supported the theoretical basis for barefoot running, concluding that humans evolved adaptations to optimise barefoot running, and that the biomechanics of such a style would minimise impact peaks, increase proprioception and foot strength and thus help prevent injury regardless of the choice of footwear(24). There remains a lack of conclusive evidence proving or refuting the proposed advantages of barefoot running, however. Such evidence will require long-term longitudinal studies and further understanding of the biomechanics and implications of barefoot running. To date, the failure to conclusively explain the implications of barefoot running on injury risk and performance appear to be the result of four factors:

- i. The complexity of injury aetiology – injuries are rarely the result of a single risk factor, and the physiological and biomechanical changes associated with barefoot running can only ever address part of the complex array of causative factors for injury.
- ii. Large variability in mechanics between individuals, both with respects to shod running and in the barefoot condition.
- iii. Differences in study design and methodology, such as overground and treadmill running, minimalist, shod and barefoot conditions.
- iv. The volume of data acquired from biomechanical and neuromuscular analysis during running gait is often not analysed appropriately and lead to spurious conclusions.

The aim of this review is to evaluate the merits of the theoretical factors driving the current scientific interest in barefoot running. These theoretical factors include anthropological/evolutionary theories, biomechanical factors associated with injury and performance outcomes. Understanding the rationale for barefoot running's purported benefits is important, since it drives future research approaches and methods to confirm or refute those benefits. We aim to evaluate current research evidence on the effectiveness of barefoot running as a mean to reduce injury risk and improve performance, and suggest necessary future research to enable definitive and practical conclusions for clinicians, researchers and ultimately, runners.

### **2.3 Factors driving the promotion of barefoot running**

#### *i.) The evolutionary/anthropology explanation and the epidemiology of injury*

A recent series of articles have proposed that among the many distinctive characteristics of humans, the ability to run long distances may have been instrumental in the evolution of the present human form(5), and have led to the description of barefoot running as the most natural means of running(24).

An extension of this theory is the mismatch hypothesis, where humans are suggested to be maladapted to wearing shoes in ways that may influence injury development(24). Limited foot proprioception, altered running form and weak and inflexible feet are the primary maladaptions proposed to prevent the lower limbs from adapting to external forces and loads, controlling for excess movement and adjusting to ground surface types appropriately(25,26).

These claims and hypotheses remain unproven in the scientific literature. Lieberman also emphasises that "how one runs probably is more important than what is on one's feet, but what is on one's feet may affect how one runs" referring back to the unnatural environment that shoes provide the body(24).

With respects to the evolution of footwear, evidence exists that humans have worn footwear such as sandals or primitive moccasins for the last 50,000 years(27), and that humans gradually adapted to increased use of footwear(27,28). However, significant changes occurred as a result of the increased participation in running as a form of exercise for health. In the 1970s, the appeal of mass participation in endurance running was popularised as a means to prevent and manage chronic diseases of lifestyle(29), and ushered in the era of the modern running shoe.

Data gathered since has shown the prevalence of running related injuries to range between 50 and 79% per annum(3,4,25,30,31). The research response to injury has focused on the forces applied to the body and “abnormal” joint angle changes of the body, with the working hypothesis that excessive forces or extreme movements during the gait cycle expose the body to extreme stresses which significantly increase injury risk (26,32).

Perhaps the simplest example of this is the reported association between bone stress fractures and higher ground reaction forces(33). Subsequently, an emphasis to reduce ground reaction forces and joint motion were introduced through technologies such as an increased heel bevel, softer and thicker sole cushioning, and dual-density medial midsole support(32), with the expectation that these excessive kinetic and kinematic changes could be reduced below a safe stress limit to allow injury-free running.

However, the initial hypothesis that minimising impact forces and joint angle changes to reduce injury risk has since been revealed as oversimplified(34). Indeed, it has even been challenged as fundamentally flawed(32), with impact forces either being only part of, or completely unrelated to, the development of injury. Instead, it has been proposed that neuromuscular adjustments, made in response to impact forces, regulate the degree of soft tissue vibration and stress and the degree of cushioning on the foot is largely irrelevant (32).

Of interest is that the incidence of running related injuries has remained unchanged despite these modern running shoe interventions(9,11,12,13), with critical reviews stating that there is no scientific evidence supporting the prescription of a shoe with an elevated cushioned

heel and pronation control system(35). The concurrent evolution of modern shoes, the lack of evidence for shoe prescription, and the persistently elevated prevalence of running injuries has been proposed as evidence that shoe technologies are ineffective, and with a somewhat large leap in logic, that barefoot running would provide the effective and viable alternative. The apparent failure of modern shoe technology to impact the running injury rate may however be due to numerous confounding factors. Primary among them is that while numerous risk factors relating to training volume and intensity and injury history are known to exist, research has still not identified a single common mechanical variable that predicts a range of running-related injuries(25).

Another factor that must be borne in mind is that injury statistics must be interpreted in the context of running as a past time today, compared to running as a sport in the 1970s. For example, the New York Marathon saw 14,546 runners participate in 1983, compared to 31,791 runners in 1999 and >47,000 runners in 2011(36). Arguably, as participation grew exponentially, the biomechanical, anthropological and training characteristics of runners will have changed over time, with modern runners displaying a far greater heterogeneity, and possibly unfavourable characteristics. Since each characteristic can be implicated in injury aetiology (for example, higher body mass, less training history, and generally reduced athleticism), one hypothesis is that in the absence of modern shoe technology, the modern running group would present with even higher injury rates – these individuals may not, to borrow from a popular lay publication from above, be “Born to run”, and running shoes may in fact be reducing their injury risk compared to the shoes they would have run in many years before. Simply pointing to injury prevalence statistics and the co-incident development of shoes as evidence that modern shoes are ineffective is an inadequate oversimplified argument(35).

#### *ii.) The biomechanical justification*

The biomechanical justification for barefoot running centers on the concept that the differences between barefoot running are favourable and reduce the risk of injury.

Therefore, it is constructive to evaluate these differences, and asks whether literature exists to support the notion that the shod to barefoot change results in biomechanical differences that are injury-preventative. For example, Lieberman et al. (2010) have recently proposed that the most favourable difference between shod and barefoot running is the significant reduction in impact transient or loading rate in the barefoot condition(17). This is deemed significant because the magnitude of this impact transient has been correlated with the risk of tibial stress injuries(37).

This approach is complicated significantly by the aetiology of running injuries, and in some instances, conflicting evidence around the strength of the association between certain factors and injury risk. Therefore, our theoretical approach to evaluating the merits of barefoot running is by no means definitive or conclusive. However, it may provide a) practical and clinical application of research on barefoot running biomechanics for the management or prediction of injury, and b) highlight where future research can strengthen theoretical concepts for barefoot running.

***a) Practical and clinical application of barefoot running for the management or prediction of injury.***

The table below summarises the barefoot running research and its potential implications for injury risk. For each injury, we have summarised the biomechanical factors known to be associated with common running injuries, including bone stress fractures of the tibia and foot; patellofemoral pain; musculoskeletal injury and achilles tendinopathy(38–45). The biomechanical factors are not necessarily causal, but known to be present in runners with these injuries. We then summarise the changes associated with barefoot running, and suggest whether this change is beneficial or potentially detrimental. These concepts are discussed in detail subsequently (Table 2.1).

**Table 2.1.** Biomechanical and neuromuscular risk factors associated with major running related injuries and the possible theoretical and clinical implications barefoot running may have on them.

Variable/injury	Changes associated with injury in published literature	Changes associated with barefoot running (17,46)	Theoretical implication	Summary and potential clinical outcome (if known)
<i>Stress fractures of the tibia</i> (47,48)	Increased hip adduction	Unknown	Unknown	Potential to reduce risk of tibial stress fractures, but only if impact forces are lower, may depend on other factors. Clinical case series suggests increased risk early during adaptation
	Increased rearfoot eversion	Increased rearfoot eversion	Increased risk	
	Increased free moment	Unknown	Unknown	
	Increased impact peak	Decreased impact peak in some runners	Reduced risk	
	Increased ground reaction force	Decreased ground reaction force in some runners	Reduced risk	
<i>Stress fractures of the metatarsals</i> (39,49,50)	Increased peak pressure under metatarsal head	Increased peak pressure under metatarsal heads Decreased peak pressure heel, midfoot and hallux	Increased risk Unknown	Barefoot running may increase risk of metatarsal stress fractures as greater application of force for both initial contact and propulsion is experienced
	Earlier peak rearfoot eversion	Unknown	Unknown	
	Increased forefoot loading	Increased forefoot loading	Increased risk	
<i>Patello-femoral pain</i> (38,51–53)	Increased impact peak	Decreased impact peak	Decreased risk	Barefoot running may reduce forces experienced by the knee.
	Increased eccentric load on knee	Unknown for BF but conscious forefoot strike may decrease eccentric load	Decreased risk	
	Poor gluteal strength	Unknown	Unknown	
	Hamstring inflexibility	Unknown	Unknown	
<i>Achilles tendinopathy</i> (55–57)	Increased rearfoot eversion	Increased rearfoot eversion	Increased risk	Barefoot running may result is greater eccentric loading on the ankle. Chronic high velocity eccentric loading during running may increase the risk of injury. However, eccentric loading maybe be beneficial in relieving Achilles tendionpathy if controlled(54)
	Increased ankle dorsiflexion at impact	Increased ankle plantarflexion at impact	Decreased risk	
	Decrease leg abduction	Unknown	Unknown	
	Decreased knee range of motion	Decreased knee flexion at ground contact	Increased risk	
	Decreased <i>tibialis anterior</i> , <i>gluteus medius</i> and <i>rectus femoris</i> activity	Increased <i>gastrocnemius</i> activity	Unknown	
	Early pronation	Unknown	Unknown	
<i>Plantar fasciitis</i> (58)	Increased vertical ground reaction force	Decreased ground reaction force in some runners, significantly increased in others	Risk dependent on individual response to BF running	Barefoot running may aid in attenuating the associated risk factors. However, these beneficial changes may be acquired only after habituation to BF running in some individuals
	Increased loading rates	Decrease loading rates in some runners, increased in others	Beneficial	
	Lower medial longitudinal arch	Raised medial longitudinal arch	Decreased risk	
	Increased foot pronation	Unknown	-	
	Decreased ankle dorsiflexion range of motion at impact	Decreased ankle dorsiflexion range of motion at impact	Increased risk	

i.) *Footstrike*

There has been something of a pre-occupation with the footstrike as a marker for clinical risk with barefoot running, presumably since it is relatively easily measured. The fundamental premise is that a forefoot strike, associated with flatter foot placement at touchdown(23,59), greater plantar flexion, and greater knee flexion angle on impact, distribute the impact force across a greater surface area than the heel alone, thus cushioning the impact. Further, it has been proposed that the plantar fascia is used to create a support system for the arch of the foot and acts as a shock absorber and facilitate elastic restitution during running(23,60), and the shift to a more anterior footstrike changes the distribution of eccentric forces across the joints, with an increase in ankle eccentric work and concomitant decrease in loading on the knee joint(61).

Complicating the discussion, however, is disagreement in findings relating footstrike to running speed. Hasegawa et al. (2004) and Hayes and Kaplan (2012) found that forefoot striking is more prevalent among faster runners, whereas Larson et al. (2011) found no difference in footstrike amongst recreational runners with varying performance abilities(62–64). Further, discrepancies may have also been a result of both sample population (recreational *versus* competitive) and size. The strict characterisation of barefoot runners as forefoot strikers and shod runners as heel-strikers is an oversimplification, and possibly incorrect (63,64). Indeed, a recent study by Hatala and colleagues showed that heel-striking was relatively common among a habitually barefoot population, with 72% landing on their heels at their preferred running speed(65). Although, as running speed increased, footstrike shifted towards the forefoot, but a significant percentage (40%) remain heel-strikers. Thus, the suggestion that barefoot running is synonymous with forefoot striking is thus inaccurate and may obscure the real kinematic differences and their effects on injury risk(65). Interestingly, landing surfaces have been shown to influence the footstrike pattern in runners similarly to the different shoe conditions (and the absence of shoes). Thus, these

surface differences may explain discrepancies and unusual findings in different studies and should be noted in future studies involving running(66).

Nevertheless, numerous studies have associated footstrike with injury risk. Most recently Daoud et al. (2012) found that runners who habitually rearfoot strike incur a higher injury rate of repetitive stress injuries when compared to runners who mostly forefoot strike(19). The authors propose that the absence of the impact peak in the ground reaction force during a forefoot strike compared with a rearfoot strike may contribute to lower rates of injury. If this hypothesis is correct, there may be many implications for the running community. However, it must be noted that this study did not account for performance ability, and the small sample size of 52 runners were divided into 36 rearfoot strikers and 16 forefoot strikers in each group, suggests that further research is required, with larger populations, equally distributed strike types, the same type of runners and over a longer period. Alongside this to categorise footstrike patterns in three clusters may be somewhat reductionist when footstriking has been shown to exist as a spectrum(67).

The argument for barefoot running based on this research must however be understood in the light of research from Lieberman et al. (2010), which found that some habitually shod individuals who run barefoot experience greater impact peaks and rates of loading than habitually barefoot runners(17). This is presumably because they do not adjust their footstrike and continue to land on the heel, exposing them to loading rates seven-fold greater than when in shoes(17). Thus, barefoot running is not by itself sufficient to produce this purported reduction in injury risk, and the transition, which is the logical clinical implication of the advice given to runners, may increase risk, albeit transiently.

*ii.) Lower limb and foot*

Evidence from habitually shod runners indicate that barefoot running may increase the risk of stress fractures of the lower limb and foot(44). Salzler et al. (2012) presented a case-series of 10 runners who experienced stress fractures primarily on the 2<sup>nd</sup> and 3<sup>rd</sup>

metatarsal when transitioning to barefoot running. Also, a case of a calcaneal stress fracture was presented(44). This latter injury is typically the result of direct loads through the heel, and may further indicate that not all runners instinctively adopt a forefoot striking pattern on initial exposure to barefoot running, as discussed previously(44). Those who do adopt a forefoot landing may be susceptible to increased risk of stress fractures of the metatarsals, based on the increased forefoot loading and documented cases of such injuries occurring(68).

*iii.) Ankle and Foot*

Arendse et al. (2004) found that when runners consciously adopted the POSE technique (a forefoot landing pattern with the absence of a heelstrike) while still wearing shoes, there was a decrease in net moments around the knee but an increased net moment around the ankle(61). These findings were suggested to have positive implications for knee injury, since previous research has attributed knee injuries to high eccentric workloads on the joint. This theory, extended to the ankle, however, would predict an increased risk of ankle and calf muscle or Achilles tendon injury, and this has indeed been documented as a potential risk factor by Salzler et al. (2012)(44). However, whether the POSE technique is indeed typical of barefoot running remains questionable.

It may also be suggested that barefoot running would be most beneficial to runners suffering or recovering from plantar fasciitis. Previous research has associated this injury with increased forces, loading rates and decreased range of motion (58), all factors that barefoot running is known to alter favourably in those individuals who adopt a favourable landing pattern (Table 2.1). Once again, the research of Lieberman et al. (2010) suggests that some runners may actually experienced increased forces and loading rates(17). At this early stage, this has only been associated with footstrike, but future research will need to investigate why some runners experience significantly higher forces (seven-fold higher, as per Lieberman et al. (2010)) when running barefoot, particularly initially.

With respects to Achilles tendinopathy, research has linked ground contact sole angle, greater plantar- and dorsiflexion torque, and earlier and increased foot pronation as causative factors(56). Additionally, Azevedo et al. (2008) found lower knee range of motion at contact to mid-stance and lower calf muscle activity in achilles tendinopathy patients, though this may be the result of, rather than the cause of the injury(55). Given this evidence, in particular the greater plantarflexion torque, it may be that barefoot running, with increased plantar-flexion on impact and eccentric work on the ankle, may further increase the risk of Achilles tendinopathies. Alternatively, it may be argued that the ankle joint changes associated with habitual barefoot running may alter factors such as foot pronation, thus reducing the injury risk. This is an illustrative case of how oversimplified the barefoot-injury relationship is.

The ability for the neuromuscular system to coordinate the lower limbs appropriately when barefoot running has yet to be fully explored. Some evidence has shown that the calf muscle group activity is greater in the barefoot condition(23), and this may be indicative of increased strain on the calf muscle and resultant increased risk of achilles tendinopathy or a stimulus for the body to adapt. Alternatively, the increased muscle activity may be beneficial, as it may dampen and control the forces applied to the joints and research has shown that triggering the calf with an eccentric load may be a treatment modus for Achilles tendinopathy(57).

#### *iv.) Knee*

It has been found that a forefoot striking running technique (POSE technique) is associated with reduced eccentric loading of the knee and preparatory knee flexion prior to landing(61). This is suggested to be of potential benefit to athletes with patello-femoral pain, since previous research had linked eccentric work on the knee to this injury(52). However, patello-femoral pain has also been associated with weak gluteal strength and hamstring flexibility(38,51,52), and so the interaction of these factors, with barefoot running make any suggestion regarding its benefits tenuous.

Another factor, not limited to the knee, but also the ankle and hip, is that many researchers have reported a reduction stride length and an increase in step frequency during barefoot running. These are biomechanical 'outcome' variables of joint mechanics, but may also affect the loading rate and magnitude of loading on all joints. To date, most studies have correlated these changes to performance rather than injury(69–71), but it must be acknowledged that this change, while not specific to a joint, may be an important factor in understanding injury in terms of a loading rate model or explanation.

In conclusion, the complexity of running injuries, which have a multi-factorial aetiology, and the highly variable response of many kinetic and kinematic factors associated with barefoot running, make definitive statements about potential benefits impossible. Only with longitudinal intervention studies will evidence emerge regarding the risk of injury when running barefoot, while mechanisms may require significantly more research to elucidate.

***b) Future research that may improve practical barefoot running recommendations***

*i.) The skill acquisition of barefoot running*

An as yet unexplored area of barefoot running theory is the process by which biomechanical adaptations occur, and whether these are universally learned. This is crucial both clinically and practically, because some individuals may be incapable of achieving the potentially favourable biomechanical changes. These individuals may be exposed to increased risk of injury according to the previously described factors, particularly early on, and fully understanding the process by which the barefoot condition changes biomechanics is crucial to the clinical and performance management of an athlete.

Research has demonstrated immediate adjustments in factors such as ankle and knee angle on impact, and resultant changes in footstrike, but that these changes do not occur equally for all runners. Lieberman et al. (2010) found that when habitually shod runners ran barefoot, 83% continued to heelstrike, at least during the laboratory testing period(17). In this condition (barefoot and heel-striking), the impact force was 8.6% greater than shod,

while the rate of loading was approximately 700% greater. Thus, the acute response of a majority of runners to barefoot running exposes them to impact forces and loading rates that are significantly higher than when shod. As we described previously, these runners may face substantially more risk when barefoot, and confirms previous research which found that habitually shod runners exhibit higher loading rates when barefoot than in the shod condition(17,22,23).

Several important questions are raised as a result of these findings. First, the widely popularised theory that shod runners heelstrike whilst barefoot runners shift to a forefoot landing is a generalisation and oversimplification, since 50% of runners participating in a 6-week minimalist running shoe intervention remained heel-strikers(17). A more recent study found that even in habitually barefoot individuals, 72% were heel-strikers at comfortable running speeds, and the simple allocation of barefoot runners to the forefoot striking group is clearly false(65). Studies do show a significant change in ankle angle on impact, but this is often not sufficient to change footstrike pattern, and as mentioned, may expose those runners to increased impact forces and loading rates.

Secondly, the findings of Lieberman et al. (2010) compel the question of whether biomechanical changes in the barefoot condition are learned responses, and thus whether all runners can achieve these adjustments equally(17). Since habitually barefoot runners present with markedly different kinematic and kinetic characteristics than novice barefoot runners, it is reasonable to propose that a substantial learning component exists. Lieberman et al. (2010) found, for example, that six weeks of training with minimalist shoes designed to simulate barefoot running resulted in changes in the simple outcome variable of footstrike pattern. Approximately half of the initial heel-strikers had shifted to a forefoot landing pattern after six weeks of minimalist shoe training, despite no conscious instruction or feedback(17).

What is intriguing is whether the other half, who were heel-strikers on first exposure to barefoot running and after six weeks of training, would remain as such or whether they too

would slowly achieve the biomechanical changes that would ultimately characterise them as forefoot strikers. These researchers did not present kinetic data on these individuals, and measured footstrike patterns only at 0 and 6 weeks, thus the temporal changes of other biomechanical variables are not known.

Some studies have investigated minimalist interventions over both 4- and 12-week periods (72,73). Both studies found greater plantar- and knee flexion, alongside an observed forefoot striking pattern as a result of barefoot training. However, Warne & Warrington (2013) provided conscious instruction with regard to gait modification, lower limb strength and flexibility exercises. McCarthy et al. (2014) state that no instruction was provided, but for safety reasons advised their participants to avoid heelstriking. Thus, the only training interventions of which we are aware have both, to varying degrees, provided instruction to runners, and found that runners are capable of adapting to the forefoot striking pattern with conscious effort. What is perhaps more important is whether these individuals would all achieve the supposedly favourable changes in kinematics and reductions in impact force and initial loading rate without instruction, since this is more realistic for the typical runner.

Given this question, it seems premature to advocate that barefoot running or the associated biomechanics of barefoot running are desirable, because certain individuals may be incapable of achieving the adjustments and thus may be at increased risk of injury. It may be that individuals who fail to adjust their running biomechanics favourably do not persist with barefoot running. In contrast, runners who succeed barefoot, without injury or discomfort, may be those runners who are able to quickly make favourable changes to their running mechanics. Thus, the ability to run barefoot with proposed favourable reductions in impact force and loading rate may determine the longer term clinical outcome. However, the changes in biomechanical variables occurring over time have not been studied.

It would seem likely that habitually shod runners transitioning to barefoot running would achieve progressive changes in kinematics such as increased plantarflexion and knee flexion angle, and resultant reductions in impact force and loading rate. Accordingly,

barefoot running may not be immediately effective, but rather is learned as a skill, with favourable running mechanics the result of achieving a certain skill level.

This skill acquisition must reflect altered neuromuscular activation patterns at various stages during the gait cycle, including altered activation of the calf muscle group to facilitate plantarflexion prior to impact, as well as of the quadriceps to allow for observed differences in knee flexion during the impact phase(23,74). Supporting this, studies have found that the muscle activity in the calves when running barefoot was significantly higher than when shod (23,75). It was proposed that the higher pre-activation of the lower limb muscles when running barefoot with shorter strides and higher stride frequency may lead to a reduction in impact peak and subsequent reduction of the mechanical stress during running(23). The rate at which the muscle-tendon structures and neuromuscular control of the lower limb can be learned over time may determine successful transition to barefoot running.

Research is required to differentiate between these theories, and more importantly, to discover whether this “skill” can be learned equally by all runners. This is important for the practical application and proponents of barefoot running, because the initial exposure to barefoot running may increase the risk of injury by virtue of the higher impact forces and loading rates(22,26). Thus, prescribing barefoot running as a clinical treatment modus is premature, however, it appears changing ones footstrike when injured or recovering from injury may assist in alleviating or preventing further specific classes of injury(76).

*ii.) Fatigue (as an indicator of adaptation)*

An under-researched but likely crucial factor for barefoot running is the effect of fatigue on running mechanics, muscle function and joint integrity. Running consists of repetitive muscle contractions which unavoidably subjects the body to various levels of muscular fatigue (inability to maintain a given level of force production)(77,78). It has been proposed that muscle is essential for dissipating large dynamic loads experienced in the lower extremity during movement(79). This is primarily achieved through the stretch-shortening

cycle and possible muscle tuning. Interestingly, Nigg and colleagues have proposed that muscle tuning may have the capacity to dampen impact peaks during running(32). This hypothesis may have bearing on fatigue (adaptation) as the inability for the muscle tune appropriately may result in reduced dampening of impact forces, with a resultant increase in force transmission elsewhere(80). However, as fatigue develops over the duration of exercise, the protective neuromuscular mechanism of the muscle diminishes(79).

Exercising in a fatigued state increases stress, strain and impact forces, particularly on the lower extremity(81). Although these loads in isolation may not be above the physiological threshold for injury, it has been hypothesised that they accumulate and lead to various overuse injuries (31,82). For example, Mizrahi et al. (2000) have shown that fatigue influences the lower extremity limb mechanics during running, with altered contraction of the muscle on the shank (an increase in *gastrocnemius* and decrease in *tibialis anterior* activity), imbalances in the transfer of mechanical energy between eccentric and concentric muscle contractions and slower muscle reaction time(33,83).

Further, after localised muscle fatigue has been induced, there are significant altered patterns of ground reaction forces and reduced ankle joint dorsiflexion during running(78). It was concluded that localised muscle fatigue may influence many common lower extremity running injuries.

All of these factors affect the resilience of the neuromuscular system to consistently dampen these large forces. Thus, as fatigue develops, the ability to maintain the desired angular displacements during the stance phase may be compromised and subsequent injury may occur(84,85). Larson et al. (2011) described footstrike patterns of runners at the 10km and 32km mark of a marathon, and found a 5.2% increase in rearfoot striking as the race progressed(64). These changes provide broad insight on the influence of fatigue on the ability of the body to execute the most preferred gait.

Given the previously described changes in neuromuscular activation, as well as the changes in joint loading that occur with barefoot running, it seems reasonable to assume that fatigue is a crucial factor that may significantly compromise the body's ability to adapt to the mechanical and muscular changes occurring during barefoot running(86). Barefoot running introduces potentially unfamiliar stress on muscle and joints and fatigue may exacerbate the potential risk associated with these stresses(60). Fully understanding the risks and benefits of barefoot running, particularly during the early phases of adaptation, requires that the potential effects of fatigue are acknowledged. To date, research has been mostly limited to laboratory studies of non-fatigued runners, which reduce the external validity of these findings, since fatigue is a crucial and almost ubiquitous component of running.

*iii.) Performance (indicated by metabolic and whole-body physiological changes)*

Currently the most researched performance-related variable for barefoot running is its effect on oxygen cost of running. Studies have found that barefoot running is associated with an improved oxygen cost of running, though this is widely accepted to be the result of a decrease in mass (absent shoes). Alternatively, it is suggested to be due to the effect of elastic compliance from the foot and the influence of shoe construction on gait(87,88).

Because of the mass effect, it is important that studies control for the absence of shoes on economy. Failing this, findings such as that of Hanson et al. (2011), who found improved oxygen cost of transport in the barefoot compared to shod condition, are not surprising(87). Divert et al. (2008) questioned this difference as the result of shoe construction (wearing shoes alters the gait) or the additional mass of the shoe. When mass was corrected using thin diving socks, they continued to find that oxygen cost of running was improved when barefoot. It was concluded that the metabolic component was a result of the mass and the net efficiency was due to mechanical alterations in the lower limbs(88).

In contrast, Perl et al. (2012) recently found that runners were more economical in minimalist shoes than in traditional cushioned shoes when controlling for shoe mass, stride frequency and strike patterns(20). They did not assess a barefoot condition, however, Franz et al. (2012) disputed this finding, finding that being barefoot was not more economical than running in lightweight cushioned shoes. No study has compared the minimalist shoe of Perl et al. (2012) to pure barefoot, lightweight and traditional cushioned shoes, making direct comparison impossible. Currently, the theory is that the difference may be due to the greater elastic energy storage and release as a result of stiffer minimalist shoes, and that no metabolic advantage exists for running barefoot compared to lightweight cushioned shoes when controlling for footstrike pattern and mass(89).

Although adding mass to the foot predictably worsens the oxygen cost of transport, a lightweight (<150g) but cushioned shoe maybe more economical than barefoot running. This implies that shoe cushioning may influence oxygen cost of transport to a point where shoe mass would prevail over the cushioning effect.

Franz et al. (2012) hypothesised that the barefoot oxygen cost of transport would improve with practice/training(89). Consequently, Warne and Warrington (2013) also studied changes in oxygen cost of transport over the 4-week minimalist running training intervention. They found an 8.1% improvement in oxygen cost of transport from pre- to post-test in the minimalist condition and a 6.9% improvement when compared to the shod condition(90). However, possible biomechanical or neuromuscular changes responsible for these significant changes were not fully explored. Hence investigating the change in oxygen cost of transport in response to barefoot training would provide a novel explanation of possible physiological conditioning of the muscles and increased efficiency in the elastic storage capacity of the lower limbs during running.

*iv.) Clinical studies of injury rehabilitation through barefoot running*

Finally, given the potential link between mechanics and risk factors for injury, and the documented changes occurring for various joints during barefoot running (Table 2.1), it is intriguing to consider whether barefoot running may be prescribed as a treatment modality for certain individuals. For instance, Diebal et al. (2012) found that using a forefoot strike intervention resolved symptoms of anterior compartment syndrome in 10 patients(76). This study suggests that biomechanical changes, achieved consciously in the form of instruction, can be used to treat common running injuries. Barefoot running, which may induce similar changes without the need for instruction and potentially supervision, offers the same potential, though is an area that warrants further research, and which may be prefaced by the recognition or better understanding of barefoot running as a skill, as described previously.

## **2.4 Conclusion**

We have described the rationale, the biomechanical justification, and two of the crucial unknown aspects of barefoot running. It is clear little is known about barefoot running and injury and performance. The current promotion of barefoot running is based on oversimplified, poorly understood, equivocal and in some cases, absent research, but remains a trend in popular media based solely on an evolutionary/epidemiological hypothesis and anecdotal evidence. Here, we have described that while the evolutionary hypothesis may be credible, it assumes a great deal and cannot by itself be the justification for barefoot running. In terms of biomechanics, it is clear from current evidence that barefoot running influences the body acutely, and likely has a significant impact on kinetic and kinematic factors associated with injury. However, no causal relationships, and the high variability and complexity of both injury and barefoot running make this justification tenuous.

Finally, we suggest that barefoot running may be a skill that is not instinctively acquired, but that requires substantial practice in order for the body to adapt. Even then, it is unclear how this adaptation may occur, and whether every runner can achieve it. The process of adaptation needs to be clearly understood before training and clinical advice is disseminated to athletes.

In conclusion, there remain more questions than answers at present. This thesis aims to address some of these questions. The specific research questions examined in each study are described in more detail subsequently.

## 2.5 Research questions

**Question 1:** *Do all runners reduce initial loading rate and change joint kinematics when first exposed to barefoot running?*

It is known that kinematic and kinetic differences exist between shod and barefoot running(23,60,89). We aimed to explore this further, by exposing trained runners to barefoot running and attempting to identify whether all display the typical changes during overground running. We hypothesised, in accordance with previous research, that the loading rate when barefoot would increase as a general finding, but that certain runners would present with a reduction in loading rate and associated changes in joint kinematics.

**Question 2:** *Can acute biomechanical measures identify potential favourable responders to barefoot or minimalist running, according to a collision force theory of injury prevention?*

A significant driver of barefoot running is the research which showed reduced collision forces in habitually barefoot runners(17). While the link between these collision forces and injury risk is tenuous, it remains an often-investigated variable in the barefoot running literature(17,60,91–93). If any association exists between loading rate and injury risk, then runners transitioning to barefoot or minimalist running would benefit from recognising which factors may produce an increase in loading rate. Therefore, we aim to determine whether runners who increase loading rate on first exposure to barefoot running can be characterised as kinematically different from those who achieve acute decreases in loading rate.

**Question 3:** *Do all runners transitioning to barefoot running reduce initial loading rate as a result of a progressive 8-week pure barefoot running programme?*

It is known that habitually barefoot runners exhibit lower initial loading rates when compared to habitually shod runners(17). We aimed to observe whether runners were able to instinctively reduce their initial loading rate as a result of a progressive increase in barefoot running volume. We studied runners during overground running, without providing

conscious instruction as has been done before. We hypothesised that not all runners would reduce their initial loading rate at the conclusion of the 8-week training period.

**Question 4:** *Which factors may be associated with the observed changes in loading rate after completion of an 8-week pure barefoot training programme?*

It is known that overall leg compliance at initial ground contact is significantly associated with the initial loading rate, but other factors may contribute(17). We aimed to describe lower limb kinetic and kinematic associations before and after the 8-week training intervention. We hypothesised that learned neuromuscular pre-activation strategies are associated with a reduced initial loading rate.

**Question 5:** *Does the oxygen cost of transport differ between barefoot and shod conditions during overground running, and does this change as pure barefoot running volume increase?*

A highly debated question, current literature suggests that differences between barefoot and shod condition may exist as a combination of mass or an intrinsic physiological-biomechanical effect(20,69,88–90,94). In order, to isolate the influence of the barefoot condition, we aim to assess the differences in oxygen cost of transport before and after the 8-week training intervention in both barefoot and shod conditions. We hypothesise that changes in oxygen cost of transport due to barefoot training would be found in the barefoot but not shod condition.



## **CHAPTER 3**

**LOADING RATE INCREASES DURING BAREFOOT  
RUNNING IN HABITUALLY SHOD RUNNERS:  
EVIDENCE FOR INDIVIDUAL VARIABILITY**

### 3.1 **Abstract:**

**Aim:** The purpose of this study was to examine the effect of barefoot running on initial loading rate, lower extremity joint kinematics and kinetics, and neuromuscular control in habitually shod runners with an emphasis on the individual response to this unfamiliar condition.

**Methods:** Kinematics and ground reaction force data were collected from 51 trained habitually shod runners during overground running trials in a barefoot and shod condition. Joint kinetics and stiffness were calculated with Newton-Euler inverse dynamics. Inter-individual initial loading rate variability was explored by separating groups into high and low loaders and calculating a barefoot/shod ratio to determine acute responders/non-responders. All data were compared using paired t-tests and relationships analysed using Pearson correlations.

**Results:** Mean initial loading rate was 84.9% greater in the barefoot when compared to the shod condition (168.4 vs. 91.1 BW·s<sup>-1</sup> BF vs. SHOD, respectively, p<0.001). Differences between high- and low-initial loading groups and acute responders/non-responders were found at peak sagittal ankle angle and ankle angle at initial ground contact (p<0.01). Correlations were found between barefoot sagittal ankle angle at initial ground contact and the barefoot/shod ratio (p<0.001) and barefoot initial loading rate (p<0.001).

**Conclusions:** A high variability in biomechanical responses to barefoot running was found. A majority of habitually shod runners do not exhibit previously reported benefits in terms of reduced impact loading rates when barefoot. Cushioned shoes were found to reduce loading rate in runners who increased loading rate when barefoot. The reduction returned loading rates, to those previously noted in habitually barefoot runners who adopt a forefoot-landing pattern, despite increased dorsiflexion when shod.

**Key words:** Shoes, kinetics, kinematics, electromyography, injury.

### **3.2 Introduction:**

Barefoot and minimalist running is promoted as a natural form of running and a means to reduce the incidence of running related injury(17,24). This is particularly true in the lay media and to the public, despite research that is only in its infancy, as described in Chapter 1 of the present thesis. Whether barefoot or minimalist running is accepted and implemented as an effective method of reducing injury risk and improving performance will be strongly influenced by the strength of evidence from research studies that either support or refute performance and injury claims. Currently, behaviour is driven largely by anecdotal evidence and testimonies of influential coaches and runners, and has been sufficient to drive the emergence of a barefoot running industry.

A conclusive study, particularly a long-term prospective injury study, is yet to appear. However, given the complexity of injury aetiology(95) combined with the as yet poorly understood individual variability in response to barefoot running(17), it may be unrealistic to expect such a study to be definitive. Instead, it is important to better understand the individual responses in the acute biomechanical changes occurring between shod and barefoot running, so that prospective study findings can be better explained as a function of predicting which runners might respond positively or negatively to the various footwear conditions.

Previous research has focused on factors known or hypothesised to be associated with running injuries(11,22,95,96), assessing differences between shod and barefoot running that may predict injury risk. Early barefoot running research focused on one such factor, initial loading rate (gradient of the vertical force experienced between initial ground contact and the first impact peak). This variable, previously associated with some typical running injuries(37), was found to be significantly reduced in habitual barefoot runners who land on their forefoot rather than their heel(17,23). As such, it became central to the advocacy of barefoot running, implying causation between initial loading rate and injury, with barefoot running proposed as a means to reduce this purported injurious factor.

It must be emphasised that this single-factor focus is an oversimplification in the biomechanical approach to barefoot running, given that numerous predictors have been identified(95), and because the specific role of impact forces has been questioned, with some research suggesting no association with injury risk(32,97). As we explain in Chapter 1 and Chapter 2, the research of Lieberman et al. (2010) has become central to the barefoot running debate, and so notwithstanding the recognised simplification and tenuous link between impact forces and injury. A closer examination of kinematic and kinetic factors, with a focus on loading rate, is justified.

This is particularly significant because the purported benefit – reduced loading rate – does not exist for all runners when barefoot, though this was not overtly acknowledged in that study(17). That is, the proposed favourable reduction in loading rate when barefoot was present only in those runners who assumed a forefoot landing(17), and who may thus be considered ‘responders’ to barefoot running. In contrast, runners who continue to heelstrike (56% of the group, who may be considered ‘non-responders’), experienced loading rates 3-7 fold greater than when shod(17,60). In support of this, Willy & Davis (2014)[91].recently found higher loading rates in minimalist shoes than traditional running shoes, and numerous other studies have linked heelstriking to injury risk as a result of higher loading rate(42,58,91,96,98).

The implication of these findings is important for potential adoption of barefoot or minimalist running, because they suggest the need for individualised recommendations to runners. However, such recommendations cannot be comprehensive until the variability in biomechanical response to barefoot running is better understood. This will remain true even after long-term prospective studies to examine injury risk have been conducted, since any differences in injury outcomes in those studies may be explained by individual differences in neuromuscular, kinematic and kinetic variables, which currently are not understood.

Accordingly, the aim of the first study of this thesis was to examine the immediate effects of barefoot running on initial loading rates, lower extremity joint kinematics and kinetics, and

neuromuscular control in habitually shod runners. We also investigated the biomechanical and neuromuscular differences between those runners whose initial loading rate increased or decreased when barefoot compared to shod. We hypothesised that runners who continued to land on the heel (with ankle dorsiflexion) in the barefoot condition (“non-responders”) would present with significantly greater loading rates, and aimed to identify neuromuscular, kinematic and kinetic changes that were associated with this increase.

Further, it was hypothesised that running shoes would reduce loading rates in this “non-responder” group, irrespective of foot-strike, indicating that with respects to kinetic factors, the cushioning provided by the modern running shoe has a greater benefit for some runners than others, though we acknowledge the simplification of isolating impact loading rate as a predictive variable. Lastly, we aim to explore secondary changes in loading patterns at the lower extremity joints that would provide detailed joint-specific information as to the propagation of the increased loading rate into the mechanical environment of each joint.

### **3.3 Materials and Methods**

#### **3.3.1. Participants**

Fifty-one habitually shod runners volunteered to participate in this study. Participants were able to run 10km in <55 minutes and were injury free for six months prior to the study. Participants provided written informed consent and were fully aware of the benefits and potential risks associated with the study and were free to voluntarily withdraw at any stage. The study was performed in accordance with the principles of the Declaration of Helsinki (Seoul, 2008) and ethical approval was granted by the Human Research Ethics Committee of the University of Cape Town (HREC REF: 504/2011).

#### **3.3.2. Experimental conditions:**

Biomechanical testing was conducted under two different conditions. (1) Barefoot and (2) in the running shoe in which they were currently completing the most training mileage (herein called shod). All shod midsoles comprised of traditional ethylene-vinyl acetate (EVA) and were not controlled for mileage, shore count or heel-toe drop.

#### **3.3.3. Instrumentation:**

Running trials were conducted on a 40 m indoor synthetic running track. Three-dimensional marker trajectories were captured using an 8-camera VICON MX motion analysis system (Oxford Metrics Ltd, Oxford, UK), sampling at 250 Hz. Ground reaction force data were collected using two 900 x 600 mm force platforms (AMTI, Watertown, MA, USA), sampling at 2000 Hz. Reflective markers were attached bilaterally on the base of the second metatarsal head, the posterior calcaneus, the lateral malleolus, on the distal third of the shank, lateral aspect of the flexion-extension axis of the knee, the lateral distal third of the femur, the posterior superior iliac spine and anterior superior iliac spine. The capture volume had a length of 9 m, allowing adequate distance for the absence of acceleration and deceleration. Electromyography (EMG) was measured for all conditions in four right lower limb muscles, namely *vastus lateralis* (VLO), *biceps femoris* (BF), *tibialis anterior* (TA) and

*gastrocnemius lateralis* (LG). Prior to placement, the skin areas where the electrodes were placed were shaved and vigorously cleaned with ethanol swabs(99). Two circular surface electrodes (Blue Sensor, Ambu, Medicotest, Denmark) were placed on the muscle according to SENIAM guidelines(100). Data were sampled at 2000 Hz (Noraxon 2400T G2, Noraxon, Arizona, USA). The leads and pre-amplifiers connected to the electrodes were secured with medical grade tape to avoid artefacts from lower limb movement during running. The transmitter unit was secured in a harness strapped to the participant's back.

#### **3.3.4. Procedures:**

Participants completed 6 clean overground running trials in each condition (barefoot, shod). This was performed in a randomised order. The speed of overground running trials was set based on the participant's current 10-km performance pace, since we wished to evaluate running biomechanics at a comfortable self-selected speed, and avoid forcing unrealistic speeds on participants. Trials were accepted if the velocity was within  $\pm 5\%$  of the target speed. During these runs, synchronised collection of marker motion, force platform and EMG measurements were obtained with VICON Nexus (VICON, Oxford Metrics, Oxford, UK). A successful trial was defined as one within the specified velocity range, where all markers were in view of the cameras and there was no visual evidence of force platform targeting.

Marker trajectory and force platform data were filtered using a low-pass fourth-order Butterworth filter with a cut-off frequency at 8 and 60 Hz respectively. For each trial, one complete gait cycle was analysed. The lower body PlugInGait model (VICON, Oxford Metrics, Oxford, UK) was used to calculate three-dimensional lower extremity joint angles and net resultant joint moments using a Newton-Euler inverse dynamics approach as developed by Davis et al. (1991)(101). Specifically, segmental mass, mass centre location and mass moment of inertia are approximated based on the relationships of Dempster et al. (1959)(102) Joint angles and moments were described using the joint coordinate system(103). Three-dimensional joint moments were expressed as external moments

normalised to body mass ( $\text{Nm}\cdot\text{kg}^{-1}$ ).

### **3.3.5. Data analysis:**

Joint angles and moments were extracted for statistical analysis using a customised MATLAB (Mathworks Inc., Natick, USA) program. The data for each participant's right limb were averaged over the 6 trials for each condition, normalised to stance phase. Stance phase was defined as the time over which a vertical force exceeded 1 standard deviation (SD) above baseline force platform noise and continued to elevate. Sagittal, frontal and transverse plane ankle, hip and knee angles (degrees) and moments ( $\text{Nm}\cdot\text{kg}^{-1}$ ) are presented. Specifically, discrete variables at initial ground contact, maxima during stance and at toe-off were extracted. Further, peak vertical, anterior-posterior and medio-lateral ground reaction forces (vGRF, apGRF and mlGRF in body weight (BW) units respectively) and initial vertical loading rate ( $\text{BW}\cdot\text{s}^{-1}$ ) were quantified between 200N and 90% of the first impact peak of the vGRF(17,104). When no distinct first impact peak was present, the same parameters were measured using the average percentage of stance  $\pm 1$  SD as determined for each condition in trials with an impact transient(17). Sagittal plane joint stiffness for the ankle joint was calculated as the angular distance from initial touchdown to the maximum dorsiflexion angle during stance, as was the magnitude of the moment at the same points. A linear fit of the slope of the torque-angle profile produced the magnitude of the ankle stiffness(105). Knee joint stiffness was calculated similarly.

The raw digital EMG signal was processed using Noraxon's Myoresearch XP software (Version 1.8.07). Data were rectified, filtered using a 15-500 Hz band pass filter and smoothed using root mean squared analysis, at 50ms moving window(99). Average EMG activity was calculated for pre-activation and stance phase, reported in  $\mu\text{V}\cdot\text{s}^{-1}$ . Pre-activation was defined as the EMG activity during the 100ms before ground contact.

To explore the barefoot changes between barefoot and shod running, participants were divided into runners whose loading rate was lower than the group mean barefoot loading rate and runners who presented with loading rates higher than the mean barefoot loading rate. This method divides the sample into groups with high- and low-initial loading rates as previously described ( $>150 \text{ BW}\cdot\text{s}^{-1}$  in both barefoot and shod regardless of footstrike pattern)(17). This method enables us to understand runners who present with high- or low-barefoot loading rates, but does not allow comparison of the interaction between conditions. Of particular interest to us was the acute ability to present lower initial loading rates when barefoot compared to shod. Consequently, for ease of comparison, where the shod loading rate was greater than the barefoot loading rate, the ratio was expressed as SHOD>BF and where the barefoot loading rate exceeds the shod loading rate, it is expressed as BF>SHOD. This ensures a similar magnitude of the ratio and uniform spread of values across the participants.

Thus the primary outcome of this study was to determine the differences in initial (i.e. acute) loading rate, ground reaction forces and ankle kinematics. Secondary variables of interest included knee and hip kinematics, joint stiffness and moments and EMG. Data were screened for normality of distribution and homogeneity of variances using a Kolmogorov-Smirnov normality test and a Levene test, respectively. *t*-tests were used to investigate differences between barefoot and shod conditions for the variables of interest defined above. Additionally, two-way ANOVAs were used to test for differences between conditions and groupings, with a Bonferroni post-hoc test conducted where applicable. Pearson correlations were used to determine relationships between variables of interest. Statistical significance was set at  $p<0.05$ . Data are presented as means(standard deviations). Statistical analysis was performed using Statistica version 12 (StatSoft, Inc. Tulsa, Oklahoma, USA) and Prism 5 (GraphPad Software, Inc, La Jolla, California).

### 3.4 Results

#### 3.4.1. Group descriptive characteristics

Descriptive data of the trial participants are shown in Table 3.1.

**Table 3.1.** Descriptive characteristics of participants

	Mean (SD)
<i>n</i>	51
Age (yrs)	28.2(5.0)
Body mass (kg)	74.7(10.7)
Height (m)	1.8(0.1)
BMI (kg·m <sup>-2</sup> )	23.1(1.2)
10-km personal best (min)	44.3(5.8)

SD, standard deviation; BMI, body mass index

The mean running speed during over-ground running trials was  $3.5 \pm 0.5 \text{ m}\cdot\text{s}^{-1}$  and there were no differences in running speed between the footwear conditions.

#### 3.4.2. Group kinematics and kinetics

Table 3.2 displays the overall differences between shod and barefoot running between groups. We found a number of condition effects, including ankle plantar-dorsiflexion angle at ground contact, toe-off and peak during stance, and peak ankle adduction angle and ankle internal rotation at ground contact.

With respect to the knee, ground contact flexion and adduction were greater in the barefoot than the shod condition ( $p < 0.05$ ), whereas peak knee internal rotation was greater in the shod condition ( $p < 0.01$ ). Knee flexion and rotation and ankle adduction/abduction range of motion were greater in the shod than the barefoot condition ( $p < 0.05$ ).

No differences were found in hip flexion, but hip adduction and internal rotation was greater in the barefoot condition at ground contact and toe-off ( $p < 0.01$  and  $p < 0.05$ ).

Peak ankle adduction moment was higher in the shod condition ( $p < 0.001$ ). Ankle stiffness was lower in the barefoot compared to the shod condition ( $p < 0.01$ ).

### **3.4.3. Ground reaction forces**

Mean loading rate was significantly greater in the barefoot condition ( $168.4 \pm 140.6$  vs.  $91.1 \pm 53.7$   $\text{BW} \cdot \text{s}^{-1}$  for barefoot and shod respectively,  $p < 0.001$ ). No differences in peak vertical, medio-lateral or braking ground reaction forces were found between footwear conditions (Table 3.2).

**Table 3.2** Group mean (SD) kinematic and kinetic parameters in the barefoot and shod condition

	Barefoot	Shod	Barefoot	Shod	Barefoot	Shod
<b>Ground contact forces</b>						
Initial rate of loading ( $BW \cdot s^{-1}$ )	168.4(140.6)	91.1(53.7)**				
Peak apGRF ( $BW$ )	-0.1(1.5)	-0.2(1.5)				
Peak mlGRF ( $BW$ )	0.17(0.3)	0.21(0.3)				
Peak vGRF ( $BW$ )	2.6(0.2)	2.6(0.2)				
	<i>Sagittal plane</i>		<i>Frontal plane</i>		<i>Transverse plane</i>	
<b>Ankle</b>						
<i>Joint Angle (<math>^{\circ}</math>)</i>						
Initial ground contact	-2.0(9.6)	8.6(9.6)**	-1.7(2.7)	-2.7(4.1)	7.4(14.4)	10.6(15.6)*
Toe-off	30.0(10.6)	25.0(9.3)**	-3.4(2.7)	-3.7(3.6)	16.2(13.0)	15.5(13.5)
Peak stance	20.4(9.0)	23.2(8.6)*	1.9(2.6)	2.5(3.6)*	15.9(13.4)	15.7(15.2)
Range of motion	47.0(13.8)	46.6(14.0)	5.3(2.4)	6.3(2.4)*	26.5(7.0)	27.0(7.4)
<i>Moment (<math>Nm \cdot kg^{-1}</math>)</i>						
Initial ground contact	-0.1(0.2)	0.0(0.2)	-0.1(0.3)	-0.13(0.4)		
Peak stance	2.6(1.2)	2.5(1.2)	0.1(0.1)	0.2(0.2)*		
<i>Joint Stiffness (<math>Nm \cdot degrees^{-1}</math>)</i>						
	10.6(7.2)	14.0(13.0)*				
<b>Knee</b>						
<i>Joint Angle (<math>^{\circ}</math>)</i>						
Initial ground contact	15.9(6.6)	14.1(6.1)**	5.1(8.2)	4.5(7.3)**	-19.53(13.9)	-19.4(12.7)
Toe-off	12.3(6.4)	12.3(6.3)	4.3(6.7)	4.4(6.3)	-20.6(15.0)	-20.6(13.4)
Peak stance	55.4(13.4)	59.1(15.0)	15.0(13.5)	15.9(12.9)	1.2(13.8)	3.6(12.6)*
Range of Motion	38.2(15.6)	41.4(15.9)*	12.6(7.7)	12.4(6.9)	23.0(9.6)	24.8(9.5)*
<i>Moment (<math>Nm \cdot kg^{-1}</math>)</i>						
Initial ground contact	-0.6(0.4)	-0.7(0.3)	0.1(0.3)	0.1(0.3)		
Peak stance	2.4(2.6)	2.3(1.4)	1.0(0.8)	1.1(0.7)		
<i>Joint Stiffness (<math>Nm \cdot degrees^{-1}</math>)</i>						
	9.7(9.8)	7.1(4.7)				
<b>Hip</b>						
<i>Joint Angle (<math>^{\circ}</math>)</i>						
Initial ground contact	39.3(4.8)	38.8(5.3)	3.9(2.8)	4.3(2.9)*	9.7(14.2)	8.0(13.3)*
Toe-off	-4.9(3.7)	-4.5(4.2)	-5.7(2.1)	-6.2(2.0)	9.0(15.0)	6.9(14.5)*
Peak stance	39.8(7.1)	39.3(8.5)	8.2(4.5)	8.7(5.4)	19.2(15.0)	18.8(14.7)

vGRF- Vertical ground reaction force; mlGRF – medio-lateral ground reaction force; apGRF – anterior-posterior ground reaction force; Sagittal plane: +ve values – dorsiflexion; -ve values – plantarflexion. Frontal plane: +ve values – adduction; -ve values – abduction. Transverse plane: +ve values – internal rotation; -ve values – external rotation.

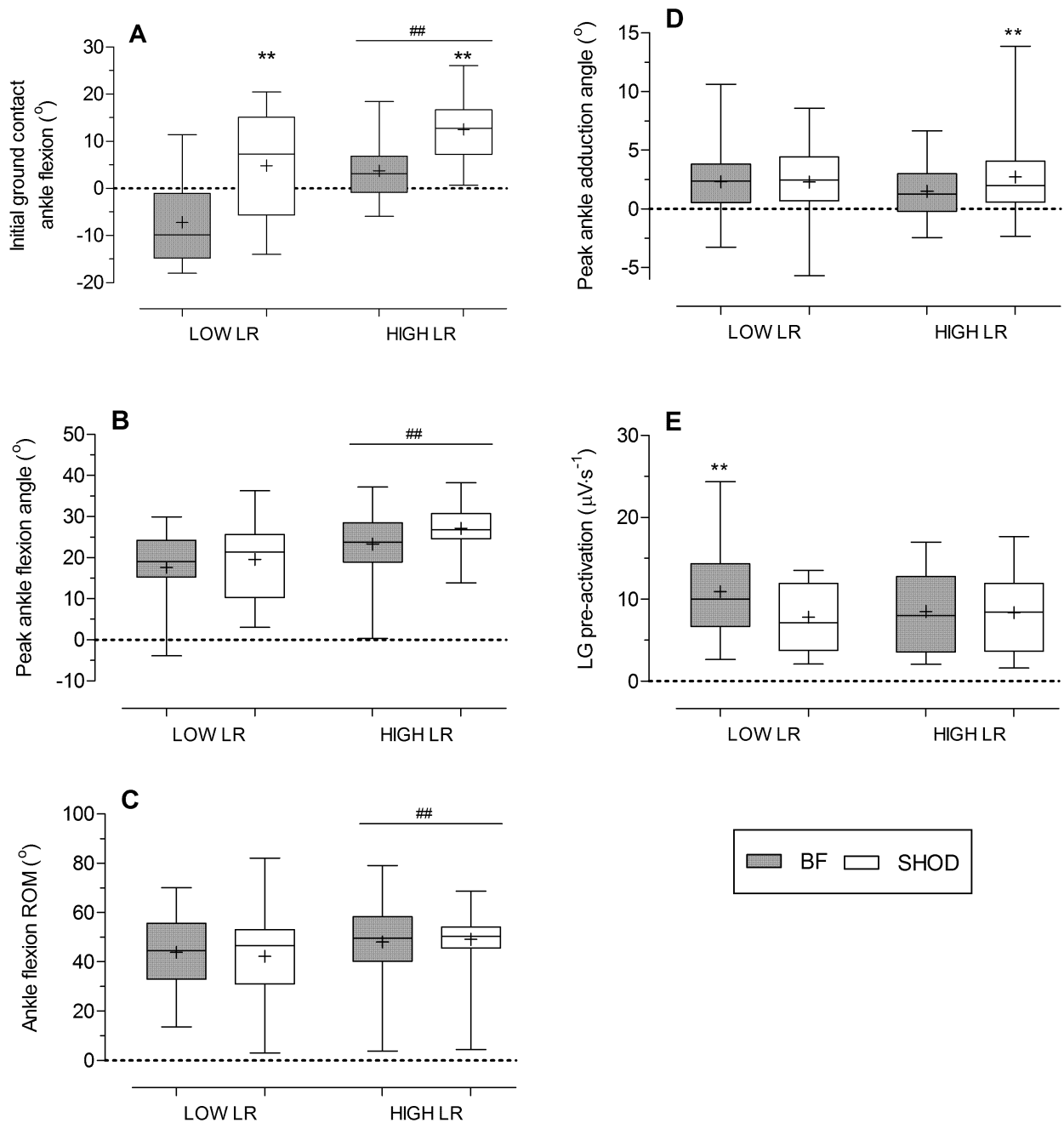
\*significant footwear condition difference (\*p<0.05, \*\*p<0.01)

#### 3.4.4.i. High- and low-loading rate groups in the barefoot condition

The variability in loading rate was significantly greater in the barefoot condition. Loading rates ranged from 12.3 to 622.8  $\text{BW}\cdot\text{s}^{-1}$  in the BF trial compared to 27.2 to 315.3  $\text{BW}\cdot\text{s}^{-1}$  in the shod trial. To investigate this variability, we divided participants into runners whose loading rate was lower than the group mean barefoot loading rate of 168  $\text{BW}\cdot\text{s}^{-1}$  (LOW LR,  $n=23$ ) and runners who presented with loading rates higher than the mean barefoot loading rate (HIGH LR,  $n=28$ ). The two groups thus created were similar in magnitude of loading rate to what was observed by Lieberman et al. (2010)(17,104) in terms of runners presenting with high and low initial loading rates ( $>150 \text{ BW}\cdot\text{s}^{-1}$  in both barefoot and shod regardless of footstrike pattern). We then compared the other outcome variables between these groups at ground contact and during stance when barefoot and shod, and present the significant findings in Figure 3.1.

In the LOW LR group, the ankle angle on ground contact was more plantarflexed than the HIGH LR group, who landed in dorsiflexion in both the barefoot and shod conditions (Figure 3.1A,  $p<0.01$ ). Ankle angle was influenced similarly by footwear in both groups, increasing significantly when shod (Figure 3.1A,  $p<0.01$ ). Peak ankle dorsiflexion (Figure 3.1B,  $p<0.01$ ) and ankle plantar-dorsiflexion range of motion during stance (Figure 3.1C,  $p<0.01$ ) were significantly greater in the HIGH LR group. There was no effect of footwear on these variables in either group.

Peak ankle adduction angle was lower in the HIGH LR when barefoot (Figure 3.1D,  $p<0.01$ ). LG pre-activation was greater in the barefoot condition in the LOW LR, whereas footwear did not influence LG pre-activation in HIGH LR (Figure 3.1E,  $p<0.01$ ).

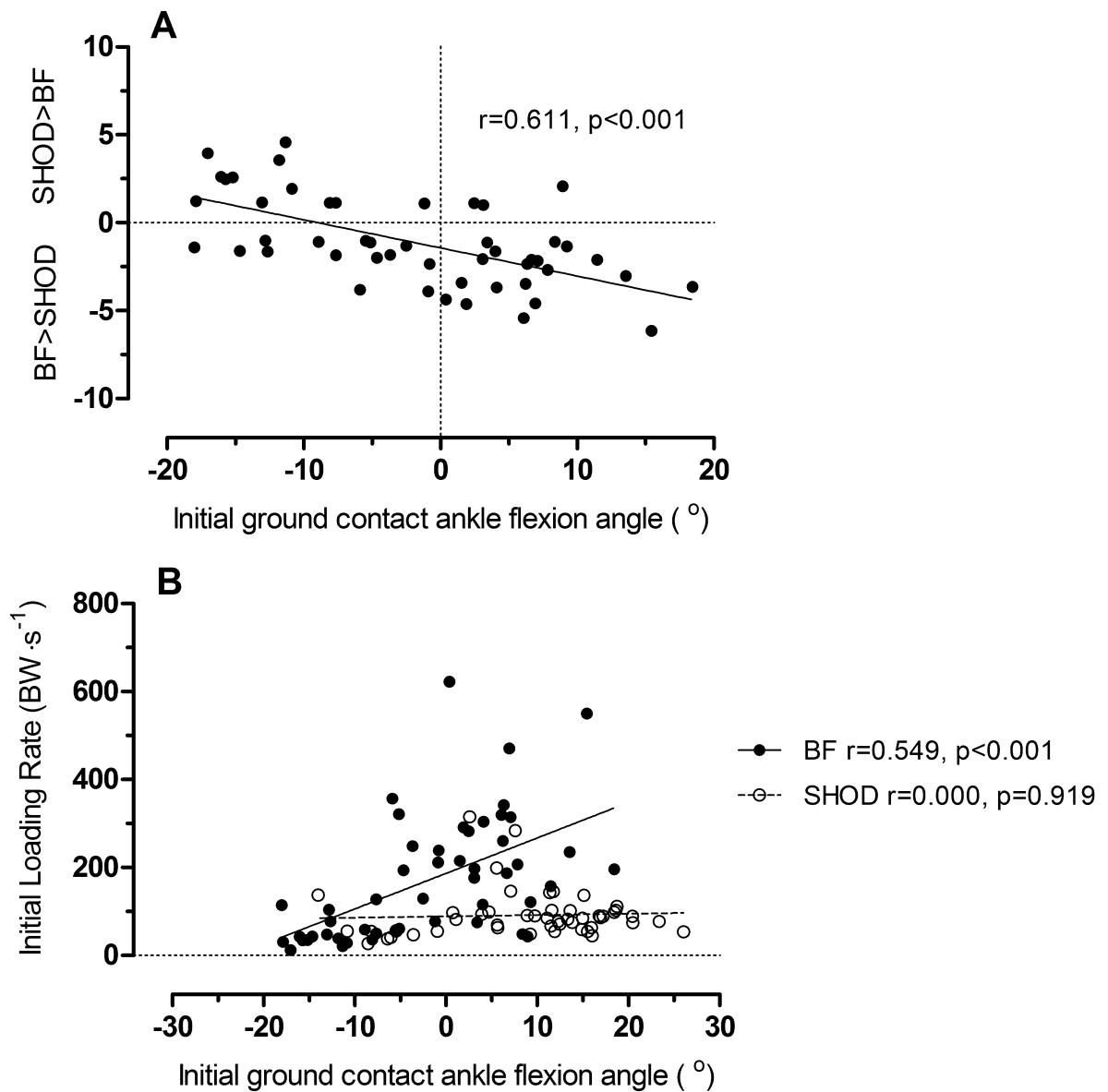


**Figure 3.1** Differences in initial ground contact ankle flexion angle (A); peak ankle flexion angle (B); ankle flexion range of motion (ROM)(C); peak ankle adduction angle and *gastrocnemius lateralis* (LG) pre-activation (E) between runners with high (HIGH LR) and low loading rates in barefoot (BF) and shod (SHOD) conditions. \* - significant condition difference ( $**p < 0.001$ ), # - significant group difference ( $##p < 0.001$ ).

#### **3.4.4.ii. Acute responders vs. non-responders**

There were 16 runners who presented with a shod loading rate greater than barefoot, and 35 whose barefoot loading rate exceeded their shod loading rate (Figure 3.2A). We used the ankle angle on impact as a proxy for footstrike, with accepted limitations, since dorsiflexion on impact suggests the likelihood of heel striking, while plantarflexion on impact is generally indicative of a more mid or forefoot strike(67). This analysis reveals a significant negative correlation between BF:SHOD loading rate and ankle angle, such that runners who landed in dorsiflexion had loading rates greater when barefoot than shod ( $r=-0.611$ ,  $p<0.001$ ). In contrast, higher plantarflexion angle on ground contact when barefoot was associated with a lower BF:SHOD ratio, indicating that BF loading rate is lower than SHOD loading rate (Figure 3.2A).

Further, initial loading rate was significantly associated with the ankle angle at ground contact in the barefoot condition only (Figure 3.2B,  $r=0.549$ ,  $p<0.001$ ), and not when shod ( $r=0.000$ ,  $p<0.919$ ).



**Figure 3.2** The relationship between the ratio indicating individuals with a barefoot greater than shod (BF>SHOD) and shod greater than barefoot (SHOD>BF) initial loading and initial ground contact ankle flexion angle (A). The relationship between individual initial loading rate and initial ground contact ankle flexion angle in the barefoot (BF) but not shod condition (B).

Table 3.3 and Figure 3.3A-E present further analysis of these two sub-groups, as divided by BF:SHOD ratio. Differences between groups were found for ankle dorsiflexion at initial ground contact ( $p < 0.001$ ) (Figure 3.3B). The BF>SHOD group landed with significantly greater dorsiflexion than the SHOD>BF group, though both groups displayed a significant increase in dorsiflexion when wearing running shoes (Figure 3.3B).

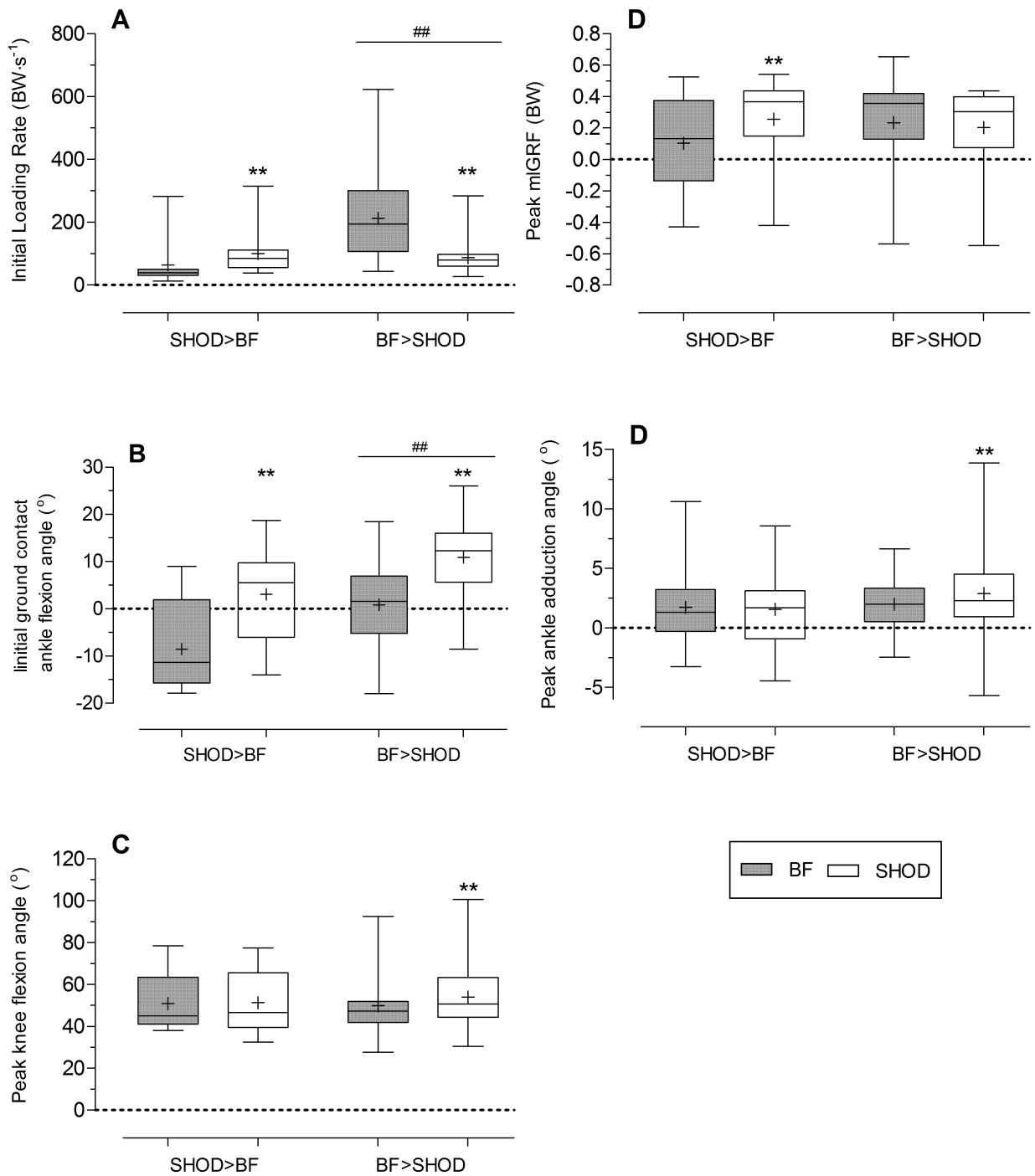
Finally, interaction effects were found where BF>SHOD had greater knee flexion at impact when barefoot compared to shod ( $p < 0.05$ ). Whereas, in the SHOD>BF group, there was no difference in knee flexion at impact associated with footwear (Figure 3.3C). Peak ankle adduction during stance was higher in the shod condition in the BF>SHOD group, whereas no difference was found in the SHOD>BF group (Figure 3.3E,  $p < 0.05$ ). The last interaction effect was found in peak medio-lateral GRF, where the SHOD>BF group had lower medial forces in the barefoot condition ( $p < 0.020$ ) and the BF>SHOD was not significantly different between conditions (Figure 3.3).

**Table 3.3.** SHOD>BF and BF>SHOD kinematic and kinetic parameters in the two different conditions

	SHOD>BF (n=16)		BF>SHOD (n=36)	
	Barefoot	Shod	Barefoot	Shod
<b>Ground contact forces</b>				
Initial rate of loading (BW/s)	76.9(88.7)	95.2(69.6)**	209.7(140.8)##	88.1(44.6)###**
vGRF (BW)	2.6(0.2)	2.6(0.2)	2.5(0.6)	2.5(0.5)
mIGRF (BW)	0.1(0.3)	0.3(0.3)**	0.2(0.3)	0.2(0.3)
apGRF (BW)	-0.3(1.1)	-0.4(1.2)	-0.0(0.1)	1.7(1.6)
<b>Ankle</b>				
<i>Sagittal plane angle (degrees)</i>				
Initial ground contact	-8.4(8.3)	3.8(10.7)**	0.9(8.7)##	10.9(8.2)###**
Peak stance	17.7(19.0)	9.4(8.5)	21.6(8.6)	25.0(8.0)
<i>Frontal plane angle (degrees)</i>				
Initial ground contact	-2.1(2.6)	-3.2(3.5)	-1.6(2.7)	-2.4(4.4)
Peak stance	1.8(3.4)	1.7(3.5)	2.0(2.2)	2.9(3.6)**
<i>Transverse plane angle (degrees)</i>				
Initial ground contact	7.5(14.3)	11.1(15.8)	7.4(14.5)	10.4(15.5)
Peak stance	15.1(14.8)	15.2(15.9)	16.2(12.7)	15.9(15.0)
<b>Knee</b>				
<i>Sagittal plane angle (degrees)</i>				
Initial ground contact	19.5(6.3)	18.1(5.2)	20.1(7.0)	17.4(6.5)
Peak stance	52.3(13.8)	54.4(18.8)	49.9(13.8)	54.0(15.2)**
<i>Frontal plane angle (degrees)</i>				
Initial ground contact	3.7(5.2)	2.8(5.2)	2.8(9.2)	1.6(8.1)
Peak stance	9.5(15.4)	9.3(15.2)	9.3(12.7)	9.1(11.9)
<i>Transverse plane angle (degrees)</i>				
Initial ground contact	-22.8(12.1)	-22.1(12.6)	-17.5(14.8)	-17.7(12.8)
Peak stance	-1.4(14.9)	0.8(15.0)	2.8(13.3)	5.3(11.3)

vGRF- Vertical ground reaction force; mIGRF – medio-lateral ground reaction force; apGRF – anterior-posterior ground reaction force; Sagittal plane: +ve values – dorsiflexion or flexion; -ve values - plantarflexion or extension. Frontal plane: +ve values – adduction; -ve values – abduction. Transverse plane: +ve values – internal rotation; -ve values – external rotation.

\*- significant condition difference (\*p<0.05, \*\*p < 0.01); # - significant group difference (# p<0.05, ###p<0.01)



**Figure 3.3** Differences in initial loading rate (A); initial ground contact ankle flexion angle (B); peak ankle flexion angle (C); peak medio-lateral ground reaction force (mIGRF)(D); peak ankle adduction angle (E) between runners grouped as shod greater than barefoot (SHOD>BF) initial loading rate or vice versa (BF>SHOD) in the barefoot (BF) and shod (SHOD) condition. \* - significant condition difference (\*\* $p < 0.001$ ), # - significant group difference ( $^{##}p < 0.001$ ).

### 3.4.5. Group muscle activity

Greater VLO and BF activity during ground contact was found in the shod condition ( $p < 0.001$  and  $p < 0.05$ , respectively)(Table 3.3). In the shank segment, both pre-activation and ground contact TA activity were greater in the shod condition ( $p < 0.001$  and  $p < 0.013$ , respectively), whereas in the LG, ground contact activity was greater in the shod condition ( $p < 0.001$ ), but was significantly greater during the pre-activation phase when barefoot ( $p < 0.002$ ) (Table 3.3).

**Table 3.4** Lower limb muscle activity in the two different conditions

	<b>Barefoot</b>	<b>Shod</b>	<b>Barefoot</b>	<b>Shod</b>
	<i>Pre-activation</i>		<i>Ground Contact</i>	
<i>Vastus lateralis</i> ( $\mu\text{V}\cdot\text{s}^{-1}$ )	18.3(10.8)	17.7(10.4)	57.9(18.5)	66.2(21.9)**
<i>Biceps femoris</i> ( $\mu\text{V}\cdot\text{s}^{-1}$ )	19.3(9.6)	19.4(9.8)	30.5(17.1)	34.0(18.9)**
<i>Tibialis anterior</i> ( $\mu\text{V}\cdot\text{s}^{-1}$ )	18.1(8.3)	23.2(9.0)**	14.8(6.5)	16.7(5.3)*
<i>Gastrocnemius lateralis</i> ( $\mu\text{V}\cdot\text{s}^{-1}$ )	11.7(9.3)	9.9(8.6)**	48.6(18.0)	55.0(20.9)**

\*- significant condition difference ( $*p < 0.05$ ,  $**p < 0.01$ )

### 3.4 Discussion

The primary hypothesis of this study was that habitually shod runners would present with increased initial loading rates when barefoot. Our first finding confirms this hypothesis, since barefoot initial loading rate was significantly greater when shod, with 35 of the 51 tested runners increasing loading rate when barefoot. This refutes the idea that a reduction in initial loading rates, one of many factors associated with injury(95), and which has been proposed as a benefit of barefoot or minimalist running, occurs in the majority of habitually shod runners.

This group, whose loading rate increases when barefoot, and which we classify as non-responders, has been observed without being specifically discussed in previous studies(17,73). They are however a significant group for our understanding of possible benefits of barefoot running, since they display increased loading rates, in many instances despite greater plantarflexion of the ankle on ground contact in the barefoot compared to shod condition. Ankle plantarflexion, an indication of a more forefoot strike, has been hypothesised by some researchers to be sufficient to reduce the initial loading rate(98), which our findings refute as a general rule.

Previous research provides conflicting evidence on the general effects of barefoot or minimalist running on initial loading rate, with some studies finding a reduction in loading rate in habitually barefoot runners(17,69) and habitually shod runners(93) while others document increased loading rates either in minimalist shoes(91) or when barefoot in habitually shod runners(60). None of these studies, however, have focused on the individual variability in responses to barefoot running. We have found a large range of responses in loading rate, with up to five-fold increases and reductions, and with an overall average increase in barefoot loading rate.

Further investigation revealed that sagittal ankle angle was significantly associated with loading rate when barefoot, but not when shod. Runners who continued to land with ankle

dorsiflexion, indicative of heelstriking, presented with significantly higher loading rates than when shod. This is not surprising, since landing on the heel reduces the ability of the ankle to attenuate forces at initial ground contact. Lieberman et al. (2010) found that overall leg compliance was greater and was correlated with lower loading rates during a forefoot landing than a rearfoot landing(17). Our finding suggests a similar relationship for ankle angle (a proxy for footstrike), but emphasises that current recommendation either for or against barefoot or minimalist running must be balanced by a realisation that large variations in individual responses exist. This may produce entirely different outcomes with potential theoretical and clinical implications for injury risk, and runners who do not adopt a forefoot strike may require different advice to those who do(16).

Furthermore, preferred footstrike patterns have been found to lower damping coefficients for soft tissue vibrations. This may influence metabolic and neuromuscular control of gait(106), and we would suggest that factors other than initial loading rate may influence preferred footstrike, such that progressive transition periods may alter preferred footstrike over time in the barefoot condition(95).

The second important finding is that regardless of footstrike, cushioned shoes reduce the loading rate to levels typically seen in habitually barefoot runners(17,69), and to levels similar to those measured in runners who reduce loading rate when barefoot in the present study. This finding is significant, because a) it demonstrates that shoes do not influence kinematics or collision forces equally in all individuals, and b) it has been suggested that runners wearing conventional running shoes experience detrimental changes in running technique, including heelstriking, which lead to increased initial loading rates compared to barefoot running(17,19).

Our finding contradicts this theory, supporting not only that shoes reduce the loading rate in general(91), but also that a subset of runners who continue to heelstrike when barefoot experience significant reductions in loading rate when shod, despite continuing to heelstrike with even greater dorsiflexion than when barefoot. The significance of this reduction in

loading rate is equivocal. As we have described, previous research has associated heelstriking with an increased risk of injury as a result of higher loading rates(24,42,48,96,98), and inferred that increased dorsiflexion and heelstriking caused by running shoes(42,81,107,108) may increase the risk of certain injuries. This is disputed(32,97), and given the complexity of injury aetiology outlined in Chapter 2, single associations are likely ineffective and highly oversimplified(95). However, as described, the purported benefits of barefoot running include a reduction in loading rate, and by this acknowledged limited standard, our findings for habitually shod runners question this purported benefit for the general population, and more specifically for two-thirds of the sample who increased loading rate when barefoot.

We have found a significant, though moderate association between the loading rate and ankle angle in the barefoot but not shod condition. This suggests the influence of factors other than sagittal ankle angle on collision forces(60,109,110), perhaps including neuromuscular activity and coupling in the lower extremity(79,111). Factors including training and footwear history, performance level and testing modality may also contribute to the measured loading rate. through

The greater loading rate in the barefoot condition may have required reactive adjustments to assist in tolerating the unfamiliar magnitude. These adjustments may include our findings of a reduction in the peak ankle adduction angle and increased knee flexion during stance to facilitate the high initial loading rates. Interestingly, the SHOD>BF group experienced a lower peak lateral GRF when barefoot, whereas the BF>SHOD group displayed similar lateral GRF in both footwear conditions.

With respects to the measured muscle activation, we found that *vastus lateralis* and both plantar- and dorsiflexors were significantly more active when shod than in the barefoot condition during the ground contact phase. This may imply increased firing bursts of the muscles to maintain running speed due to shoe cushioning rather than to absorb the load

during initial ground contact, which may accelerate the onset of fatigue and subsequent injury risk(112).

The assumption that ankle plantar/dorsiflexion angle at foot contact is indicative of footstrike pattern (i.e. mid/forefoot strikers vs. heelstrikers) is important to clarify. While it is possible that the two variables do not agree for all individuals, it is intuitive that the more plantarflexed the ankle joint is at initial ground contact, the more distal the contact between the foot and the ground is, and vice versa. Further, the present study examined the initial loading rate between footwear conditions. To truly understand whether barefoot running is appropriate or inappropriate for individuals, it would be necessary to elucidate whether initial loading rates may be beneficial or not. As all runners in this cohort were male it is acknowledged that males and females exhibit different joint level biomechanical and neuromuscular patterns(113–115) and therefore future work is needed to determine whether not these results could be extended to the female running population.

The complexity and variability of the biomechanical responses to barefoot and minimalist running makes the advocacy of this running modality questionable at this stage. This study demonstrates that loading rate, a tenuous and debated factor for injuries, shows such large individual responses that advocating its reduction, as a benefit of minimalist or barefoot running cannot be justified.

Although, subject stratification into different groups may confound or bias study outcomes of this study by overlooking the magnitude of the data and various other data that may prove more discriminatory. This may negatively influence the conclusivity and generalizability of our findings. However, based on historical argument for initial loading rate and its influence on injury risk, both methods of stratification appeared apt.

Nevertheless, we have identified runners who appear to show unfavourable biomechanical adjustments to barefoot running, judged against published theoretical benefits and risk factors. We have termed these runners non-responders, and suggest that they can be

characterised by elevated loading rates when barefoot, insufficient plantarflexion, altered neuromuscular strategy and subsequent joint stiffness, resulting in a failure to minimise rate of loading and peak mIGRF.

The identification of these non-responders required the post-hoc stratification of our participants into one of two groups. Given the complexity of injury aetiology (Chapter 2), and the mechanical responses to running, we acknowledge that this simple stratification into two groups is likely somewhat of an oversimplification, since a spectrum is likely to exist. However, our post-hoc analysis of loading rate using the methods of Lieberman et al (2010) revealed very distinct groups with respect to loading rate, such that there was no overlap between them. Thus, we felt it was appropriate to pursue analysis of these two groups. But, we recognize that further research is required to fully understand the individual and complex responses to shod and barefoot running

Further research investigating whether the transition to the barefoot running results in a change in footstrike coupled with favourable kinetic, kinematic and neuromuscular factors may improve our understanding in this regard. An improved understanding of the magnitude of loading rate and injury risk is also required, regardless of footwear. This may require a longitudinal injury prediction study with computational musculo-skeletal modelling to account for inter-individual biomechanical and neuromuscular variability. Future studies, particularly long-term prospective injury research, will further elucidate the individual responses to barefoot running, and investigate the possibility of characterising individuals as potential responders or non-responders based on kinetic, kinematic or technique and footstrike related variables, as we suggest based on the present findings.

### **3.5 Conclusions**

This study found that a majority of habitually shod runners do not exhibit previously reported benefits in terms of reduced impact loading rates when barefoot. We have confirmed high variability in biomechanical responses to barefoot running, since runners do not automatically adopt a running technique and footstrike pattern that reduces loading rates when barefoot, although this does not dispute the ability for runners habituate over time with experience and practice, it may be possible to adapt the mechanical responses. Indeed, previous research has shown that instruction, provided to runners in minimalist shoes, is sufficient to increase the shift to a more forefoot-striking pattern. We address this possibility in Chapters 4 and 5 of this thesis. Further investigation of runners who were found to increase loading rate when barefoot revealed that rather than being the cause of increased ankle dorsiflexion and thus impact forces, cushioned shoes are able to significantly reduce loading rates to levels that are similar to those observed in barefoot runners who do adopt a forefoot landing pattern, despite causing increased dorsiflexion. From a clinical perspective, individuals who continue to heelstrike when barefoot display significantly increased loading rates than when in shoes, and receive significantly larger reductions in loading rates from shoes. Future longitudinal studies should investigate this as a potential determinant of injury or success in barefoot and minimalist running.

## **CHAPTER 4**

**AN 8-WEEK PROGRESSIVE BAREFOOT RUNNING  
TRAINING PROGRAMME AND ITS RELATIONSHIP TO  
INITIAL LOADING RATE:  
A CASE OF INDIVIDUAL VARIABILITY**

#### 4.1 Abstract

**Aim:** To determine whether runners are able to instinctively adopt the proposed favourable kinematic changes and reduction in loading rate after a progressive 8-week barefoot running training programme. Of secondary interest is to explore the individual responses to the barefoot stimulus

**Methods:** Twenty-six runners completed an 8-week progressive barefoot running training programme. Before and after this intervention kinematic and ground reaction force data were collected in the barefoot and shod condition. Ankle and knee kinematics, initial loading rates and spatiotemporal variables were calculated. Inter-individual responses were studied by separating runners into non-, negative- and positive-responders. All data were compared between testing trials and conditions. Pearson correlations were used to analyse relationships of changes in variables between testing trials.

**Results:** No differences were found in the group mean data before and after the intervention, however condition difference did persist. The positive responder group illustrated greater plantarflexion in both conditions between tests, negative-responders landed in greater barefoot dorsiflexion post-intervention and the non-responders did not change. A relationship was found between the change in ankle flexion angle and the change in initial loading rate ( $r=0.587$ ,  $p=0.002$ ) in the barefoot but not shod condition.

**Conclusion:** The 8-weeks of progressive barefoot running training did not change in biomechanics, but there were sub-groups of responders. It appears that changes in initial loading rate are explained by changes in ankle flexion angle at initial ground contact. Therefore, conscious instruction may be necessary in attaining favourable barefoot running biomechanics such as modification of footstrike with an emphasis on loading rate reduction.

**Keywords:** kinetics, kinematics, sport, transition, shoes, gait.

## 4.2 Introduction

As has been described in the previous chapters of this thesis, barefoot running (and associated minimalist shoe running) is often advocated for injury-reducing benefits (16,24,95). Central to the emerging evidence is that successful barefoot running may require the adoption of a favourable forefoot landing pattern, which reduces loading rate, when running barefoot(5,24).

Whether or not this occurs instinctively and in all runners is unknown, with evidence both supporting (19,20) and cautioning (44,68,116) the habitually shod. In Chapter 3 of this thesis, we showed that a majority of runners do not reduce loading rate despite a slight shift towards greater ankle plantarflexion on impact when first exposed to barefoot running.

Long-term prospective studies that are ecologically valid and that track the changes associated with barefoot training have yet to be published. Many have small sample sizes and most have utilised minimalist or barefoot-simulated shoes instead of the pure barefoot condition. Of these, the shortest minimalist shoe intervention of 2-weeks did not document any significant adaptations in the majority of the cohort. Indeed, this study also observed higher initial loading rates in some runners (116), as we did previously (Chapter 3), based on which we identified so-called non-responders. These runners are characterised as having elevated loading rates when barefoot, insufficient plantarflexion, altered neuromuscular strategy and subsequent joint stiffness (Chapter 3).

Ridge et al. (2013) studied shod runners who participated in a progressive 10-week minimalist shoe intervention with no gait retraining. After this period, half the runners presented with signs of bone oedema (a precursor to stress fractures) measured using magnetic resonance imaging of the feet (68). Although these researchers did not present any other data with regards to changes in running style and efficiency, their findings prompt caution regarding the transition to barefoot running, which may lead to more severe consequences if sufficient habituation is not allowed. Alternatively, their findings may

suggest a potentially favourable increase in bone turnover and possible gradual adaptation to increased load bearing.

Another study exposed runners to brief 4-week instructed minimalist running training. The running was complemented with specific lower limb exercises and gait retraining that included instructions to run on the forefoot, making contact with the ground as lightly as possible, shorter strides and quicker cadence(73). Consequently, the 4-week programme reduced heel pressure in the minimalist footwear and reduced maximum force during stance in both conditions(73). However, only foot sole pressures, footstrike pattern and stride characteristics were documented, and whether this effect was the result of the footwear or the conscious adjustment by runners in response to instruction is questionable.

A similar question can be asked of the study of McCarthy et al. (2014), which found that female runners who trained in minimalist shoes for twelve weeks adopted a more-forefoot strike pattern than a group running in traditional cushioned shoes. They concluded that runners seeking to run with a forefoot-striking pattern or with “barefoot” kinematics might benefit from a 12-week transition programme helpful regardless of footwear.

However, this conclusion is questionable, given that the authors instructed runners to avoid rearfoot striking patterns for “safety reasons”, despite claiming that participants were free to develop their own running style(72). As such, the findings of this study, and those of Warne et al. (2013), may be attributed to instructed gait intervention rather than footwear alone. Whether or not the average runner is able to instinctively transition and adapt to the proposed benefits of barefoot running without increasing injury risk remains unknown and an ecologically valid question, because most runners will explore barefoot running without technical coaching or advice(73).

Of importance is that the previously discussed longer-term training studies did not document the associated changes in kinetic factors during barefoot or minimalist running. One such factor, loading rate, has previously been found to be a risk factor for tibial stress

fractures and other running related injuries(37,117). Lieberman et al. (2010) proposed that this variable would decrease as one transitions to barefoot running(17), since habitually barefoot runners were found to present with significantly lower loading rates than novice barefoot runners. However, the acute response of the average shod runner when running barefoot is a higher loading rate, which has been found to be linked to footstrike pattern(98). Our previous finding suggests that footstrike patterns are only part of the contribution to loading rate, since we have found only weak correlations between ankle angle and loading rate (Figure 3.2, Chapter 3).

Ultimately, many questions persist around the understanding and practice of barefoot running, including the effect of pure barefoot training on whether the typical shod runner is able to instinctively reduced their initial loading rate as a result of familiarity with barefoot running. The practicality and functionality of barefoot running, and its influence on the biomechanical and neuromuscular systems during the shod to barefoot transition is also unknown. Thus, the primary purpose of this study is to investigate whether runners are able to instinctively adopt the proposed favourable kinematic changes and reduction in loading rate after a progressive 8-week barefoot running training programme. Of secondary interest is to explore the individual responses to the barefoot stimulus, to describe the kinematic and kinetic differences between individuals with positive (decrease in loading rate), negative (increase in loading rate) and no-changes in initial loading rates.

## **4.3 Materials and Methods**

### **4.3.1 Participants**

Twenty-nine habitually shod runners volunteered to participate in this study. Participants were able to run 10km in <60 minutes, trained at least 4 hours a week (5 sessions per week), had no previous experience or had not engaged in barefoot running within 6 months of the study and were injury free in the lower limbs for six months prior to the study. Participants provided written informed consent and were fully aware of the benefits and potential risks associated with the study and were free to voluntarily withdraw at any stage. The study was performed in accordance with the principles of the Declaration of Helsinki (Seoul, 2008) and ethical approval was granted by the Human Research Ethics Committee of the University of Cape Town (HREC 504/2011).

### **4.3.2 Study design:**

The study was an 8-week progressive barefoot running training programme, where participants performed laboratory trials before and after an 8-week period. All visits included experimental overground running trials. All trials were performed within two days of a fortnightly testing schedule.

### **4.3.3 Progressive Barefoot Training Programme:**

To maintain training status and document any training associated discomfort, participants were requested to keep training logbooks. The progressive barefoot training programme proportionally replaced segments of the participants' current training programme on any three days per week. This gradually introduced barefoot running in increasing amounts over the 8-week period as described below. Participants added these prescribed barefoot sessions to the end of their current training sessions, which were shortened by the length of the barefoot session.

Participants were asked to maintain their typical overall training volumes for the 8-weeks of involvement in the study. For example, in Week 1, where a 10-minute barefoot session was prescribed, participants who normally run 45-minutes ran 35-minutes, with the supervised barefoot session added on. The progression of barefoot running was conservative to ensure that the risk of injury was minimized, and was developed by a trained distance running coach according to the principles of progressive overload and recovery. The barefoot training was phased into typical training to ensure that no physical deconditioning occurred over the 8-weeks, and so that the changes found could be attributed to barefoot running alone.

During this entire period, training logbooks were kept in order to assess and maintain their habitual training programme as to prevent any training effects not associated with barefoot running. The logbook also contained session rating of perceived exertion and muscle pain scores on a 1-10 scale (1-no pain and 10-intolerable pain), and if it became intolerable and/or severe, provision for physiotherapy was provided for possible injury diagnosis and treatment.

During the 8-week training programme, the participants reported for supervised training (by the investigator). Supervised training consisted of three sessions per week, as described in Table 4.1. Initially the participants exercised in an indoor environment i.e. Sports Science Institute of South Africa's indoor running track. After week 2 the participants exercised on a safe outdoor surface such as a sports field (firm grass athletics track). After week 4 the participants trained on various surfaces for the remainder of their training sessions including road, concrete etc. Participants were not briefed whether they should adopt any type of footstrike pattern and were instructed to run in a manner that maximised their subjective comfort.

**Table 4.1.** 8-week progressive barefoot running training programme

<b>Week 1</b>	<b>Week 2</b>	<b>Week 3</b>	<b>Week 4</b>
2'R 2'W 2'R 2'W 2'R	3'R 2'W 3'R 2'W 3'R	8'R 3'W 8'R	10'R 3'W 10'R
2'R 2'W 2'R 2'W 2'R	4'R 2'W 4'R 2'W 4'R	8'R 3'W 8'R	12'R 2'W 12'R
3'R 2'W 3'R 2'W 3'R	5'R 2'W 5'R 2'W 5'R	10'R 3'W 10'R	15'R
<b>Week 5</b>	<b>Week 6</b>	<b>Week 7</b>	<b>Week 8</b>
12'R 2'W 12'R	10'R 3'W 10'R 3'W 5'R	15'R 3'W 10'R 3'W 5'R	30'R
15'R 2'W 15'R	15'R 3'W 10'R	15'R 3'W 15'R	20'R 3'W 20'R 3'W 10'R
20'R	25'R	30'R	40'R

'R-minute run; 'W- minute walk

#### **4.3.4 Experimental conditions:**

Participants reported to the laboratory pre- and post-programme, with measurements obtained in two different conditions: (1) Barefoot and (2) the typical shoe in which they were currently completing the most training mileage (hereafter called shod). All shod midsoles comprised of traditional EVA and were not controlled for mileage, shore count or heel-toe drop. Footwear conditions were tested in a randomised order.

#### **4.3.5 Instrumentation:**

Running trials for the experimental condition were conducted on a 40 m indoor synthetic running track. Three-dimensional marker trajectories were captured using an 8-camera VICON MX motion analysis system (Oxford Metrics Ltd, Oxford, UK), sampling at 250 Hz. Ground reaction force (GRF) data were collected using two 900 x 600 mm AMTI force platforms (AMTI, Watertown, MA, USA), sampling at 2000 Hz. A standard PlugInGait marker set was used with sixteen 14 mm reflective markers were attached bilaterally on the base of the second metatarsal head, posterior calcaneus, lateral malleolus, on the lateral

aspect of the distal third of the shank and thigh, lateral epicondyle of the knee, the anterior and posterior superior iliac spine. The capture volume had a length of 9 m and a height of 1.5 m to allow adequate distance for the absence of acceleration and deceleration. Participants were free to warm-up and down the track, as they felt necessary.

#### **4.3.6 Procedures:**

Participants completed 6 clean overground running trials in each footwear condition. During these runs, synchronised collection of marker motion and force platform data were obtained with VICON Nexus (VICON, Oxford Metrics, Oxford, UK). A successful trial was defined as one within the specified velocity range of  $3.5 \text{ m}\cdot\text{s}^{-1}$ , where all markers were in view of the cameras, the right foot made full contact with a force platform and there was no obvious visual evidence that the runner targeted the force platform or altered their gait prior to force platform contact.

Marker trajectory and kinetic data were filtered using a low-pass fourth-order Butterworth filter with a cut-off frequency of 8 and 60 Hz, respectively. For each trial, one complete gait cycle was analysed. The lower body PlugInGait model calculated three-dimensional lower extremity joint angles and net resultant joint moments using a Newton-Euler inverse dynamics approach using this data. Joint angles were described using the joint coordinate system(103). Three-dimensional joint moments were expressed as external moments normalised to body mass ( $\text{Nm}\cdot\text{kg}^{-1}$ ).

#### **4.3.7 Data analysis:**

Knee and ankle joint angles and moments, were extracted for statistical analysis using a customised MATLAB (Mathworks Inc., Natick, USA) program. The data for each participant's right limb were averaged over the 6 trials for each condition and graphed over approximate stance phase. Stance phase was defined as the time over which a vertical force exceeded one standard deviation (SD) above baseline force platform noise and continued to elevate until toe-off. Specifically, discrete variables at initial ground contact,

maxima during stance and toe-off were extracted. Stance time for variable extraction was defined as the time over which a vertical force exceeded one SD above baseline force platform noise. Further, peak anterior-posterior, medio-lateral and vertical ground reaction forces (in body weight (BW) units) and vertical initial rate loading rate ( $\text{BW} \cdot \text{s}^{-1}$ ) were quantified between 200 N and 90% of the impact transient peak (first peak prior to maximum). When no distinct impact transient was present, the same parameters were measured using the average percentage of stance  $\pm 1$  SD as determined for each condition in trials with an impact transient(17).

To explore the individual response to the progressive barefoot training programme, individuals were divided into one of three groups according to a change greater than 1 SD ( $20 \text{ BW} \cdot \text{s}^{-1}$  in loading rate pre- and post-training programme) of the initial barefoot loading rate group mean. Resultant sub-groups included runners who were considered non-responders ( $<1$  SD), positive responders (decreased  $>1$  SD) and negative responders (increase  $>1$  SD).

Data were screened for normality of distribution and homogeneity of variances using a Kolmogorov-Smirnov normality test and a Levene's test, respectively. A student's *t*-test was applied to time related changes of the entire sample population in either barefoot or shod condition. A Two-factor ANOVA was used to investigate differences between the pre- and post-training programme factoring for footwear condition and different group responses for the variables of interest mentioned above. A Tukey's post-hoc analysis was used for multiple comparisons among the groups when appropriate and effect sizes (differences between the means divided by a pooled SD) were calculated between differences. Relationships between variables were further assessed with Pearson correlations. Differences were deemed statistically significant at  $p < 0.05$ . Data are presented as mean(SD). Statistical analysis was performed using Statistical Package for Social Sciences (SPSS) version 22.0 (IBM Corp. Armonk, New York, USA) and Prism 5 (GraphPad Software, Inc., La Jolla, California, USA).

#### 4.4 Results

Of the 29 runners that volunteered to participate, 26 runners completed the full duration of the study. One of the runners performed the first two weeks of the programme and subsequently did not attend the supervised training programmes and was therefore excluded from the study due to non-adherence. Two runners did not commence the training programme after pre-testing as one athlete was diagnosed as having a labral tear and the other iliotibial band syndrome. The resultant group of runners' characteristics are detailed in Table 4.2.

**Table 4.2** Descriptive characteristics of runners participating in the 8-week barefoot running training programme

	Mean(SD)
<i>n</i>	26
Age (yrs)	28.8(5.4)
Body mass (kg)	73.2(11.0)
Height (m)	1.8(0.1)
BMI (kg·m <sup>-2</sup> )	22.6(1.2)
10-km personal best (min)	42.3(5.8)

BMI, body mass index

Table 4.3 depicts the changes in initial loading rate and ankle and knee kinematics at initial ground contact for the entire group in both barefoot and shod conditions, before and after the 8-week barefoot running training programme. No statistically significant changes in initial loading rates were observed after the 8-week programme for any kinetic or kinematic measures during barefoot running. Condition differences were found throughout the training intervention. These included greater loading rate ( $p < 0.001$ ), greater ankle plantarflexion ( $p < 0.001$ ) and greater knee flexion in the barefoot condition ( $p < 0.001$ ).

Spatiotemporal differences included higher stride frequency, shorter ground contact time and shorter stride length in the barefoot condition ( $p < 0.001$ , Table 4.3). An interaction effect was found for stride length, which increased in the shod condition but not in the barefoot condition after the 8-week programme ( $p < 0.05$ ,  $ES = 0.60$ , moderate effect).

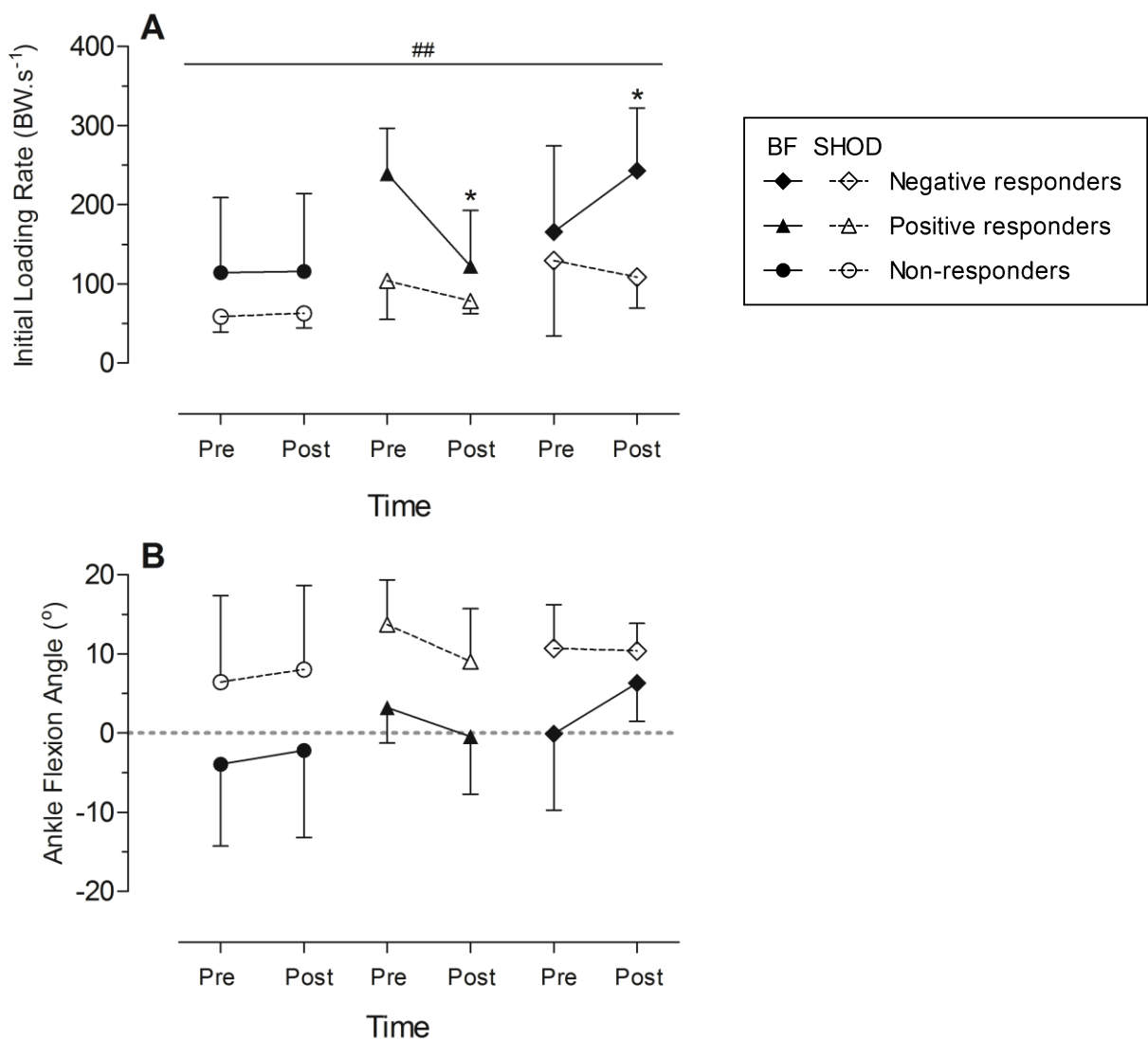
**Table 4.3** Pre- and post- 8-week barefoot training programme changes in ground reactions forces and spatiotemporal variables in the barefoot and shod condition.

Barefoot training	Barefoot		Shod		$\Delta$	
	Pre	Post	Pre	Post	Barefoot	Shod
<b>Ground reaction forces</b>						
Initial loading rate ( $BW \cdot s^{-1}$ )	159.9(101.5)	147.0(99.8)	87.2(59.1) <sup>##</sup>	74.4(29.4) <sup>##</sup>	-12.9	-9.8
Peak apGRF ( $BW$ )	-0.05(0.1)	-0.05(0.1)	-0.07(0.1)	-0.06(0.1)	0.0	+0.01
Peak mlGRF ( $BW$ )	0.29(0.2)	0.31(0.2)	0.34(0.1)	0.31(0.2)	+0.02	-0.03
Peak vGRF ( $BW$ )	2.5(0.2)	2.5(0.2)	2.5(0.2)	2.5(0.2)	0.0	0.0
<b>Spatiotemporal</b>						
Ground contact time (s)	0.26(0.02)	0.26(0.02)	0.27(0.02) <sup>##</sup>	0.28(0.02) <sup>##</sup>	0.00	+0.01
Swing time (s)	0.46(0.04)	0.47(0.08)	0.47(0.04)	0.41(0.20)	+0.01	-0.06
Stride length (m)	2.24(0.21)	2.24(0.27)	2.32(0.24) <sup>##</sup>	2.63(0.70) <sup>*##</sup>	0.00	+0.29
Stride frequency (Hz)	1.39(0.08)	1.38(0.15)	1.35(0.08) <sup>##</sup>	1.27(0.31) <sup>##</sup>	-0.01	+0.08
<b>Kinematics</b>						
<b>Initial ground contact</b>						
<i>Sagittal plane</i>						
Ankle	-1.11(9.18)	0.24 (9.34)	9.38(9.00) <sup>##</sup>	8.84(8.28) <sup>##</sup>	+1.35	-0.54
Knee	15.95(6.04)	16.61(4.95)	14.14(5.54) <sup>##</sup>	14.87(5.98) <sup>##</sup>	+0.66	+0.73
<i>Frontal plane</i>						
Ankle	-1.22(2.85)	-1.46(1.93)	-1.17(3.07)	-1.98(2.46)	-0.24	-0.82
Knee	4.85(5.42)	5.13(4.15)	4.47(4.91)	4.42(4.91)	+0.28	-0.05
<i>Transverse plane</i>						
Ankle	4.60(14.91)	5.39(9.75)	4.62(13.85) <sup>##</sup>	9.09(9.60) <sup>##</sup>	+1.87	+4.88
Knee	-230(13.3)	-21.0(11.0)	-20.6(13.9)	-21.3(11.8)	+2.01	-0.71

\*- significant time difference (\* $p < 0.05$ ; \*\* $p < 0.001$ ); #- significant condition difference (<sup>#</sup> $p < 0.05$ ; <sup>##</sup> $p < 0.001$ ).

The cohort was divided into sub-groups on the basis of the change in barefoot loading rate over the course of the 8-week programme ( $p < 0.001$ ). We identified 13 runners who showed minimal change ( $< 20 BW \cdot s^{-1}$ , average change of  $1.4 BW \cdot s^{-1}$ ) (non-responders), seven with a decrease in loading rate (positive responders) after training (more than  $20 BW \cdot s^{-1}$  lower) and six who increased loading rate by more than  $20 BW \cdot s^{-1}$  after 8 weeks of barefoot running (negative responders).

There were significant differences between the three groups for initial loading rate prior to the training intervention (Table 4.4). The positive responder group had a significantly higher initial loading rate pre-training ( $239.3 \pm 57.4 \text{ BW}\cdot\text{s}^{-1}$  vs.  $114.4 \pm 94.7 \text{ BW}\cdot\text{s}^{-1}$  and  $165.8 \pm 108.6 \text{ BW}\cdot\text{s}^{-1}$  for the non-responder and negative responder groups, respectively). The positive responder group decreased loading rate by  $116.8 \text{ BW}\cdot\text{s}^{-1}$  after training, while the non-responders had a  $77.3 \text{ BW}\cdot\text{s}^{-1}$  increase in loading rate. No significant differences in initial loading rate in any of the three groups were found when shod. The training-related changes in loading rate are shown in Figure 4.1A.



**Figure 4.1** Initial loading rate (A) and initial ground contact ankle flexion angle (B) differences between non-; positive- and negative-responders before and after the 8 week barefoot running training programme. \*- significant time difference (\* $p < 0.05$ ); #- significant condition difference ( $##p < 0.001$ ).

**Table 4.4** Pre- and post- 8-week barefoot training programme changes in ground reactions forces and spatiotemporal variables in the barefoot and shod condition in three different responders.

	<i>n</i>	<b>Barefoot</b>		<b>Shod</b>		<b>Δ</b>	
		<i>Pre</i>	<i>Post</i>	<i>Pre</i>	<i>Post</i>	<i>Barefoot</i>	<i>Shod</i>
<b>Ground contact forces</b>							
<i>Initial loading rate</i>							
Non-responder	13	114.4(94.7)	115.8(98.3)	58.8(19.6)	62.7(18.3)	+1.4	+4.0
Positive responder	7	239.28(57.4)	122.53(70.43)**	103.8(48.8)	78.21(15.7)	-116.8	-25.6
Negative responder	6	165.8(108.6)	243.1(78.7)**	129.5(95.2)	108.5(39.0)	+77.3	-21.0
<b>Spatiotemporal</b>							
<i>Ground contact time (s)</i>							
Non-responder	13	0.25(0.01)	0.26(0.02)**	0.26(0.02)	0.27(0.02)**	+0.01	+0.01
Positive responder	7	0.26(0.02)	0.28(0.02)**	0.26(0.02)	0.29(0.02)**	+0.02	+0.03
Negative responder	6	0.25(0.02)	0.25(0.02)	0.26(0.03)	0.27(0.02)	0.00	+0.01
<i>Swing time (s)</i>							
Non-responder	13	0.47(0.04)	0.50(0.08)	0.48(0.04)	0.46(0.13)	+0.03	-0.02
Responder	7	0.45(0.03)	0.44(0.08)	0.45(0.04)	0.45(0.02)	-0.01	0.00
Negative responder	6	0.47(0.05)	0.46(0.06)	0.48(0.02)	0.47(0.11)	-0.01	-0.01
<i>Stride length (m)</i>							
Non-responder	13	2.24(0.21)	2.29(0.28)	2.33(0.24) <sup>##</sup>	2.29(0.17) <sup>##</sup>	+0.05	-0.04
Positive responder	7	2.24(0.23)	2.19(0.28)	2.28(0.29) <sup>##</sup>	2.26(0.17) <sup>##</sup>	-0.05	-0.02
Negative responder	6	2.26(0.24)	2.19(0.27)	2.33(0.19) <sup>##</sup>	2.28(0.17) <sup>##</sup>	-0.07	-0.05
<i>Stride frequency (Hz)</i>							
Non-responder	13	1.40(0.08)	1.33(0.11)**	1.36(0.09)	1.35(0.27)	-0.07	-0.01
Positive responder	7	1.39(0.05)	1.42(0.20)**	1.35(0.07)	1.35(0.30)	+0.03	0.00
Negative responder	6	1.40(0.11)	1.43(0.17)**	1.35(0.08)	1.35(0.29)	+0.03	0.00

\* - significant time difference (\* $p < 0.05$ ; \*\* $p < 0.001$ ); <sup>##</sup> - significant condition difference (<sup>#</sup> $p < 0.05$ ; <sup>##</sup> $p < 0.001$ )

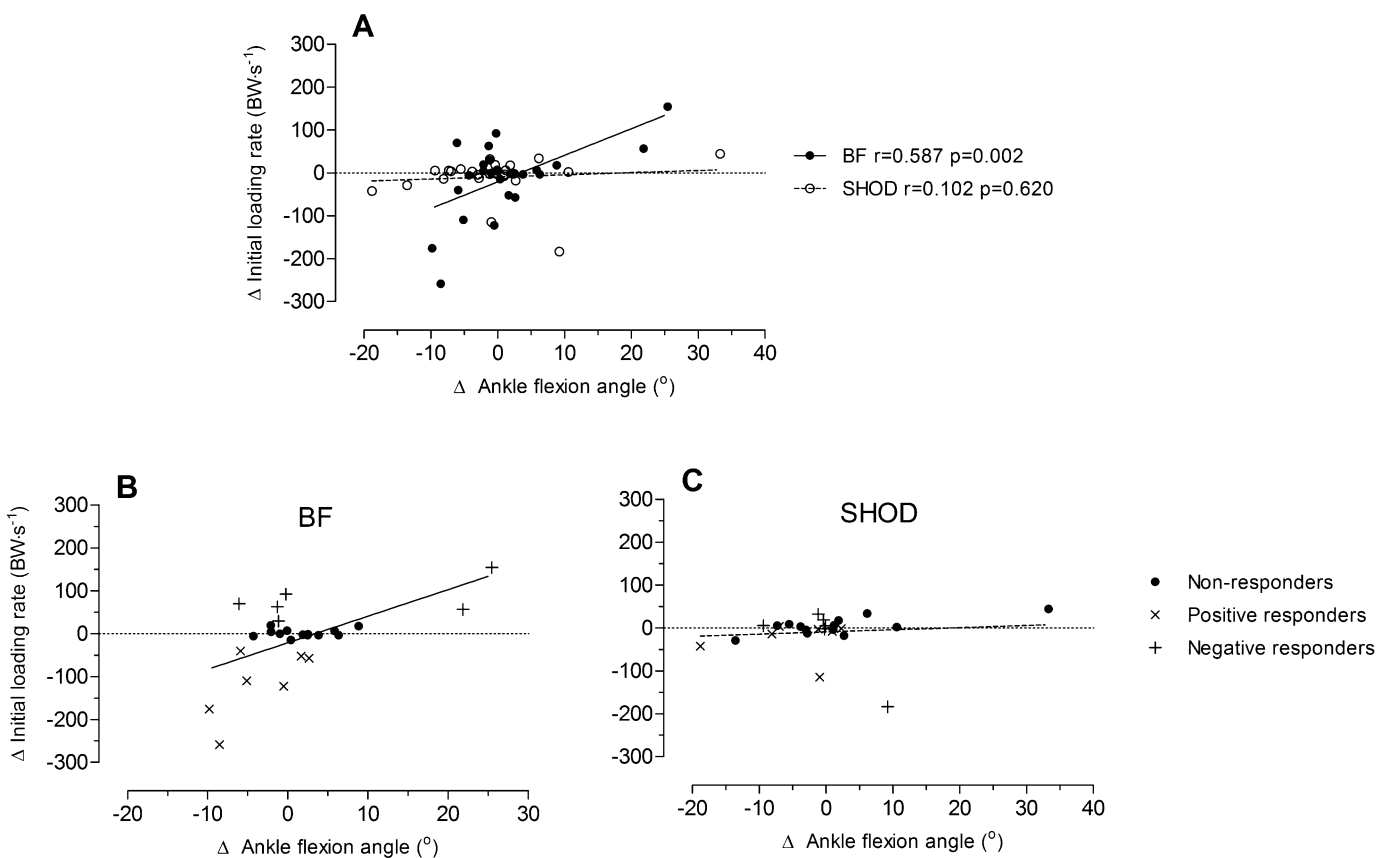
**Table 4.5** Pre- and post- 8-week barefoot training programme changes in sagittal, frontal and transverse plane kinematics in the barefoot and shod condition at initial ground contact in three different responder groups.

	<i>n</i>	<b>Barefoot</b>		<b>Shod</b>		<b>Δ</b>	
		<i>Pre</i>	<i>Post</i>	<i>Pre</i>	<i>Post</i>	<i>Barefoot</i>	<i>Shod</i>
<b>Sagittal plane</b>							
<i>Ankle angle (degrees)</i>							
Non-responder	13	-3.9(10.4)	-2.2(11.0)	6.4(10.9)	8.0(10.7)	+1.7	+1.6
Positive responder	7	3.22(4.5)	-0.4(7.3)**	13.7(5.7)	9.0(6.7)**	-3.7	-4.7
Negative responder	6	-0.1(9.6)	6.3(4.8)**	10.7(5.5)	10.4(3.5)	+6.4	-0.3
<i>Knee angle (degrees)</i>							
Non-responder	13	15.0(6.1)	17.7(5.0)	13.1(4.7)	16.6(5.0)	+2.7	+3.5
Positive responder	7	15.4(3.7)	14.4(3.4)	15.4(5.1)	11.6(4.7)	-1.0	-3.8
Negative responder	6	18.7(8.0)	16.9(6.2)	14.9(8.0)	14.9(6.6)	-1.8	0.0
<b>Frontal plane</b>							
<i>Ankle angle (degrees)</i>							
Non-responder	13	-1.1(2.9)	-1.6(1.9)	-0.8(3.0)	-2.1(2.2)	-0.5	-0.4
Positive responder	7	-1.2(3.9)	-1.1(2.2)	-1.2(4.4)	-0.8(2.6)	0.2	0.4
Negative responder	6	-1.5(1.5)	-1.6(1.0)	-2.0(1.0)	-3.1(2.7)	-0.1	-1.1
<i>Knee angle (degrees)</i>							
Non-responder	13	15.0(6.1)	17.7(5.0)	13.1(4.7)	16.6(6.0)	+2.8	+4.1
Positive responder	7	15.4(3.7)	14.4(3.4)	15.4(5.1)	11.6(4.7)	-2.3	-0.1
Negative responder	6	18.7(8.0)	16.9(6.2)	14.9(8.0)	14.9(6.6)	-0.4	-2.3
<b>Transverse plane</b>							
<i>Ankle angle (degrees)</i>							
Non-responder	13	1.0(13.1)	6.3(8.4)	3.5(13.7)	8.4(8.8)	+1.9	+2.0
Positive responder	7	4.7(19.9)	2.4(11.5)	3.2(19.8)	7.6(7.1)	+2.2	+5.1
Negative responder	6	7.2(8.6)	7.0(11.4)	8.5(3.5)	12.4(14.0)	+0.2	+7.9
<i>Knee angle (degrees)</i>							
Non-responder	13	-23.6(15.4)	-19.9(12.4)	-19.1(15.1)	-18.8(13.4)	+3.7	+0.3
Positive responder	7	-23.4(12.8)	-24.6(7.4)	-21.3(13.9)	-25.3(8.5)	-1.2	-4.0
Negative responder	6	-21.4(10.9)	-19.3(11.9)	-23.0(13.1)	-22.2(11.9)	+2.1	+0.8

\*- significant time difference (\*p<0.05; \*\*p<0.001);

Figure 4.1B shows the ankle flexion angle at ground contact. Ankle plantarflexion increased in both barefoot and shod running in the positive responder group (moderate effect, ES=0.6). In contrast, the non-responders displayed a 6.4° increase in ankle dorsiflexion when barefoot (moderate effect, ES=0.84). Sagittal ankle angle did not change over the training intervention in the non-responders (Table 4.4).

Figure 4.2 depicts the relationships between the change in loading rate and the change in ankle angle during barefoot running after the training programme. An increase in ankle dorsiflexion angle at initial ground contact was positively associated with an increase in initial loading rate over the intervention period (Figure 4.2A,  $r=0.59$ ,  $p=0.002$ ). This relationship was not found in the shod condition ( $r=0.10$ ,  $p=0.620$ ). The three sub-groups are identified with different symbols for the barefoot (Figure 4.2B) and shod (4.2C) conditions.



**Figure 4.2** The relationship between the change ( $\Delta$ ) in initial loading rate and change ( $\Delta$ ) in initial ground contact ankle flexion angle (A). This relationship is further broken down into the non-, positive- and negative-responders for both barefoot (BF) (B) and shod (SHOD) (C) conditions.

The training programme did not produce any injuries or symptoms that forced participants to miss or postpone training sessions. Muscle pain scores for the barefoot programme ranged between 1-6 and 1-5 at week one and eight, respectively (Table 4.5).

**Table 4.6** Mean (SD) session rating of perceived exertion and muscle group pain scores at week 1 and 8 of barefoot running training

	<b>Barefoot</b>		<b>Range</b>	
	<i>Week 1</i>	<i>Week 8</i>	<i>Week 1</i>	<i>Week 8</i>
<b>Session</b>				
RPE (1-10)	4.9(1.5)	5.7(1.1)	2-7	4-8
<b>Muscle group pain scale (1-10)</b>				
<i>Gastrocnemius</i>	3.3(2.5)	3.0(1.7)	1-9	1-5
<i>Tibialis anterior</i>	2.1(1.9)	1.9(1.7)	1-7	0-5
Quadriceps	2.3(2.1)	2.0(1.8)	1-7	0-5
Hamstrings	2.1(2.2)	2.1(2.3)	1-7	0-7
Gluteal	1.9(1.7)	1.7(1.7)	1-6	0-5

#### 4.5 Discussion

This prospective study aimed to evaluate the changes in kinematic and kinetic variables in habitually shod runners who undertook a progressive 8-week pure barefoot running programme. We wished to investigate whether these runners displayed adaptations in kinematic and kinetic factors as a result of barefoot running without overt instruction, and whether these adaptations would occur in a direction that is purportedly favourable for injury risk.

Our first important finding was that no kinematic or kinetic variables changed across the group as a result of the 8-week training intervention. Specifically, given previous published literature showing that habitually barefoot runners have significantly lower loading rates than habitually shod runners when running barefoot(17), we focused on initial loading rate. This variable has also been associated with injury risk and used to advocate for a potential benefit of barefoot running(17,37) and is thus of particular interest and relevance to the barefoot running debate for clinical and practical purposes. However, we found no overall change in this variable in either the barefoot or shod condition after training.

This is the first study of a prospective nature to investigate both kinematic and kinetic adaptations to pure barefoot running. Previous research has investigated adaptations, primarily footstrike and foot pressures, associated with running in minimalist shoes. For instance, McCarthy et al. (2014) found that female runners progressed towards a purportedly favourable forefoot strike pattern over the course of a longer 12-week training intervention period using minimalist shoes(72). We have found no such changes and attribute their different finding to a relatively small sample size (n=9) and perhaps more significantly, their brief instruction prior to onset of the study that stated “*Participants were free to develop their own running pattern during minimalist training. However, for participant safety reasons, participants were advised at the start of the transition program that overstriding or adopting an rear-foot striking pattern in the minimalist footwear may increase the likelihood of pain or injury and were thus best avoided*”(72).

Thus, participants in the above-mentioned study cannot be considered free to adopt an individual running pattern, and the advice provided by the researchers may have prompted a conscious change in footstrike pattern as has been seen in other minimalist and simulated barefoot running training studies(73,116). We chose not to provide any instruction to our participants, because we wished to test the effect of footwear without conscious technique changes, which we consider more valid and representative of what a typical runner may do when transitioning from cushioned shoes.

Other expected changes associated with the familiarity of barefoot running, including increased plantarflexion and increased knee flexion, did not occur on average after the 8-week barefoot programme. Condition differences persisted in both sagittal ankle flexion angle at initial ground contact and initial loading rate after the training intervention. Abundant research has examined acute condition differences between barefoot and various types of footwear, with most observing higher initial loading rates in the barefoot than shod condition (93,116,118), including Chapter 3 of this thesis. These studies have examined habitually shod runners' response to barefoot running, with only Lieberman et al. (2010) studying the initial loading rate in habitually barefoot runners (17). They found that habitually barefoot runners had significantly lower loading rates than habitually shod runners, which invited the hypothesis of the present study that initial loading rate would be among the variables to change with barefoot familiarity.

This did not occur, and the typical differences between footwear conditions persisted after our 8-week programme. These differences between footwear conditions have equivocal implications, and may not necessarily indicate a successful adaptation to barefoot running and lower injury risk, as previously mentioned(95). At first glance it could be concluded that an uninstructed 8-week barefoot running programme did not change gait biomechanical characteristics. However, upon closer investigation of initial loading rate data this appears not to be the case for all individuals in the sample population.

We investigated the individual responses to training, since we have previously found that

the acute response to barefoot running is highly individual (Chapter 3). This revealed the presence of runners who displayed large positive changes, large negative changes and those who showed little change in initial loading rate after 8-weeks of barefoot running. The change in loading rate identifying the positive and negative sub-groups can again be characterised, at least in part, by their change in ankle angle on impact, since the positive responders increased ankle plantar-flexion after 8-weeks. In contrast, those runners who increased loading rate displayed increased dorsiflexion of the ankle after the training intervention (Table 4.3 and Figure 4.1).

Consequently, there was a positive association between the change in loading rate and the change in sagittal ankle angle, such that a shift towards greater plantarflexion predicts a reduction in loading rate (Figure 4.2A). Of note is that this relationship existed only for barefoot, but not shod running. Collectively, this relationship between the ankle angle on impact and the initial loading rate confirms our previous findings regarding acute differences between barefoot and shod running, where runners who landed in ankle dorsiflexion when barefoot could be predicted as having a greater loading rate in the barefoot condition. This study extends that relationship to the adaptation of barefoot running biomechanics within certain individuals.

An important consideration is that the identified positive responders began the 8-week programme with significantly higher loading rates than the non- and negative responders (Figure 4.1A and Table 4.4). As we showed previously (Chapter 3), runners with high initial loading rates on first exposure to barefoot running tend to have greater ankle dorsiflexion. We found a similar magnitude of difference in sagittal ankle angle here (Figure 4.1B), though the smaller sample size may have prevented it from being statistically significant. However, we did observe that the positive responders increased plantarflexion while negative responders changed in the direction of dorsiflexion after training. Thus, it may be that positive responders to barefoot training can be identified as having higher loading rates and more dorsiflexion initially. This creates an important question as to who is more suited to

barefoot running: individuals with lower loading rate initially, but who may increase with time, or those who respond with a decrease in loading rate as a result of high initial values? This is a concept for future research to explore.

These observations support our hypothesis that not all runners instinctively adopt the favourable changes often purported by evolutionary biologists (24). Instead, it may be that a majority of individuals require individualised training approaches and gait instruction, and may not be responsive to the barefoot stimulus alone. Other, biomechanical variables that may identify a priori for different responses beside ankle flexion angle at initial ground contact remain equivocal. However, possible neuromuscular variables may shed some light in this regard.

It must be acknowledged that a gradual progression to 40 minutes of barefoot running over 8 weeks may not be sufficient time or barefoot running volume to drive changes in barefoot running biomechanics in all individuals. Robbins and Hanna (1987) suggested that full barefoot adaptation may require a lifestyle commitment to the barefoot condition, which they found changed both the morphological as well as the dynamic properties of the lower limb including the structure and function of the foot(17,22). Our analysis reveals that some runners display large kinematic and kinetic adjustments within the 8-weeks (Figure 4.2), while others do not. Whether these non-responding runners would display biomechanical changes with greater exposure to barefoot running is unknown.

It has been shown that conscious instruction is effective in changing running biomechanics. This has been shown in studies where both in-depth instruction including specific exercises related to the lower limb(73) and even minor cues(72) have been provided. These studies noted shifts to the purported favourable kinematics such as increased plantarflexion and greater mid-/forefoot strike pattern and possible associated kinetics, though these were not measured.

Samaan et al. (2014) provided conscious instruction to runners while running barefoot and found that all loading variables were reduced compared to the shod condition, even on first exposure. This further emphasises that runners choosing to embark on transitioning to barefoot running may require gait retraining(92). However, this must be undertaken with caution, since the unfamiliarity may increase injury risk in other areas. For example, increased bone stress injury has been shown to occur over a 10-week transition to minimalist running(68).

Changes in muscle activation patterns and the application of force to unaccustomed joints may further increase risk of injury(112). We describe the changes in muscle activation after barefoot training in a subsequent chapter (Chapter 5), but previous studies have noted increased gastrocnemius pre-activation during barefoot running(75), and concluded that collateral noxious effects may arise such as metatarsal stress injuries, shin splints, and muscular and tendon injuries if not carefully and progressively conducted(119). Further prospective studies should determine whether the barefoot transition towards a consistent mid- or forefoot pattern is achievable and not defer injury risk such as Achilles tendinopathy(75).

We found no significant injuries (forcing rest and requiring treatment) in our sample of 26 runners. Minor foot discomfort was reported, particularly early during the programme, as a result of foot and sole interaction with the external environment. These included blisters and tender feet. Calf muscle and plantar fascia tightness and soreness were another common symptom, but did not require any participants to miss training days. This is the result of our very conservative approach towards introducing barefoot running, particularly given that all the runners were well trained and thus adapted to running.

This 8-week barefoot transition programme was prescribed on time rather than mileage or training intensity to encourage adherence as well as familiarity and comfort during training. However, this limited the ability to exactly determine the training “dose” of barefoot running for each individual. Of note, this study utilised overground running trials that allowed for

ecological biomechanical and neuromuscular evaluation of the runners in the two different footwear conditions. We also chose not to use a control group who would continue running their normal distances in cushioned shoes. This was done for practical reasons, and we argue that there would be no reason to expect a change in biomechanics in this control group, and nor would there be a placebo effect, making the control group unnecessary. Instead, we utilised a phased introduction of barefoot running as an intervention in a group that would otherwise have maintained the same biomechanics.

Further prospective trials should be conducted to determine whether positive changes could possibly continue to evolve or be initiated and whether the negative responders may eventually adapt. . This may be elicited with a longer training study as 8-weeks may be insufficient to stimulate beneficial changes. Additionally, studies should also prospectively evaluate injury prevalence and frequency.

#### **4.6 Conclusion**

This study found large variation in the responses to barefoot training, with the result that mean kinematic and kinetic barefoot running characteristics were unchanged over an 8-week progressive pure barefoot running programme. Within the group, we identified positive and negative responders, who can be characterized in part by the changes in ankle angle on impact. This questions the generalisability of the instinctive ability for all humans to adopt the typical barefoot running gait as suggested by previous researchers.

These findings confirm previous research that identifies potential responders to barefoot running by ankle kinematics, and suggests that conscious instruction may be required to facilitate biomechanical changes, at least in the short term.

## **CHAPTER 5**

### **THE ASSOCIATION OF INITIAL LOADING RATE AND LOWER LIMB MUSCLE PRE-ACTIVATION AFTER AN 8-WEEK BAREFOOT RUNNING TRAINING PROGRAMME**

## 5.1 Abstract

**Aim:** To describe changes in neuromuscular activity during pre-activation and stance phase, and relate them to the initial loading rate when barefoot and shod after an 8-week barefoot training programme.

**Methods:** Twenty-one runners completed an 8-week progressive barefoot running training programme. Before and after this intervention, ground reaction force and surface electromyography data were collected in the barefoot and shod condition. Pre-activation and stance phase activity of the *gluteus medius* (GM), *biceps femoris* (BF), *rectus femoris* (RF), *peroneus longus* (PL), *tibialis anterior* (TA) and *gastrocnemius lateralis* and *medialis* (LG and MG) were assessed, along with initial loading rate.

**Results:** LG and MG pre-activation were greater in the barefoot condition before and after the training intervention. This difference was also seen in the LG during stance phase. GM activity during stance phase was increased post-training intervention in both footwear conditions. MG pre-activation was associated with lower initial loading rates before the training programme, while after GM, PL and TA pre-activation when barefoot were associated with initial loading rate after training. Runners who decreased loading rate after training displayed increased BF and GM activity and decreased RF activity when barefoot.

**Conclusion:** The inverse relationship between loading rate and posterior muscle group pre-activation and the positive relationship with TA activation suggests that a neuromuscular strategy, which presumably alters the stiffness and kinematics of the lower limb joints, contributes to ground reaction forces. Training-induced changes in GM activity, and the specific changes occurring in the positive responders who reduce loading rate, suggest that neuromuscular strategies can be acquired through training, though the extent and nature of these changes requires further investigation.

**Keywords:** exercise, sport, biomechanics, electrophysiology.

## 5.2 Introduction

We have previously found that an 8-week progressive barefoot running training programme does not alter mean kinematic or kinetic variables, but that large individual responses to barefoot training occur. Further, runners can be categorised as belonging to groups that either respond with a decrease, increase or no change in initial loading rate (Chapter 4). This difference in response, while arguably complex and multi-factorial, was related in part to the change in ankle flexion angle on initial ground contact, with those runners decreasing their initial loading rate presenting with greater plantarflexion after the training programme.

The relationship between ankle angle and loading rate, which we have found for both acute barefoot and shod differences (Chapter 3)(23,60,120), and after 8-weeks of barefoot training (Chapter 4)(72,73), suggests the importance of kinematics prior to landing on ground contact kinetics. These different loading rate responses may be affected by the neuromuscular control of lower limbs segments. As such, underlying neuromuscular activation patterns may further reveal the mechanisms and strategies that explain the different responses to barefoot running, both acutely and with repeated exposure.

Previous research has suggested that muscle activation strategies and resultant kinematics prior to initial ground contact influence loading rate(69,117). This has been shown using neuromuscular modelling of muscle activity and lower limb segment velocity prior to ground contact(34,74,75) to determine its influence on the loading of structures during stance. Previous research has found that an increased quadriceps muscle activity is associated with a reduction in initial loading rate during walking, and this may be practically relevant as clinicians may be able to focus on modulation of certain muscle groups to affect treatment or prevention of injury(121,122).

As initial loading rate occurs early during stance, it may be of value to consider muscle activation immediately prior to ground contact. The modelled effect of muscle activation during the swing phase on the initial loading rate found that increased hip flexor

(quadriceps) activity throughout swing phase decreases initial loading rate and the impact peak by modulating mid-swing kinematics and reducing landing velocity(34,74).

Also of interest may be the pre-activation of muscle, that activity which occurs within 100ms of contact(75,123,124). This muscle activation is proposed to influence the stiffness of the joints and prepare the locomotor system for the landing and the subsequent ground contact(34,111). It was recently shown that *gastrocnemius lateralis* pre-activation increases while *tibialis anterior* pre-activation decreases when runners are asked to run with a mid-foot strike(75,98). This was associated with a reduction in loading rate, presumably as a result of the footstrike. Nevertheless, it is worth considering whether our previous findings regarding the variability in acute and trained responses to barefoot running may be influenced by the ability of the runner to adapt their muscle activation strategy as part of being able to achieve the kinematic adaptations associated with the changes in loading rate.

Accordingly, the aim of the present study was to describe the neuromuscular activity and examine the initial loading rate, before and after a systematic and progressive 8-week pure barefoot training programme. Based on our previous findings that loading rate is positively associated with ankle angle on ground contact, we hypothesised that posterior muscle groups including ankle plantarflexors (*lateral* and *medial gastrocnemius*) would display increased muscle activity during the pre-activation phase in runners with lower loading rates. Further, we hypothesised that the muscles around the hip (*gluteus medius*, *biceps femoris* and *rectus femoris*) that both mobilise and stabilise this joint and the lower limb would be related to the initial loading rate. This would be the result of learned neuromuscular responses prior to landing that modulates the landing posture, joint moments and energy absorption of the lower limb prior to ground contact in response to the barefoot training programme.

## **5.3 Materials and Methods**

### **5.3.1. Participants**

Twenty-one habitually shod runners participated in this study. Participants were able to run 10 km in <60 minutes, trained at least 4 hours a week (5 sessions per week), had no previous experience or had not engaged in barefoot running within 6 months of the study and were injury free in the lower limbs for six months prior to the study. Participants provided written informed consent and were fully aware of the benefits and potential risks associated with the study and were free to voluntarily withdraw at any stage. The study was performed in accordance with the principles of the Declaration of Helsinki (Seoul, 2008) and ethical approval was granted by the Human Research Ethics Committee of the University of Cape Town (HREC 504/2011).

### **5.3.2 Study design:**

The study was an 8-week progressive barefoot running training programme, where participants performed laboratory trials before and after an 8-week period. All visits included experimental overground running trials. All trials were performed within two days of a fortnightly testing schedule.

### **5.3.3 Progressive Barefoot Training Programme:**

The detailed programme was described in Chapter 4. Briefly, the progressive barefoot training programme proportionally replaced segments of the participants' current training programme on any three days per week. This gradually introduced barefoot running in increasing amounts over the 8-week period. Participants added the barefoot sessions to the end of their current training sessions, which were shortened by the length of the barefoot session.

Barefoot training was supervised by the investigator, and was performed three times per week (Table 4.1). Participants were not briefed whether they should adopt any type of

footstrike pattern and were instructed to run in a manner that maximised their subjective comfort.

#### **5.3.4 Experimental conditions:**

Participants reported to the laboratory pre- and post-programme, with measurements obtained in two different conditions: (1) Barefoot and (2) the typical shoe in which they were currently completing the most training mileage (hereafter called shod). All shod midsoles comprised of traditional EVA and were not controlled for mileage, shore count or heel-toe drop. Footwear conditions were tested in a randomised order.

#### **5.3.5 Instrumentation:**

Running trials for the experimental condition were conducted on a 60 m indoor synthetic running track. Three-dimensional marker trajectories were captured using an eight-camera VICON MX motion analysis system (Oxford Metrics Ltd, Oxford, UK), sampling at 250 Hz. Ground reaction force (GRF) data were collected using two 900 x 600 mm AMTI force platforms (AMTI, Watertown, MA, USA), sampling at 2000 Hz. A standard PlugInGait marker set was used and the capture volume had a length of 9 m and a height of 1.5 m this allowed adequate distance for the absence of acceleration and deceleration.

#### **5.3.6 Procedures:**

Participants completed 6 clean overground running trials in each footwear condition at 3.5 m·s<sup>-1</sup>. During these runs, synchronised collection of marker motion and force platform data was obtained with VICON Nexus (VICON, Oxford Metrics, Oxford, UK). A successful trial was defined as one within the specified velocity range, where all markers were in view of the cameras, the right foot made full contact with a force platform and there was no obvious visual evidence that the runner targeted the force platform or altered their gait prior to force platform contact. Surface electromyography (EMG) was measured for all conditions in eight right lower limb muscles, namely *gluteus medius* (GM), *vastus lateralis* (VLO), *biceps femoris* (BF), *peroneus longus* (PL), *tibialis anterior* (TA) and *gastrocnemius lateralis* and

*medius* (LG and MG, respectively). Prior to placement, the skin areas where the electrodes were placed were shaved and vigorously cleaned with ethanol swabs(99). Two surface electrodes (Blue Sensor, Ambu, Medicotest, Denmark) were placed on the muscle location according to SENIAM guidelines(100) Leads and pre-amplifiers connected to the electrodes were secured with medical grade tape to avoid artefacts from lower limb movement during running. The transmitter unit was secured in a harness strapped to the participant's back. Data were sampled at 2000 Hz (Noraxon 2400T G2, Noraxon, Arizona, USA). To ensure marker placement location, steps taken for re-identification included, visible surface area devoid of hair was removed in the location of muscle belly, permanent markers pens around the electrode sites when electrodes were placed on and photographs were employed to visually focus on specific areas for replication.

After completing six successful running trials at the clamped speed, the runners then completed three maximal sprints down the athletic track in the shod condition.

### **5.3.7 Data analysis:**

A customised MATLAB (Mathworks Inc., Natick, USA) program was used to extract gait phase related data for each participant's right limb from concomitant force platform and kinematic data. Ensemble averages were obtained from the 6 trials for each condition and graphed over the gait cycle (one stride). Stance phase was defined as the time over which a vertical force from the force platform exceeded one standard deviation (SD) above baseline force platform noise and continued to elevate. Stance time for variable extraction was defined as the time over which a vertical force exceeded one SD above baseline force platform noise.

The raw digital EMG signal was processed using Noraxon's Myoresearch XP software (Version 1.8.07), processed using a 15–500 Hz band pass filter. This allowed noise or movement interference below 15 Hz and other non-physiological signals above 500 Hz to be removed. The data were smoothed using route mean squared analysis, which was

calculated for a 50 ms window.(99). The processed EMG from the fastest sprint was analysed by isolating three peak amplitude contractions from the middle of the sprint recording. The sub-maximal EMG data from clamped speed trials were expressed as a percentage of the fastest sprint (%sprint max). Average EMG activity was calculated for pre-activation and stance phase, reported as a percentage of maximal sprint activity (%sprint max). Pre-activation was defined as the EMG activity during the 100 ms before ground contact.

To explore the individual response to the progressive barefoot training programme, individuals were segmented in three groups according to a change  $>1$  SD of the initial barefoot loading rate group mean, as for Chapter 4. This produced the groups we described previously, namely non-responders ( $<20 \text{ BW}\cdot\text{s}^{-1}$  in loading rate pre- and post-training programme), positive responders (decreased  $>20 \text{ BW}\cdot\text{s}^{-1}$ ) and negative responders (increase  $>20 \text{ BW}\cdot\text{s}^{-1}$ ).

The Kolmogorov–Smirnov test with a Lilliefors significance correction was performed on all measured variables to determine their distribution and homogeneity of variances was tested using a Levene's test. A two-factor ANOVA was used to investigate differences between EMG and kinetic variables pre- and post-training programme factoring for footwear condition. Further analyses between different group responses for the variables of interest mentioned above were also assessed. A Tukey's post-hoc analysis was used for multiple comparisons among the groups when appropriate. Relationships between EMG and initial loading rate variables were further assessed with Pearson correlations. Differences were deemed statistically significant at  $p<0.05$ . Data are presented as mean(SD). Statistical analysis was performed using SPSS version 22 (IBM Corp. Armonk, New York, USA) and Prism 5 (GraphPad Software, Inc., La Jolla, California, USA).

## 5.4 Results

All twenty-one runners completed this study. Runner's general characteristics are listed in Table 5.1. The mean running speed during over-ground running trials was  $3.5 \pm 0.4 \text{ m}\cdot\text{s}^{-1}$  and there were no differences in running speed between the footwear conditions.

**Table 5.1** Descriptive characteristics of participants

	Mean(SD)
<i>n</i>	21
Age (yrs)	29.0(5.9)
Body mass (kg)	71.2(10.8)
Height (m)	1.7(0.1)
BMI ( $\text{kg}\cdot\text{m}^{-2}$ )	24.6(1.2)
10-km personal best (min)	43.2(4.2)

BMI, body mass index

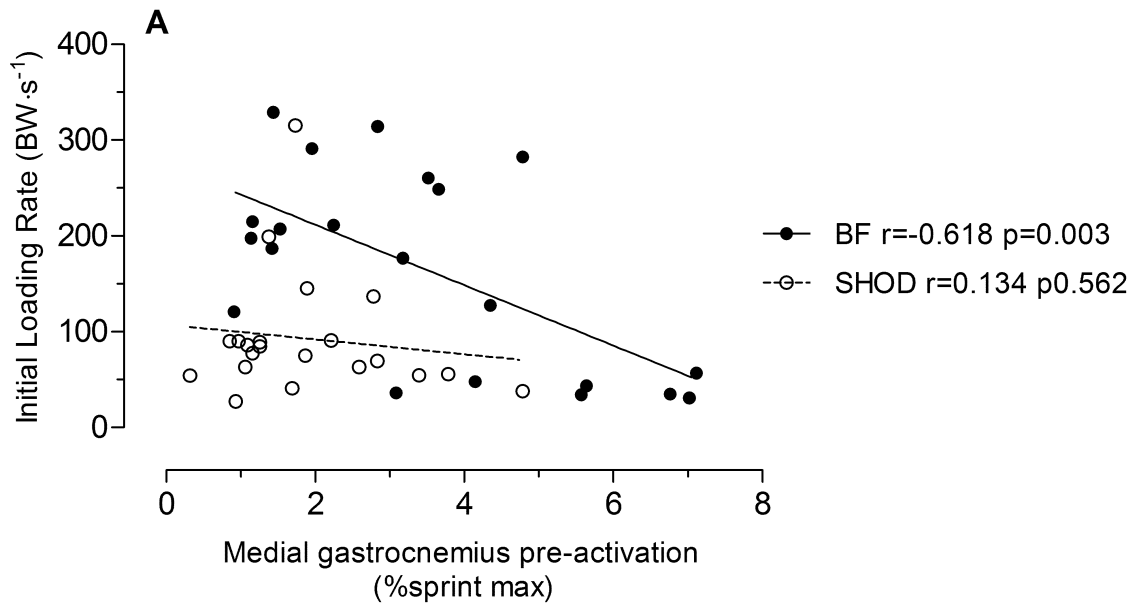
Training-induced changes in the two footwear conditions are detailed in Table 5.2. Muscle activity differences that persisted between barefoot and shod conditions after the training intervention were found in the plantarflexors. LG activity was significantly greater during stance phase in the shod condition at week 1, while LG and MG pre-activation were higher in the barefoot condition at both week 1 and 8 ( $p < 0.001$  BF vs. SHOD, Table 5.2). The GM activity increased significantly after the 8-week barefoot training programme (2.5 and 1.6% increases in the barefoot and shod condition, respectively).

Prior to 8-weeks of barefoot training, higher MG pre-activation was associated with a lower initial loading rate ( $r = 0.618$ ,  $p = 0.003$ , Figure 5.1). Following the 8-weeks of progressive barefoot running, initial loading rate was inversely associated with GM pre-activation (Figure 5.2A), PL pre-activation (Figure 5.2B) and GM activity during stance (Figure 5.2D). In contrast, loading rate was positively associated with TA pre-activation (Figure 5.2C), and BF activity during ground contact (Figure 5.2E). No significant association between initial loading rate and LG or MG activity was found after the training program.

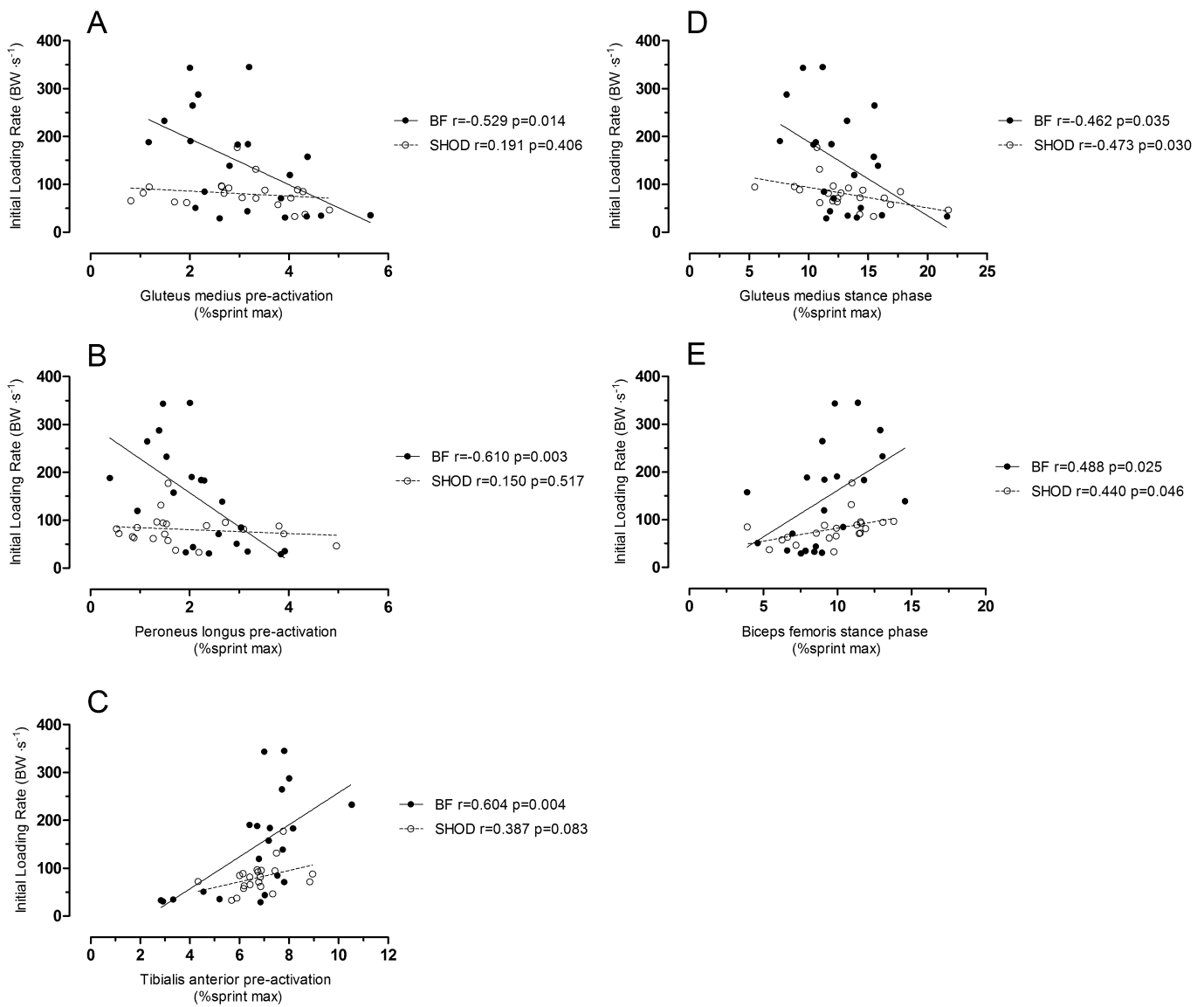
**Table 5.2** Pre- and post- 8-week barefoot training programme changes in pre-activation and ground contact muscle activity of the lower limb in the barefoot and shod condition.

Barefoot training	Barefoot		Shod	
	Pre	Post	Pre	Post
<b>Pre-activation (%sprint max)</b>				
<i>Gluteus medius</i>	3.0 (1.5)	3.1(1.2)	3.4(1.6)	3.0(1.2)
<i>Biceps femoris</i>	5.4(2.0)	5.4(1.5)	5.2(2.0)	5.1(1.4)
<i>Rectus femoris</i>	2.1(0.9)	2.0(0.8)	2.0(0.8)	1.8(0.8)
<i>Gastrocnemius lateralis</i>	2.2(1.7)	2.5(1.5)	1.8(1.3) <sup>##</sup>	1.8(1.2) <sup>##</sup>
<i>Gastrocnemius medialis</i>	3.5(2.0)	3.3(1.9)	1.9(1.1) <sup>##</sup>	2.3(1.4) <sup>##</sup>
<i>Peroneus longus</i>	2.2(1.1)	2.2(0.9)	2.0(0.9)	1.9(1.2)
<i>Tibialis anterior</i>	6.3(1.4)	6.6(1.9)	6.7(1.7)	6.8(1.0)
<b>Ground contact (%sprint max)</b>				
<i>Gluteus medius</i>	10.3(2.6)	12.8(3.2)*	11.4(2.2)	13.0(3.5)*
<i>Biceps femoris</i>	9.7(3.2)	9.2(2.6)	10.3(3.0)	9.7(2.6)
<i>Rectus femoris</i>	10.0(2.1)	12.9(1.6)	11.0(2.5)	12.9(1.6)
<i>Gastrocnemius lateralis</i>	12.2(2.3)	12.9(2.2)	13.6(3.4) <sup>##</sup>	13.2(1.5)
<i>Gastrocnemius medialis</i>	13.4(2.7)	10.7(1.7)	13.8(3.6)	10.6(1.5)
<i>Peroneus longus</i>	12.1(2.0)	12.6(1.9)	12.0(1.9)	12.4(1.8)
<i>Tibialis anterior</i>	5.3(1.8)	6.1(3.2)	5.4(2.3)	6.0(1.8)

\* - significant time difference (\*p<0.05); <sup>##</sup> - significant condition difference (p<0.001)

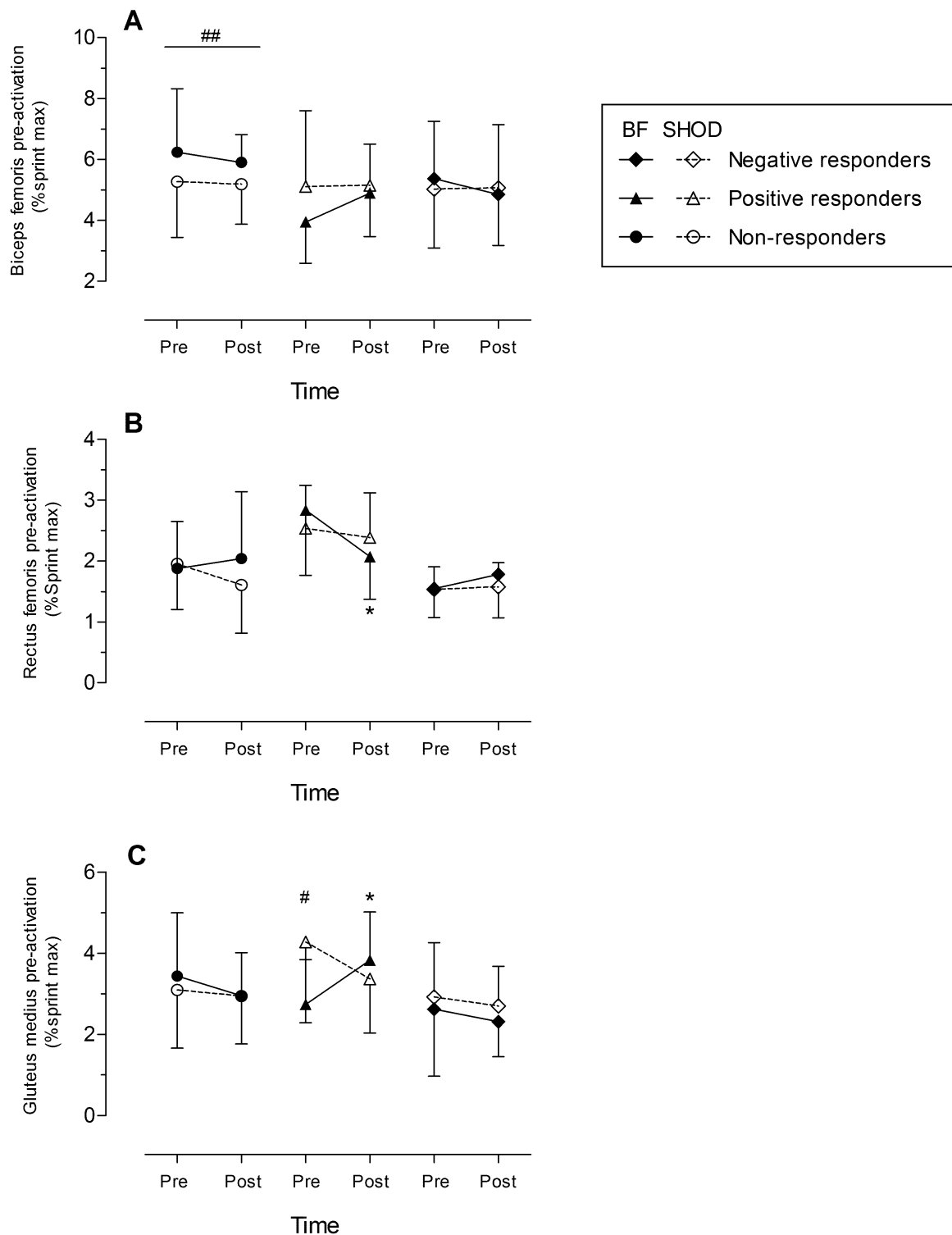


**Figure 5.1** Relationship between *gastrocnemius medialis* pre-activation and initial loading rate before commencement of the barefoot running training intervention



**Figure 5.2** The relationships between initial loading rate and the *gluteus medius* (A), *peroneus longus* (B), and *tibialis anterior* (C) pre-activation *gluteus medius* (D) and *biceps femoris* (E) muscle activation during stance phase after the training intervention.

Figure 5.3 displays the muscle activity during pre-activation and stance phase for the previously described sub-groups of non-responders, positive responders and negative responders (grouped by loading rate changes as described in Chapter 4). *Gluteus medius* pre-activation was significantly greater in the positive responder group in the shod condition before training (Figure 5.3C). After training, the positive responder group significantly increased pre-activation of the GM in the barefoot condition only (Figure 5.3A).



**Figure 5.3** Significant changes in *biceps femoris* (A), *rectus femoris* (B) and *gluteus medius* (c) pre-activation over the 8 week barefoot running training intervention in the three categorised responder groups

Pre-activation of BF was significantly greater in the non-responders before and after training (Figure 5.3B). *Rectus femoris* pre-activation decreased significantly from the start to the end of the training programme in the positive responder group, whereas no changes were observed in the non-responder or negative responder groups (Figure 5.3C).

## 5.5 Discussion

This study examined the effect of barefoot running training on muscle activity in seven muscle groups of the lower limb. We have found a number of significant differences between footwear conditions, but more notably also changes after a training programme that suggest a neuromuscular adaptation to the progressive introduction to barefoot running that has not been documented previously. We also explored relationships between muscle activation and loading rate, given the previous findings in this thesis, identifying individuals who appear to respond favourably to barefoot running and those who respond negatively.

Our primary finding is that the pre-activation of numerous muscles of the lower limb are significantly associated with loading rate when barefoot, but not shod. Thus, in the absence of shoe cushioning the neuromuscular strategy prior to initial ground contact is a potential contributor to initial loading rate, presumably partly as a result of a shift from rear-foot to mid-foot striking in the barefoot condition(75,125). We have also found this general change in footstrike, both acutely (Chapter 3) and after training (Chapter 4), but noted large variability in responses, such that increased plantarflexion occurred in only 52% of this population, even after training.

The ability of individuals to acquire the typically observed kinematic and kinetic changes when barefoot running must have a neuromuscular basis, and this formed the primary question of this study. We found that only MG pre-activation was negatively associated with initial loading rate prior to the onset of the training intervention. This finding is in general agreement with previous research that found that increased LG and decreased TA pre-activation was associated with reduced initial loading rates when a mid-foot gait was adopted(75). In this study, footstrike pattern was not manipulated, but the increased *gastrocnemius* activity when barefoot compared to shod, as well as the reduced loading rate in individuals with the highest MG pre-activation may be the consequence of a shift towards mid-foot striking. Indeed, we have related loading rate to ankle angle in previous studies (Chapter 3 and Chapter 4), which supports this possibility, and suggests a

neuromuscular strategy that underlies it. By the end of the 8-week training programme, we did not find a significant association with the MG, but instead a similar inverse relationship with PL pre-activation and a positive relationship between loading rate TA pre-activation. The latter was also found increased initial loading rate by Giandolini et al. (2013)(126). Therefore, it may be that shank muscle pre-activation activity is related to initial loading rate via the footstrike pattern or ankle dorsi-plantarflexion.

Other notable associations include decreased initial loading rate as GM pre-activation increases. The GM is responsible for balancing the weight of the body and lateral stabilisation of the pelvis(126), and running injury has been attributed to compromised lateral stability as a result of reduced GM activation(127). The relationship we have found suggests that increasing GM pre-activation reduces the loading rate, which we theorize is the result of stabilising the centre of mass to reduce forces during ground contact. It has previously been shown that muscle pre-activation is greater when running in hard-soled shoes(128), with the concept of muscle tuning proposing that changes in muscle activity occur to minimise soft tissue vibrations(34).

We cannot discern whether increased pre-activation is the consequence or the cause of reduced loading rate. The former would argue in favour of muscle tuning, suggesting that loading rate is an input signal, and that runners who present with lower loading rates pre-activate posterior muscle groups more than those with high loading rates(34,129). The latter would suggest that greater pre-activation is responsible for reducing loading rate, possibly as part of a neuromuscular strategy that may change the distribution of the outcome (initial loading rate) on the locomotor system(74).

Collectively, we have found inverse relationships between initial loading rate and the posterior muscle groups, and a positive relationship in an anterior muscle group (TA). We propose that runners who achieve the lowest loading rates when barefoot do so by increasing pre-activation of the GM and PL, while decreasing TA pre-activation. This would be part of an overall muscle activation strategy that is reflected in the pre-activation findings.

That is, greater pre-activation in the posterior muscles prepares the locomotor system for the landing and subsequent ground contact when barefoot, thus reducing the initial loading rate. In contrast, when cushioning is provided by shoes, these relationships do not exist, which suggests that the requirement to prepare for the landing through this pre-activation strategy is lessened by the cushioning.

With respects to the GM, we have also found that the loading rate is inversely associated with increased activation during the stance phase. This further supports our notion that GM activity, both prior to and during stance, contributes to reducing impact forces as a result of its role in stabilising the pelvis(126,130). Injured populations do not achieve the same level of GM activity, which may have implications for the risk of injury that go beyond the loading rate, in a multifactorial complex injury aetiology, as described in Chapter 2 and by Tam et al. (2014)(95).

Another perspective is that pre-activation may be reflective of muscle activity throughout the swing phase, which would support the notion that overall alterations in muscle activation influence loading rate. Schmitz et al. (2014) modelled muscle activation during the swing phase, and determined that the primary factor influencing the loading rate was the position of the thigh at mid-swing, since the impact peak is influenced most strongly by the foot acceleration, velocity and position during mid-swing(74). It stands to reason that kinematics during the swing phase of running would influence the impact forces, because they ultimately affect the downward velocity and momentum of the leg. This would produce a potentially smaller force and loading rate on impact consequently these kinematic changes are the consequence of muscle activation strategies is also evident(74).

The second finding results from further analysis of changes in neuromuscular strategy employed by our responder and non-responder sub-groups. GM pre-activation increased significantly in the positive responder group, who significantly reduced loading rate after training. This further supports the possibility that greater GM pre-activation reduces loading rate.

The positive responder group also experienced a decrease in RF pre-activation, which occurred in conjunction with an increase in pre-activation in BF. These are agonist-antagonist muscles, and it may be that these specific changes in muscle activation complement one another, shifting the load to different muscles without compromising the stability of the knee joint, in accordance with the proposed purpose of muscle pre-activation. With respects to the increased BF pre-activation, it must be noted that the positive responder group had significantly reduced BF pre-activation prior to training, but increased over the 8-weeks such that it was similar to all other groups upon completion. These alterations in muscle activation in the responder group may be part of a broader strategy, occurring throughout swing phase, which influences the velocity of the leg during the swing phase and altering the magnitude of the loading rate(74).

The findings of this study allow us to expand our previous characterisation of responders and non-responders to barefoot running. In both Chapter 3 and Chapter 4, we identified a group of runners who present with increased loading rates when barefoot, and termed them negative responders. These individuals were characterised as having elevated loading rates, partly attributable to continued dorsiflexion at initial ground contact when barefoot. We now extend that characterisation to include altered neuromuscular function, particularly the pre-activation of the posterior muscle groups, including MG, GM and PL. Thus, it is suggested that individuals who fail to pre-activate these muscles are more likely to present with high loading rates.

Muscle activation during the swing phase was not analysed, but rather the pre-activation period, since we wished to understand how this might affect loading rate. Future studies should relate kinematics, kinetic and neuromuscular factors throughout the gait cycle, since it is plausible that those runners who respond negatively to barefoot running differ from those who respond positively in terms of the acquired activation patterns and resultant kinematics.

Collectively, this study, which we believe to be novel with respects to its implications for kinetics during barefoot and shod running, does not allow us to surmise causation or mechanisms regarding the effect of muscle activation patterns on loading rate. However, we can speculate that the integration of activity of the leg muscles contributes to the loading rate, presumably as a consequence of its effect on the velocity of the limb as well as the stiffness of the locomotor muscles immediately prior to ground contact. This may represent the kinematic preparation prior to impact, which can be learned. Neuromuscular insight may allow the development of training programs specific to each individual.

## 5.6 Conclusion

Footwear, barefoot training and experience significantly influence the neuromuscular control of the lower limb muscles. In support of previous findings, we have shown an increase in the activity of gastrocnemius muscles in the barefoot condition. With training, our novel findings include an inverse association between initial loading rate and increased MG pre-activation prior to the onset of an 8-week progressive barefoot training programme, and a similar inverse relationship between loading rate and GM, PL post training. Further, initial loading rate was positively associated with TA pre-activation. Collectively, these findings suggest complex neuromuscular control strategies, which may exist either in response to, or in order adjust, ground reaction forces in the barefoot condition. Finally, we extend our previous characterization of potential responders to barefoot running to also include neuromuscular factors, since runners able to decrease their initial loading rate over the barefoot running training programme displayed increased GM and BF and decrease RF pre-activation, which may provide greater stabilisation of the hip and a balanced agonist-antagonist relationship during gait.



## **CHAPTER 6**

**INVESTIGATING THE EFFECT OF 8-WEEKS OF  
BAREFOOT RUNNING TRAINING ON OXYGEN COST OF  
TRANSPORT.**

## 6.1 **Abstract:**

**Introduction:** Popular interest in barefoot running has emerged over its alleged performance and injury prevention benefits. We have explored and found large individual differences between barefoot and shod biomechanics. Oxygen cost of transport however remains equivocal, but is hypothesised to improve through neuromuscular and biomechanical adaptations.

**Purpose:** To investigate the influence of 8-weeks of progressive barefoot training on oxygen cost of transport and associated spatiotemporal variables.

**Methods:** Fifteen recreational male runners participated in this study. Oxygen cost of transport, biomechanical and temporal gait characteristics including ground contact and swing time; stride length and frequency and ankle plantar-dorsiflexion were measured pre- and post-intervention.

**Results:** The oxygen cost of transport did not differ between barefoot and shod running either pre- or post-training. Running economy improved in the barefoot, but not the shod condition ( $p < 0.05$ ). Biomechanical differences between barefoot and shod conditions persisted over the training period. Ground contact time increased meaningfully in the barefoot condition after training ( $p = 0.003$ ,  $ES = 0.69$ ). A decrease in oxygen cost of transport was found to be associated with a decrease in ground contact time and a small increase in stride frequency ( $p = 0.030$ ;  $r = 0.569$ ).

**Conclusion:** Differences between barefoot and shod conditions were not found before and after the intervention. Ground contact time and stride frequency, previously associated with oxygen cost of transport, only partly contribute to a decrease in oxygen cost of transport after barefoot training. Thus, other physiological variables must influence the improvement in oxygen cost of transport after a barefoot training intervention.

**Keywords:** running economy, performance, exercise, sport.

## 6.2 Introduction:

The previous chapters of this thesis have examined biomechanical and neuromuscular variables during barefoot and shod running. We have addressed questions related to potential injury risk factors, in response to the emerging evidence and potential for barefoot running to reduce injury risk. Another aspect of barefoot running that has been touted as advantageous is the oxygen cost of transport. This variable, also referred to as running economy, is defined as oxygen consumption per unit distance or time at a given speed, and has been suggested to improve in the barefoot condition, is also under-researched. The effect of barefoot running on oxygen cost of transport is complicated by matters of footstrike pattern, running shoe design, shoe mass, as well as measurement techniques and potentially small differences between footwear types(20,94).

Barefoot running has been linked to a potential improvement in oxygen cost of transport, as a result of eliminating the mass of the shoes and the documented increase in ankle plantarflexion on landing, which results in a mid- or forefoot strike(87,88). This has been hypothesised to reduce the oxygen cost of running by more efficiently loading the Achilles tendon and calf muscle and reducing the influence of the mass of the foot(17,59,69,131).

Other gait characteristics have previously been associated with oxygen cost of transport, including ground contact time, stride frequency, swing time and stride length(132). The specific influence of these gait characteristics on the oxygen cost of transport may be reliant on familiarity, athletic ability and running speed(132–135), but barefoot running may alter them in a matter that affects oxygen cost of transport. Additional factors include changes in joint stiffness, a reduction in braking impulse and increased storage and recovery of elastic energy when running barefoot or in a simulated condition. All may be part of a collection of responses that may reduce the oxygen cost of running(17,59,69,73,87).

Oxygen cost of transport is further complicated by the mass of the footwear, as the oxygen cost of running increases by approximately 1% per 100 g of footwear mass(89). It is thus

unsurprising that when corrected for shoe mass using weights attached to the upper surface of the foot, barefoot running is found to be as economical as shod running for a given total foot mass(88). Finally, footwear material itself is also implicated in shod vs. barefoot differences, with more elastic midsole materials having been found to improve oxygen cost of transport compared to barefoot running, even without correcting for the mass of the shoe(89,136).

A final complication is that the biomechanical adaptations to minimalist or barefoot running are not consistent between individuals, as we have described extensively in the previous three chapters of this thesis. Overlooked in the published literature, it is clear that many habitually shod runners do not immediately adopt the purportedly favourable landing patterns or kinematics when running barefoot (Chapter 3)(17). Nor do many individuals acquire these changes over the course of 8-weeks of barefoot running, in the absence of verbal instruction and conscious gait changes (Chapters 4 and 5). Since the kinematic adaptations affecting footstrike have also been linked to the oxygen cost of transport changes when barefoot, such individual variability is important to understand, both in terms of acute changes and longer-term adaptations to barefoot running.

In this regard, Lieberman et al. (2010) found that 6-weeks of training with minimalist shoes (simulating barefoot running) resulted in changes in the simple outcome variable of footstrike pattern(17). Similarly, 4-weeks of minimalist shoe running was found to improve oxygen cost of transport when wearing minimalist but not cushioned shoes in well-trained collegiate athletes who adopted a forefoot strike in the minimalist condition(90). In both studies, minimalist shoes were used, rather than a pure barefoot condition. Since recent research has reported that running kinematics while barefoot are clearly different to those of running in a minimalist shoe(71), the applicability of these findings to barefoot running remains incomplete. Moreover, mechanisms for any observed changes have not been yet described. These mechanisms offer potentially valuable insights into the ability of

individuals to gradually adapt their running biomechanics when barefoot with influence on oxygen cost of transport as a marker of interest to the observed changes.

Therefore, the purpose of this study was to investigate the influence of an 8-week progressive barefoot running program on oxygen cost of transport and associated changes in spatiotemporal biomechanical parameters of the gait cycle including ankle flexion angle during initial contact, ground contact and swing time, stride length and frequency during overground running. We hypothesised that proportional replacement of traditional shod running with pure barefoot running training would decrease oxygen cost of transport in the barefoot but not shod condition. Further, changes in oxygen cost of transport would be associated with changes in ground contact times and stride frequency, as has previously been found.

## **6.2 Materials and Methods**

### **6.2.1. Participants**

Fifteen recreational male runners were recruited for this study. Inclusion criteria included no experience of barefoot running and a 10-km race time faster than 50 minutes within the previous 6 months. The Human Research Ethics Committee of the University of Cape Town approved this study (HREC REF: 504/2011), which was conducted according to the ethical principles of the Declaration of Helsinki (2008). All runners were informed about all the tests and possible risks involved and provided written informed consent before testing.

### **6.2.2. Anthropometry**

For descriptive purposes, height (cm) and body mass (kg) were determined by the use of a precision stadiometer and balance (Seca, Bonn, Germany) and the body mass index (BMI) was calculated.

### **6.2.3. Barefoot running programme**

All participants completed a barefoot running programme three days per week for 8 weeks. This programme was described in more detail in Chapter 4 of this thesis. Briefly, participants maintained their typical training volumes for the duration of the 8-week study, while gradually phasing in barefoot running according to our prescribed conservative progression. Participants added the barefoot sessions to the end of their current training sessions, which were shortened by the length of the barefoot session. The first sessions were performed in an indoor environment i.e. indoor polyurethane running track. After week 2 the participants transitioned onto a safe outdoor surface such as sports fields (firm grass athletics track) and smooth paved roads. After week 4 the participants trained on various outdoor surfaces for the remainder of their training sessions e.g. pavement, rougher paved road etc. (See Table 4.1, Chapter 4, for the comprehensive programme). Participants were not briefed whether they should adopt any type of footstrike pattern and were instructed to run in a manner that maximised their subjective comfort.

#### 6.2.4. Determination of oxygen cost of transport

All participants completed two oxygen cost of transport tests (shod and barefoot) for the purposes of this study: 1) immediately prior to the onset of the 8-week barefoot training intervention and 2) within a week of completing of the 8-week barefoot training intervention.

The oxygen cost of transport tests were performed around a 140 m indoor athletic track. Trials were performed both shod and barefoot, in a counter-balanced randomised order, with each bout separated by a 5-minute recovery period. Runners were paced around the track by LED pacing-lights embedded on the floor around the inner perimeter of the track. The lights were set at  $3.5 \text{ m}\cdot\text{s}^{-1}$  and each trial lasted six minutes.

During trials, pulmonary variables were recorded using a portable breath-by-breath gas analyser system (Cosmed K4b<sup>2</sup>, Cosmed, Rome, Italy) calibrated before each session and verified after each test. Volume and gas calibration and verification were performed according to the instructions of the manufacturers. Volume calibration was performed with a 3 L calibration syringe allowing an error  $\leq 2\%$  and gas calibration was performed automatically by the system using both ambient and reference gases ( $\text{CO}_2$ -5.0%;  $\text{O}_2$ -16.0%).

A slow increase in  $\dot{V}\text{O}_2$  during a constant-work-rate exercise performed above the lactate threshold has been described and also known as the slow component of the  $\dot{V}\text{O}_2$  (137). Thus, to ensure steady-state oxygen cost of transport values, the speed was set at  $3.5 \text{ m}\cdot\text{s}^{-1}$ , which was, for all runners, slower than the speed estimated to correspond to their lactate threshold. This was verified by confirming that the respiratory exchange ratio remained below 1.0 during the entire test for every participant.  $\dot{V}\text{O}_2$  ( $\text{mlO}_2\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) values collected during the last 30 seconds of the running trials were averaged and designated as steady-state oxygen cost of transport ( $\text{mlO}_2\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$ ) for data analysis.

### 6.2.5. Measurement of biomechanical variables

Three-dimensional kinematics and kinetics of the lower limbs and external ground reaction forces were recorded with an 8-camera VICON MX motion capture system (Oxford Metrics, Oxford, UK) sampling at 250 Hz on a 40 m runway prior to oxygen cost tests. Pre- and post-programme, runners were requested to complete six valid trials on the indoor track at the same pace run during the oxygen cost of transport trials ( $3.5 \text{ m}\cdot\text{s}^{-1} \pm 5\%$ ). The criteria for valid trials were described previously (Chapters 3 and 4). The order of testing of the different footwear conditions was counter-balanced.

Sixteen 14 mm reflective markers were attached bilaterally on the lower limbs. Marker bases were securely attached to bony landmarks to establish the co-ordinate systems of the ankle, knee and hip. Accordingly markers were placed on the base of the second metatarsal head, the posterior calcaneus, the lateral malleolus, on the lateral aspect of the distal third of the shank, lateral aspect of the flexion-extension axis of the knee epicondyle, the lateral aspect of the distal third of the femur, the posterior superior iliac spine and anterior superior iliac spine. The capture volume had a length of 7 m and a height of 1.5 m this allowed adequate distance for the absence of acceleration and deceleration.

During these runs, marker motion was obtained with VICON Nexus (VICON, Oxford Metrics, Oxford, UK). A successful trial was defined as one within the specified speed range, where all markers were in view of the cameras and there was no obvious visual evidence that the runner altered their gait when entering the capture volume.

Marker trajectory data were filtered using a low-pass fourth-order Butterworth filter with a cut-off frequency of 8 Hz. For each trial, one complete gait cycle was analysed. Stride parameters such as stride duration, stride length and frequency; ground contact time and swing time were acquired from the pipeline function utilising toe-marker trajectories for the above mentioned event detection. Also, from the PlugInGait model (VICON, Oxford Metrics, Oxford, UK) was used to calculate sagittal ankle angle at initial ground contact. All

calculations were performed using the VICON Nexus software (VICON, Oxford Metrics, Oxford, UK). All successful trials were averaged for subsequent analysis.

### **6.2.7. Statistical analyses**

Statistical analyses of data were performed using the SPSS version 21.0 (IBM Corporation, Armonk, NY, USA) and Prism 5 (GraphPad Software, Inc., La Jolla, California, USA). Data were screened for normality of distribution and homogeneity of variances using a Shapiro-Wilk Normality Test and a Levene's test, respectively. Two-factor ANOVAs between pre- and post-training programme and barefoot and shod conditions were utilised. Effect sizes (ES) were calculated according to Cohen's *d* and interpreted as small ( $>0.2$  and  $<0.6$ ), moderate ( $\geq 0.6$  and  $<1.2$ ) and large ( $\geq 1.2$  and  $<2$ ) according to the scale proposed by Hopkins et al. (2009)(138).

For secondary analysis, linear regression and Pearson's product-moment correlations assessed the relationships between the oxygen cost of transport and the different biomechanical variables. The magnitude of the effect was assessed by the Pearson coefficient (*r*) and interpreted as trivial ( $<0.1$ ), small ( $\geq 0.1$  and  $<0.3$ ), moderate ( $\geq 0.3$  and  $<0.5$ ), large ( $\geq 0.5$  and  $<0.7$ ) and very large ( $\geq 0.7$ ). Linear regression assumptions were checked using residual versus fitted, normal QQ, and Cook's distance plots. Significance for all analyses was set at  $p < 0.05$ .

### 6.3 Results

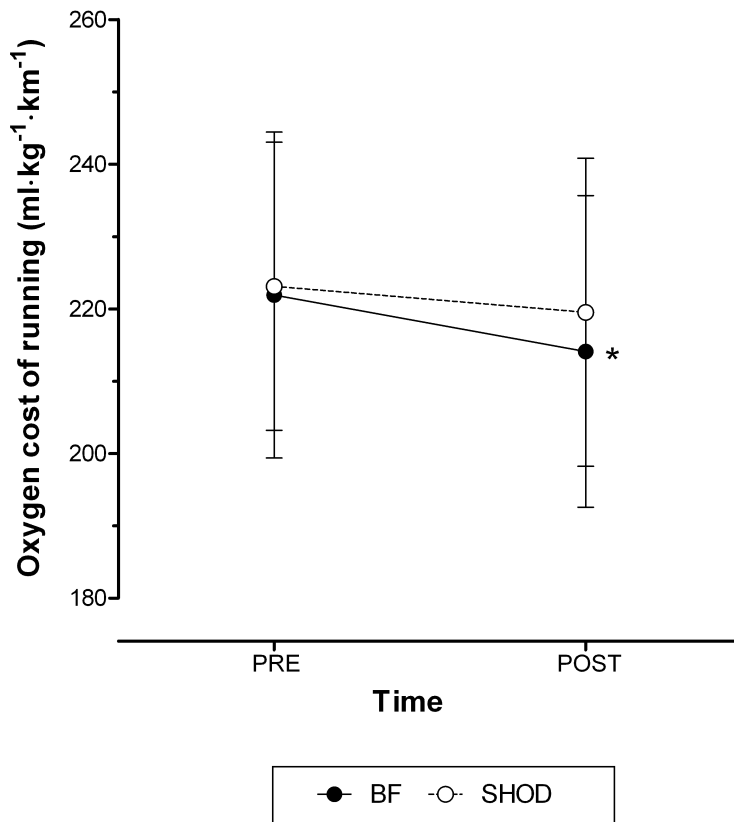
Anthropometric and descriptive characteristics of the runners are shown in Table 6.1. Participants were trained recreational runners, as indicated by their recent 10-km race time of  $42.9 \pm 3.2$  min, corresponding to a pace of  $3.9 \pm 0.4$  m·s<sup>-1</sup>. The homogeneity of the group was confirmed by a CV <10% for all anthropometrical and descriptive variables, including 10 km race time, ranging from 38 to 48.0 min (CV=7.6%). During the track runs, the average speed was maintained at 3.5 m·s<sup>-1</sup>, which produced RER values below 1.0 in all cases. During the biomechanical assessments, participants were asked to run at 3.5 m·s<sup>-1</sup>, but ran slightly slower, at speeds ranging from 3.12 to 3.22 m·s<sup>-1</sup>. There were no differences in speed between trials.

**Table 6.1** Descriptive characteristics of the participants

	Mean(SD)	CV (%)
<i>n</i>	15	
Age (yrs)	27.8(5.1)	18.0
Body mass (kg)	77.1(8.2)	10.6
Height (m)	1.8(0.1)	5.6
BMI (kg/m <sup>2</sup> )	23.8 (1.2)	5.0
10-km personal best (min)	42.9(3.2)	7.6

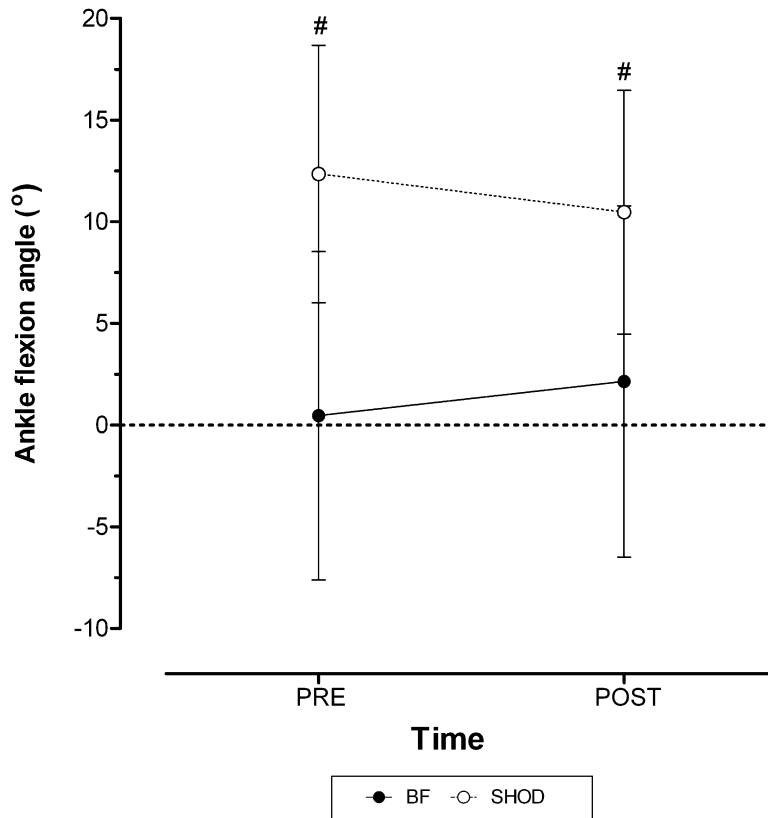
BMI, body mass index

Figure 5.1 depicts oxygen cost of transport during overground running at 3.2 m·s<sup>-1</sup> in the shod and barefoot conditions before and after the barefoot training intervention. Oxygen cost of transport decreased after the 8-week progressive running programme in the barefoot condition ( $222.9 \pm 12.8$  ml·kg<sup>-1</sup>·km<sup>-1</sup> vs.  $213.9 \pm 10.9$  ml·kg<sup>-1</sup>·km<sup>-1</sup> pre vs. post, respectively,  $p < 0.05$ , ES=0.75, moderate effect), but not in the shod condition (ES=0.33, small effect, Figure 6.1). The oxygen cost of transport was not significantly different between the barefoot and shod conditions at either the pre- (ES=0.14, trivial effect) or post-intervention stages (ES=0.38, small effect).



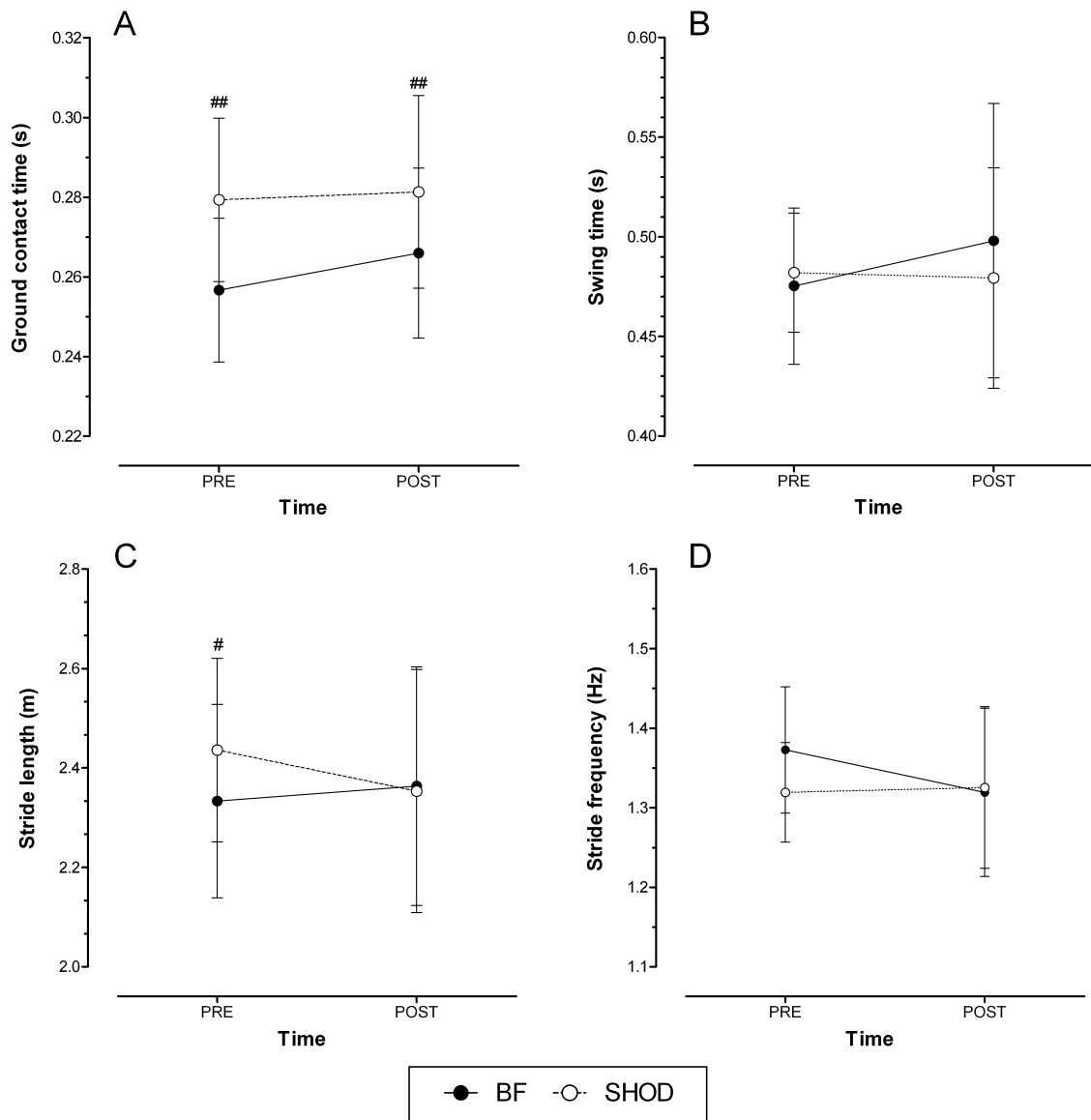
**Figure 6.1** Changes in oxygen cost of running before and after the 8-week barefoot running training intervention in the barefoot (BF) and shod conditions. \* - significant time difference (\*  $p < 0.05$ )

With respects to the biomechanical changes that have previously been associated with oxygen cost of transport, we used ankle flexion angle as a proxy for footstrike, with accepted limitations described in Chapter 3, as well as spatiotemporal gait characteristics. Ankle flexion angle at initial ground contact did not change during either shod or barefoot running after the training intervention (Figure 6.2). There were condition differences at both measurement stages, with greater plantarflexion observed in the barefoot condition both pre- ( $p < 0.001$ , ES= 1.88, large effect) and post-intervention ( $p < 0.001$ , ES=1.39, large effect, Figure 6.2).



**Figure 6.2** Barefoot vs. shod differences persist before and after the 8-week barefoot running training intervention. # - significant condition difference ( $^{\#} p < 0.05$ )

Ground contact times were shorter in the barefoot than the shod condition before ( $0.26 \pm 0.02$  s vs.  $0.28 \pm 0.02$  s,  $p < 0.001$ ,  $ES = 1.17$ , large effect) and after the training intervention ( $0.27 \pm 0.02$  s vs.  $0.28 \pm 0.02$  s,  $p < 0.001$ ,  $ES = 0.72$ , moderate effect) (Figure 6.3A). No changes in ground contact time were observed as a result of training, although there was a trend towards increased ground contact times when barefoot after the training intervention ( $p = 0.053$ ,  $ES = 0.52$ , small effect, Figure 6.3A).



**Figure 6.3** Spatiotemporal changes before and after the 8 week barefoot running training intervention in the barefoot (BF) and shod conditions. # - significant condition difference ( $\# p < 0.05$ ,  $\#\# - p < 0.001$ )

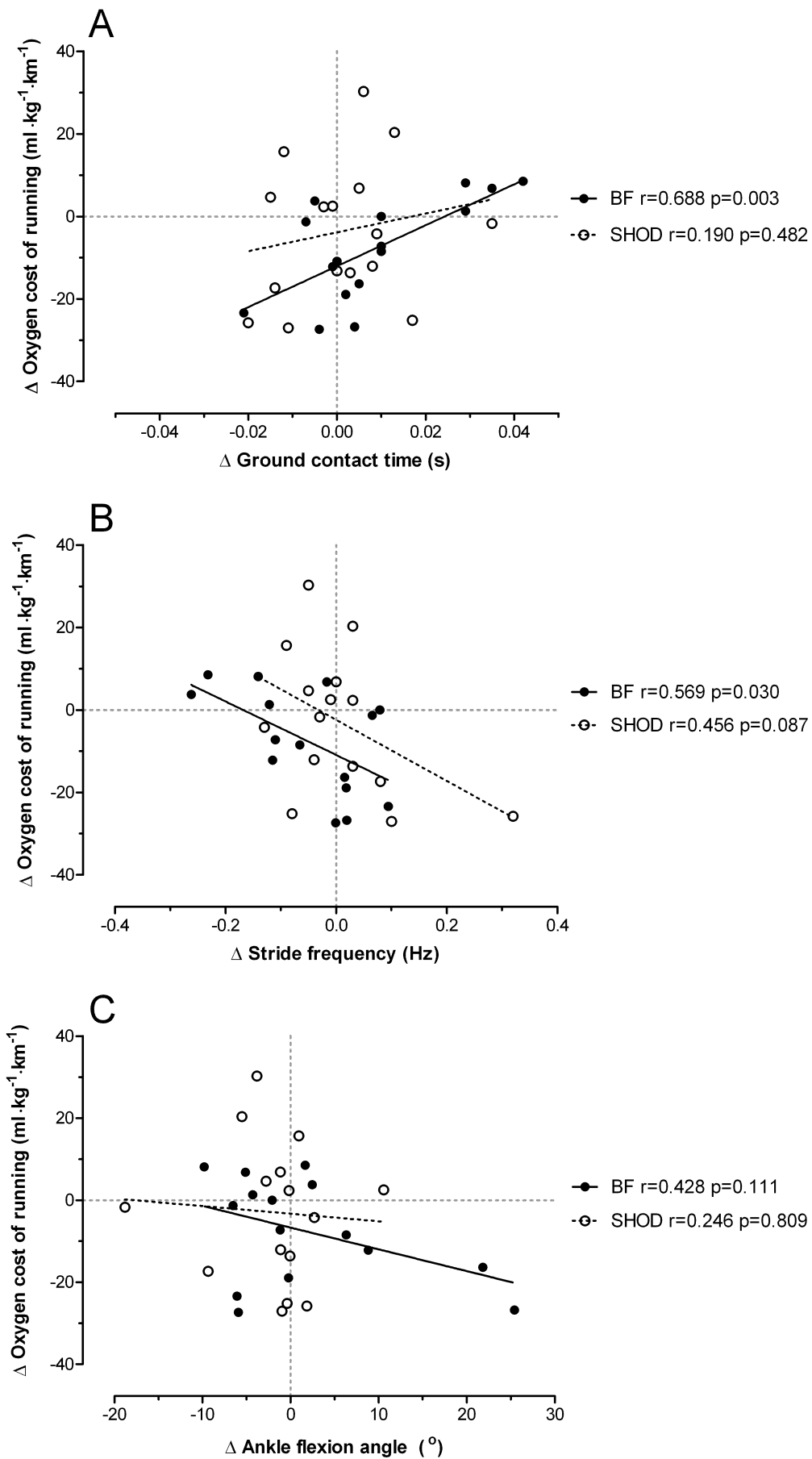
Swing time was not different between the barefoot and shod condition, either pre- or post-intervention, and no changes were observed as result of the barefoot training (Figure 6.3B). Stride length was shorter when barefoot compared to shod prior to the training intervention ( $2.33 \pm 0.19$  cm vs.  $2.44 \pm 0.24$  cm shod vs. barefoot, respectively;  $p < 0.01$ ,  $ES = 0.69$ , moderate effect, Figure 6.3C). After training, there was no difference in stride length between the shod and barefoot conditions ( $p = 0.820$ ,  $ES = 0.4$ , small effect). Finally, no differences in stride frequency were observed between conditions or after the training programme ( $1.37 \pm 0.06$  Hz vs.  $1.32 \pm 0.08$  Hz, change in barefoot over time,  $p = 0.051$ ,  $ES = 0.54$ , small effect, Figure 6.3D).

We further explored the training related changes in oxygen cost of transport and gait characteristics to determine whether the changes in the oxygen cost of transport might be associated with biomechanical adaptations to barefoot running (Figure 6.4).

We found a positive association between changes in the oxygen oxygen cost of transport and ground contact time in the barefoot condition ( $p=0.003$ ,  $r=0.688$ ; large effect; Figure 6.4A), such that runners who increased oxygen uptake after training tended to be those who increased ground contact time. This association was not found for shod running ( $p=0.482$ ,  $r=0.190$ , trivial effect, Figure 6.4A).

Changes in oxygen cost of transport were negatively associated with changes in stride frequency when running barefoot ( $p=0.030$ ,  $r=0.569$ , large effect, Figure 6.4B), with a tendency for significance in the shod condition ( $p=0.087$ ,  $r=0.456$ , moderate effect, Figure 6.4B).

Finally, changes in ankle flexion angle at initial ground contact were not associated with a change in oxygen cost of running in either barefoot ( $p=0.111$ ,  $r=0.428$ , moderate effect, Figure 4C) or shod conditions ( $p=0.809$ ,  $r=0.246$ , Figure 6.4C).



**Figure 6.4** Relationships between change ( $\Delta$ ) in oxygen cost of running and change ( $\Delta$ ) in ground contact time (A), stride frequency (B) and ankle flexion angle at initial ground contact (C).

## 6.4 Discussion

The primary outcome of this study was that an 8-week progressive barefoot running programme improved overground oxygen cost of transport when running barefoot but not when shod. This improvement occurred concurrent with meaningful changes in ground contact time, but no changes in ankle angle, strides frequency, stride length or swing time.

We found no difference in oxygen cost of transport between footwear conditions both before and after the intervention. Previous studies have produced varying results with respects to oxygen consumption when shod and barefoot. Franz et al. (2012) did not find improved oxygen cost of transport when barefoot compared to wearing lightweight racing shoes(89), while other studies have shown a reduced oxygen cost of transport when in minimalist shoes(20). This is likely the result of reduced mass on the foot, since correcting this mass with weights eliminated the effect(88,89,94).

The present study extends previous research on running economy into a longer-term investigation of pure barefoot training. The reduced oxygen cost of transport after barefoot training agrees with the findings of Warne & Warrington (2013), who showed improved barefoot oxygen cost of transport after 4-weeks of minimalist shoe training(90). In that study, using speeds comparable to the present study ( $13 \text{ km}\cdot\text{h}^{-1}$  vs.  $11.5 \text{ km}\cdot\text{h}^{-1}$ ), four weeks of minimalist training improved oxygen cost of transport by 8% in the minimalist condition. We found a 3.5% improvement in the barefoot oxygen cost of transport after 8 weeks of barefoot training.

We attribute the smaller magnitude of change in our study, despite a longer training programme, to the inclusion of strengthening exercises, greater training volumes and a higher calibre of runners in the previous research study(90). These additional factors, particularly specific strength training, may have further enhanced musculoskeletal adaptations and therefore improved oxygen cost of transport to a greater extent(139). Also, enabled by the better calibre of runner and the use of minimalist shoes rather than pure

barefoot running, Warne & Warrington (2013) were able to provide larger training volumes, such that their runners were doing two runs lasting 15 minutes in week 1, and four x 30 minute runs by week 4. In contrast, our relatively cautious approach dictated that week one consisted of only 9 minutes of barefoot running, increasing to 30 minute runs only by the seventh and eighth weeks of the programme(90). The greater early training volumes by Warne & Warrington (2013) could account for larger changes in oxygen cost of transport over a shorter period than we observed.

That the training-related oxygen cost of transport changes in the present study occurred only in the barefoot and not the shod condition supports our hypothesis and our previous findings (Chapters 4 and 5) that a degree of adaptation occurs when habitually shod runners undertake the novel task of running barefoot. This has important implications, as it suggests that a) the acquisition of the biomechanical (Chapter 4), neuromuscular (Chapter 5), and in this case, physiological attributes of barefoot running is not immediate and certainly not uniform for all runners, and b) the benefits of barefoot running require habituation and that not all runners may receive them.

The novel contributions of this study, having confirmed previous work showing this improvement in oxygen cost of transport with habituation to minimalist running, are to extend this finding to pure barefoot running, and to relate the observed changes to changes in gait characteristics that have previously been associated with oxygen cost of transport (132,140). In this regard, we provide some interesting and contradictory findings using a prospective longitudinal design compared to previous cross-sectional analyses.

First, no training related spatiotemporal changes were found as a result of the 8-week barefoot training programme, though we found a trend for ground contact time to increase when barefoot ( $p=0.053$ , though effect size was small, Figure 6.3A). Thus, it appears that the decrease in oxygen cost of running after barefoot training is not simply attributable to an overall change in gait characteristics that have previously been linked to this variable(135,141).

When the individual changes in oxygen cost of transport and gait characteristics were considered, we found significant associations between the change in the oxygen cost of running and change in ground contact time and stride frequency in the barefoot, but not shod conditions (Figure 6.4A and 6.4B).

The association between oxygen cost and ground contact time (Figure 6.4A) is novel, since it suggests that a reduction in oxygen cost of running is associated with a decrease in ground contact time after the barefoot training programme. This may be the result of increased leg stiffness caused by tightening of the Achilles tendon during barefoot running(142,143). Alternatively, it has been hypothesised that a shorter ground contact time reduces the braking phase during stance, increasing pre-activity of the shank muscles which increases the sensitivity of the muscle spindle potentiating stretch reflexes to enhance musculo-tendon stiffness(123,132,144,145).

Interestingly, previous literatures suggests that relationship between economy and ground contact time is equivocal(146). Our finding is in agreement with previous cross-sectional research associating shorter ground contact times with a lower oxygen cost of running(132,142), whereas other authors have reported the opposite(135,141). Thus, the influence of changes in ground contact time on oxygen cost of transport is still unclear and further underlying variables are implicated(146). Indeed, we have found a significant association, although the r-value of 0.69 (Figure 6.4A) suggests numerous other factors that may influence even this relationship.

A change in stride frequency was also significantly associated with oxygen cost of transport (Figure 6.4B). Runners who increased stride frequency after the training period presented with a reduced oxygen cost of running (Figure 6.4B). This contradicts previously published research, most of which suggests that a reduced stride frequency is associated with greater oxygen cost of transport (132). However, the absolute change in stride frequency in our group of runners appears to be small (range: -0.28 to +0.1 Hz), and is highly variable between runners. The result is that while a significant relationship exists, it must be

acknowledged that some runners presented with large reductions in oxygen cost despite no change in stride frequency, whereas others showed large changes in stride frequency without any apparent effect on oxygen cost (Figure 6.4B). This suggests that the relationship is much more complex, when considered longitudinally as a result of training, as has been documented in previous cross-sectional associations that reported improvements in the oxygen cost of transport despite stride frequency remaining unchanged.

Also, given that the participants were required to run the same speed before and after training, it is reasonable to expect that temporal gait characteristics will be altered as part of an overall gait pattern to achieve the same speed. Thus, increases in ground contact time may be offset by increases in stride frequency or stride length, with the result that isolating changes in a single gait characteristic may obscure a more complex interaction(147,148).

Lastly, we found no association between oxygen cost of transport and change in sagittal ankle angle at initial ground contact after training (Figure 6.4C). This suggests that the instinctive sagittal ankle angle changes are not significantly influential on changes in the oxygen cost of transport, as has been hypothesised. The sagittal ankle angle can be interpreted as an index of footstrike pattern, where greater than 10 degrees indicates a highly likely heelstrike(91). Although our findings are in agreement with previous research reporting no differences in oxygen cost of transport between differing strike patterns when habitual forefoot and rearfoot strikers also run in their non-preferred strike pattern(134), other studies have suggested that habitual rearfoot strikers(133,135) or even habitual forefoot strikers(145) are more economical. We have found improved oxygen cost of transport without significant changes in ankle angle and also, no association between the changes in these variables. This suggests that improvements in oxygen cost of running seen in this study may not have been greatly influenced by changes in footstrike pattern, as individuals may not have adapted fully to the proposed advantageous barefoot footstrike pattern.

Future studies may benefit from a more homogenous group of runners. They may also wish to study a larger cohort to determine the response in oxygen cost of running in runners who have and have not adapted to the proposed footstrike pattern changes associated with barefoot running to determine whether it is reliant on this factor. A further limitation is that the shod condition was not standardised across runners, but rather all runners utilised their most accustomed shoes for both pre- and post-intervention testing. Other factors to consider that may also be able to account for differences is the recently proposed test that considers the underlying substrate utilisation other than just pure oxygen cost, since this may be more sensitive for determining the oxygen cost of transport(149,150).

However, the merit in our study is the prospective nature of documenting the intra-individual response, whereas a vast majority of the above-mentioned studies are of an inter-individual cross-sectional design. Further, the inclusion of a barefoot running programme that progressively replaces the typical shod training programme and explores the instinctive ability to acquire the proposed favourable changes associated with barefoot running was novel.

## **6.5 Conclusion**

The novelty of this study was to provide insight on the influence of barefoot running on oxygen cost of transport in trained runners from a prospective rather than a cross-sectional perspective and an uninstructed and unassisted programme. We have found that an 8-week progressive barefoot training improves oxygen cost of transport when barefoot. Within individuals, improvements in oxygen cost of transport were associated with a reduction in ground contact times and a small increase in stride frequency. The nature and magnitude of these associations suggests that further physiological variables influence the improvement of oxygen cost of transport from a barefoot training intervention, possibly including musculo-tendinous adaptations, neuromuscular strength and motor control.



# CHAPTER 7

Summary and Perspectives

**THE TRAINABILITY OF BAREFOOT RUNNING:  
PRACTICAL ADVICE FROM AN 8-WEEK TRAINING  
INTERVENTION**

Since the period of marathon mania in the 1970s, when participation in marathons rose steeply, the benefits of exercise through participation in running were recognized(2). These include improved markers of mental and physical health and wellness, but are balanced by a risk of injury caused by running. Recently, interest in barefoot running emerged in both scientific and popular media circles, which drove subsequent trends in minimalism by the running shoe industry. This occurred without substantiated claims of injury prevention and improved performance(1,35). Advocacy for barefoot running is often defended with the evolutionary theory of running(5) and further argued because of the failure of the modern running shoe to reduce the prevalence of running related injury(13,24). Industry and runners alike have implemented this concept without fully understanding its repercussions for injury and performance(68,88,89).

As is the case with many health fads or trends, barefoot running is often adopted without acknowledging that individuals will respond differently, despite the fact that a majority of runners are habitually shod for most of their life. Hence, attaining a typical (and purportedly favourable) habitual barefoot running style may be a skill acquired through practice, and if not performed appropriately will result in injury(44,68,151,152).

This thesis was borne out of the need for an objective prospective study to evaluate claims associated with barefoot running(24). These include a reduced initial loading rate (associated with a reduction in risk of stress fractures of the tibia) and improved performance predictors (decrease in the oxygen cost of transport)(17,20). Notably, previous training studies have not addressed the concept that “barefoot running” is indeed pure barefoot running and is not the often perceived minimalist or simulated barefoot condition(72,73,90).

We used an 8-week progressive barefoot running training programme in habitually shod runners to assess these claims. Pre- and post-testing included three-dimensional motion capture, ground reaction force data in tandem with surface electromyography of the lower

limb and metabolic changes measured using a portable gas analysis. All data were collected during constant pace overground running.

The main findings of this thesis were the following:

- i. The acute response to barefoot running in individuals is highly variable in habitually shod runners. A majority of runners do not exhibit the purported advantageous biomechanics seen in habitually barefoot runners, and were found to increase initial loading rate when barefoot.
- ii. Barefoot ankle plantarflexion is greater than when shod. This is a typical kinematic change, suggesting a shift towards a more mid- or forefoot landing pattern.
- iii. Ankle flexion angle at initial ground contact predicts initial loading rate when running barefoot. This relationship was confirmed in the 8-week training study, which also found that the change in initial loading rate after training is associated with the change in ankle flexion angle over the same period.
- iv. The relationship between ankle flexion angle and initial loading rate in the shod condition does not exist. Shoe cushioning is thus sufficient to reduce the initial loading rate, irrespective of footstrike (as predicted indirectly by ankle angle). This suggests that runners who continue to heel-strike when barefoot may benefit more from shoe cushioning and may be unsuited to barefoot running (with respects to loading rate)
- v. Not all runners adopt the purported kinematic and kinetic barefoot running characteristics over an 8-week progressive pure barefoot running programme. We found that there were non-, negative- and positive responders. This finding also questions the generalisability of the favourable biomechanical responses of barefoot running as instinctive, as previously suggested by evolutionary biologists. Conscious instruction to runners may be required in order to acquire habitual barefoot running characteristics.

- vi. Neuromuscular differences between the barefoot and shod condition may reflect motor control adjustments to the absence of cushioning. Footwear condition differences were found between gastrocnemii and gluteus medius activity.
- vii. The positive-responders to barefoot running presented with increased GM and BF and decreased RF pre-activation. This finding suggests that increased activation of the posterior and decreased anterior muscle group activation during barefoot running may contribute to a reduction in the initial loading rate. This may influence the compliance of the ankle and knee joints, though we cannot distinguish whether this is a proactive or reactive mechanism.
- viii. This posterior-anterior muscle activation pattern is confirmed by the negative association between initial loading rate and posterior lower limb muscle pre-activation, while the association was positive for the anterior shank muscles. Collectively, these findings reveal the complex neuromuscular control required to prepare for external environment interactions to optimize human locomotion in the absence of shoe cushioning.
- ix. Oxygen cost of transport is improved when barefoot after an 8-week progressive barefoot running training programme. Spatiotemporal changes associated with this improvement include a decrease in ground contact time and increase in stride frequency. However, the nature and the magnitude of these changes implicate other intrinsic changes such as musculo-tendinous adaptations, neuromuscular strength and motor control

Large variability in both initial and trained neuro-mechanical outcomes were described during the transition to barefoot running. These may be explained by unique changes adopted in the lower body kinetic chain by neuromuscular and biomechanical responses that adapt to the novelty of barefoot running. Future studies to describe these specific changes may help us understand the benefits and compromises associated with each adaptation. In order to do so, future investigations should employ musculoskeletal, finite element and multivariate modelling of adaptation to enhance our understanding of the

interaction between neuromuscular control, the consequent joint biomechanics and interaction with the external environment.

Further, the ability to better understand the segment or inter- and intra- gross joint specific changes may also reveal specific adaptations that could be overlooked. For example, foot morphology has been found to vary greatly amongst individuals with resultant variability in flexibility and stiffness. These variables may greatly influence one's ability to successfully adapt to barefoot running. Additional documentation of such factors will enhance our perspective of the potential favourable biomechanical changes.

This thesis is a key stepping-stone in the direction to further understand the multifaceted underlying interactions between the human body, the fundamental evolutionary capability of endurance running and associated injury. Barefoot running has been touted as a probable answer to running injury prevention and performance enhancement. However, this thesis reveals that acquiring such benefits associated with barefoot running may not be as simple as discarding running shoes. Indeed, the findings from this thesis promote a cautious approach to such trends or fads. It also exposes the non-generalizability of the mismatch hypothesis between running shoes and endurance running.

Construction of a screening tool that will enable both clinical populations and interested runners to better understand their likelihood of barefoot and minimalist running success is the ultimate goal of this body of research. We have identified and characterized negative-responders, both acutely and with training, as runners who present with elevated loading rates, partly attributable to continued dorsiflexion at initial ground contact when barefoot. They also display altered neuromuscular function, particularly the pre-activation of the posterior muscle groups, including MG, GM and PL.

Even long-term prospective studies, such as that which we present in Chapter 4 of this thesis, will require these concepts or tools in order to fully appreciate the injury outcomes. Thus, this thesis takes the first step towards predicting successful adaptation and identifying

characteristics of potentially successful barefoot runners. It is possible that barefoot running is a quixotic endeavour for a majority of runners, and even prolonged exposure, conscious training and gradual exposure may be insufficient to overcome sociological, developmental, practical and environmental factors.

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