Understanding Risk of Injury in Novice Runners: Exploring the Link Between Runner Characteristics, Biomechanics and Injury Outcome

By

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DECLARATION

I, Devon Ross Coetzee, hereby declare that the work on which this dissertation/dissertation is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university.

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List of Abbreviations Found in this Dissertation

VALR	vertical average loading rate
ILR	initial loading rate
vGRF	vertical ground reaction force
BW	body weight
n	number
VILR	vertical instantaneous loading rate
VIP	vertical impact peak
FSA	foot strike angle
RFS	rear foot strike
FFS	forefoot strike
MFS	midfoot strike
TC	traditionally cushioned
RC	reduced cushioned
CON	concentric
ECC	eccentric
BMI	body mass index
MRI	magnetic resonance imaging
STIR	short TI inversion recovery
NRS	numeric rating scale
GRF	ground reaction force
BW/s	body weight per second
mm	millimetre
cm	centimetre
m	metre
g	gram
kg	kilogram
THOM	modified Thomas test
AKE	active knee extension
HTD	heel-toe differential
HSH	heel stack height
FFSH	forefoot stack height
MI	minimalist index
IRR	incidence risk ratio

RRR	relative risk ratio
OR	odds ratio
P/D	pain or discomfort
yrs	years
COMB	combined
SD	standard deviation
ES	effect size
ROM	range of motion
min	minute
GR	gait retraining

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Dissertation Abstract

The high prevalence of running related injury, particularly in novice runners has prompted the investigation into interventions to mitigate the risk of injury. This dissertation set out to investigate the effects of a progressive 12-week running intervention in novice runners wearing footwear with reduced cushioning.

The aim was to understand how intrinsic characteristics of novice runners, namely body composition, strength and flexibility, influence running biomechanics and ultimately injury outcome, and whether footwear structure effects this relationship. Prior to the intervention, participants were assigned to wearing footwear with reduced cushioning (RC) or footwear with traditional cushioning (TC). Three-dimensional running biomechanics were collected during over ground running at 3.0 meters per second in their prescribed footwear. Other measured variables included lower limb strength, by means of an isokinetic dynamometer, lower limb flexibility, full body composition by means of Duel Energy X-Ray Absorptiometry and lower leg bone oedema by means of magnetic resonance imaging. Throughout the intervention, pain or discomfort was assessed. All variables were reassessed after the intervention.

The programme used in this thesis resulted in a 11.1 % prevalence of injury, which is considerably lower than other studies. No differences in injury incidence, bone oedema or pain or discomfort prevalence were found between footwear groups, however the RC group experienced pain or discomfort more frequently. Footwear with reduced cushioning was found to promote kinematic strategies, including a lower foot strike angle (FSA), more flexed knee angle at foot strike and reduced knee range of motion during stance phase to compensate for the lack of cushioning. Whilst most novice runners adopted a rear foot strike pattern throughout the intervention, the RC group were four times more likely to reduce FSA. Intrinsic characteristics of novice runners may not be indicative of injury, however the intervention resulted in changes to these variables. These included improvements in movement-specific strength, increased passive hip flexor flexibility and weight loss. Footwear had no effect on these variables. Greater mass characteristics resulted in kinematic adaptations in the knee.

This dissertation highlighted the importance of a conservative training structure to mitigate injury risk in novice runners. Additionally, footwear has limited effect on injury risk and thus should not be prescribed to promote biomechanical change, but rather to compliment a runner’s current biomechanics and intrinsic characteristics.

Chapter One

Running Related Injury in Novice Runners: What Factors Should Clinicians Consider?

A review of the literature highlighting risk factors for injury in novice runners

1.1) Abstract

Running is a widely practiced activity, due to its simplicity and accessibility. Despite having several health benefits, it also poses a risk in the form of injury, especially in novice runners. Research has explored the potential mechanisms of running related injury, however the prevalence of injured runners remains high. While risk factors for injury have been proposed, the variability in individual response in running biomechanical data has resulted in contrasting evidence to support potential links between runners and injury.

Training related errors such as progressing load too quickly are widely accepted to contribute to sustaining a running related injury. Additionally, unfavourable intrinsic characteristics, including high body mass index, poor strength and non-optimal flexibility of the lower limbs have been proposed as contributors to injury. Biomechanical factors have also been considered, as they represent the link between runner and injury and potentially offer insight into mechanisms of injury. Key biomechanical variables include high initial loading rate, where a high value is linked to both bone and soft tissue injuries, and foot strike pattern, which has implications in loading rates and injury risk. The potential role of footwear to influence these biomechanical variables has been explored, with focus on footwear with reduced cushioning. The premise of this footwear is to promote a change in foot strike pattern from the commonly adopted rear foot strike to a forefoot strike pattern. This potentially reduces loading rates and by inference, running related injury, assuming the link between loading rate and injury holds true.

In this chapter, we review the literature assessing the prevalence and incidence rates of running injury, as well as the potential risk factors for injury. We further explore research that has assessed the effect of footwear with reduced cushioning on running biomechanics and injury, with the aim to outline the factors that should be considered throughout the dissertation. Finally, we describe the layout of the dissertation.

The following chapter aims to outline the variables that need to be considered when determining the risk of injury in novice runners, and how intrinsic characteristics, biomechanical variables and footwear may influence this risk. A general search of published literature was conducted, with inclusion of studies that addressed the potential links between any key focuses of this thesis. These included runners' intrinsic characteristics, biomechanical variables, injury predictors or injury.

1.2) Introduction

Running is one of the most popular forms of physical activity due, in part, to its simplicity and accessibility. Interest in running continues to increase as previously sedentary individuals take up the activity. This can be seen in the number of participants who finished road running races in western countries, which has doubled from 2001 to 2012 (Scheerder et al. 2015), and more recently in the growth of community-organized Park Runs around the world (Ingle 2018). The ease of participation, coupled with the lack of required equipment, allows people of all populations to take part. Additionally, running offers a number of important health benefits, including improved cardiovascular fitness, weight loss and improved adherence to quitting smoking (Reuser et al. 2009; Koplan et al. 1982; Marti 1988).

However, like all physical activity, running also creates a risk of injury. A systematic review on running-related injuries revealed that the incidence of lower limb injuries in long distance runners ranged from 19.4 % to 92.4 % (Van Gent et al. 2007). One study prospectively tracked 87 runners who trained > 20km per week for six months (Lun et al. 2004). They reported that 79 % of these runners sustained a running related injury, defined as any musculoskeletal symptom of the lower limb that required a reduction or stoppage of normal training, with half of these being recurring injuries. Additionally, 24 % of the injuries were severe enough to prevent running for more than seven days, with nearly half seeking medical advice. The knee (25 %), lower leg (20 %), foot (16 %) and ankle (15 %) are most frequently injured, with one study reporting that these locations accounting for more than two thirds of all running injuries (Epperly & Fields 2014). This risk of running related injury thus imposes several burdens on runners, ranging from medical costs to forced absence from any physical activity, with resultant negative health implications. These risks may also act as a deterrent for potential runners.

Despite the popularity of running and the awareness of injuries amongst runners, there have been minimal improvements in the reduction in injury prevalence. The applicability of findings from studies is often limited due to their retrospective nature. Often, studies aim to identify contributing mechanisms for running injury, rather than assessing the effect of modifiable risk

factors. Whilst the latter may not be a novel approach, it is often overlooked as it requires a prospective design. These studies are becoming more frequent, but the complex nature of injury results in weak or tenuous findings. An example of this approach to running injury research can be highlighted when comparing the assessment of a runner from a clinical point of view and a typical research point of view. Where clinicians often ask, “What can I change in my patient to minimize risk of injury”, a traditional research question is “What factors cause injury?”. The study design for these two questions is similar, but the subtle difference in perspective or approach may allow the clinical approach to improve applicability of the findings, and thus may have a beneficial effect on running injury prevalence.

In this chapter, we discuss variables that have been identified as risk factors for running related injury by reviewing the literature on clinical, biomechanical and anthropometrical data. A specific focus is on risk in novice runners, who are at greater risk of injury compared to trained runners (Videbæk et al. 2015). Given the increase in popularity of running over the last few decades, it is important to better understand how novice runners respond to these risk factors and what attributes they might have that could protect them from injury. Therefore, the primary focus is novice runners, and the identification and quantification of risk factors that they may be exposed to as they embark on a 12-week running intervention. The aim is to gain a better understanding of which factors increase and which attenuate the risk of sustaining a running related injury, with the goal of proposing interventions for clinicians to consider when advising their patients.

1.3) Risk of Injury in Novice Runners

To date, most studies on running related injury have focused on recreational and trained runners. Although this provides necessary insight to the scope of running injury, it overlooks the population that is most prone to injury, namely novice runners, defined as not having run on a regular basis in the previous year, compared to recreational runners who have been running two to six times per week for several years (Buist et al. 2008; Hespanhol Junior et al. 2012). A meta-analysis on running injury reported that novice runners were more than twice as likely to sustain a running related injury when compared to recreational runners (Videbæk et al. 2015). Additionally, Buist et al. (2008) compared the effect of a gradual, 13-week running programme against an 8-week running programme on the risk of sustaining a running related injury, with the goal to train novice runners to run four miles. Although no differences in injury outcomes were found between the programmes, approximately 65 % of injuries occurred in the first half of the programmes (Buist et al. 2008), suggesting that increased exposure to unaccustomed impact related forces associated with running may be partly responsible for injury.

In another meta-analysis on injury, Van Mechelen (1992) stated that two key causative factors for sustaining a running related injury are:

1) lack of running experience

2) excessive weekly mileage (van Mechelen 1992).

Further, it has been estimated that 60 % of all running related injuries can be attributed to increasing mileage too quickly (Hreljac 2005; Jacobs & Berson 1986), which has popularized the “10 % rule” that suggests increasing weekly mileage by more than 10 % per week my increase your risk of injury. Although other factors such as intensity, training frequency and baseline starting mileage may complicate this rule, it highlights the necessity for novice runners to follow well-structured training programmes that address these factors to minimize their risk of injury. However, the simplicity and accessibility of running, while advantageous, also exposes the novice runner to risk since there are few limiting factors preventing an initial unfavourable increase in volume and intensity. Novice runners may thus under-estimate the importance of a well-designed training programme, leading to over-training and an increased risk of injury.

Another reason for novice runners being at increased risk to injury is that they often possess unfavourable intrinsic characteristics that have been linked to injury. These intrinsic characteristics, which can also be defined as characteristics that are inherent to a runner that cannot be changed acutely, include body composition, strength and flexibility. For example, greater body mass has been found to increase the risk of sustaining a running related injury (Fuller et al. 2017; Buist et al. 2010; Buist & Bredeweg 2011; Nielsen et al. 2014; Nielsen et al. 2013), whereas poor strength and sub-optimal flexibility of the lower limb have also been found to affect injury risk, though the evidence supporting this is weaker (Hartig & Henderson 1999; Biering-Sorensen 1984; Esola et al. 1996; Witvrouw et al. 2001; Leetun et al. 2004; Niemuth et al. 2005). Nevertheless, gaining a better understanding of how these intrinsic characteristics may influence injury risk allows clinicians to provide better injury prevention advice that can be tailored to their patients.

Moreover, the concept that running may be a skill is often overlooked by novice runners, further increasing the risk of injury. In this model, running as a skill implies that its execution, measurable as kinematic and kinetic outcomes, determines injury risk. This concept has driven researchers to investigate the potential link between running biomechanics and injury.

1.4) Running Biomechanics

1.4.1. Impact Force as a Key Risk Factor for Running Injury

The premise that running biomechanics may influence risk of injury has promulgated the need to improve our understanding of the key biomechanical variables in running. Impact forces have received substantial attention, with vertical average loading rate (VALR), also referred to as initial loading rate (ILR) being highlighted as an important variable to consider when assessing injury (Cavanagh & Lafortune 1980; Milner et al. 2006; Zifchock et al. 2006; Crowell et al. 2010). ILR is defined as the rate of rise in vertical ground reaction force after ground contact. Whilst methodology of measuring ILR varies amongst studies, the most commonly used approach calculates ILR between 20 % and 80 % of the impact transient peak (Crowell & Davis 2011; Cheung & Rainbow 2014; Milner et al. 2006). Using this commonly used approach allows for better inter-study comparison.

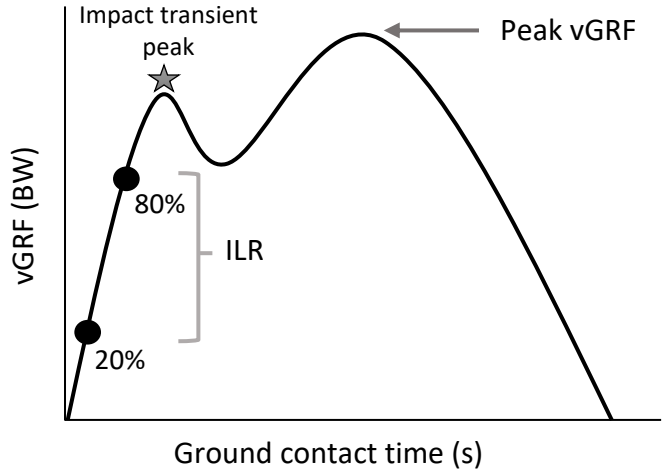

Figure 1.1: Calculating initial loading rate (ILR) using vertical ground reaction force (BW – body weight) during ground contact time (seconds)
vGRF; vertical ground reaction force

The mechanism linking ILR with musculoskeletal injury, in particular bone stress fractures, was first proposed by Schaffler et al. (1989), who found that a more rapid application of force (strain rate) results in a more severe damage to bone. Additionally, repetitive loading led to stress fractures and cartilage damage in rabbits (Schaffler et al. 1989).

The extrapolation of this finding to humans, especially within a running context, has been a focus of many researchers as stress fractures of the lower limb make up nearly 16 % of all running injuries (Chen et al. 2013). Several studies have reported that excessive impact forces are associated with the risk of sustaining certain types of injuries. For example, Milner et al.

(2006) compared a group of 20 well-trained (> 32 km per week), rear foot striking female runners with a history of tibial stress fractures, to an age, gender and mileage matched group of runners (n = 20) who had never experienced a tibial stress fracture. Ground reaction forces were measured with force plates during over ground running at 3.7 m/s. The previously injured group exhibited significantly greater initial loading rates (78.97 ± 24.96 vs 66.31 ± 19.52, BW/s; $p < 0.01$) and a trend towards higher peak tibial shock, which is a proxy for ILR, ($p = 0.057$, ES = 0.51) when compared to the uninjured group. This provides a link between impact forces and stress fractures, albeit retrospectively, and thus cannot establish whether loading rate predicts injury risk, or is an outcome of previous injury (Milner et al. 2006).

Subsequent research further explored the relationship between ILR and stress fractures by assessing kinetic asymmetry between runners with and without a history of stress fractures (Zifchock et al. 2006). The participants and methods used in this study were similar to those reported in the aforementioned study by Milner et al. (2006). However, participant numbers were greater, with 25 runners in the uninjured group and 24 runners in the group who had experienced a previous tibial stress fracture. The previously injured group had greater ILR and peak tibial shock values when compared to the uninjured group, which validates the findings of their previous study. However, the involved (stress fracture) leg of the previously injured group had greater tibial peak shock values when compared to the uninvolved (no stress fracture) leg. This finding further emphasizes the specificity of the biomechanical link between impact forces and injury, though again the direction of this link is unclear.

A fixed-effect meta-analysis conducted by Zadpoor and Nikooyan (2011) found that runners with a history of tibial and metatarsal stress fractures had greater average loading rates when compared to runners with no history of stress fractures (Zadpoor & Nikooyan 2011). Although these studies support the link between high ILR values to stress fractures, the relationship between ILR and other musculoskeletal injuries remains less certain, as stated by Nigg et al. (1997): “impact loading for cartilage and soft tissue structures falls within the acceptable window for moderate and intensive running and that impact loading for bone may sometimes fall outside the acceptable window for intensive running”. This suggests that ILR may not be responsible for soft tissue injuries, which may be caused by other biomechanical variables. Research aimed at injuries such as plantar faciitis, which is commonly experienced by runners, has improved our understanding of ILR as a key risk factor for injury.

In a cross-sectional study conducted by Pohl et al. (2009), runners with a history of plantar fasciitis presented with ILR values that were greater than non-injured runners, offering a potential link between high initial loading rates impact and soft tissue injuries (Pohl et al. 2009). Similar findings were presented by Ribeiro et al. (2015), where experienced runners with both

acute and chronic plantar fasciitis presented with higher ILR values than non-injured controls (Ribeiro et al. 2015).

To conclude that loading rates increase injury risk based on these cross-sectional, retrospective studies require some assumptions, which may limit the validity of the results. Since these participants were uninjured at the time of testing, the first assumption is that the biomechanical variables measured in these previously injured runners existed prior to the study, and that no biomechanical modifications were made in an attempt to avoid further injury, or as a result of injury. The second assumption is that these runners who received medical attention and advice were not made aware of the possible mechanism of their injury and did not alter their gait or undergo any form of gait retraining to minimize the risk of future injury. These assumptions offer limited application of the findings, essentially questioning whether ILR is a risk factor for injury. This possibly presents ILR as a simplistic injury mechanism since the true aetiology of running related injury is believed to be complex and multi-factorial.

Prospective studies on injury are more appropriate when determining possible associations between biomechanical factors and injury. Davis et al. (2016) recruited 249 rear foot strike pattern female recreational runners (> 32 km per week). Participants ran across an embedded force plate at a speed of 3.7 m/s. Variables measured were:

- vertical instantaneous loading rate (VILR)
- vertical average load rate (VALR, also known as ILR)
- vertical impact peak (VIP)

Thereafter, participants were tracked for a period of two years by means of a custom developed web-based database programme, where they reported severity of pain, location of pain and weekly mileage. After the two-year period, participants were assigned to an injured (experienced pain, n = 144) or an uninjured (did not experience pain, n = 105) group. The injured group was further sub-divided into a self-reported injury group (n = 41) and a medically diagnosed injury group (n = 103). The uninjured group was also further sub-divided into runners who had experienced an injury prior to the study (n = 84), and a group that had never been injured before (n = 21). To investigate the potential link between impact-related forces such as ILR (reported as VALR in this study) and injury, the main comparison was performed between the medically diagnosed injury group and the never injured before group.

An initial loading rate threshold of 66 BW/s was proposed, where participants with values below and above this threshold would have decreased and increased risk of injury, respectively. They found that both VIP and VALR were significantly higher in the medically diagnosed injury group, even when taking previous injury into consideration, as this has also

been reported as a risk factor for injury. In addition, having a VALR greater than 66 BW/s increased the likelihood of sustaining an injury by nearly three-fold. Finally, a variety of injuries, both bone and soft tissue were linked to high VALR, thus emphasizing the possible link between initial loading rate and all injury types, not just stress fractures (Davis et al. 2016).

This study offers insight into both training and impact loading risk factors for injury; however, it overlooks the potential link between kinematics and kinetics. The measurement of kinetic variables without a full understanding of the associated kinematic variables limits the applicability of findings since kinetic variables cannot be manipulated without the influence of kinematic variables, or possibly extrinsic variables such as footwear. A more clinically applied approach of understanding running related injury would improve the understanding of the potential link between modifiable variables such as running technique or footwear on these kinetic variables. Therefore, to better understand running related injury, the knowledge of how runners respond, or adapt to unfavourable kinetics such as high ILR is required.

In a recent study conducted by Kuhman et al. (2016), 24 well-trained cross country athletes were tracked for one season (Kuhman et al. 2016). Prior to the season, lower extremity three dimensional kinematic and kinetic data were collected by means of motion capture and force platform measurements, respectively. Over ground running was tested at 4.5 m/s for male and 4.0 m/s for female participants. After the conclusion of the athletics season, participants completed a custom online survey where they reported any injuries. Five participants were excluded from analysis due to non-running related injuries. Of the remaining 19 participants, 10 sustained injuries, including lower back spasms (n = 1), compartment syndrome (n = 1), tibial stress fracture (n = 1), medial tibial stress syndrome (n = 2), plantar fasciitis (n = 2), iliotibial stress syndrome (n = 1) and Achilles tendinopathy (n = 1) as a result of running (diagnosed by a trainer). No differences in ILR were found between the injured and uninjured group, questioning the relationship between ILR and injury. However, several factors may explain this finding. Firstly, the injured group presented with greater eversion range of motion, as well as rate of eversion. These two kinematic mechanisms may attenuate forces during running (Nigg 2001; Gojanovic 2013). A study conducted by Hreljac et al. (2000) found that previously injured runners had a greater ILR than their uninjured counterparts, however, the uninjured runners had greater maximal pronation velocity values, suggesting that eversion may attenuate impact forces. Secondly, the runners assessed in the study by Kuhman et al. (2016) had low body mass (62 kg), which may have lessened the effect of ILR on injury risk. Finally, as these were cross country runners who run predominantly on grass trails, the ILR values measured within a laboratory setting may not have been representative of the forces that they experienced throughout the season. This is supported by Dixon et al. (2000) who found that running on more compliant surfaces is associated with a reduction in ILR when

compared to harder surfaces (Dixon et al. 2000). Nevertheless, lower limb joint kinematics and surface compliance appear to play a role in the relationship between ILR and injury. More importantly, these variables, namely joint kinematics, body weight and surface compliance all represent variables that can be modified by a clinician by means of gait retraining, diet, and footwear prescription, respectively. Thus, knowledge of these contributing variables aids in the implementation of the clinically applied approach.

Understanding this relationship in novice runners is important and represents a gap in the literature. Since novice runners are most prone to injury, further investigation may potentially offer more insight into the cause and effect of mechanisms of injury.

1.4.2. Modifying Impact Forces: The Proposed Role of Foot Strike Pattern

The interpretation of kinetic variables together with kinematic variables is an important step towards improving the applicability of findings from research studies to runners. The modification of variables such as ILR is often achieved by means of gait retraining, which focuses on kinematic manipulation (Crowell & Davis, 2011). Studies have thus aimed to find potential links between kinetics and kinematics.

Daoud et al. (2012) found that the angle between the sole of the foot and the ground at ground contact, termed the foot strike angle (FSA), has implications for the risk of sustaining a running related injury. Generally, a positive FSA is indicative of a rear foot strike (RFS) pattern, where the heel of the foot contacts the ground prior to the forefoot. A negative FSA represents a forefoot strike (FFS) pattern, where the forefoot contacts the ground before the heel. A midfoot strike, where the heel and forefoot contact the ground simultaneously, has a FSA of approximately 0°. However, due to the large variability in vGRF (the presence or absence of an impact transient) associated with a midfoot strike pattern (Almeida et al. 2015), it was not considered for this dissertation. Thus, any positive FSA was considered a RFS and any negative FSA was considered a FFS pattern.

In this study by Daoud et al. (2016), competitive cross-country runners who landed with a RFS pattern were approximately twice as likely to report repetitive stress injuries over a period of four years compared to runners who ran with a FFS pattern. This finding agreed with a survey-study in which runners who self-reported a RFS pattern experienced a two-fold higher rate of injury when compared to experienced self-reported FFS pattern runners (Goss & Gross 2012). Additionally, landing with a RFS pattern was associated with injuries such as

- hip pain
- knee pain
- lower back pain
- tibial stress injuries
- plantar fasciitis
- stress fractures of lower limb bones excluding the metatarsals (Daoud et al. 2012).

These findings suggest foot strike pattern has implications on injury. A meta-analysis on foot strike patterns found that “natural rearfoot strikers exhibited significantly higher VLRs compared to natural forefoot strikers when running in a shod condition”. This study reported that “natural forefoot strikers running in the shod condition also have a greater knee flexion angle at initial contact compared to natural rearfoot strikers. This is likely due to the shorter stride length associated with this foot strike pattern, which is significant since shorter stride lengths have recently been associated with reduced loads to the hip and knee, thereby potentially reducing injury risk to these areas” (Almeida et al. 2015). This inter-joint relationship provides a good example of assessing the body as a kinetic chain, whereby changes in biomechanical variables have direct implications of other variables.

The precise effect that FSA and foot strike pattern has on injury risk remains unknown. This is, in part, due to the equivocal role that initial loading rate has in injury risk. Given the uncertainty around how initial loading rate affects injury rates, the effect of foot strike pattern, which may influence this kinetic variable in a complex manner, is even more unclear.

If ILR does in fact predict injury risk, then it may be of concern, since over 85 % of recreational runners have been found to adopt a RFS pattern (Larson et al. 2011; Kasmer et al. 2013). Research has shown that the majority of elite runners, during race conditions, land with a RFS pattern, with only the fastest runners in the race presenting as more likely to have a FFS pattern (Hasegawa et al. 2007). Specifically, in a half marathon event that included elite athletes, only 62 % of runners that placed in the top 50 (out of 415 participants) landed with a RFS pattern. These results suggest that running speed may influence foot strike pattern, with faster runners less likely to land with a RFS pattern than slower runners.

Given that recreational runners are running considerably slower than these research participants, it would be reasonable to assume that the RFS is largely over-represented in all runners, particularly when wearing shoes. If it is true that landing with a RFS pattern increases the risk of injury, as has been hypothesized (Daoud et al. 2012; Lieberman et al. 2010; Goss & Gross 2012), then a potential intervention to reduce injury risk would be to change the foot

strike pattern, or at least to change the FSA in a direction that is more towards a FFS pattern. On one hand, one should also consider why runners, largely uninstructed and doing what is natural for them, would adopt this foot-strike pattern if causes higher loading rates and greater injury risk. Certainly, the delay in injury outcome mitigates this being a reason for the runner to change. However, if higher loading rates can be experienced by a runner, and could be changed by changing landing pattern, then it is interesting to consider why more runners do not naturally find the lower loading rates (and thus theoretical injury rates) available to them through kinematic changes such as shorter strides and forefoot landing. Possibly, this highlights that the biomechanics of running are complex and that runners are employing kinematic or kinetic strategies to optimize much more than simply loading rate.

Research focused on footwear, or the lack thereof, has provided important insight into this link between foot strike pattern and impact forces.

1.4.3. Modifying Impact Forces: A Potential Role for Footwear

Although kinetic variables such as ILR provide insight into the mechanism of running related injury, they cannot be assessed in isolation. When excessive initial loading rates were first linked to running related injury, cushioning was added to the midsole of running shoes to dampen these forces. Unknown at the time, changing the specifications of footwear had implications for kinematics, as the additional cushioning allowed runners to comfortably land with a RFS pattern (Chambon et al. 2014; Horvais & Samozino 2013). These changes in footwear specifications did not affect the high incidence of running related injury. This may be the result of enabling a population with different and potentially greater intrinsic risk factors (training status, weight etc.) to run. However, research into the influence of footwear on running biomechanics continued, and most recently, has involved advocacy for the complete removal of shoes (barefoot running) and the adoption of minimalist shoes.

This footwear-kinetic interaction occurs, at least in part due to, or perhaps as the result of, alterations in the kinematic variables during running. Indeed, Lieberman et al. (2010) examined how footwear influenced landing pattern, and showed that in traditionally cushioned shoes, as worn by the majority of runners, all participants landed with a RFS pattern. However, in traditionally barefoot individuals (Kenyan children, in this case, who are accustomed to walking and running barefoot), the proportion of RFS pattern was only 29 % (Lieberman et al. 2010). This was argued as evidence to support that cushioned shoes may increase the risk of injury, and that barefoot running may be beneficial by lowering the risk of injury through this mechanism of lowering the ILR by changing the foot strike pattern.

However, Tam et al. (2016 and 2017) showed, in two different studies, that upon first exposure to barefoot running, most previously shod runners do not adopt this FFS pattern (N Tam et al. 2016; N Tam, Prins, et al. 2017). Instead, approximately half of the cohort remained rearfoot strikers, despite the lack of cushioning that is normally provided by footwear. The result was that more than 70 % of the participants presented with higher loading rates when barefoot than when in shoes, possibly due to the lack of cushioning beneath the heel. This supports Lieberman's concept that ILR was greater in traditionally shod runners who maintained a RFS when running barefoot (Lieberman et al. 2010).

The implication of these studies is that caution must be exercised, even within the currently uncertain theoretical framework relating injury risk to ILR. That is, loading rate may be higher when running barefoot as people do not always adjust their running biomechanics in response to changes in footwear.

Running barefoot has since been deemed impractical due to the risk of acute puncture wounds. Allied to commercial incentives, this prompted the development and growth of a minimalist shoe market. These shoes are designed with minimal cushioning yet offer sufficient plantar protection. The premise of these shoes is to mimic the potentially beneficial biomechanics of running barefoot to ultimately reduce the risk of sustaining a running related injury. The popularity of these shoes predated any evidence for their scientific efficacy, which has resulted in lawsuits against shoe companies advocating the use of minimalist shoes to prevent injury (R Tucker 2014).

The impact of minimalist shoes on kinematics and kinetics has been researched. Willy and Davis (2014) investigated the potential kinematic and kinetic differences that exist between running in traditionally cushioned and minimalist shoes (Willy & Davis 2014). Fourteen habitually shod rear foot striking males were recruited. These participants were required to be injury-free for the six months prior to the study and were required to be a ''novel'' minimalist shoe wearer, defined as "never having previously run in minimalist shoes". Three dimensional and kinetic data was recorded during treadmill running at 3.33 m/s in both traditionally cushioned and minimalist footwear. Results from this study found that when the two footwear conditions were compared, FSA was similar, and based on the standard deviations reported for foot inclination angles, it is unlikely that any of these participants landed with a FFS pattern, even in minimalist shoes. Additionally, running in minimalist shoes resulted in a significantly higher ILR when compared to traditionally cushioned shoes (85.4 ± 24.6 vs 52.7 ± 13.2 BW/s). This supports the finding of Willson et al. (2014), who found that greater ILR values were observed amongst runners wearing minimalist footwear who preferred a RFS pattern after two weeks of training compared to those with a non RFS pattern (Willson, Bjorhus, Iii, et al. 2014).

Together, these studies emphasize the importance of running biomechanics rather than running footwear, as footwear alone may be insufficient to acutely alter foot strike patterns.

Hollander et al. (2015) conducted a randomised crossover study that included 35 injury-free recreational distance runners who had never run barefoot or in minimalist footwear. Three dimensional kinematic and kinetic data was collected during treadmill running at 3.33 m/s in four footwear conditions, namely

- barefoot
- uncushioned minimalist shoes
- cushioned minimalist shoes
- standard running shoes.

They reported that the amount of cushioning offered by the shoe was positively correlated with the prevalence of landing with a RFS pattern (58.6 %, 62.9 %, 88.6 % and 94.3 % of the participants landed with a RFS pattern in each of the footwear conditions, respectively). This finding supports the work by Chambon et al. (2014) and Horvais & Samozino (2013) which shows that footwear structure does influence landing pattern, though it may not result in a complete change in foot strike pattern (Hollander et al. 2015).

When considering the effect of longer transition periods on foot strike pattern, one study found that more than half of runners who ran in minimalist footwear for longer than two years, changed to a FFS pattern (compared to no runners adopting a FFS when acutely transitioning to minimalist footwear described by Willy and Davis, 2014), suggesting that a longer transition period is necessary for runners to adapt to the reduced cushioning found in minimalist footwear (Goss & Gross 2012).

A limitation of this study was that runners were not tracked throughout the two years; therefore, no pre- vs post-comparison was provided. It is possible that runners who persisted with running in minimalist footwear for longer than two years were those who had already adopted a FFS pattern, ultimately providing an over representation of FFS pattern runners because it may be a necessary kinematic trait to succeed in minimalist shoes. In contrast, Tam et al. (2017) also assessed a group of habitual minimalist footwear runners, defined by running exclusively in minimalist footwear for longer than a year, and found that nearly all landed with a RFS pattern (N Tam, Darragh, et al. 2017). These inconclusive findings suggest that without gait retraining to promote a FFS pattern, minimalist shoes may be ineffectual at promoting outright transitions on foot strike pattern.

Warne et al. (2014) investigated whether a 4-week familiarization period in minimalist footwear had any effect on plantar pressure and foot strike patterns when compared to the same familiarization protocol in cushioned footwear, using a prospective, randomized cross-over study design. Ten injury-free, trained female runners (± 45 km per week) who had no experience in running with minimalist shoes were recruited for the study. Regional pressures, mean maximum force, mean maximum pressure and foot strike pattern by means of the foot strike index (Altman & Davis 2012) data were obtained during treadmill running at 3.0 m/s in both footwear conditions. The 4-week familiarization programme included supplementing total mileage in their preferred footwear, with progressive mileage in minimalist footwear, until 25 % of the total weekly mileage was completed in minimalist footwear. Injury prevention exercises and running technique cues were also provided to reduce the risk of sustaining a running related injury.

Prior to the familiarization period, only 30 % of the runners landed with a FFS pattern. This increased to 80 % post-intervention. Interestingly, despite the transition period and the running technique advice, 20 % of the participants maintained a RFS when running in minimalist footwear, suggesting that some runners may find it more comfortable to adopts a RFS pattern when running in minimalist footwear. Further, mean maximal force decreased in both the minimalist and cushioned footwear conditions, however, mean maximal pressures in the region of the heel only decreased in the minimalist footwear condition. Finally, this study showed that regardless of foot strike adaptation, higher mean pressures were found in the minimalist footwear condition both prior to and after the familiarization period. These findings suggest that the ability to transition from a RFS to a FFS pattern when wearing minimalist footwear is largely dependent on technique advice and a FFS is not likely to be adopted intuitively. This study, however, did not measure biomechanical changes between a familiarization period that included gait retraining, thus making it difficult to distinguish between the effect of the footwear and the effect of the gait retraining.

1.4.4. Defining Minimalist Footwear

A lack of agreement in biomechanical adaptations to minimalist footwear is, in part, due to the absence of agreement in defining a minimalist shoe in terms of structural specifications. It is therefore necessary to outline the criteria that define minimalist footwear for two reasons. Firstly, for future studies to standardize prescribed footwear which could reduce the biomechanical and clinical variability associated with these shoes. Secondly, it would allow clinicians to provide more specific footwear prescription to their patients, to both rehabilitate and reduce the risk of future injury.

This process of identifying and defining the structural characteristics of minimalist shoes is an important undertaking, which will be addressed by this dissertation. In Chapter Three, we consider this question by comparing literature published on the biomechanical effects of running in minimalist shoes to the structural specifications of the footwear used in these studies. (Esculier et al. 2015; Chambon et al. 2014; Horvais & Samozino 2013; Squadrone et al. 2014).

1.5) Footwear Prescription for Novice Runners: A Clinician's Approach

Runners frequently turn to footwear to either prevent or rehabilitate injuries. Although footwear has been found to influence running biomechanics and by inference, less is known about the implications for injury. Studies have found that in some runners, changing footwear specifications is enough to promote biomechanical adaptations whilst others seem to maintain set biomechanical traits, regardless of footwear structure (Goss et al. 2015). This suggests that some shoes may be effective for some runners, but incorrect footwear prescription may have detrimental injury implications for others. This raises the need to not only understand the changes, or lack thereof, that may be induced by footwear specifications, but also to fully understand the underlying biomechanical mechanisms that may contribute to clinical outcomes such as injury.

Chapter Six of this dissertation will look into various factors such as intrinsic characteristics for injury strength, flexibility and body composition as these are often considered in a clinical setting when assessing injury but overlooked when prescribing footwear to individuals. It is important to address this, so that more specialised prescription may be offered by clinicians, ultimately improving the efficacy of running footwear in preventing or rehabilitating injury.

1.6) The Clinically Applied Approach for Investigating the Effect of Impact Forces, Foot Strike Pattern, Footwear and Intrinsic Characteristics on Running related Injury

The current scientific research approach favours the grouping of runners by means of injury outcome (i.e. injured versus non-injured) and investigates differences in running biomechanics. This is important as it allows for an outcome-driven approach. However, we propose a clinically driven approach whereby runners should be grouped in terms of:

- kinetic variables (i.e. high ILR versus low ILR)
- foot strike pattern (RFS versus FFS)
- footwear (cushioned versus minimally cushioned)

- intrinsic risk factors (high mass versus low mass)

so that not only can injury outcomes be prospectively assessed, but their risk factors as well.

This represents a more applicable approach, as these proposed groupings represent modifiable variables rather than outcomes. Additionally, by assessing risk factors rather than only injury, more information can be gained on the mechanisms of injury, so that prevention strategies or risk stratification can be implemented. Essentially, clinicians can both measure and modify these variables by means of interventions such as gait retraining, footwear prescription and diet/exercise, respectively.

1.7) The Aims of this Dissertation

To better understand the effect of footwear on running related injury, more insight is required into how novice runners respond to a 12-week progressive running programme. Questions of interest include:

- What biomechanical adaptations take place when running is 'practiced' without advice on running technique or form?
- What are the implications of these adaptations for running related injury?
- How does footwear with varying structural specifications influence biomechanics and injury?
- How do body composition, flexibility and strength of a novice runner influence risk of injury?

These questions represent a significant gap in the literature, particularly with reference to novice runners. These questions are important as they will hopefully be able to provide more accurate insight into footwear prescription as well as to better understand how footwear influences risk of injury.

Therefore, the focus of this dissertation is to firstly outline the risk of injury associated with novice runners participating in a 12-week running programme, and to subsequently determine the kinetic and kinematic mechanisms associated with these outcomes.

Additionally, the effect of intrinsic risk factors such as strength, flexibility and body composition on injury will be explored to better understand why some individuals succeed at running and others sustain a running related injury.

Finally, this dissertation offers suggestions on clinical applications of the findings for novice runners so that they can:

1) minimize injury risk
2) make informed decisions about footwear and considerations regarding the successful transition into that footwear.

This dissertation includes the following chapters:

Chapter Two

Dissertation Concept, Study Design and Methodology

Aim:

To outline the model proposed for the dissertation and describe the methodology implemented for each of the studies

Chapter Three: Part One

Conceptualizing Minimalist Footwear: An Objective Definition

Aim:

To provide an objective and quantified definition for minimalist footwear by investigating upper threshold values for important structural specifications.

Chapter Three: Part Two

Defining Minimalist Footwear within the Minimalist Index: A Complementary and Comparative Perspective on Two Approaches

Aim:

To integrate this proposed definition with an already established Minimalist Index, to further refine the concept of minimalist footwear.

Chapter Four

Study One

Novice Runners and Running related Injury: Does a Progressive Training Programme and Running Footwear Influence Injury Risk?

Aims:

To determine the incidence of running related injury in novice runners during a progressive 12-week running intervention.

To determine whether footwear influences the risk of sustaining a running related injury by means of assessing clinical imaging for bone stress reactions and subjective scores of pain and discomfort.

Chapter Five

Study Two

The Biomechanical Link to Running related Injury: How Novice Runners Respond to Running in Footwear with Reduced Cushioning

Aims:

To determine whether clinical measures of injury, including pain or discomfort and bone oedema, may be explained by certain biomechanical mechanisms.

To describe the biomechanical adaptations that occur as a result of running in footwear with reduced cushioning for 12 weeks, with specific focus on whether a) a forefoot strike pattern is adopted intuitively and b) any kinematic changes result in kinetic adaptations that may be linked to the risk of sustaining a running related injury?

Chapter Six

Study Three

The Effect of Intrinsic Variables on Running related Injury Risk and Biomechanics

Aims:

To investigate the effects of body mass components, namely fat mass and lean mass, on the risk of running related injury and whether these variables have any influence on biomechanical factors that have been assessed in Chapter Three of this dissertation.

To assess the adaptations in strength and flexibility during a 12-week running intervention in novice runners.

Chapter Seven

Clinicians Guidelines for Reducing Injury Risk in Novice Runners

Aims:

To answer the key questions put forth by the model guiding this dissertation, to outline the clinical relevance of the findings derived from this dissertation, and to provide insight into the application of the findings for clinicians, researchers and runners.

This summary chapter has been presented in the form of questions linking runners to injury by means of their biomechanics, as well as common questions asked by clinicians. The questions are as follows:

1) What intrinsic characteristics of novice runners are important for clinicians to consider to minimise injury risk, and how does a conservative running programme in footwear with reduced cushioning affect these intrinsic characteristics?

2) Do intrinsic characteristics of novice runners influence their running biomechanics?

3) Do novice runners adapt their running biomechanics throughout a 12-week running programme, and does footwear influence their biomechanics?

4) Are running biomechanics indicative of injury outcomes, and what variables should clinicians be assessing?

5) Is a conservative and progressive running programme effective at reducing injury risk in novice runners, and how does footwear influence this risk?

6) What structural specifications are important to consider when prescribing footwear?

7) What factors should a clinician consider when prescribing injury prevention advice to novice runners?

8) Should minimalist shoes be prescribed to prevent injury?

Chapter Eight

Limitations and Future studies

Aims:

To outline the limitations of this dissertation and how future studies can use the findings of this dissertation to further the field of running injury, running biomechanics and footwear prescription.

Chapter Two

Dissertation Concept, Study Design and Methodology

2.1) Abstract

Current literature investigating running injury has been successful in identifying risk factors and highlighting populations that are at heightened risk of injury. However, the mechanism of injury remains uncertain. This chapter proposes a model that links intrinsic characteristics of novice runners to injury outcomes by means of a biomechanical risk factors, which represents the mediatory step in better understanding the mechanism of injury.

The methodology of the dissertation is described. Fifty-four novice runners were assigned to either the traditionally cushioned (TC) footwear group (n = 32) or the reduced cushioned (RC) footwear group (n = 22). Runners participated in a progressive and supervised 12-week running intervention that consisted of 36 running sessions, with three sessions taking place per week. Baseline and post-intervention testing included three-dimensional motion capture and force plate analysis of over ground running at 3.0 m/s in their prescribed footwear. Bilateral ankle (concentric and eccentric) and knee (concentric only) strength was assessed using an isokinetic dynamometer at two speeds (60°/s and 180°/s). Bilateral lower limb flexibility was assessed using the following tests: calf and Achilles tendon – lunge test, hip flexors and quadriceps – modified Thomas test, hamstrings – active knee extension. Bone oedema was assessed with bilateral magnetic resonance imaging and full body composition was assessed using duel energy absorptiometry. Pain or discomfort scores were assessed weekly throughout the running intervention by means of logbook recordings, and symptoms were recorded on a scale from 0 – 10 (10 being the most severe pain or discomfort) and described by location of symptoms.

2.2) Dissertation Concept

Two key questions that underpin research in the field of running epidemiology are: i) Which runner is most at risk of sustaining an injury?; and ii) What characteristics do they possess that create this increase in risk? The corollary is to identify runners who are relatively more protected against injury, and to determine which factors, either intrinsic or extrinsic, modify their risk downwards.

The complexity of running injury aetiology has prevented a complete understanding of the mechanisms for injury. Several studies have identified risk factors for injury, as well as

identifying populations with heightened risk, one of which is novice runners (Videbæk et al. 2015; Buist et al. 2007).

As a result of these studies, and to address the questions posed above, a common model that exists in the literature (Figure 2.1) assesses the extent to which intrinsic characteristics influence either biomechanical adaptation or injury outcome can be summarized as follows:

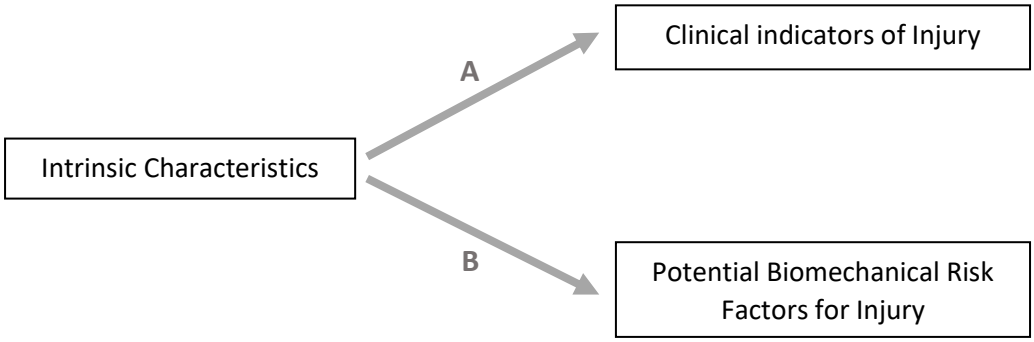

Figure 2.1: Current outlook on runners' intrinsic characteristics with the resultant biomechanical changes and clinical indicators that could be used to predict running injury risk factors

Intrinsic characteristics are defined as those characteristics that belong to the runner and exist independent of the external stimulus of training (running). Intrinsic characteristics that have been linked to running injury include:

- body composition (Buist & Bredeweg 2011; Buist et al. 2010; Fuller et al. 2017; Nielsen et al. 2013; Nielsen et al. 2014),
- strength (Leetun et al. 2004; Niemuth et al. 2005),
- flexibility (Biering-Sorensen 1984; Esola et al. 1996; Hartig & Henderson 1999; Witvrouw et al. 2001).

Other intrinsic characteristics include gender and structural alignment of the lower limb. Whilst these are important, they will not be discussed in-depth throughout this dissertation.

Clinical indicators of injury may be defined as measurable signs or symptoms that may exist prior to the onset of injury and may lead to injury if the causative factor is not mitigated. Clinical indicators of injury include pain or discomfort and bone oedema.

As the model above depicts, these intrinsic risk factors have been associated with clinical indicators of injury (Path A), or with biomechanical factors that have been associated with or hypothesized to increase injury risk (Path B). Despite numerous studies associating the runner's intrinsic characteristics and injury or biomechanics, they are often retrospective.

More importantly, biomechanical outcomes of intrinsic characteristics and the actual clinical outcomes/indicators of injury have not been linked in research studies. Thus, a link between running biomechanics and injury has also been researched extensively and proposed (Dudley et al. 2017; Gojanovic 2013; Bredeweg et al. 2013; Davis et al. 2016), but given the complexity and variability of running biomechanics between runners, confounders such as intrinsic characteristics are often excluded. The result is an incomplete model that provides important insight into why runners get injured but overlooks the question of who gets injured.

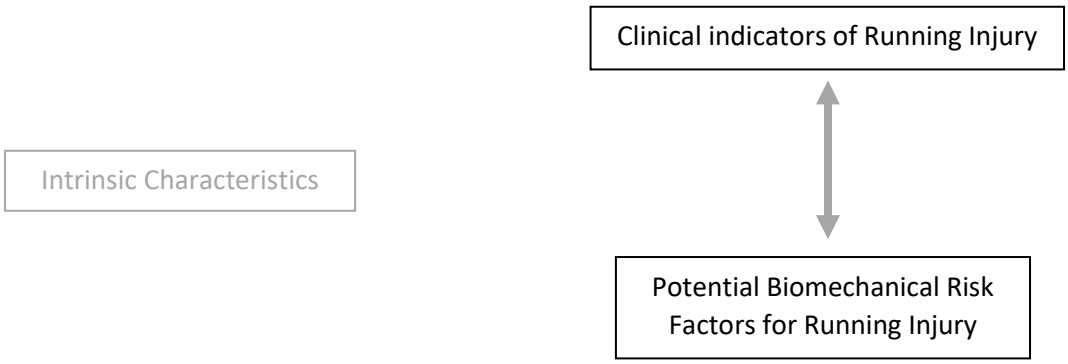

Figure 2.2: Predictive model for running injury linking biomechanical risk factors to clinical indicators of injury, omitting intrinsic characteristics

To integrate these two parallel concepts (who gets injured and why?), we propose and use a conceptual model where intrinsic characteristics including body composition, strength and flexibility, influences running biomechanics, which in turn modifies injury risk and clinical outcomes:

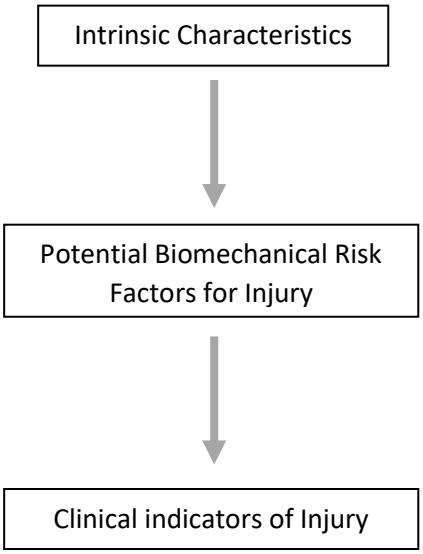

Figure 2.3: Dissertation conceptual model of running injury, highlighting the linear causative relationship

This model holds that running biomechanics are a potential mediator of intrinsic characteristics and thus running injury, and that the link between the two may provide further insight into the mechanism of running related injury. Additionally, this linear model emphasises a causative relationship between intrinsic risk factors and clinical outcomes. This is important since the key questions of who gets injured and why are most effective when asked prior to injury, or ideally before the commencement of running. Theoretically, this sequential conceptual model will allow biomechanical risk factors and injury to be determined and thus to be modified, or for training to be adjusted to reduce the likelihood of injury.

This aim of this dissertation is to assess this model within the context of a prospective running intervention in novice runners. The aims are to understand how intrinsic characteristics affect running biomechanics and injury risk, and to develop insight that may in future assist clinicians in whether these relationships are modifiable either at the level of the intrinsic risk factors, or the running biomechanics.

Based on the model outlined above, then, we can summarize this dissertation and its component research studies (chapters) by the following schematic diagram:

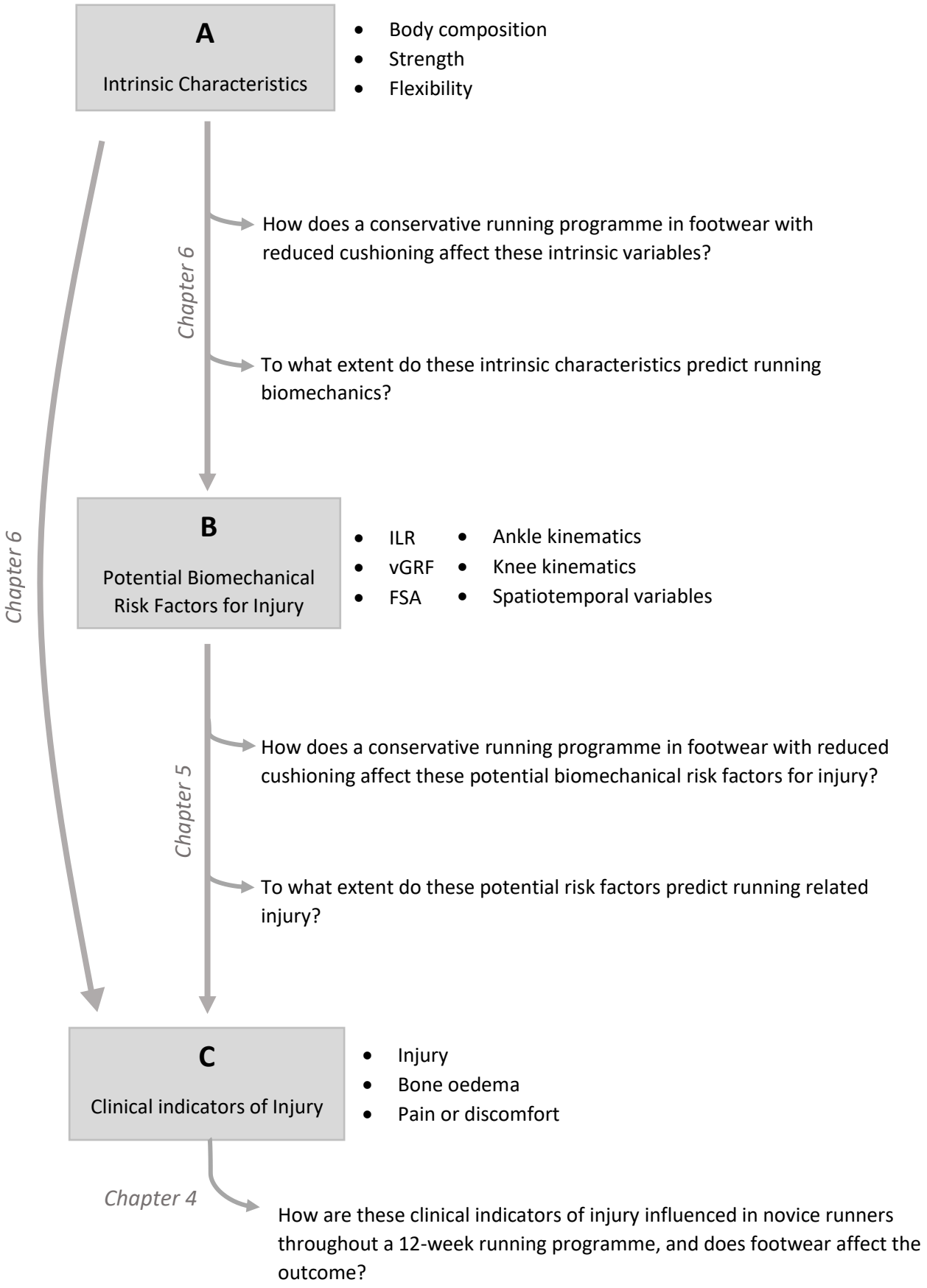

Figure 2.4: Conceptual model of running injury layout for dissertation chapters

ILR; initial loading rate, vGRF; vertical ground reaction force, FSA; footstrike angle

The clinical outcome-driven approach of this dissertation is intended to provide a framework to determine potential risk factors for running related injury by studying who gets injured or is at risk of injury. Secondly, it aims to determine why they may be at risk as a result of running biomechanics. Thereafter, we wish to theorize whether clinicians can assess novice runners and make recommendations based on body composition, strength and flexibility, given associations we are exploring between these intrinsic characteristics and biomechanical variables that may potentially increase injury risk. Finally, the implementation of this clinical outcome driven approach may provide insight into the potential effectiveness of running in footwear with reduced cushioning, be it in clinical variables, potential risk factors for injury or injury and injury predictors.

In this model (Figure 2.4), the clinical outcome is either running injury or indicators of running injury including signs of bone oedema and pain or discomfort. Including injury indicators within the model is necessary as it provides insight into which runners may sustain a running related injury prior to the attainment of a clinically relevant threshold for injury. Since footwear prescription, especially footwear with reduced cushioning, has become a popular method of preventing or rehabilitating injury, it is important to understand the effects that footwear structure specifications has on running biomechanics and further, to identify whether footwear choice may affect injury risk and outcome. Chapter Three of this dissertation will review available literature and assess the biomechanical modifications that runners make as a result of footwear type, with the aim of defining minimalist footwear, which drives the concept of reducing cushioning in footwear. Thereafter, Chapter Four of dissertation will present original data on the incidence and prevalence of running related injury in novice runners over a 12-week running intervention and determine whether running in footwear with reduced cushioning influences risk of injury or presence of injury predictors.

Since the primary outcome of this dissertation is to better understand the effect of intrinsic characteristics easily measurable in a clinical setting on biomechanical variables that may influence injury, the studies were powered using key biomechanical variables, e.g. initial loading rate (ILR). This is important, because the premise described above uses injury as a research endpoint. However, we could not embark on a training programme designed to induce injury in all participants, and instead wished to deliver as many as possible of the participants to the end of the 12-week training period without injury. To this end, our conservative programme was successful, with only six (out of 54) novice runners sustaining injuries over the 12-week programme (as described in Chapter Four). The injury aspect of the study is thus not sufficiently powered to report the findings without requiring the use of indicators of injury, rather than injury itself. However, the assessment of these indicators of

injury permitted the implementation of the clinical outcome driven approach as it allowed for the categorization of participants based on their risk of sustaining an injury.

Once we were able to ascertain which participants sustained injuries or presented with indicators of injury, we could assess and compare key biomechanical variables between them and participants who successfully completed the intervention without injury or indicators thereof. Chapter Five of this dissertation therefore aimed to determine whether novice runners who sustained injuries or presented with indicators of injury differed with respect to pre-intervention biomechanics compared to the group of runners who successfully completed the intervention without any injury or injury indicator. Biomechanical variables that have previously been highlighted as potential risk factors for injury were compared. Additionally, the effect of training in footwear with reduced cushioning was assessed over the 12-weeks since the premise of this footwear is to promote biomechanical adaptations that are said to be beneficial for injury prevention.

We acknowledge that the association between biomechanical variables and injury is complex, may be influenced by numerous confounders and may only be weak for certain injuries. However, gaining a better understanding of the effects of habituating to a shoe with reduced cushioning may provide insight into injury mechanism and biomechanical adaptation.

The final step of our clinical outcome-driven approach was to determine whether commonly assessed intrinsic characteristics may provide insight into injury risk by influencing running biomechanics or injury outcomes. The ease and regularity with which these factors, such as body composition, strength and flexibility, can be measured in a clinical setting makes them attractive and potentially valuable to understand as risk factors in novice runners. Reasons for assessing these intrinsic characteristics last, despite being the initial step in clinical assessment, promotes an outcome-driven approach. Using injury and indicators of injury allows for categorization which aids in biomechanical analysis and interpretation. Likewise, knowing which runners are at heightened risk of injury, and whether their running biomechanics potentially contribute to this heightened risk allowed for the assessment of intrinsic characteristics with foresight of biomechanics and injury outcome. Chapter Six of this dissertation will present data on the potential link between running biomechanics and body composition, strength and flexibility.

2.3) Study Design

The studies conducted for this dissertation were prospective randomised control trials where novice runners were placed into the Reduced Cushioning (experimental) or the Traditionally Cushioned (control) group. The obvious nature of the footwear types meant that participants were not blinded to their group allocation, however limited information was given about footwear purpose, structure or function. The intervention included a baseline testing period, a 12-week intervention and a post-intervention testing period. Outcome variables are described subsequently.

2.4) Methods

A full description of the methods used in the study is provided in the following section. In each chapter, the methods are summarized, with referral to these more detailed descriptions should they be desired.

2.4.1. Participant criteria

The participants were novice runners between the ages of 18 and 45 years. To be considered novice runners, participants were required to not have run consistently in the previous year, defined as running for three or more consecutive weeks. If they had run, they could not have run more than twice a week, for a total of five kilometres or 30 minutes per week, for at least one year prior to study participation. If participants did run at levels below this prior to the study, they were required to have run in a traditional shod shoe. These shoes are defined in Chapter Three of this dissertation as having a heel toe differential >7 mm and heel stack height >20 mm, regardless of material composition (Coetzee et al. 2018).

All participants were injury free (any orthopaedic injury causing the participant to have sought medical treatment or causing them to miss exercise sessions) for at least six months prior to commencing the study. Further, participants were excluded if they had a body mass index (BMI) outside a range of 18.0 - 27.0 kg/m^2. Finally, participants with any form of surgical material (metal plates, screws etc.) were excluded from the study. All participants signed an informed consent form. Ethical approval for this study was granted by the Human Research Ethics Committee of the University of Cape Town.

Sample size for this study was calculated using data from previous studies conducted by this research group assessing biomechanical changes due to footwear structure. Variables considered were of a biomechanical nature (foot strike angle and initial loading rate), which

represent the link between injury outcome and intrinsic variables. Using α = 0.05, power = 0.8 and 15 % difference representing a significant change, 17 participants were needed to adequately power the biomechanical studies. Given the injury nature of the other studies, we could not power these studies sufficiently due to the complexity and cost of the testing procedures, and the nature of the intervention. We therefore recruited additional participants (between 20 and 32 per group) to provide sufficient power for the other studies including body composition, strength, flexibility, and predictors of injury. Further, this sample size is equivalent to other studies of similar design.

2.4.2. Footwear prescription

Participants were assigned to a traditional cushioned (TC) neutral shoe or a reduced-cushioned (RC) shoe. The TC group were provided with adidas Supernova Glide BOOST (heel-toe differential = 10 mm, heel height = 32 mm, forefoot height = 22 mm) and the RC group were provided either adidas Gazelle (n = 13, heel-toe differential = 7 mm, heel height = 19.75 mm, forefoot height = 12.75 mm) or adidas Adizero Feather Prime (n = 9, heel-toe differential = 6 mm, heel stack height = 17 mm, forefoot stack height = 11 mm) shoes. Two different RC shoes were used for availability and logistical reasons, as the adidas Gazelle shoe was discontinued between the second and third intake of participants. The specifications of both these shoes met the required criteria for a minimalist shoe, as described in Chapter Three of this dissertation, and elsewhere (Coetzee et al. 2018; Esculier et al. 2015). The group is referred to as reduced cushioning since the one shoe used (Gazelle) was marketed as minimalist, whereas the other shoe (Feather Prime) was marketed as a racing flat, both of which have reduced cushioning when compared to a traditionally cushioned shoe.

2.4.3. Participant intake and testing logistics

Participants were recruited in three intakes:

Table 2.1: Participant intake for the 12-week intervention

Intake number	Start date	TC (n)	RC (n)	Total (n)
1	September 2014	11	6	17
2	February 2015	15	7	22
3	September 2015	6	9	15
Total		**32**	**22**	**54**

Participants were randomly allocated to the two groups with the intention to match the size of the TC and RC groups. However, limited availability of sizes in the RC shoes during intake 1 and intake 2 rendered this impossible.

2.4.4. Overview of testing procedure

Each participant visited the Sports Science Institute of South Africa during the week prior to the commencement of their 12-week training programme for baseline testing. This included anthropometric measurements, bilateral magnetic resonance imaging (MRI), biomechanics assessments, strength measures and flexibility testing, all described in detail subsequently. Post-intervention MRI scans were conducted within a week of concluding the 12-week programme. Throughout the 12-weeks of running, measures of pain, injury and discomfort were recorded weekly.

2.4.5. Training programme

The 12-week training programme consisted of 36 running training sessions. Three sessions were completed each week with two of these sessions being supervised by the research team and run as a group and the third session of each week being prescribed for the participant to complete in their own time and recorded in logbooks to assess adherence. All participants met up before each group run and started as a group, then partially regrouped during the walking periods. This allowed each participant to run at their own comfortable pace. All sessions were completed on asphalt/tar. During these supervised training sessions, distances and paces were recording using commercially available GPS watches. Total distance and time were measured during the supervised sessions, with the assumption that the pace run during the third unsupervised session was similar to that of the supervised sessions, since participants were always encouraged to run at their own preferred pace rather than the pace of the group. No verbal instruction was provided during the supervised sessions with regards to running technique and style.

The programme incorporated a run/walk system whereby periods of running were interspersed with periods of walking. Over time, the running period increased progressively with the walking time remaining constant, resulting in an increase in the run:walk ratio over the 12 weeks (Figure 2.5). The number of periods spent running and walking differed depending on the required mileage covered in each session. The large increase in run:walk ratio seen in the last two weeks is due to significantly reduced number of walking intervals.

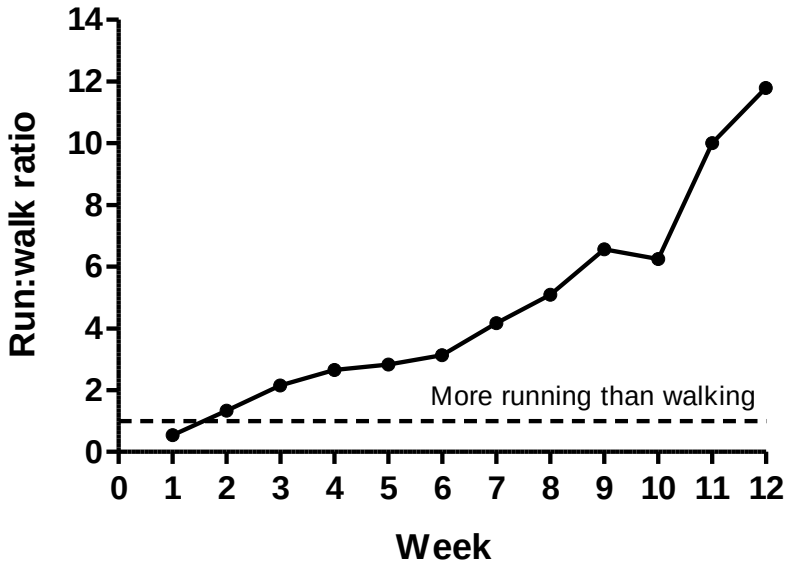

Figure 2.5: The ratio of running to walking per week over the 12-week running intervention

The 12-week running intervention covered approximately 202 km in 36 running sessions. This represents the distance covered by a mid-pack novice runner (average speed of 6:50 min/km), with faster and slower runners covering more and less distance respectively (paces ranged from approximately 5:00 – 8:00 min/km). The intervention included a total of 1090 minutes of running and 285 minutes of walking per participant who completed the 12-weeks.

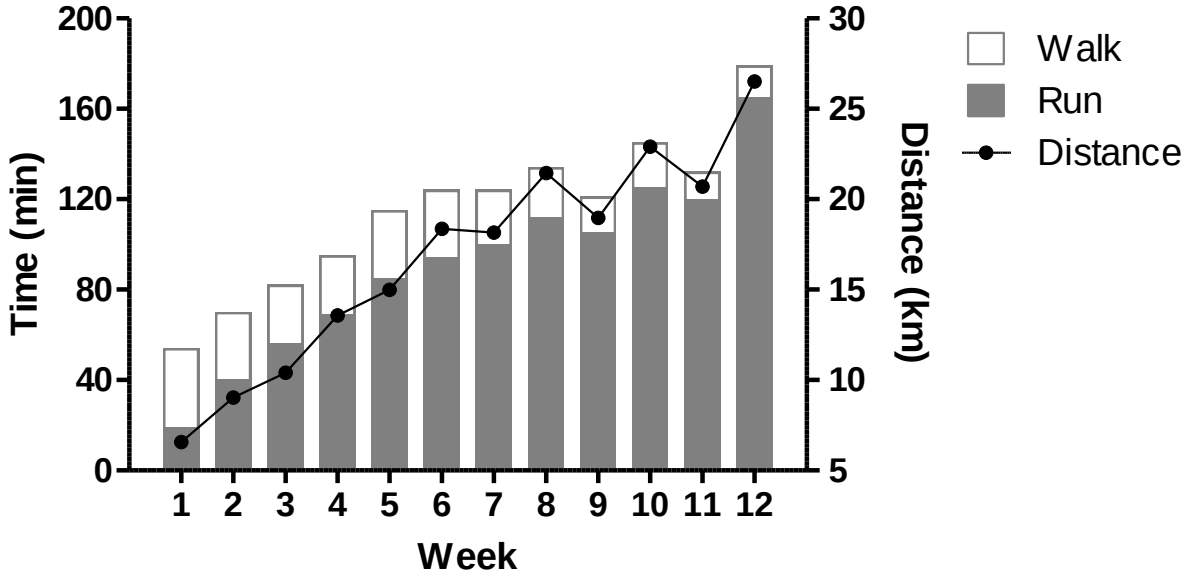

Figure 2.6: A weekly breakdown of time spent running, time spent walking and distance covered during the 12-week running intervention

Participants were required to complete a minimum of 70 % (25 of 36) of the running sessions and could not miss three consecutive sessions. Any participants who missed more than 11 running sessions (or three consecutive running sessions) were excluded from the final analysis due to non-compliance. A 70 % adherence rate was set as this coincides with the number of supervised sessions, where attendance could be marked off in person with certainty.

The total time spent both running and walking over the 12-weeks was 1375 minutes. The collective total distance covered, and time spent running and walking by the participants (excluding those who dropped out due to non-compliance) was approximately 9 396km and 1 071.1 hours respectively.

2.4.6. Magnetic resonance imaging

2.4.6.1. Instrumentation

MRI scans were taken using 1.5T MRI extremity scanner (GE Optima MR430S, General Electric, USA). Participants underwent bilateral magnetic resonance imaging of the lower leg, ankle and foot. The ankle of interest was placed in the 160/180mm cylindrical RF transmit/receive coil in an isocenter position within the magnet. The field of view included the hindfoot and distal aspect of the tibia and fibula. Short TI Inversion Recovery (STIR) Sag Sequence was used to acquire sagittal images performed with a 16 cm field of view, 320 x 256 matrix, 4 mm thickness and 0.4 mm spacing, 3500 ms TR, 35 ms TE, and 120 ms inversion time. This imaging technique is a fat saturated sequence that is fluid sensitive and thus effective for assessing bone oedema. With this sequence, signs of bone oedema are represented by elevated T2 signals.

2.4.6.2. Procedure

Magnetic resonance imaging (MRI) scans were conducted prior to (baseline) and after the 12-week intervention (post-intervention). Scans were taken in the morning and participants were instructed not to run the day before the MRI scan.

2.4.6.3. Magnetic resonance imaging data analysis

Bone oedema was scored according to a system based on a method used previously (Lazzarini, Troiano, & Smith, 1997; Ridge et al., 2013). Subsequently, bone oedema was scored on a 5-point scale, where a score of 0 indicates no signs of oedema and a score of 4 indicates a stress fracture (Table 3.2). Low level oedema, indicated by a score of 1, is said to be advantageous as it represents osseous remodelling (Anderson & Greenspan 1996). Therefore, only scores of 2 - 4 were considered as significant clinical signs of bone

oedema. Scoring was provided by an independent experienced radiologist who was blinded to the identity and footwear type of the participants.

Table 2.2: Bone oedema scores and corresponding interpretations

Bone Oedema Score	MRI Appearance	Interpretation
0	No oedema	Normal
1	Increased T2 signal in < 25 % of the bone	Remodelling
2	Increased T2 signal in 25 – 50 % of the bone	Stress reaction – some cause for concern
3	Increased T2 signal in > 50 % of the bone	Stress injury – definite cause for concern
4	Fracture line	Fracture

2.4.7. Injury, pain and discomfort scores

2.4.7.1. Injury definition

An injury was defined as any physical complaint related to running that caused the participant to miss a minimum of one week of training (three sessions). This time loss definition has been used in previous studies (Buist et al. 2010; Lysholm & Wiklander 1987; Bennell et al. 1996; Buist et al. 2008; Kluitenberg et al. 2015). Where a participant missed one or two sessions, it was documented, but not classified as an injury for the purposes of this study and they could thus re-enter the intervention once pain-free. A time loss of 24 hours, another injury definition used in research, was deemed unsuitable for the present study, since running sessions were often three days apart (Saturday to Tuesday), rendering this definition less sensitive. Any participant who sustained an injury was excluded from the study and could not re-enter the intervention when the injury had resolved since the pain or discomfort would have been severe enough for the participant to miss three consecutive sessions (one week), thus disqualifying them as non-compliant.

2.4.7.2. Procedure

Participants were required to complete a logbook after each week during the 12-week intervention. Any pain or discomfort experienced throughout the week was recorded with mention to the site of pain or discomfort. The term pain or discomfort was used as it

encompasses both severe and less severe symptoms. Each site was separately rated on a Numeric Rating Scale (NRS) with 0 indicating “no pain” and 10 indicating “unbearable pain”. Prior to the intervention, participants were educated about the symptoms of delayed onset muscle soreness associated with excessive or unfamiliar exercise. They were then instructed to not report delayed onset muscle soreness symptoms, but rather only report pain or discomfort that they believed was unusual and may possibly lead to injury.

2.4.7.3. Pain or discomfort categorisation

Sites of pain in the lower extremity were grouped into two areas for analysis. The first area, Area A, included the calf (posterior shank), Achilles tendon, ankle and foot. The second area, Area B, included the shin (anterior shank), knee and thigh. These area groupings were based on joint moments associated with different foot strike patterns, and potentially different footwear. A FFS pattern is associated with greater ankle plantarflexion moments, which impose greater stress on the calf, Achilles tendon, ankle and foot (area A), whilst a RFS pattern is associated with greater knee extension moments, which impose greater stress on the tibialis anterior, knee and thigh (area B). See diagram below:

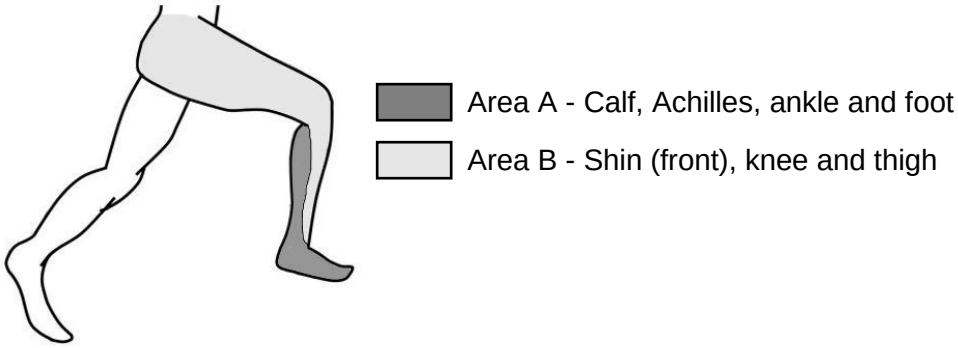

Figure 2.7: Area groupings for pain or discomfort scores

Pain or discomfort scores were split into two groups; scores between zero and 7 represent mild to moderate pain, while scores of 7 and above represent significant pain. This cut-off value was chosen because Boonstra et al. (2016) had previously assessed 2854 patients and found that scores of 7 or greater were associated with a loss of function according to the Pain Disability Index, while scores below 7 did not interfere with function (Boonstra et al. 2016).

2.4.8. Biomechanical analysis

2.4.8.1. Procedures

Footwear was prescribed to participants between two days and one week prior to baseline testing, depending on when their baseline testing was scheduled. This allowed for them to wear their shoes in by means of casual walking (they were not allowed to run prior to the study). During baseline and post-completion testing, participants completed six successful over ground running trials in their prescribed shoe. All trials were performed at a speed of 3.0 m/s. A successful trial was defined as one within the specified velocity range (± 5 % deviation, measured by gait timers), where all motion capture markers were in view of the cameras, and there was no obvious visual evidence that the runner targeted the force platform or altered their gait prior to force platform contact.

2.4.8.2. 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 × 600 mm AMTI force platforms (AMTI, Watertown, MA, USA), sampling at 2000 Hz. Sixteen 14 mm reflective markers were attached bilaterally on the lower limb at the following sites: Anterior superior iliac crest, posterior superior iliac crest, mid-section of the lateral femur, lateral epicondyle, mid-section of the fibular, lateral malleolus, posterior calcaneus and the head of the second metatarsal. Marker bases were securely attached to bony landmarks to establish the coordinate systems of the ankle, knee and hip. These markers were placed according to a modified Helen-Hayes marker set (Ramakrishnan & Kadaba 1991).

2.4.8.3. Biomechanical data analysis

Marker trajectory and GRF data were filtered using a low-pass fourth-order Butterworth filter with cut-off frequencies of 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. Joint angles were described using the joint coordinate system (Grood & Suntay, 1983). Discrete sagittal joint angles of the ankle and knee were extracted using a customized computer program (Matlab, Natick, MA, USA). The data for each participant were averaged over the six trials for each condition. Specifically, discrete variables at initial ground contact; toe-off and maximal values measured during stance were extracted. Foot strike angle (FSA) was determined by the angle created between the ground and the vector created from the heel to toe marker at initial ground contact in the sagittal plane (Altman & Davis 2012) and is

reported as the average FSA over three consecutive foot strikes. Further, peakvertical GRF (in body weight (BW) units) and vertical initial rate loading rates (BW/s) were quantified between 20 %and 80 % of the impact transient peak. When no distinct impact transient was present, the same parameters were measured using the average percentage of stance ±1 standard deviation as determined for each condition in trials with an impact transient (Lieberman et al., 2010).

2.4.9. Body composition

Whole body mass (referred to as total mass), fat mass, body fat percentage (%) and lean mass were measured using DEXA (Hologic Discovery-W, software version 12.1, Hologic Bedford Inc., Bedford, MA, USA). All measures were conducted prior to the 12-week programme, and on completion, allowing for pre- vs post comparisons. The regional placement of markers to delineate the arms, legs and trunk was determined by the manufacturer algorithm. In vivo precision coefficient of variation for this machine has been determined for fat-free tissue mass (0.7 %), fat mass (1.67 %) and WB bone mineral content (0.9 %) by measuring 30 individuals twice on the same day with repositioning.

For descriptive purposes, height (cm) and body mass (kg) were recorded using a high-precision balance (Seca 899, Seca, Germany) and a stadiometer (Charder HM200P, Charder Electronic, Taiwan) and the body mass index (BMI) was calculated. All mass values are presented in kg.

2.4.10. Flexibility

Three tests were used to measure lower limb flexibility and were conducted by a registered clinician. These three tests were selected as they focus on sagittal plane range of motion and assess the hip, knee and ankle joints, which are assessed biomechanically during gait analysis. Goniometer and tape measure readings were recorded to the nearest degree and millimetre, respectively. The order of testing was as follows:

2.4.10.1. Passive hip flexor and quadricep flexibility

Passive hip flexor and quadricep flexibility was measured using the modified Thomas test (Harvey 1998). Lying in a supine position on a plinth, participants held the contralateral (non-tested) knee to their chest with straight arms to ensure a neutral pelvic position and to support the lumbar spine. The ipsilateral (tested) leg hung passively off the edge of the plinth. Passive hip flexor flexibility (Thomas hip) was measured by placing the axis of rotation of the goniometer on the greater trochanter of the femur of the ipsilateral leg, with

the stationary arm lined up with the line of the torso and the moving arm lined up with the lateral femoral epicondyle. A negative angle represented passive hip flexion and a positive angle represented passive hip extension. Quadricep flexibility (Thomas knee) was measured by placing the axis of rotation of the goniometer on the lateral epicondyle of the femur, the stationary arm lined up with the greater trochanter of the femur and the moving arm with the lateral malleolus of the tibia. This procedure was performed bilaterally.

2.4.10.2. Active hamstring flexibility

Active hamstring flexibility was measured using the active knee extension (AKE) test (Kane & Bernasconi 1992). Lying in a supine position on a plinth, participants actively flexed their hip until their femur was in a vertical position. The knee was then extended/straightened as far as possible while keeping their upper leg (femur) fixed in the vertical position. Upon reaching end range (defined as the participant reporting a limiting discomfort or a block in movement), the angle of knee flexion was measured by placing the axis of rotation of the goniometer on the lateral femoral epicondyle of the tested leg. The stationary arm was lined up with the greater trochanter of the femur and the moving arm with the lateral malleolus of tibia. A greater angle represented more knee flexion or less active hamstring flexibility. The contralateral leg was strapped to the plinth to avoid any inaccurate readings. This procedure was performed bilaterally.

2.4.10.3. Ankle dorsiflexion

Ankle dorsiflexion was measured using the Lunge test as an indicator of Achilles tendon and Triceps surae (Medial gastrocnemius, Lateral gastrocnemius and Soleus) flexibility. Prior to performing the Lunge test, a line was drawn on the participant's heel bisecting the calcaneus. The participant stood facing the wall with the tested foot perpendicular to the wall. The knee of the tested leg was moved forward (ankle dorsiflexion) until contact was made between the knee and the wall. If the participant could perform this with elevating the calcaneus off the ground and maintaining a perpendicular calcaneal angle to the wall, they were instructed to increase the distance from the front of their foot to the wall and repeat the test by trying to move their knee forward in order to make contact with the wall. At all times during the test, the tested foot remained planted without the calcaneus lifting off the ground. The test was repeated until the participant achieved the maximum distance from the most anterior aspect of their foot and the wall without lifting their calcaneus. When measuring the maximum dorsiflexion achieved, the line drawn on the participant's heel had to remain perpendicular to the ground to ensure true dorsiflexion. The distance between the most anterior aspect of the foot and the wall was measured by using a tape measure. This procedure was performed bilaterally.

The flexibility measurements were performed in the order listed above, and then the sequence was repeated to ensure accurate readings. If the intra-class coefficient (Table 2.3) was within accepted limits, the second reading was used. If the intra-class coefficient was below 0.75 and thus outside of accepted limits (Koo & Li 2016), an average of the first and second readings was calculated.

Table 2.3: Intra-rater reliability for flexibility tests

Test	ICC	95 % CI
AKE left	0.92	0.85 – 0.97
AKE right	0.90	0.80 – 0.96
Thomas hip left	0.87	0.76 – 0.94
Thomas hip Right	0.91	0.86 – 0.98
Thomas knee left	0.94	0.89 – 0.98
Thomas knee right	0.89	0.81 – 0.94
Lunge left	0.96	0.88 – 0.98
Lunge right	0.96	0.90 – 0.98

ICC – intraclass coefficient; CI – confidence interval

All tests had acceptable intra-rater reliability (Table 2.3), thus second readings were used for analysis.

2.4.11. Isometric strength

Lower limb strength was assessed before and after the 12-week programme and consisted of isokinetic testing of the ankle and knee using an isokinetic dynamometer (Biodex 3, Biodex Medical Systems Corp., NY, USA). Participants visited the laboratory on two occasions, with no more than three days separating the two visits. The first visit included a familiarization protocol where participants performed several repetitions of all the testing conditions, until they felt comfortable with the process.

On the second visit, participants performed the experimental trial. Each participant was positioned on the seat in the upright position and the upper body secured to minimise accessory movement. For ankle joint assessment the lateral malleolus was aligned with the axis of rotation of the dynamometer. After determining the range of motion, maximal voluntary plantarflexion was recorded as a reference point and the limb was weighed at 15º from the reference position. Seven repetitions of concentric (CON) ankle dorsi- and plantarflexion were performed at 60º/s, followed by 30 repetitions performed at 180º/s with a four-minute break separating the two speeds. Eccentric (ECC) ankle dorsi- and plantarflexion was measured by performing seven repetitions at 60º/s only. CON actions were performed through 100% of

range of motion and ECC plantarflexion and dorsiflexion were limited to 90% and 85% respectively.

Knee strength was only assessed concentrically, as maximal eccentric testing was deemed too uncomfortable and required several familiarization trials to record accurate measurements. To test concentric knee strength, the lateral femoral condyle was aligned with the axis of rotation of the dynamometer. After setting range of motion, maximal knee extension was recorded as the reference point and the limb was weighed at 15º from the reference position. CON knee testing was performed at 100 % of range of motion. Results are reported as average peak torque relative to body weight and are expressed as a percentage. The average peak torque represents the peak torque achieved on each repetition of a protocol, divided by the number of repetitions in that protocol. These protocols were selected as they have been used in other studies assessing isokinetic strength of runners (Luna et al. 2012).

Chapter Three: Part One

Conceptualizing Minimalist Footwear: An Objective Definition

This chapter was published in the Journal of Sports Sciences in 2018 (Volume 36, Issue 8, Pages 949 – 954), titled "*Conceptualizing Minimalist Footwear: An Objective Definition*", by D. Coetzee; Y. Albertus; N. Tam; R. Tucker.

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Changes have been made to fit the scope of this dissertation.

3.1.1) Abstract

Running has been plagued with an alarmingly high incidence of injury, which has resulted in the exploration of interventions aimed at reducing the risk of running related injury. One such intervention is the introduction of footwear that mimics barefoot running. These have been termed minimalist shoes.

Minimalist footwear aims to reduce the risk of injury by promoting adaptations in running biomechanics that have been linked to a reduction in both impact and joint forces. However, some studies have found that minimalist footwear may be beneficial to the runner as they promote favourable biomechanical adaptations, whilst other studies have found the opposite to be true.

Reasons for these conflicting results could be attributed to the lack of a definition for minimalist footwear. The aim of this review article is to provide a structural definition for minimalist footwear based on studies that have examined the influence of footwear on biomechanical variables during running.

Based on current literature, we define minimalist footwear as a shoe with a highly flexible sole and upper that weighs 200g or less, has a heel stack height of 20mm or less and a heel-toe differential of 7mm or less.

3.1.2) Introduction

Running was once considered a sport for the elite in which only well-trained athletes took part. Since the running boom in the 1980's, the sport has seen a diversification of participants. No longer are runners lean and well-trained, but rather better represent the demographics and composition of the global population. This has ultimately led to a high incidence in running related injury.

One method of mitigating the risk of injury is the modification of running footwear. When running increased in popularity, many believed that the high incidence of injury was due to the excessive impact forces experienced whilst running. This led to the introduction of thicker midsoles within running footwear, as it was believed that more cushioning would dampen these impact forces (McNair & Marshall 1994). Interestingly, this did little to influence the incidence of running related injury (Goss & Gross 2012; Van Gent et al. 2007; Tam et al. 2014).

This lack of reduction in running injury incidence has drawn the attention of many researchers and minimalist running has been touted as a method for reducing such injuries. The premise of minimalist running is to utilize minimalist footwear that mimics the supposedly beneficial biomechanics associated with barefoot running (Lieberman et al. 2015; Franz et al. 2012; Bonacci et al. 2014), whilst still providing sufficient plantar protection (Rixe et al. 2012).

Numerous studies have focused on determining whether minimalist shoes do in fact promote biomechanics similar to running barefoot (Hollander et al. 2015; McCallion et al. 2014; Warne et al. 2014; Sinclair 2014; Squadrone et al. 2014; Wit et al. 2000). However, this topic is widely debated since the evidence is equivocal since very few definitions as to what structurally constitutes minimalist footwear exist. One working definition states that minimalist footwear "incorporates design aspects which aim to reduce mechanical and /or sensory interference between the shoe and the foot" (Rixe et al. 2012). This definition focuses on only one aspect of the functional outcomes of minimalist footwear, however, there is little agreement as to what structural specifications must be adhered to for a shoe to be considered as minimalist.

Esculier et al. (2015) acknowledged this lack of a standardised definition and conducted a consensus based study whereby they asked experts within the field of running footwear to rank shoes in terms of their degree of minimalism as well as propose and rank characteristics that should be included in the definition of minimalist footwear (Esculier et al. 2015). Although enlightening, some of the characteristics used to define the degree of minimalism of a running shoe are often inaccessible or unknown to runners who buy the shoes, and even clinicians who prescribe the shoes.

For a definition to be applicable to the end user, it needs to include objective information on variables that are easily understood and attainable. Specifications such as mass, heel stack height and heel toe differential (Figure 3.1.1) are offered as background information of most shoes, whereas values for flexibility and materials used in the upper and toe box width are less common (Esculier et al. 2015).

Heel-toe differential (HTD) = HSH – FFSH

Figure 3.1.1: The structure of a typical running shoe and its important specifications

These variables are important to consider, since shoe mass, heel stack height and heel toe differential have been found to affect the biomechanics of running (Squadrone et al. 2014). For example, Franz et al. (2012) found that shoes with less mass replicate the biomechanics of running barefoot since increasing the mass at the distal end of the leg has a profound influence on running economy (Franz et al. 2012). Heel stack height (HSH) describes the amount of cushioning beneath the base of the heel of the runner, and may be associated with a reduction in impact force (Mcnair & Marshall 1994). HSH is measured from the upper part of the innersole to the lower aspect of the outer sole of the shoe (depicted in Figure 3.1.1). Finally, heel-toe differential (HTD) is defined as the difference in stack height from the heel to the forefoot of the shoe (depicted in Figure 3.1.1), where a lower HTD has been found to replicate barefoot running (Horvais & Samozino 2013).

In addition, it is generally considered that HSH and HTD are positively correlated to foot strike angle (FSA) (Horvais & Samozino 2013). FSA refers to the angle that the sole of the foot makes with the ground at initial contact and is a determinant of the foot strike pattern, the point of contact of the foot with the ground. Foot strike pattern can be broadly categorised into a rear foot strike (RFS), midfoot strike (MFS) and forefoot strike (FFS) pattern. FSA is considered a strong indicator of global running biomechanics as it is influenced by changes in both knee and ankle kinematics. The use of an RFS pattern is associated with a high initial loading rate due to the presence of an impact transient (Lieberman et al. 2015) and higher knee extension moments (Kerrigan et al. 2009). Both of these biomechanical variables may be associated with greater risk of injury (Zadpoor & Nikooyan 2011; Cavanagh & Lafortune

1980; Milner et al. 2006; Zifchock et al. 2006; Crowell et al. 2010; Kerrigan et al. 2009; Bonacci et al. 2014).

Not only is there uncertainty around the biomechanical adaptations associated with various footwear structural specifications, but also around the actual specifications that define minimalist footwear. Therefore, the aim of this article is to assess the current literature that has measured the effects of structural specifications in shoes, such as heel stack height, heel-toe differential and mass on FSA, and to determine the upper thresholds of these variables to define a minimalist shoe.

3.2.2.4. *Heel stack height*

Squadrone et al. (2014) attempted to determine the effect of minimalist shoes with different specifications on running biomechanics, and unsurprisingly found that shoes with a lower heel stack height were more successful at promoting running biomechanics that were representative of the barefoot condition (Squadrone et al. 2014). To the best of our knowledge, only one study has looked at the influence on midsole thickness (heel stack height) on running biomechanics, whilst controlling for other structural specifications (Chambon et al. 2014). This study found that the presence of a midsole is enough to cause significant differences between barefoot and shod conditions, possibly explaining why most runners adopt similar biomechanics when running in minimalist and traditionally cushioned shoes. In terms of a quantitative value for HSH, Sinclair (2014) found that a minimalist shoe with a relatively greater heel stack height of 26.0 mm resembled the biomechanics of running in traditionally cushioned shoes rather than running barefoot, thus refuting the idea that all shoes that are labelled as minimalist actually mimic barefoot running biomechanics (Sinclair 2014).

3.2.2.4. *Heel-toe differential*

Squadrone et al. (2014) also examined the effects of minimalist shoes running biomechanics with regards to heel-toe differential, finding that a lower HTD was more successful at promoting running biomechanics that were representative of the barefoot condition (Squadrone et al. 2014). In terms of quantitative values for HTD, both Squadrone & Gallozzi (2009) and Sinclair (2014) reported that running in a minimalist shoe with very little cushioning and a zero millimetre heel-toe differential results in similar kinetics and kinematics at foot strike when compared to running barefoot (Squadrone & Gallozzi 2009; Sinclair 2014).

3.2.2.4. *Effects of structural specifications on FSA*

Horvais & Samozino (2013) assessed the influence of HSH and HTD on FSA and found that both variables were positively correlated with FSA. Furthermore, when HSH and HTD were assessed independent of one another, the biggest discrepancy in FSA occurs with a heel

stack height of 25mm and a heel-toe differential of 10mm (Figure 3.1.2B). Finally, a change in heel-toe differential has little and inconsistent effects on FSA when the heel stack height is 25mm.

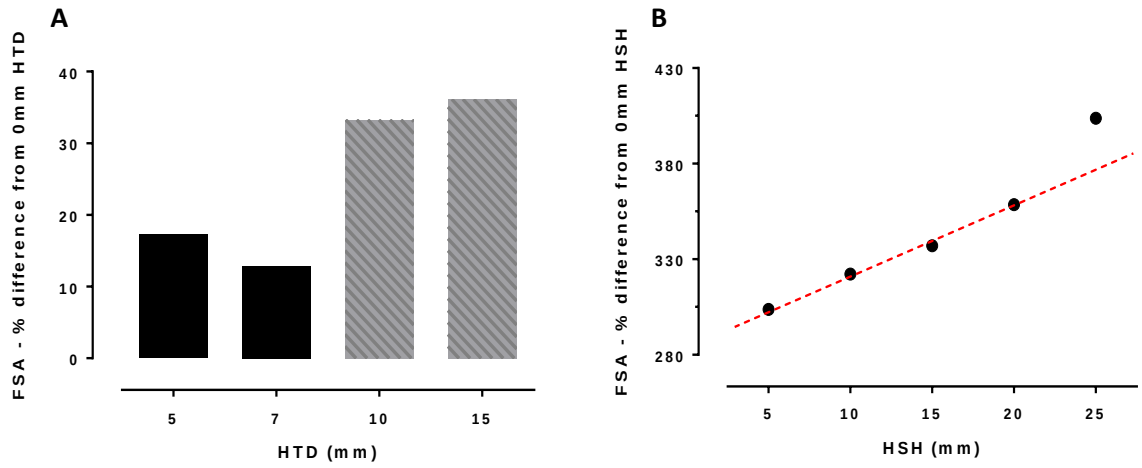


Figure 3.1.2: A) The percentage increase in foot strike angle (FSA) relative to the foot strike angle adopted in a shoe with a 0mm heel stack height (HSH) when independently assessing various heel-toe differential (HTD) values. B) The percentage increase in foot strike angle relative to the foot strike angle adopted in a shoe with a 0 mm heel toe differential when independently assessing various heel stack height values. These graphs were independently constructed by using data from Horvais & Samozino 2013.

From Horvais and Samozino's work, certain quantitative conclusions can be drawn. Firstly, when controlling for heel stack height during running at 3.9 m/s, there is a pronounced increase in FSA when heel-toe differential is increased from 7 mm to 10 mm, whilst insignificant changes occur between 5 mm and 7 mm, as well as from 10 mm to 15 mm (Figure 3.1.2A). When assessing the influence of heel stack height independent of heel-toe differential, FSA increases linearly with heel stack height from 5 mm – 20 mm. However, there is a disproportionately large increase in FSA when heel stack height is 25 mm (Figure 3.1.2B).

From this we can propose the upper thresholds of heel-toe differential and heel stack height by means of their influence on proximal kinematics. That is, the maximum heel-toe differential is 7 mm, while the upper limit for heel stack height is 20 mm. It must be noted that these limits are proposed with the best possible resolution provided by evidence to date, since the increments used in the research are large. It is possible that larger increments could change these limits slightly. Although these data represent the averages of 12 participants that ran in a total of 16 midsole geometry combinations, there are enough data points to take individual variation into account, whilst being able to assess each variable independently.

The lack of a formal definition of minimalist footwear has resulted in shoes with large discrepancies in structural specifications all being labelled as minimalist. This has led to variability of footwear specifications found within studies that aim to assess the effect of minimalist shoes on running biomechanics. Table 3.1.1 depicts the variability of specifications found within shoes that have been studied and marketed as minimalist, as well as to the degree to which they were found to mimic barefoot running biomechanics (Squadrone et al. 2014; Sinclair 2014; Bonacci et al. 2013; Hollander et al. 2015).

Table 3.1.1: The variability in specifications for minimalist shoes used in current publications and their effectiveness in simulating barefoot running.

Author (year)	Shoe	Mass (g)	HSH (mm)	HTD (mm)	Variable considered	Similar to barefoot condition	Different from shod condition
Squadrone et al. (2014)	Saucony Kinvara 2	215	28.5	5.5	FSA	No	No
	Nike Free 3.0 V4	213	26.0	9.0	FSA	No	No
	Inov8 Bare-X 200*	200	8.0	0	FSA	Yes	Yes
	Newton Running MV2	171	22.0	0	FSA	No	No
	New Balance MR00GB*	165	13.0	1.0	FSA	Yes	Yes
	Vibram Fivefingers*	127	7.0	0.0	FSA	Yes	Yes
Sinclair (2014)	Vibram Fivefingers*	127	7.0	0.0	Patellar tendon force	Yes	Yes
	Inov8 Evoskin*	135	3.0	0.0	Patellar tendon force	Yes	Yes
	Nike Free 3.0	213	26.0	9.0	Patellar tendon force	No	No
Bonacci et al. (2013)	Nike Free 3.0	196	26.0	9.0	Sagittal ankle angle at contact	No	No
	Nike LunaRacer2 (racing flat)	187	24.0	7.0	Sagittal ankle angle at contact	No	No
Hollander et al. (2015)	Nike Free 3.0	189	26.0	4.0	Sagittal ankle angle at contact	No	No
	Leguano	137	NA	0	Sagittal ankle angle at contact	No	Yes

* - indicates which shoes have a HSH of 20 mm or less, as well as a HTD of 7 mm or less.

3.2.2.4. *Mass of shoe*

We compared these proposed maximum thresholds for HSH and HTD (20 mm and 7 mm respectively), across previous studies that utilized various footwear described as minimalist. Additionally, we included an assessment of the shoe's effect on functional variables, such as FSA, patellar tendon force and sagittal ankle angle at contact (which have all been found to differ significantly between shod and barefoot running). We find that of all the shoes listed in Table 3.1.1, only five meet the proposed criteria relate to HSH and HTD. Interestingly, all five of these shoes promote biomechanics similar to that of barefoot running and are different to shod running, thus supporting our biomechanical outcome based upper thresholds for these specifications. However, this only takes HSH and HTD into account, and as previous definitions of minimalist footwear have suggested, the mass of the shoe is equally important. Of the five shoes that meet the proposed criteria, the Inov8 Bare-X 200 is the heaviest with a mass of 200g. This specification therefore represents the maximum value that when assessed in conjunction with HSH and HTS, adheres to the functional definition of a minimalist shoe i.e. to promote biomechanics similar to that of running barefoot.

3.1.3) A New Definition of Minimalist Footwear

As previously mentioned, the functional definition of a minimalist shoe is one that promotes kinematic similarities to that of running barefoot. According to this functional definition, by assessing previous literature we were able to determine the maximal specifications that constitute a minimalist shoe:

Mass: ≤ 200 grams

Heel stack height: ≤ 20 millimetres

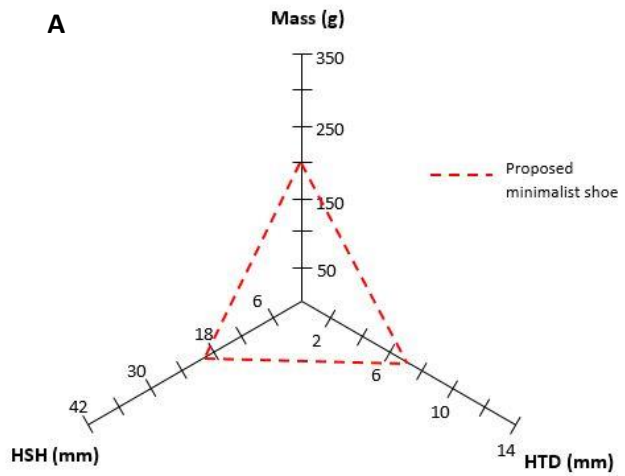
Heel-toe differential: ≤ 7 millimetres

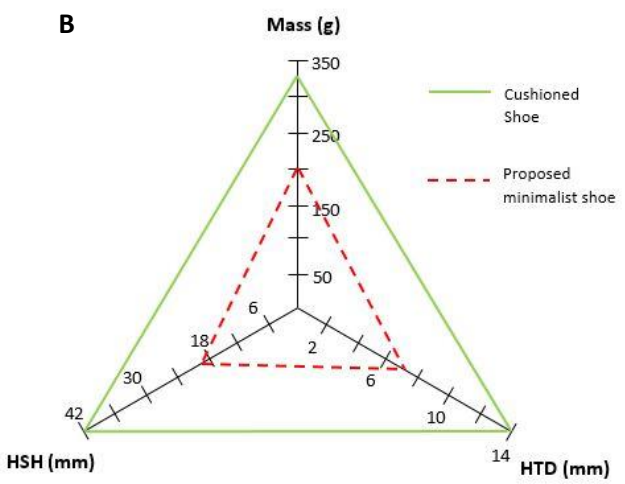
These values represent the upper thresholds for their respective specifications, and therefore only values equal to or lower than these proposed thresholds constitute minimalist footwear. Importantly, a shoe must meet all three requirements to be considered as minimalist. Further, a minimalist shoe cannot possess any other device that is intended to control the motion of the shoe, such as a medical support, a stiff carbon fibre plate or any structure that alters the interaction of the shoe with the ground. Mass is calculated using a men's size 9 UK and a women's size 5 UK.

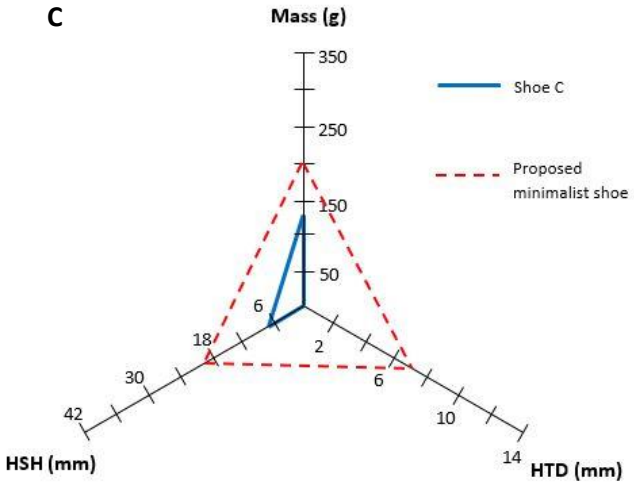
Reasons for excluding a measure of shoe flexibility and upper material construction stems purely from the difficulty in obtaining these specifications objectively, since this requires specialised equipment and construction information. Furthermore, it remains impractical since

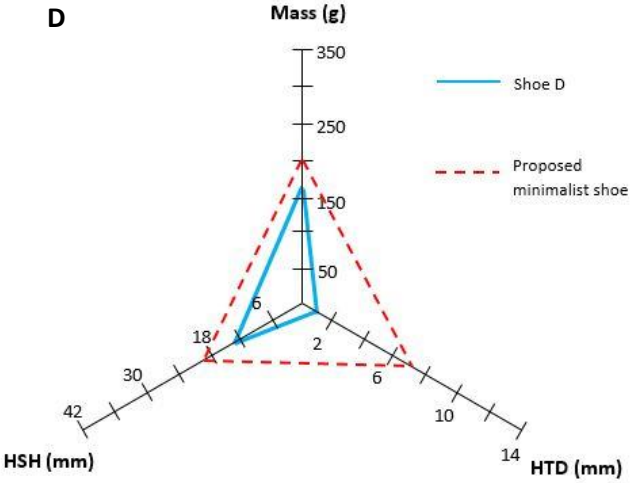
retailers rarely have objective information describing the flexibility of a shoe. Therefore, although flexibility is a highly important variable when defining a minimalist shoe, it remains impractical to the user, and future research may focus on assessing how flexibility influences biomechanics to add to the definition proposed here.

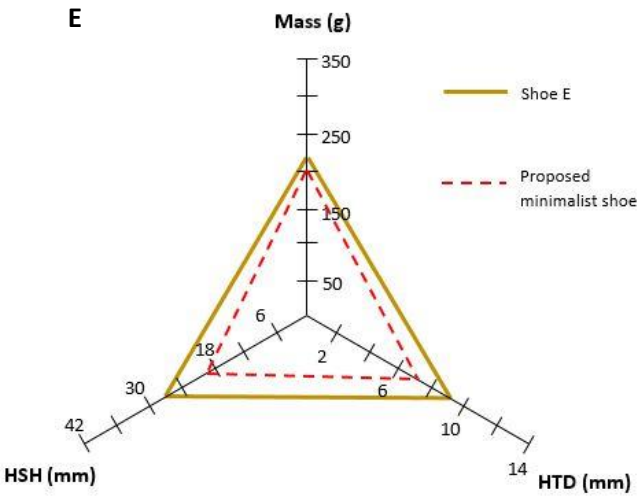
Below are comparisons between the shoes that were tested in the study conducted by Squadrone et al., and the upper thresholds for key specifications that we propose in our definition of a minimalist shoe. We have used a mass of 200g, heel stack height of 20 mm and heel toe differential of 7 mm for the purposes of this comparison. The figures below represent these key structural variables on a system of three axes, with other shoe variants presented for comparative purposes.


A
Mass (g)
350
250
150
50
6
18
30
42
2
6
10
14
HSH (mm)
HTD (mm)
Proposed minimalist shoe


B
Mass (g)
350
250
150
50
6
18
30
42
2
6
10
14
HSH (mm)
HTD (mm)
Cushioned Shoe
Proposed minimalist shoe


C
Mass (g)
350
250
150
50
6
18
30
42
2
6
10
14
HSH (mm)
HTD (mm)
Shoe C
Proposed minimalist shoe


D
Mass (g)
350
250
150
50
6
18
30
42
2
6
10
14
HSH (mm)
HTD (mm)
Shoe D
Proposed minimalist shoe


E
Mass (g)
350
250
150
50
6
18
30
42
2
6
10
14
HSH (mm)
HTD (mm)
Shoe E
Proposed minimalist shoe

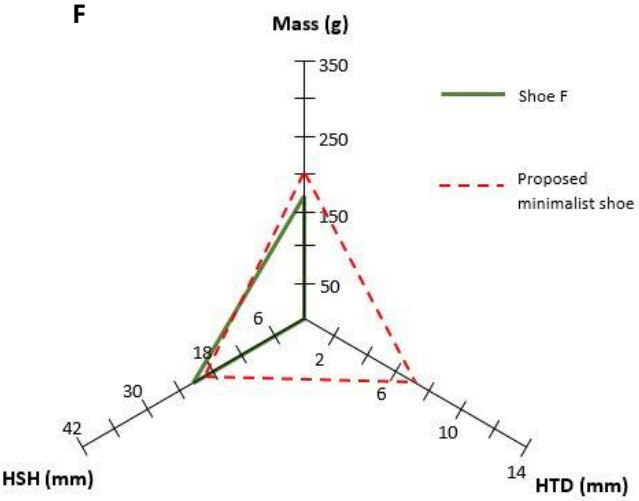

F
Mass (g)
350
250
150
50
6
18
30
42
2
6
10
14
HSH (mm)
HTD (mm)
Shoe F
Proposed minimalist shoe

Figure 3.1.3: Comparison between shoes marketed and studied as minimalist [data used from Squadrone et al. (2014)]) and a proposed objective classification of minimalist shoes based on mass, heel-toe differential and heel stack height.

The dashed line represents the proposed upper thresholds of mass, heel stack height and heel-toe differential of a minimalist shoe, with solid lines depicting the same variables in a range of five shoes. B) The proposed upper thresholds of a minimalist are compared to a traditionally cushioned shoe, and C-F) four minimalist shoes that are currently available in the market.

The figures represent the following shoes (represented as solid lines):

B – Saucony ProGrid Glide; C – Vibram FiveFingers Seeya; D – New Balance MR00GB; E – Nike Free 3.0V4; F – Newton Running MV2

From Figure 3.1.3B, we can see that the traditionally cushioned shoe does not meet any of the criteria for a structural minimalist shoe, whereas shoes C and D do, and therefore can be classified as minimalist shoes. Shoes E and F, although marketed as minimalist, fall outside of the proposed upper thresholds, and would therefore not be considered as minimalist shoes according to this proposed definition.

Final definition of a minimalist shoe: a shoe with a highly flexible sole and upper that weighs 200g or less, has a heel stack height of 20 mm or less and a heel-toe differential of 7 mm or less.

3.1.4) Clinical and Scientific Implications

Based on this definition, clinicians can advise their patients regarding to what constitutes a minimalist shoe.

Future studies should look at the efficacy of minimalist shoes that promote kinematic adaptations in terms of reducing the risk of running related injury, rather than drawing conclusions on minimalist footwear by grouping runners that adapt biomechanically, and those that do not.

Future studies should look at increasing the resolution of data as to provide a more accurate and scientifically validated set of upper thresholds for minimalist footwear specifications.

Chapter Three: Part Two

Defining Minimalist Footwear Within the Minimalist Index: A Complementary and Comparative Perspective on Two Approaches

3.2.1) Abstract

As running injuries continue to affect many runners, focus has been turned to the construction of running footwear and its effect on running biomechanics. Minimalist footwear has been advocated to reduce the risk of sustaining a running related injury, however, results have been inconsistent as there is little agreement as to what constitutes minimalist footwear. A minimalist index was created by Esculier et al. (2015) to compare differing footwear by means of their structural specifications, but it fails to define or categorize minimalist footwear.

The purpose of this paper is to integrate an objective definition of minimalist footwear proposed by Coetzee et al. (2017) into the minimalist index to allow for both the categorization of minimalist footwear, as well as the comparison of all shoes by means of structural specifications.

The integration of the objective definition with the minimalist index allows for minimalist footwear to be defined as "footwear with a highly flexible sole and upper that weighs 200g or less, has a heel stack height of 20 mm or less and a heel-toe differential of 7 mm or less". Furthermore, minimalist footwear can be categorized by a score of 72 or greater on the minimalist index.

3.2.2) Introduction

The lack of a formal, objective definition of minimalist footwear has led to inconsistent, and even harmful outcomes regarding their use. As mentioned in Chapter Three: Part One, the variability of structural specifications used in studies assessing minimalist shoes has further complicated the understanding of their biomechanical and clinical effects. To address this, Esculier et al. (2015) sought to develop a definition of minimalist footwear by seeking consensus from a number of experts within the field of running biomechanics and footwear (Esculier et al. 2015).

The results of this important work led to a subjective definition of minimalist footwear as "footwear providing minimal interference with the natural movement of the foot due to its high flexibility, low heel to toe drop, weight and stack height, and the absence of motion control and stability devices". The authors of this consensus advanced this definition by creating a rating scale to determine the degree of minimalism of running shoes and termed this the Minimalist Index (MI). The MI allows for a comparison of shoes, where a score of 0% represents an extreme maximalist shoe, and 100% represents an extreme minimalist shoe.

The purpose of the definition and MI was to "orientate the running community when selecting their running shoes" and to "help design and interpret future research pertaining to the effects of minimalist shoes on biomechanics and running related injuries and may help recreational runners and the medical community in decreasing injury rates due to inappropriate transition between running shoes".

This was a crucial first step in both the application of footwear science to the running community, and to provide the direction required to improve the quality of research that drives this application. However, we believe that the natural evolution of the MI and consensus definition would be the inclusion of specified and measurable cut-off values for the classification of minimalist shoes.

This was in fact recognized by Esculier et al. (2015), who identified the need for additional research to determine the upper threshold values for MI so that the subjective definition for minimalist footwear would be supported by objective criteria. Furthermore, a gap in the practical generation of a minimalist definition was that no measure of running biomechanics outcomes were used to help define these limits.

As a result of these observations, we sought to determine a biomechanical outcome-based definition of minimalist footwear by proposing objective, quantifiable characteristics (i.e. the upper thresholds for easily accessible structural specifications) of these shoes by evaluating studies that had used different footwear and measured their effect on running biomechanics.

Esculier et al. (2015) had suggested that footwear that encourages kinetics and kinematics similar to running barefoot are important contributing factors to defining minimalist footwear. However, our perspective is that if minimalist footwear is to mimic the biomechanics of barefoot running, then these variables should be considered as outcomes, rather than contributing factors.

Our approach was informed by this subtle difference and aimed to build on the important first steps taken by Esculier et al. (2015), to acknowledge and then to add to their definition using an evidence-based approach to provide objective cut-off values.

In Chapter Three: Part One, we explored whether a shoe changed the FSA relative to running barefoot as an outcome for the classification of minimalist shoes that have been used in previous studies. Further, we only assessed heel toe differential (referred to as heel toe drop in Esculier et al. (2015)), heel stack height and mass, because these specifications are objective and more accessible to the public/consumers as they are often reported by footwear manufacturers. Specifications such as flexibility, although important, are not commonly known, rendering their objective quantification less practical.

Based on our findings, we defined minimalist footwear as “a shoe with a highly flexible sole and upper that weighs 200g or less, has a heel stack height of 20mm or less and a heel toe differential of 7mm or less”. This offers an objective understanding of minimalist footwear as well as allowing the absolute categorization of minimalist footwear, rather than the comparison between footwear that the MI proposes.

The integration of this objective definition with the expert driven definition is an important step for the field of running footwear and biomechanics. Therefore, the aim of this brief paper is to integrate our objective definition of minimalist footwear with the MI so that the MI can be used to a) compare the degree of maximalism/minimalism of footwear and b) to categorize minimalist footwear.

3.2.3) Methods

To do so, we first examined the MI scoring system, and compared it to the definition of minimalist shoes that we proposed based on the ability of the shoe to cause functional changes in the FSA.

According to the proposed definition, a minimalist shoe must have a mass less than 200g, a heel stack height less than 20mm and a heel-toe differential of 7mm or less. Considering the scoring system used by the MI to rate running shoes:

Table 3.2.1A: A scoring system to determine the Minimalist Index (MI) of a shoe, as proposed by Esculier et al. (2015). Bold text and the * symbol indicate that the score agrees with the 'cut-off' definition by Coetzee et al. (2017).

Score	*Weight (g)*	*Stack height (mm)*	*Heel toe drop (mm)*	*Stability and motion control technologies*
5	less than 125g	less than 8	Less than 1mm	**None ***
4	125g – less than 175g	8 – less than 14	1 – less than 4	1 device
3	**175g – less than 225g ***	**14 – less than 20 ***	**4 – less than 7 ***	2 devices
2	225g – less than 275g	20 – less than 26	7 – less than 10	3 devices
1	275g – less than 325g	26 – less than 32	10 – less than 13	4 devices
0	> 325g	Greater than 32	Greater than 13	5 – 6 devices

Note that for stability and motion control technologies, although not included in our definition, the presence of any devices renders a shoe unable to be classified as minimalist, as it interferes with the natural function of the foot.

Table 3.2.1B: A scoring system for flexibility to determine the Minimalist Index (MI) of a shoe, as proposed by Esculier et al. (2015). * indicates the score that the definition by Coetzee et al. (2017) agrees with.

Flexibility

Longitudinal flexibility: Using a pinch grip with thumb, index and middle fingers from both hands, apply a superiorly-directed force to the anterior and posterior parts of the shoe. How would you rate longitudinal flexibility?

2.5	Minimal resistance to longitudinal bending (the shoe can be rolled on itself more than 360 degrees)
2.0*	**Slight resistance to longitudinal bending (anterior tip of shoe sole reaches posterior tip of shoe sole in a maximal bending of 360 degrees)**
1.5	Moderate resistance to longitudinal bending (anterior tip of shoe sole doesn't reach posterior tip of shoe sole, but anterior and posterior parts of the shoe can form an angle of at least 90 degrees)
1.0	High resistance to longitudinal bending (anterior and posterior parts of the shoe can form an angle between 45 and 90 degrees)

0.5	Very high resistance to longitudinal bending (longitudinal deformation is possible, but anterior and posterior parts of the shoe form a maximum angle of 45 degrees)
0	Extreme resistance to longitudinal bending (longitudinal forces don't significantly change the orientation of the anterior part of the shoe relative to the posterior part)

Torsional flexibility: Using a pinch grip with thumb, index and middle fingers from both hands, apply a medially directed torsional force (pronation) to the anterior part of the shoe. How would you rate torsional flexibility?

2.5	Minimal resistance to torsion (anterior part of the shoe is turned 360 degrees; anterior outsole faces inferiorly after a complete twist while posterior outsole faces inferiorly)
2.0*	**Slight resistance to torsion (anterior part of the shoe is turned at least 180 degrees but less than 360 degrees; anterior outsole faces at least superiorly while posterior outsole faces inferiorly)**
1.5	Moderate resistance to torsion (anterior part of the shoe is turned more than 90 degrees but less than 180 degrees; anterior outsole faces at least laterally while posterior outsole faces inferiorly)
1.0	High resistance to torsion (anterior part of the shoe is turned more than 45 degrees but less than 90 degrees; anterior outsole can't face laterally while posterior outsole faces inferiorly)
0.5	Very high resistance to torsion (torsional deformation is possible, but anterior part of the shoe reaches less than 45 degrees)
0	Extreme resistance to torsion (torsional forces don't significantly change the orientation of the anterior part of the shoe relative to the posterior part)

For flexibility values, our definition stated that a shoe needs to be "highly flexible" to be considered as minimalist. As previously mentioned, the objective classification of flexibility is impractical as very few retailers and consumers have access to this information. However, since it is clearly important to the identification of minimalist shoes, it needs to be consolidated between the two methods, and so we suggested that a score of ≥ 2.0 represents "highly flexible".

3.2.4) Results

When we applied our proposed definition to the above criteria (indicated by *), the following scores were used to calculate the cut-off points for minimalist footwear:

Table 3.2.2: Scores achieved after the integration of the objective definition for minimalist footwear with the Minimalist Index

Structural specification	**Score**
Weight	3
Heel stack	3
Heel toe drop/differential	3
Stability and motion control technologies	5
Total flexibility	
Longitudinal flexibility	2.0
Torsional flexibility	2.0
Total score	18
MI (total score multiplied by 4):	**72**

Therefore, when integrating our definition to the MI, we concluded that minimalist footwear can be categorized as any shoe that scores 72 or more. That is, based on research studies examining the change in FSA as a consequence of footwear, an MI of 72 or more is sufficient to identify a shoe that produces the purported barefoot FSA changes.

3.2.5) Discussion

In this regard, there is remarkable similarity between the two methods or approaches, because our criteria, established by examining the biomechanical changes that occur in a given pair of shoes, matches the middle range (for a score of 3) established by Esculier's survey method almost exactly (see Table 3.2.1A).

We acknowledge that several cut-off values that we proposed fall within a range proposed by Esculier et al. (2015) (e.g. upper threshold for heel stack, we proposed a value equal to or less than 20 mm, whereas Esculier et al. (2015) propose 14 to less than 20 mm). However, as they are very close, for this comparison they have been merged.

Figure 3.2.1: Minimalist Index depicting the cut-off value defining minimalist footwear

3.2.6) Conclusion

We believe the use of a functional outcome, namely changes in running biomechanics when running in a given shoe, rather than subjective opinion to determine a spectrum of structural specifications for minimalist footwear advances the understanding of minimalist shoes. However, this coupled with the integration of the MI proposed by Esculier et al. paints a more comprehensive picture in terms of defining minimalist footwear as it not only allows the comparison between shoes, but also the outright classification of minimalist shoes.

The MI thus provides a spectrum of scores for a shoe, factoring in flexibility, mass and heel-stack and heel-toe dimensions that allows researchers, clinicians and shoe buyers to understand their shoe choices more comprehensively. The cut-off definition we have recently attempted to apply to minimalist shoes helps those same stakeholders know with certainty whether a shoe can be classified as minimalist, based not only on the subjective assessment of experts (thanks to the work of Esculier et al), but also because evidence suggests that shoes meeting those criteria do change running biomechanics in the purported way.

The definition proposed by in Chapter Two: Part One will allow for future studies to standardize footwear category when assessing minimalist footwear. This will hopefully yield more accurate and consistent findings and clarify any misconceptions about the biomechanical and injury implications of running in minimalist footwear. Further, the use of the MI with the integration of this objective definition of minimalist footwear will allow for runners to make informed decisions based on the structural specifications of their footwear as they will be able to compare the degree of maximalism/minimalism of shoes, and aid clinicians classifying footwear for prescription purposes.

With regards to the progression of this dissertation, the implementation of a definition for minimalist footwear is crucial given that more than one shoe model was used for the Reduced Cushioned group. Based on the definition, we can group these models as footwear with reduced cushioning as they promote similar biomechanical modification.

Chapter Four

Novice Runners and Running Related Injury: Does Footwear Influence Injury Risk?

4.1) Abstract

The heightened risk of injury in novice runners has highlighted the importance of proper training load progression to reduce injury incidence. This study aimed to determine the injury outcomes associated with novice runners during a supervised, conservative and progressive 12-week running intervention in footwear with reduced cushioning. Fifty-four novice runners were assigned to the traditionally cushioned (TC) footwear group (n = 32) or the reduced cushioned (RC) footwear group (n = 22). Bilateral bone oedema of the lower leg was measured using bilateral magnetic resonance imaging and pain or discomfort was recorded throughout the intervention. Location and severity of pain or discomfort was rated on a scale of 0-10 (10 being most severe symptoms).

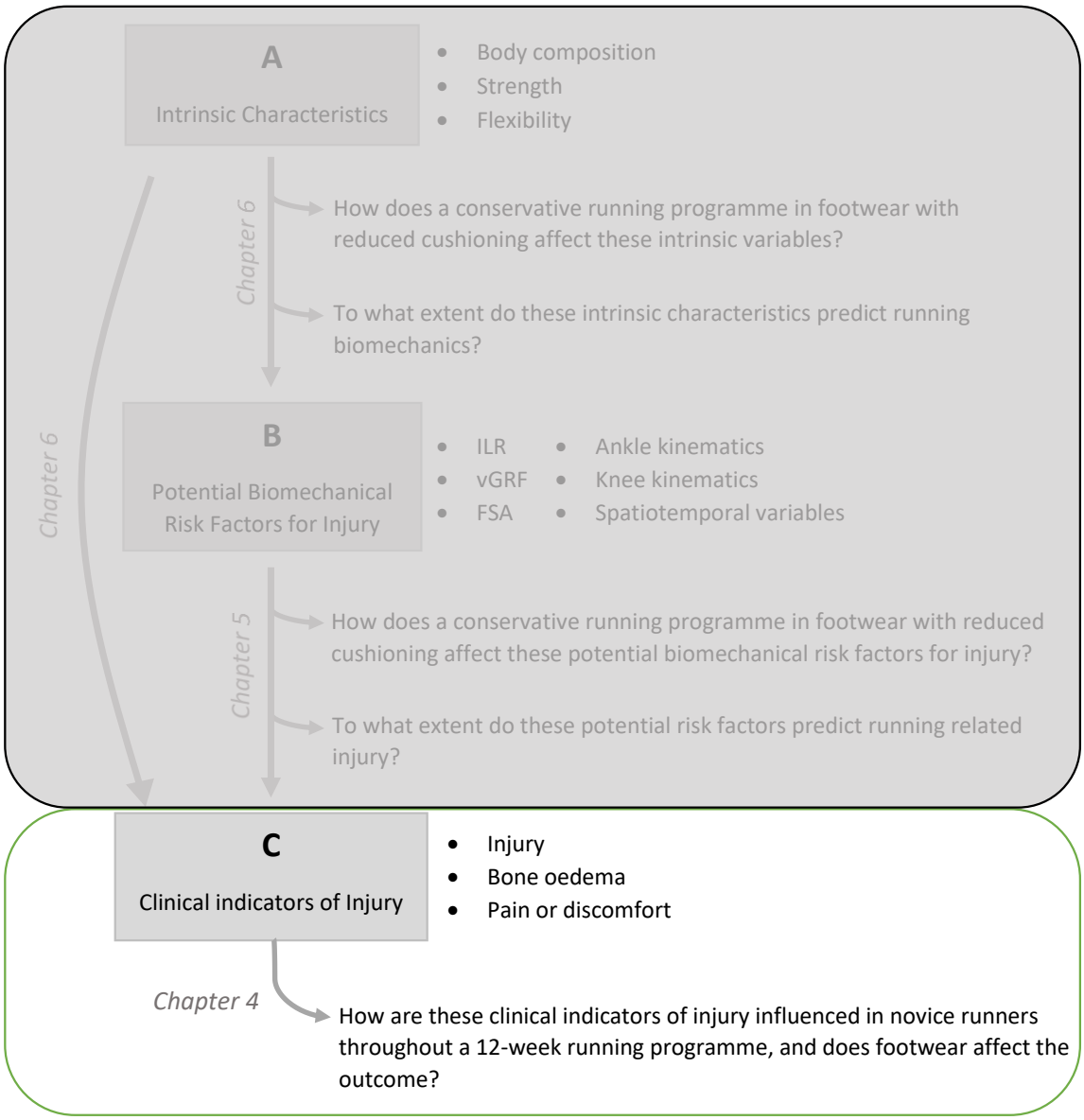
Ten participants did not complete the intervention, with three dropping out due to non-injury related reasons (adherence and illness). The prevalence of injury was 11.1 %, with only six (TC = 5, RC = 1) participants dropping out as a result of running related injury. The incidence of injury was 3.4 injuries per 1000 runs, 0.64 injuries per 1000 km and 5.6 injuries per 1000 hours. These rates were considerably lower than similar published studies. A Kaplan-Meier model was applied and showed no significant rate of injury between the RC and TC groups.

Five (TC = 2, RC = 3) of the 44 participants that finished the intervention presented with significant signs of bone oedema with no difference between footwear groups. Significant pain or discomfort was not different between groups, however the RC group experience significant pain or discomfort more frequently in the entire lower limb when compared to the TC group (IRR: 1.81, p = 0.04). No association between bone oedema and pain or discomfort was found.

Running footwear structure has little effect on injury, however footwear with reduced cushioning may increase significant pain or discomfort. With regards to training structure, supervision and a conservative progression in training load, coupled with a low mileage first week of running may improve the success of a training programme.

Having proposed objective criteria that can be assimilated into a definition for minimalist shoes, we can consider how footwear that lies clearly in one of the two classifications influences running mechanics, and, as per the model introduced in Chapter Two, the risk of injury.

Chapter Four will introduce the outcome driven approach of the dissertation and will investigate the final step of our proposed model for gaining a better understanding of running related injury and its contributing risk factors. This chapter therefore provides insight into running injury prevalence as well as sets up potential risk stratification groups in which future chapters can further unpack the contributing factors for injury. It focuses on the following sections of the model:



4.2) Introduction

Running has been associated with many health benefits, including cardiovascular fitness and weight loss (Reuser et al. 2009; Koplan et al. 1982). This, coupled with the innate simplicity of running has resulted in many sedentary individuals taking up the activity, as seen by the rise in participation in running events (Jokl et al. 2004). Running has also been associated with a high incidence of injuries, with novice runners being at greater risk compared to trained runners (Nielsen et al. 2012; Goss & Gross 2012). A meta-analysis of running injuries found that novice runners experience 17.8 injuries per 1000 hours of running, which is 2.5 times greater than a category defined as recreational runners by Videbæk et al. (2015) (Videbæk et al. 2015).

This has driven research aimed at identifying risk factors for running related injuries. These studies highlight the complex and multifactorial nature of injury, often with inconclusive findings (van der Worp et al. 2015). A review on running injuries found that training related aspects including inexperience and excessive weekly mileage were amongst the most common risk factors (van Mechelen 1992). Additionally, the majority of running related injuries can be attributed to increasing mileage too quickly (Hreljac 2005). Running programme structure may be an effective strategy to minimise the risk of injury, especially in novice runners. The premise of these programmes is to gradually increase mileage, usually by no more than 10% per week, so that the musculoskeletal system has sufficient time to adapt to the impact loads associated with running (Johnston et al. 2003). This process is referred to as the stress-frequency relationship (Hreljac 2004).

In addition to training structure, specific running footwear has been highlighted as a possible means to reduce injury risk (Rixe et al. 2012). Evidence suggests that structural specifications such as the amount of cushioning found within the midsole of running shoes may influence biomechanical variables that have been linked to running injury. In an epidemiology survey, Goss et al. (2012) found that runners wearing traditionally cushioned shoes were 3.4 times more likely to report running related injuries when compared to those wearing minimalist footwear. In this study, the runners wearing minimalist shoes were more experienced, and may have had other innate or intrinsic characteristics, as yet unidentified, that were potentially protective against running injury. The study does however question how footwear choice may influence success on a given training programme (Goss & Gross 2012).

Stress fractures to the lower limb are amongst the most common injuries experienced by runners and have been surmised to be affected by footwear. Ridge et al. (2013) assessed bone oedema, a precursor to stress fractures, measured by means of magnetic resonance

imaging (MRI), before and after a 10-week transition period to wearing shoes with reduced cushioning. Running in shoes with reduced cushioning was associated with increased signs of bone oedema, while no significant signs of bone oedema were noted in the group of runners who wore traditionally cushioned shoes (Ridge et al. 2013).

In support of this, Ryan et al. (2014) found that experienced runners who had previously been running in traditionally cushioned footwear experienced an increase in pain and discomfort when transitioning to shoes with reduced cushioning (Ryan et al. 2014). Pain and discomfort are potentially important subjective indicators, since they may be indicative of future injury. These findings suggest that minimalist shoes may increase the likelihood of injury in trained runners, contradicting the findings by Goss and Gross (2012).

As novice runners have not yet had the opportunity to develop habitual running biomechanics, it may be hypothesized that they are more capable of adapting to footwear with reduced cushioning compared to trained or experienced runners. However, novice runners are also at a greater risk of sustaining a running related injury due to unfamiliarity and the lack of adaptation to the high impact forces associated with running. To date, no studies have assessed the effect of footwear specifications on the risk of sustaining a running related injury in novice runners during a progressive running intervention. Additionally, no studies have assessed both bone oedema and pain or discomfort, which together may provide a more complete insight into injury risk.

The aim of this study is to identify the incidence of running related injury in novice runners during a progressive 12-week running intervention so that groupings based on injury outcome could be made. We further aim to determine whether footwear with reduced cushioning influences the risk of sustaining a running related injury by assessing clinical imaging for bone stress reactions and subjective scores of pain and discomfort.

We hypothesize that the RC group will not have an increased injury rate, however they will present with signs of bone oedema as well as greater pain or discomfort when compared to the TC group.

4.3) Methods

4.3.1. Participant criteria

Refer to Chapter Two, Section Three, Section 2.3.1.

4.3.2. Footwear prescription

Refer to Chapter Two, Section Three, Section 2.3.2.

4.3.3. Overview of testing procedure

Refer to Chapter Two, Section Three, Section 2.3.4

.

4.3.4. Training programme

Refer to Chapter Two, Section Three, Section 2.3.5.

4.3.5. Magnetic resonance imaging

Refer to Chapter Two, Section Three, Section 2.3.6.

4.3.6. Injury and pain or discomfort scores

Refer to Chapter Two, Section Three, Section 2.3.7.

4.3.7. Participant criteria

Refer to Chapter Two, Section Three, Section 2.3.1.

4.4) Statistical analysis

To compare incidence rates between previously published studies, incidence of running related injury was calculated with three different methods, namely the number of injuries per 1000 “exposures” (runs), the number of injuries per 1000 km and the number of injuries per 1000 hours. All were reported with 95% confidence intervals. Jakobsen et al. (1994) highlighted the importance of expressing the injury rates relative to time spent running, as it allows for comparisons between studies with varying programme structures (Jakobsen et al. 1994).

Survival analysis was carried out using an injury as an event, taking drop-outs due to non-compliance and illness into consideration. Once a drop-out occurred, that participant was excluded from further survival analysis. A Kaplan-Meier model was applied to estimate the survival rate at each time point. A log rank test (post hoc analysis) was then applied to compare survival rates between the RC and TC groups.

Pain or discomfort scores were reported weekly. Any participant who reported a weekly score of ≥ 7 at any time during the 12-week intervention was considered to have had significant pain or discomfort, regardless of whether they experienced these symptoms on one or more occasions (weeks). Participants were considered free of significant pain or discomfort only if they did not report any pain or discomfort scores greater than 7.

Frequency of pain or discomfort was calculated by assessing only participants in each group who reported significant pain or discomfort at least once throughout the 12-week intervention.

Participants who did not report significant pain or discomfort were excluded from this analysis as to not skew the data due to different group sizes. Pain or discomfort (P/D) frequency was calculated using the following formula:

$$\frac{\text{Sum total of weeks that significant P/D was reported by all participants}}{\text{Sum total of weeks completed by all participants}}$$

Incidence risk ratios (IRR) were calculated for bone oedema as well as pain or discomfort scores between RC and TC groups. Pain or discomfort scores were further localized to different areas within the lower limb. IRR values of 1 indicate no difference between RC and TC groups; IRR values < 1 indicate that the TC group had higher risk of an injury outcome than the RC group; and IRR values > 1 indicate that the RC group had higher risk of an injury outcome than the TC group. Pain and discomfort scores were normalised to the number of participants, as well as the total number of weeks completed.

4.5) Results

4.5.1. Participants

54 novice runners volunteered to take part in this study, 32 of whom were randomly allocated to the TC group, and 22 to the RC group. The following tables describe the participant characteristics for the study and subsequent analyses (Table 4.1A and 4.1B):

Table 4.1A: Participant characteristics in the traditionally cushioned (TC) and the reduced cushioning (RC) groups.

Group	N	Male/Female	Age (yrs)	Height (cm)	Weight (kg)
TC	32	12/20	29.5 ± 6.5	172.3 ± 9.4	71.2 ± 11.2
RC	22	7/15	29.7 ± 4.7	173.4 ± 7.8	71.2 ± 11.4

Table 4.1B: Characteristics of participants included in the bone oedema and pain or discomfort analyses between the traditionally cushioned (TC) and the reduced cushioning (RC) groups.

		Group	N	Male/Female	Age (yrs)	Height (cm)	Weight (kg)
Bone oedema	YES	TC	2 *(8.3 %)*	0/2	26.6 ± 6.8	174.6 ± 2.1	61.8 ± 0.3
		RC	3 *(15.0 %)*	2/1	30.2 ± 7.3	175.9 ± 9.0	79.2 ± 20.4
	NO	TC	22 *(91.7 %)*	8/14	28.2 ± 4.1	171.3 ± 9.6	69.5 ± 10.1
		RC	17 *(85.0 %)*	4/13	28.9 ± 5.4	172.3 ± 7.9	69.1 ± 9.8
Pain or discomfort	YES	TC	9 *(33.3 %)*	3/6	29.2 ± 4.3	172.6 ± 10.9	68.8 ± 9.5
		RC	12 *(54.5 %)*	5/7	28.7 ± 5.0	172.9 ± 9.2	72.2 ± 10.5
	NO	TC	18 *(66.7 %)*	6/12	29.0 ± 4.1	171.6 ± 8.4	72.0 ± 10.6
		RC	10 *(45.5 %)*	2/8	29.7 ± 6.0	174.0 ± 6.2	70.0 ± 12.8

4.5.2. Attrition

Ten participants (18.5 %) dropped out of the study. Specifically, three were excluded from the analyses for non-compliance (TC = 3), while one participant contracted bronchitis (RC) and six participants sustained a running related injury (TC = 5, RC = 1), defined using the seven-day time loss definition as described.

Table 4.2 describes the injuries sustained and the time at which the participants dropped out.

Table 4.2: Description of reported injuries

Group	Description of injury	Location of injury	Time of injury occurrence (weeks)
TC	Biceps Femoris insertional tendinopathy	Knee	2
TC	Achilles tendinopathy	Calf	4
TC	Bilateral compartment syndrome	Calf	4
RC	Plantar faciitis	Foot	9
TC	Rectus Femoris strain	Hip	10
TC	Biceps Femoris strain	Thigh	10

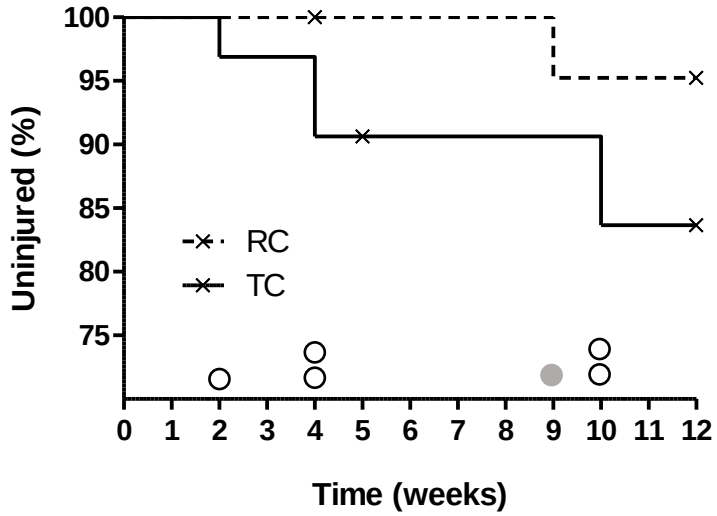


Figure 4.1: Kaplan-Meier plot of survival illustrating the time sequence of injury (noted by ○ for TC injury and ● for RC injury) and non-injury dropouts (noted by x) between the RC and TC groups

A Kaplan-Meier analysis with a Log-rank (Mantel-Cox) post hoc test found no significant difference in the likelihood of sustaining a running related injury between the RC and TC group (p = 0.20).

4.5.3. Incidence of running related injury

The prevalence of running related injuries amongst all participants in this study was 11.1 %. Incidence of running related injury was 3.4 [1.38 - 7.06] per 1000 runs, 0.64 [2.59 - 13.28] injuries per 1000 km of running and 5.6 [2.27 - 11.65] injuries per 1000 hrs of running (Table 4.3).

Table 4.3: Prevalence and incidence of running related injuries in all runners

Injury outcome	Value	95% confidence interval
Prevalence	11.1%	-
Incidence per 1000 runs	3.4	1.38 – 7.06
Incidence per 1000 km	0.64	2.59 - 13.28
Incidence per 1000 hours	5.6	2.27 - 11.65

4.5.4. Effect of Running Footwear on Clinical outcomes

4.5.4.1. Bone Oedema

Five of the 44 participants (11.4 %) who completed the intervention showed signs of significant oedema (scores greater than 1). No differences in lower leg oedema scores were found between the TC and RC groups (IRR = 1.80 [0.33 - 9.74], p = 0.49). The highest score noted was 2, suggesting that no participants in either group experienced stress injuries or fractures (a score of 4).

4.5.4.2. Pain and Discomfort

Five of the 54 participants who took part in the study did not return/complete their logbook data. Therefore, pain and discomfort data were analysed for 49 participants (RC = 22, TC = 27).

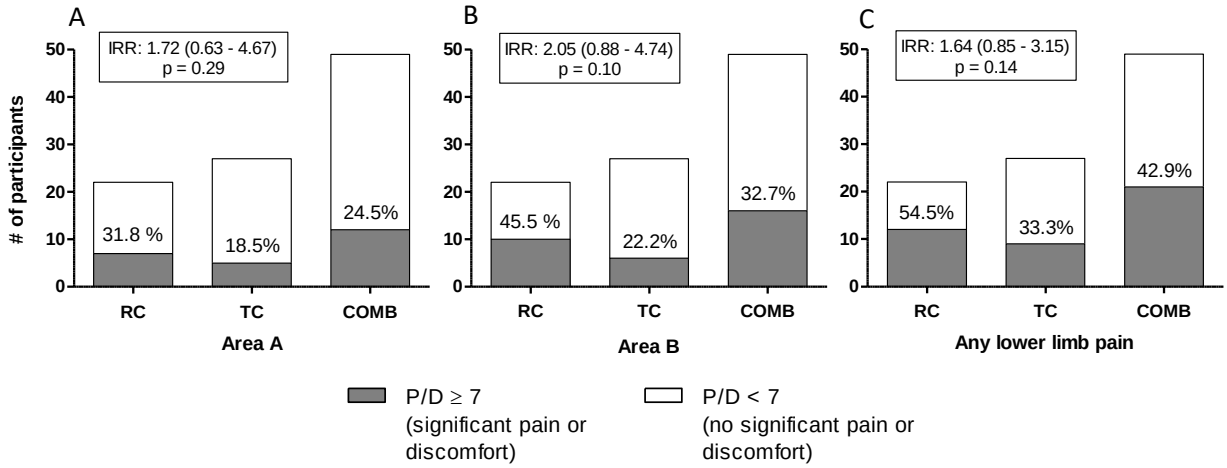


Figure 4.2: Number of participants in each footwear condition who reported pain and discomfort at various levels in Area A (A, calf, Achilles tendon, ankle and foot), Area B (B, knee, thigh and hip) and Areas A and/or B (C) (COMB). The proportion of participants in each group who reported P/D greater than 7 is shown by filled shading and indicated by the percentage on the bars. Incidence risk ratios are calculated between the RC and TC group in each area of the leg.

54.5 % of runners in the RC group experienced significant lower limb (area A and/or B) pain or discomfort at least once during the 12-week intervention (C), compared to 33.3 % in the TC group (C), IRR = 1.64 [0.85 - 3.15]. Collectively, 42.9 % of novice runners experienced significant pain or discomfort at least once during the 12-week intervention (C). No differences in reported pain or discomfort prevalence was found between groups in areas A, B and the entire lower limb.

To assess the frequency of reported pain or discomfort, the number of runner-weeks that symptoms were reported was assessed as a percentage of all completed runner-weeks. Runner weeks is calculated as the product of participants and weeks of training completed. The RC group reported significant pain or discomfort scores more frequently in Area A (RC = 6.2 % vs TC = 2.1 %, IRR: 3.03 [1.2 - 7.6], $p < 0.05$), Area B (RC = 8.6 % vs TC = 2.7 %, IRR: 3.12 [1.4 - 6.9], $p < 0.01$) and in the entire lower limb (RC = 14.8 % vs TC = 4.8 %, IRR: 3.08 [1.7 - 5.6], $p < 0.01$). Collectively, novice runners experienced significant pain or discomfort in the lower limb during 9.5 % of weeks completed, regardless of footwear.

From a clinical perspective, it is of interest to consider how pain or discomfort presents throughout the intervention. Since the incidence risk ratio may be skewed by a few participants who report symptoms frequently, it is important to understand where the risk of experiencing pain or discomfort arises. To do this, we considered the frequency and persistence of pain or discomfort in only those participants who reported it by assessing the cumulative runner-

weeks for which significant pain or discomfort scores were reported in each area between the RC and TC groups.

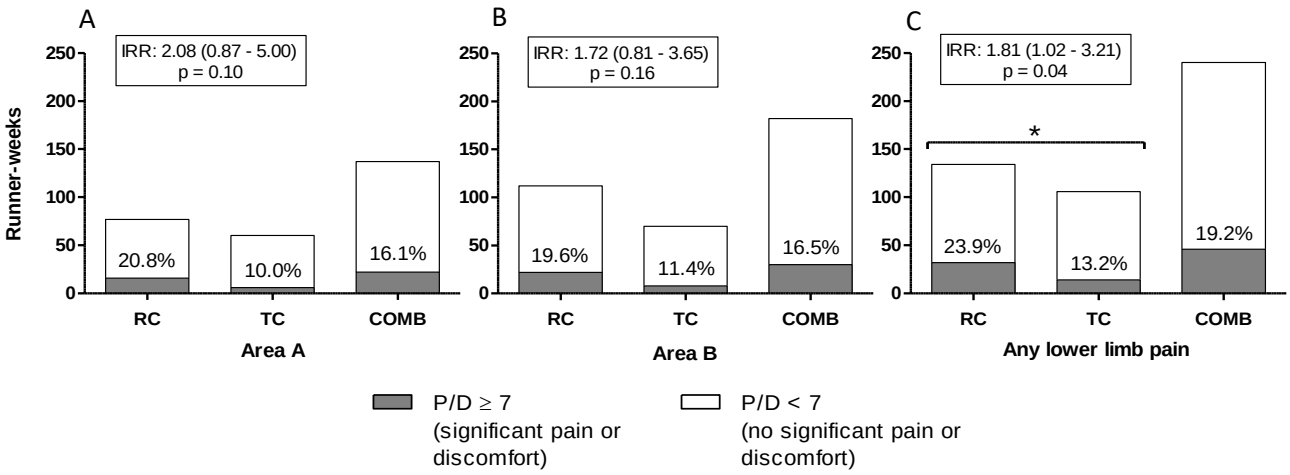


Figure 4.3: The number of runner-weeks that participants in the RC and TC groups, as well as all participants combined (COMB) reported significant pain or discomfort (≥ 7). Data presented as a percentage of the all weeks completed by participants who presented with significant pain or discomfort in A) Area A, B) Area B and C) Areas A and/or B. Incidence risk ratios are calculated between the RC and TC group in each area of the leg. Percentages indicate proportion of each group with P/D ≥ 7.

Figure 4.3 compares the frequency of pain or discomfort after excluding all participants who did not report pain or discomfort at all during the 12-week intervention. No differences in symptom frequency and persistence were found between the RC and TC group in Area A (RC = 16 runner-weeks between 7 participants; TC = 6 runner-weeks between 5 participants; p = 0.10) or Area B (RC = 22 runner-weeks between 10 participants; TC = 8 runner-weeks between 6 participants; p = 0.16). When assessing the entire lower limb regardless of area, participants in the RC group who reported significant pain or discomfort reported these symptoms more frequently throughout the 12-week intervention when compared to the TC group (RC = 31 runner-weeks between 12 participants; TC = 14 runner-weeks between 9 participants; IRR: 1.81 [1.02 - 3.21], p =< 0.05).

4.5.4.3 Association Between Bone Oedema and Pain or Discomfort

Table 4.4: The association between bone oedema and pain or discomfort in Area A.

Pain or discomfort		No (≤ 1)	Yes (> 1)
	Yes (≥ 7)	n = 10 (RC = 5; TC = 5)	n = 2 (RC = 2)
	No (< 7)	n = 34 (RC = 14; TC = 20)	n = 3 (RC = 1; TC = 2)

Bone oedema

Only two participants (RC = 2) who presented with bone oedema in the distal tibia/fibula, ankle and foot, reported with significant pain or discomfort in the corresponding area (Area A). Thirty-four participants (RC = 14; TC = 20) showed no signs of bone oedema after the intervention and no significant pain or discomfort during the intervention. Three participants (RC = 1; TC = 2) presented with signs of bone oedema in the distal tibia/fibula, ankle and foot, without reporting pain or discomfort scores ≥ 7 in this corresponding area (Area A). Ten participants (RC = 5; TC = 5) who reported significant pain or discomfort in Area A during the intervention showed no signs of bone oedema in the corresponding area.

4.6) Discussion

The purpose of this study was to determine the incidence rate and prevalence of running related injuries in a group of novice runners during a progressive 12-week running intervention. Furthermore, this study aimed to ascertain whether the cushioning properties of running footwear may influence the risk of sustaining bone oedema or experiencing limiting pain and discomfort.

4.6.1. Incidence of injury and training programme structure

The training programme used in this study yielded an overall injury incidence of 5.6 injuries/1000 hrs, which is one-third of that reported in a meta-analysis on running injury, where novice runners experienced 17.8 injuries/1000 hrs (Videbæk et al. 2015). In that meta-analysis, the lowest injury rate reported in novice runners was 8.9 injuries/1000 hrs, which is still greater than the injury rate in the present study. The meta-analysis also reported an injury rate of 1.07 injuries per 1000 km of running, which is greater than our present study (0.64 injuries per 1000 km).

This low injury incidence is further apparent when comparing this study to other studies with similar populations and injury definition (Kluitenberg et al. 2015; Buist et al. 2008). Kluitenberg et al. (2015) assessed a 6-week training programme aimed at preparing novice runners to run for 20-minutes without walking. They reported a similar prevalence of injury (10.9 %), but a significantly higher injury incidence of 27.5 injuries per 1000 hours of running (Kluitenberg et al. 2015). This is four times greater than found in the present study, despite the present study achieving higher overall volumes, with the ability to run for 60 minutes with a two-minute walking period after 30 minutes.

A study by Buist et al. (2008) intended to train novice runners to be able to run a 4-mile event by using a conservative 13-week programme which adhered to the 10% weekly volume increase principle. The study reported a 2-fold greater injury prevalence (20.8 % vs 11.1 %) and a 5-fold greater incidence of injury (30.0 vs 5.6 injuries/1000 hrs) when compared to the present study.

Differences in injury rates between the present study and others may arise due to the time spent running during the first few weeks. The present study implemented a very conservative progression (by comparison of run:walk ratios and initial running weeks) when compared to other studies that had higher injury rates (Kluitenberg et al. 2015; Buist et al. 2008). Those studies implemented programmes that comprised of between 25 and 30 minutes of running within the first week, compared to the 19 minutes of total running used in week one of the present study. This initial running volume may be of significance as it has been reported that novice runners with a high BMI are at increased risk of sustaining a running related injury when running more than 3 km within the first week of training (Nielsen et al. 2014). Considering the average running speed of runners in the present study was just under 7 min/km and that they were more likely to run slower in the first week of the programme, we can assume that very few runners ran more than 3 km in a session during the first week of the programme. Given that this study excluded any participants with a BMI > 25 kg/m^2, and incorporated a conservative initial week of training, it is unsurprising that the injury rate was low.

Additionally, supervision of the training programme may influence injury rate as it promotes adherence and proper progression of mileage. Some studies do not standardize the number of sessions per week, which may improve the specificity and individualization of a programme, but may result in greater variability in training volumes with implications for injury risk (Kluitenberg et al. 2015).

In the present study, 67 % of all runs were supervised, which helped to ensure that each participant was exposed to the same training stimulus. All participants completed the same time spent running as well as the same route for these runs. The greater injury incidence in

other studies may be the result of a lack of supervision, as only one run was supervised per week in the study by Kluitenberg et al. (2015), and no supervision was offered in the study by Buist et al. (2008). Further, a lack of programme structure may contribute to greater injury rates, since the third run of each week was optional in the study by Kluitenberg et al. (2015). When the progression of mileage is the responsibility of the runner, there is a possibility that mileage may be increased too rapidly, resulting in a greater risk of injury. Alternatively, some runners may not increase mileage sufficiently, thus hindering adaptation. This presents a risk when transitioning to footwear with varying structural specifications. Whilst increasing time or distance run per session may be standardised, the pace at which participants ran was self-selected. This allowed for better adherence as it may have improved enjoyment and comfort during the sessions. This could have further explained the low injury rates.

4.6.2. Bone Oedema

Of the 44 novice runners that completed the 12-week running intervention, only five individuals presented with signs of significant bone oedema within the ankle and foot (11 %), with no differences between footwear groups, which disproves our initial hypothesis. The limited number of participants with bone oedema could explain this, since the prevalence of bone oedema is lower than reported by Ridge et al. (2013), where 10 of 19 participants (53 %) who transitioned from traditionally cushioned footwear to minimalist shoes showed signs of significant bone oedema in the bones of the foot, distal tibia and distal fibula. Differing results may be due to the type of runners assessed, the specifications of the minimalist shoes used and the structure of the training, given the previously mentioned conservative start of the current training programme.

The minimalist footwear used by Ridge et al. (2013) had very little cushioning (heel stack height: 7 mm, heel-toe differential: 0 mm), thus differing from the reduced cushioning shoes used in the present study which had slightly more cushioning properties. Additionally, Ridge et al. (2013) studied habitually shod recreational runners, not novice runners. Studies suggest that approximately 80 % of habitually shod runners land with a RFS pattern (Larson et al. 2011; Hasegawa et al. 2007), which, coupled with the training status of the runners, may result in already-developed biomechanical traits that are not easily altered by means of a change in footwear structure. That is, the way participants ran in traditionally cushioned shoes may not have differed from the way they ran in minimalist footwear (Willson, Bjorhus, Williams, et al. 2014). The absence of adequate cushioning, if accompanied by a lack of appropriate biomechanical modification including a transition to a forefoot strike pattern, may have resulted in a two to three-fold increase in initial loading rate when wearing minimalist shoes (Willson, Bjorhus, Williams, et al. 2014; Goss et al. 2015). This may have heightened their risk of developing bone oedema (Milner et al. 2006; Zifchock et al. 2006; Zadpoor & Nikooyan 2011).

In addition to the straining status of the participants and the footwear prescribed by Ridge et al. (2013), the transition from traditionally cushioned shoes to minimalist shoes was not standardized. The participants were instructed to continue running in cushioned footwear, but to increase the proportion of mileage run in minimalist footwear according to comfort. This may have led to some participants increasing their mileage too rapidly, resulting in unaccustomed forces being placed on the structures of the lower extremities, whilst others may not have progressed their mileage in minimalist shoes sufficiently, leading to a lack of exposure and ultimately maintaining biomechanics that are conducive to running in footwear with adequate cushioning. In the present study, all participants ran exclusively in their prescribed footwear, and progressed mileage and time spent running equally, thus minimizing further variability.

4.6.3. Pain and Discomfort

The number of participants from each group that experienced significant pain or discomfort during the intervention was similar (Figure 4.2), which further supports the lack of difference found in injury and bone oedema between the RC and TC groups. Despite a similar pain or discomfort prevalence between the groups, the RC group reported significant pain or discomfort more frequently than the TC group during the 12-week running intervention (Figure 4.3). This suggests that those participants in the RC group who had significant pain or discomfort either experienced these symptoms for longer durations than the TC group, or had recurring bouts of pain of discomfort throughout the 12-week intervention. This supports our hypothesis, however this was only apparent when assessing the entire lower limb as a whole (Area A and/or B), since no differences were found in symptom frequency when isolating Area A and Area B. This finding agrees with Ryan et al. (2014) who found that runners who transitioned to footwear with reduced cushioning reported greater pain or discomfort, although differences between anatomical locations were uncommon. Regardless, this finding holds important implications since reoccurring or extended periods of pain or discomfort may discourage novice runners to persist with running.

Despite the greater frequency of pain or discomfort, only one participant from the RC group in this study sustained a running related injury (plantar faciitis in week nine), compared to five from the TC group. Further, significant pain or discomfort was not reported in the weeks prior to dropping out due to injury in these participants, suggesting that the onset of injury symptoms was very abrupt, or that pain or discomfort may not be effective indicators of running injury.

Two possibilities for this poor correlation between symptoms of pain or discomfort and injury are put forth. Firstly, symptoms of pain or discomfort may result in the modification of lower limb running biomechanics (Dixon et al. 2000), as to alleviate the perceived stressor of the

symptoms. These potential biomechanical modifications will be explored in the following Chapter. Secondly, the structure of the running programme may have been conservative enough to prevent pain or discomfort from persisting for more than a couple runs. The gradual progression in mileage may allow participants to adapt to the increased load, notwithstanding tolerable levels of discomfort, allowing structures of the body to adapt to the stimulus, and ultimately alleviating pain or discomfort. If this is in fact the case, this would further validate why a low incidence of injury was found in this study. We hypothesise that a programme that increases mileage at a faster rate (Nielsen et al. 2014; Kluitenberg et al. 2015), running related injuries may have been developed in individuals who experienced pain or discomfort.

There appears to be no obvious link between pain or discomfort and oedema, as five of the participants who presented with bone oedema did not report location specific pain or discomfort throughout the 12-week running intervention (Table 4.4), though the low prevalence of both pain and oedema means we lack the sample size to explore this possible relationship. This finding agrees with previous studies that suggest nearly half of all bone oedema cases are asymptomatic (Bergman et al. 2004; Kiuru et al. 2005; Trappeniers et al. 2003). It is therefore important to find a stronger link between variables that runners may be aware of including spatiotemporal variables, impact forces and clinical measures of injury (bone oedema). This will enable runners to a) recognize risk factors for injury without the costly and impractical need for an MRI scan, and b) modify these risk factors to prevent the onset of injury. This potential link between biomechanical variables and injury will be explored in further detail in the following chapters of this dissertation.

4.7) Limitations

Given that the programme was as successful as it was in developing novice runners without injury, it had insufficient sample to detect significant differences in injury incidence. Since a key aim of this dissertation was to determine biomechanical mechanisms associated with clinical measures of injury, the sample size was calculated according to biomechanical outcomes rather than injury outcomes. Future studies that assess injury as an outcome would need to recruit approximately 250 participants per programme to detect an effect of an intervention at the injury incidence found in our programme.

The conservative and progressive approach used in the 12-week running programme thus creates two limitations. Firstly, only six injuries occurred, making it impossible to statistically explore risk factors for injury. Secondly, bone oedema was rare, so most participants who reported pain or discomfort did not show signs of bone oedema, making the association between pain or discomfort and clinical measures of injury, as well as injury itself, difficult. Had

the programme been more aggressive, links between injury and clinical measures of injury may have been more apparent.

Finally, injured participants in this study did not undertake MRI scans after dropping out, therefore we were unable to determine whether these participants presented with signs of bone oedema or not. However, no injured participants suffered bone injuries in the lower leg, ankle or foot, suggesting that post drop out MRI scans would not have showed signs of bone oedema. Additionally, the onset and thus recession of bone oedema has been found to occur in less than one week (Trappeniers et al. 2003). Participants may have had bone oedema during the 12-week intervention which may have coincided with pain or discomfort, but resolved prior to finishing the intervention and was thus not present during the post-intervention scan.

4.8) Clinical implications

Clinicians often turn to footwear to prevent or rehabilitate injuries. Whilst there is evidence to support the need for this intervention, this study suggests the importance of a conservative and progressive running programme. Clinicians may therefore focus more on training structure, rather than footwear, when giving advice to novice runners. Additionally, novice runners may benefit by investing in a conservative training programme to minimize the risk of sustaining a running related injury.

4.9) Future research

This complex link between pain or discomfort and the onset of injury requires further investigation as it is often considered as an important indicator of injury. Studies that assess pain or discomfort scores over a longer period with a greater number of participants will potentially provide further insight into whether clinicians can use pain or discomfort of injury to provide preventative advice on future injury.

To better understand the effect that training structure has on injury prevalence, future studies should also compare a conservative and progressive training programme with both a more aggressive programme, and a programme that is progressed without structure according to each runner.

4.10) Conclusion

The incidence of injury in this study was lower than reported by other studies on novice runners with similar design. Supervision and monitoring the progression of mileage, coupled with a very conservative initial week of running appear to be beneficial at reducing the risk of sustaining a running related injury in novice runners. Whilst running in footwear with reduced cushioning may not increase the risk of developing bone oedema when compared to running in traditionally cushioned footwear, significant pain or discomfort is experienced more often in those wearing footwear with reduced cushioning which may prevent adherence to a training programme. The association between injury and pain or discomfort remains unclear, warranting further investigation.

It is important to determine which factors predict injury, and even more important to be able to recognise, measure and potentially modify these risk factors. The following chapter will address this by assessing the biomechanical factors associated with novice runners and how they adapt to footwear of varying structure. Proposed biomechanical risk factors including initial loading rate and foot strike angle will be explored.

Chapter Five

Linking Running Biomechanics to Kinetic Risk Factors for Injury: How Novice Runners Respond to Running in Footwear with Reduced Cushioning

5.1) Abstract

The prevalence of injury in runners remains high, despite improvements in training knowledge and footwear technology. This has promoted research aiming to identify key biomechanical risk factors for injury, to better understand the mechanisms of running related injury.

This study aimed to investigate the potential link between running biomechanics and clinical measures of injury, namely pain or discomfort and bone oedema. Additionally, this study aimed to determine the intuitive kinetic and kinematic adaptations during a 12-week running intervention when running in footwear with reduced cushioning, with focus on any changes that may influence injury risk.

Baseline and post-intervention testing included three-dimensional motion capture and force plates to assess over ground running at 3.0 m/s between the traditionally cushioned group (TC = 32) and the reduced cushioning group (RC = 22). Key variables assessed included sagittal lower limb kinematics, vertical ground reaction force (vGRF) and initial loading rate (ILR).

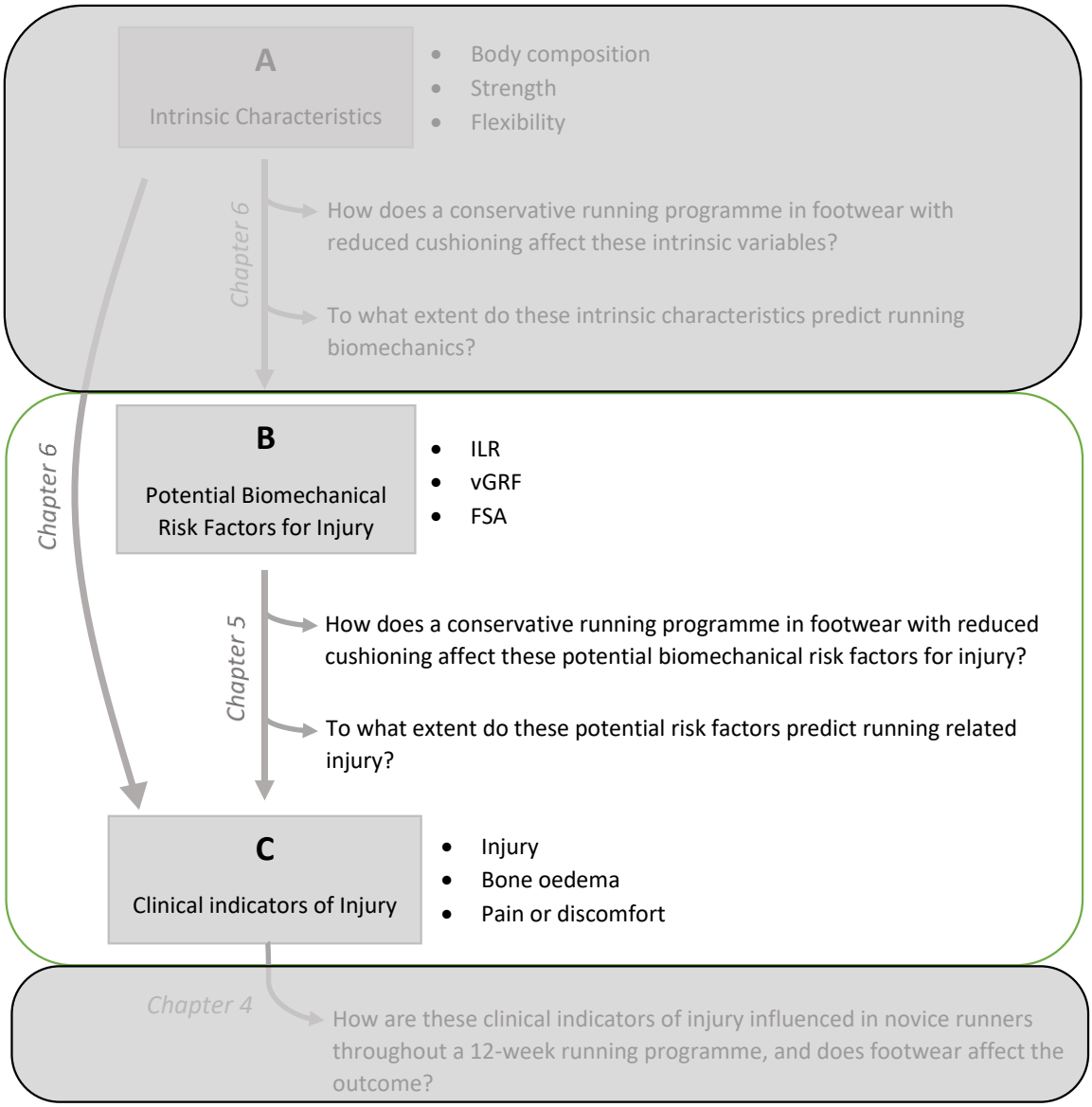
Bone oedema was associated with greater ILR, however no other relationships exited between other injury outcomes such as pain or discomfort and injury itself. Fifty-two of the 54 participants landed with a rearfoot strike (RFS) pattern, while only one participant (RC) transitioned from a (RFS) to a forefoot strike (FFS) pattern throughout the intervention. The RC group increased knee flexion angle over time (baseline of 16.10º ± 4.51 to post-intervention of 19.67º ± 3.04; $p < 0.01$) and were 3.9 times more likely to reduce foot strike angle when compared to the TC group. RC participants who reduced foot strike angle presented with a significant reduction in vGRF and accumulative load. Additionally, a reduction in angle dorsiflexion range of motion during stance phase ($r = 0.52$; $p < 0.05$) and knee flexion range of motion during stance phase ($r = 0.48$; $p < 0.05$) was associated with a reduction in vGRF over time in the RC group, but not in the TC group.

Footwear with reduced cushioning may result in lower limb kinematic strategies to dampen the loading rates that would normally be dissipated by the midsole of the shoe. This may have

important implications for risk of injury as ILR may be associated with an increased risk of developing bone oedema of the lower leg.

In the previous chapter, the first data study of this thesis established that a well-formulated, conservative approach to increasing running volume and speed was successful in delivering a high proportion of runners to the end of a 12-week running programme without injury. The consequence of this successful programme is that we do not have a large cohort of injured runners in which we can explore the relationship between risk factors and real-world, actual injury outcomes. However, we can examine the biomechanics of successful novice runners compared to the small cohort of injured or at-risk runners to further evaluate the thesis-model.

In Chapter Five we investigate the adopted, and potentially adapted biomechanics of novice runners throughout the 12-week running intervention. It therefore focuses on the mediatory step between runner and injury, which provides valuable insight for clinicians as it may highlight the mechanism of injury, not just the risk factors. This chapter explores the following sections of the model:



5.2) Introduction

The incidence of running injuries of the lower extremity ranges from 19.4 - 92.4 %, with up to 79 % of runners sustaining a running related injury within a given year (Van Gent et al. 2007). Reasons for the high incidence of injury are multifactorial and not entirely understood, which is why there has been an increased interest in research aiming to better understand running injury aetiology.

The model proposed in this dissertation emphasises the mediatory link between a runner's intrinsic characteristics and their risk of injury. This mediatory step is running biomechanics, which can be acquired intuitively or through deliberate training. If the primary goal is to

understand which runners are at increased risk of sustaining a running related injury by means of linking intrinsic characteristics to injury outcome, then understanding their running biomechanics may provide mechanistic insight into why these intrinsic characteristics are potentially detrimental. Additionally, running biomechanics may be more acutely modifiable than certain intrinsic characteristics such as body composition or flexibility. The potentially modifiable nature of running biomechanics thus provides an opportunity within the proposed model for intervention, education and skill acquisition that may ultimately mitigate injury risk.

Recent literature has highlighted key biomechanical risk factors associated with common running related injuries including stress fractures and lower limb muscle strains (Davis et al. 2016). Kinetic variables including excessive initial loading rate (ILR) and peak vertical ground reaction force (vGRF) have been researched extensively (Cavanagh & Lafortune 1980; Milner et al. 2006; Zifchock et al. 2006; Crowell et al. 2010). Upper threshold values for ILR have been proposed to better understand who is at risk of sustaining a running related injury. For example, ILR values greater than 70 BW/s have been associated with increased risk of stress fracture (Zadpoor & Nikooyan 2011); values greater than 66 BW/s (Davis et al. 2016) and 72 BW/s (Davis et al. 2010) have been associated with an overall increased risk of running related injury.

These kinetic variables are associated with the stance phase of running, suggesting that the interaction between the foot and the ground plays an important role in understanding the aetiology of running related injuries. Running footwear has been shown to influence kinetic variables associated with injury, thus becoming a popular topic of interest (Rice et al. 2016). The thickness of cushioning of the midsole has been found to influence foot-ground interaction variables. Horvais and Samozino (2013) found that running shoes with an elevated heel stack-height (amount of cushioning beneath the heel of the foot) and a significant heel-toe differential (difference between the height of cushioning beneath the heel and forefoot) were positively correlated with foot strike angle (FSA). Generally, a positive FSA is indicative of a rear foot strike (RFS) pattern, whereas a negative FSA represents a forefoot strike (FFS) pattern. Consequently, the premise of footwear with reduced cushioning is to influence foot-ground interaction variables, namely a reduction in ILR (Goss et al. 2015; Rice et al. 2016; N. Tam et al. 2016), by promoting a FFS pattern, or at least a reduction in FSA (Goss & Gross 2012; Tam et al. 2017).

Daoud et al. (2012) investigated the relationship between foot strike pattern and running related injury, and found that runners with a RFS pattern were approximately twice as likely to report repetitive stress injuries when compared to runners with a FFS pattern (Daoud et al. 2012). These kinematic differences have been linked to kinetic variables including ILR, which

may influence injury risk. Additionally, landing with a FFS pattern when running in footwear with reduced cushioning was associated with a two-fold reduction in ILR when compared to runners who landed with a RFS pattern (Goss et al. 2015). In contrast to these findings, running in footwear with reduced cushioning has also been associated with no changes in FSA (Squadrone et al. 2014) as well an increase in ILR (Willy & Davis 2014; Ryan et al. 2014). This may have unfavourable implications resulting in increased risk of injuries including stress fractures, as shown in a study by Ridge et al. (2013) that found 10 of 19 habitually shod runners who transitioned to footwear with reduced cushioning presented with significant bone oedema which is a precursor to stress fractures (Ridge et al. 2013).

A lack of habituation to footwear with reduced cushioning may be responsible for these conflicting results, as many habitually shod RFS runners do not reduce FSA, let alone adopt a FFS pattern upon primary exposure to footwear with reduced cushioning (Willy & Davis 2014). A transition period is therefore advised to allow adequate time to adapt to footwear with reduced cushioning (Ridge et al. 2013; N. Tam et al. 2016). Goss et al. (2015) found that after a two-year transition period, a greater proportion of runners wearing footwear with reduced cushioning presented with a FFS pattern, highlighting the efficacy of a transition period. However, half of all runners still landed with a RFS pattern, which may have detrimental effects on injury risk (Goss et al. 2015). That study focused only on foot strike pattern and did not measure any kinetic data associated with these habitual foot strike patterns. To date, no studies have examined the long-term changes in kinetics and kinematics associated with gradual habituation to footwear with reduced cushioning in novice runners.

The effect of clinical predictors of injury including pain or discomfort have been found to promote symptom mitigating strategies in lower limb biomechanics (Henriksen et al. 2007; Greuel et al. 2019; Seeley et al. 2013). One study found that runners with acute patellofemoral pain reduce peak plantarflexion angle during stance phase when compared to running pain free (Bazett-Jones et al. 2017). However, the biomechanical link to injury remains unclear since, as discussed in Chapter Four, the onset of injury is often asymptomatic for chronic injuries. Further, identifying contributing factors to injury are often costly, impractical or impossible, which raises the need to identify easily assessed biomechanical variables and their effect on injury. These mentioned considerations are important as they could clarify the association between biomechanical risk factors for injury and injury incidence.

Therefore, the primary aim of this study was to determine whether clinical measures of injury, namely pain or discomfort and bone oedema, may be associated with certain biomechanical characteristics. Secondly, we aim to describe the biomechanical changes that occur as a result of running in footwear with reduced cushioning for 12 weeks, with specific focus on whether

a) any runners intuitively (without instruction) shift from a rearfoot to forefoot strike pattern and b) to determine if any kinematic changes result in kinetic adaptations that may be linked to the risk of sustaining a running related injury.

We hypothesized that greater ILR values would be associated with signs of bone oedema in the distal tibia and fibula, ankle and foot. Additionally, runners who experience significant pain or discomfort would present with a modification in running biomechanics, as a means of potentially alleviating these symptoms. Further, we hypothesized that the transition from a RFS to a FFS in participants wearing footwear with reduced cushioning is unlikely, but that a reduction in foot strike angle would occur. Finally, a reduction in foot strike angle within the group wearing reduced cushioning footwear would be associated with favourable kinetics, namely a reduction in ILR.

5.3) Methods

5.3.1. Participant criteria

Refer to Chapter Two, Section Three, Section 2.3.1.

5.3.2. Footwear prescription

Refer to Chapter Two, Section Three, Section 2.3.2.

5.3.3. Overview of testing procedure

Refer to Chapter Two, Section Three, Section 2.3.4.

5.3.4. Training programme

Refer to Chapter Two, Section Three, Section 2.3.5.

5.3.5. Magnetic resonance imaging

Refer to Chapter Two, Section Three, Section 2.3.6.

5.3.6. Injury and pain or discomfort scores

Refer to Chapter Two, Section Three, Section 2.3.7.

5.3.7. Biomechanical analysis

Refer to Chapter Two, Section Three, Section 2.3.8.

5.4) Statistical Analysis

All statistical analyses were conducted on Statistica Version 13. Descriptive data are presented as means ± standard deviation (SD). Based on previous literature, a threshold value of 72 BW/s was applied to analyses of the association between ILR and clinical measures of injury as it represents the most conservative value. Relative risk ratio (RRR) analyses were performed on the individuals ILR that measured above the threshold and thus considered at risk.

Shapiro-Wilks test for normality was conducted on variables of interest. Independent t-tests at similar time points were conducted when analysing biomechanical variables between groups with different clinical outcomes (bone oedema and pain or discomfort), whereas dependent t-tests were used to test baseline versus post-intervention within these groups.

For footwear effects, when data were parametric, a repeated measures ANOVA was used to compare differences between groups (RC and TC) and over time (baseline and 12-weeks). Where a significant interaction was found, a Tukey's HSD post-hoc analysis was performed. For non-parametric data, Wilcoxon matched pairs tests were conducted to assess differences between time points in the same group, and a Friedman test was used to compare differences between groups (RC and TC) and time (baseline and 12-weeks). To describe the influence on foot strike angle on ILR and vGRF, sub-groups were formed according to changes in FSA, i.e. increased or decreased FSA over time. These data were non-parametric and Wilcoxon matched pairs tests were conducted. Odds ratios (OR) were calculated for FSA changes between RC and TC groups. OR values of 1 indicate no difference between RC and TC groups; OR values < 1 indicate that the TC group were more likely to decrease FSA than the RC group; and OR values > 1 indicate that the RC group were more likely to decrease FSA than the TC group. Significance was reported for p-values < 0.05. Hedge's g effect sizes (ES) were reported for the uneven group sizes. Hedge's g effect size (ES) of 0 - 0.2 = insignificant effect; 0.2 - 0.5 = small effect; 0.5 - 0.8 = moderate effect and > 0.8 = large effect.

5.5) Results

5.5.1. Participant characteristics

Of the 54 participants who took part in the study, 10 participants did not complete the 12-week running intervention due to injury (n = 6), illness (n = 1) or lack of compliance (n = 3). Only those who completed the entire training programme (n = 44) were included in the final analysis (Table 5.1).

Table 5.1: Participant characteristics in the traditionally cushioned and the reduced cushioning groups.

Group	N	Male/Female	Age (yrs)	Height (cm)	Weight (kg)
TC	24	8/16	29.5 ± 6.5	172.1 ± 9.4	69.0 ± 10.0
RC	20	5/15	29.7 ± 4.7	170.8 ± 7.5	70.2 ± 12.1

TC – traditionally cushioned group; RC – reduced cushioned group; values presented as mean ± SD.

Table 5.1 shows that the participants in each shoe group were of similar age, height and weight.

5.5.2. Clinical signs of injury

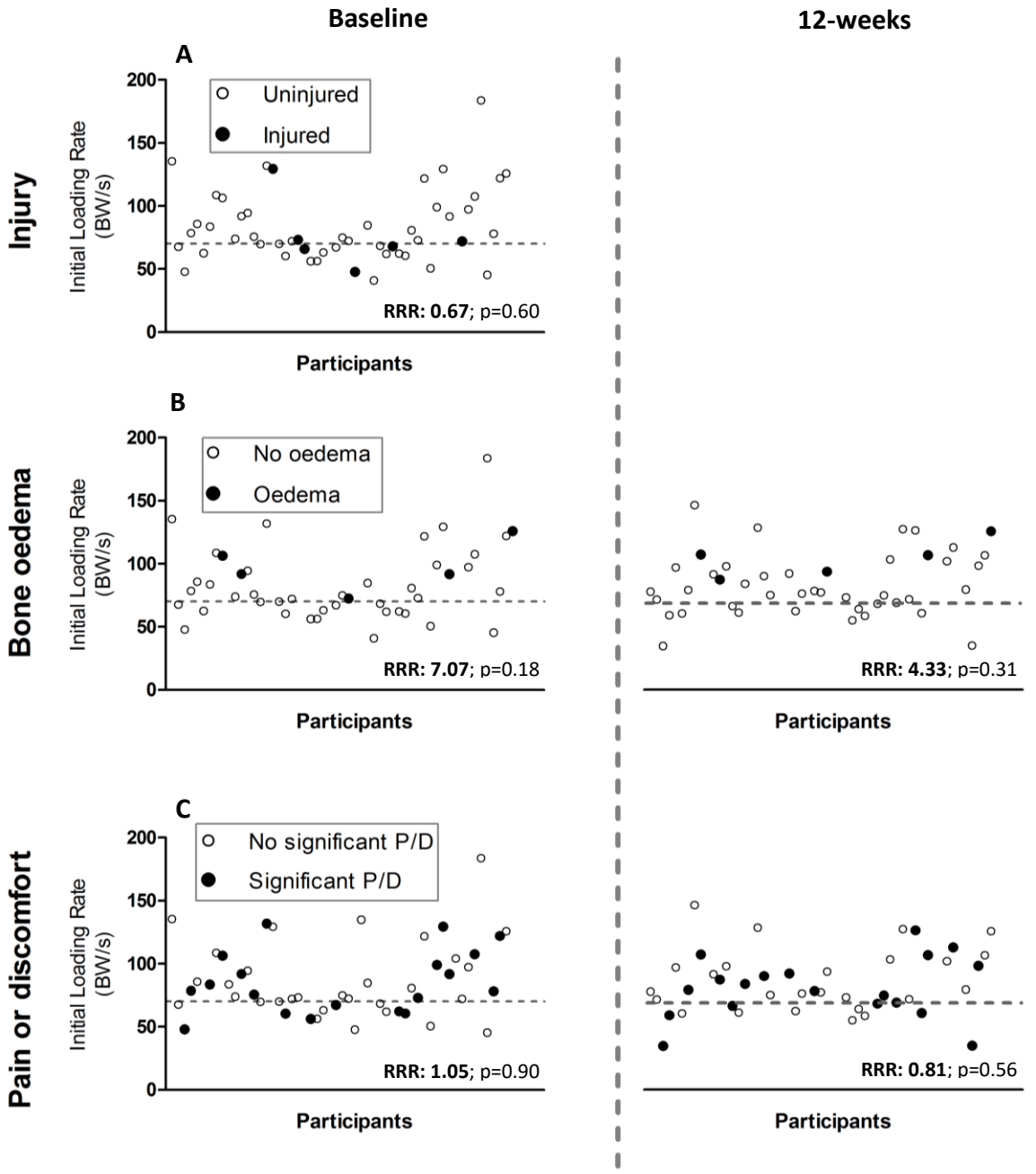


Figure 5.1: Initial loading rates of participants presenting with clinical signs of A) Injury; B) Bone oedema and C) Pain or discomfort at baseline and 12 weeks running intervention.

Threshold values for initial loading rate were set at 72 BW/s, shown by the dotted line. Each data point represents the value of an individual participant. The horizontal order of participants remains the same in each graph. RRR – relative risk ratio; P/D – pain or discomfort

When assessing the link between each participant's ILR and clinical outcomes of injury, there is no trend between ILR and injury or significant pain or discomfort as there is no tendency for the participants with injury (RRR: 0.67 [0.15 - 2.98]; p = 0.60) or significant pain or discomfort

(baseline RRR: 1.05 [0.49 - 2.25]; p = 0.90; 12-weeks RRR: 0.81 [0.40 - 1.64]; p = 0.56) to have ILR exclusively greater than the proposed threshold of 72 BW/s. However, all participants who presented with significant bone oedema (> 1) had ILR values above that of the proposed threshold of 72 BW/s for both baseline (RRR: 7.07 [0.42 - 120.30]; p = 0.18) and 12-weeks (RRR: 4.33 [0.26 - 72.92]; p = 0.31) testing (Figure 5.1B).

No differences in ILR (baseline or 12-week) were found between participants who presented with significant pain or discomfort and those who did not (Table 5.2). Participants who presented with bone oedema had ILR values that were approximately 20 BW/s higher than those who did not present with bone oedema, with these differences approaching significance (p = 0.057). Footwear effects could not be considered due to the low number of participants who presented with bone oedema.

Table 5.2: Comparison of initial loading rate between participants who presented with either A) Bone oedema or B) Pain or discomfort.

	Baseline ILR (BW/s)	**12-weeks ILR (BW/s)**	**% change**
A) Oedema (n = 5)	97.68 ± 19.9	103.85 ± 14.8	+ 6.3
No oedema (n = 39)	82.16 ± 29.7	81.69 ± 24.6	- 0.6
Repeated measures ANOVA			
Risk (group) effect		p = 0.08	
Time effect		p = 0.67	
Time*Risk effect		p = 0.62	
Hedge's g Effect Size	0.20	0.93	
B) Significant pain or discomfort (n = 19)	81.42 ± 25.1	80.33 ± 24.3	- 1.3
No significant pain or discomfort (n = 25)	85.83 ± 32.0	87.15 ± 25.0	+ 1.5
Repeated measures ANOVA			
Risk (group) effect		p = 0.43	
Time effect		p = 0.98	
Time*Risk effect		p = 0.78	
Hedge's g Effect Size	-0.15	-0.27	

ILR – initial loading rate; values presented as mean ± SD.

Differences that approached significance were further investigated by means of Hedge's g effect size calculations. A strong effect size of 0.93 between ILR values of participants with bone oedema and those without bone oedema represent a clinically significant difference. No differences in ILR were found between participants who reported symptoms of pain or discomfort and those who did not.

When assessing baseline and 12-weeks biomechanical characteristics between participants who presented with significant pain or discomfort and those who did not, no differences were found in terms of stride length, cadence, sagittal ankle or knee angle at foot strike, sagittal ankle or knee range of motion (ROM) during stance or FSA. Further, no differences were found between baseline and 12-weeks values for these variables in the participants who presented with significant pain or discomfort.

5.5.3. Kinematic and kinetic changes over 12-week intervention

Forty-two of the 44 participants presented with a RFS pattern at baseline. Only one participant from the RC group transitioned from a RFS pattern at baseline to a FFS pattern after the 12 - week intervention, whilst no foot strike pattern changes occurred in the TC group (Figure 5.2B).

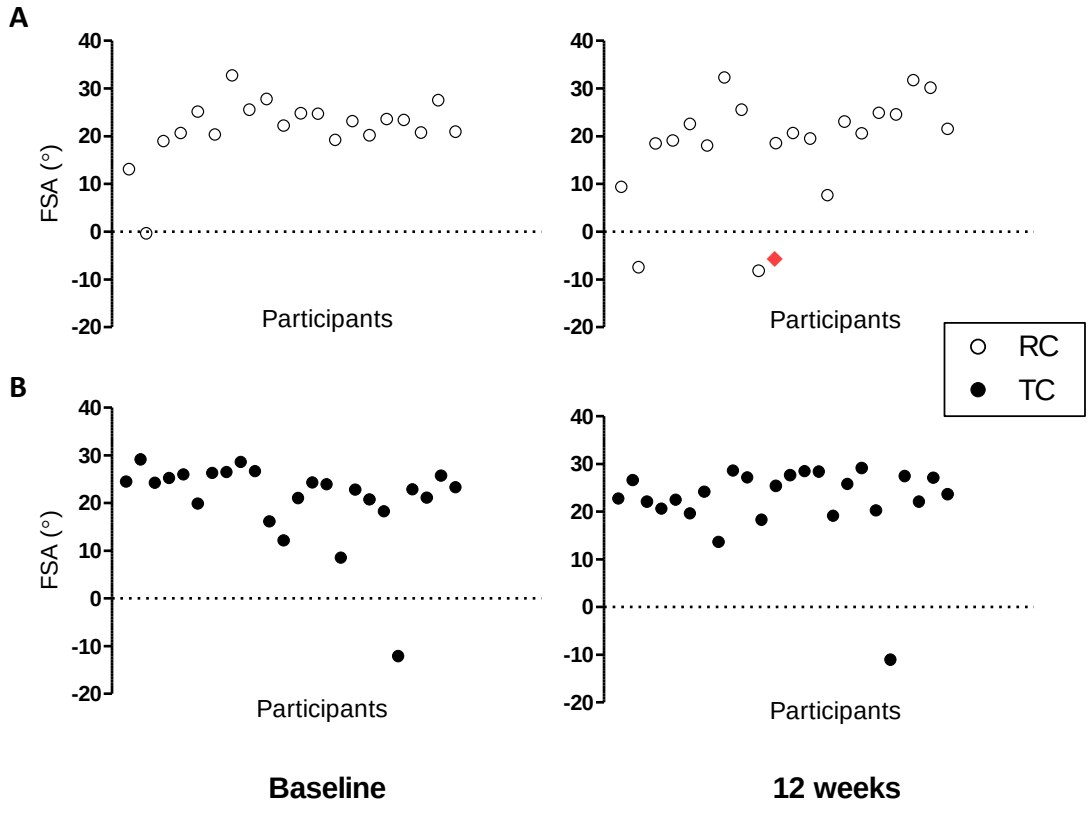


Figure 5.2: Foot strike angles of individual participants in A) Reduced cushion group and B) Traditional cushioned group, at baseline and 12-weeks intervention.

The data plotted along the x-axis represents the individual participants of their respective groups. The participants remain in the same order from baseline to 12-weeks. Positive and negative foot strike angle (FSA) represent rear foot strike (RFS) and forefoot strike (FFS) patterns respectively. ◆ (red diamond) denotes the only participant who transitioned from a RFS to a FFS landing.

No differences in average FSA were found between the RC and TC groups at baseline (21.8º ± 6.6º vs 21.1º ± 8.6º in RC and TC, respectively). Further, no significant change in average FSA from baseline to 12-weeks intervention in either RC or TC groups (Figure 5.3).

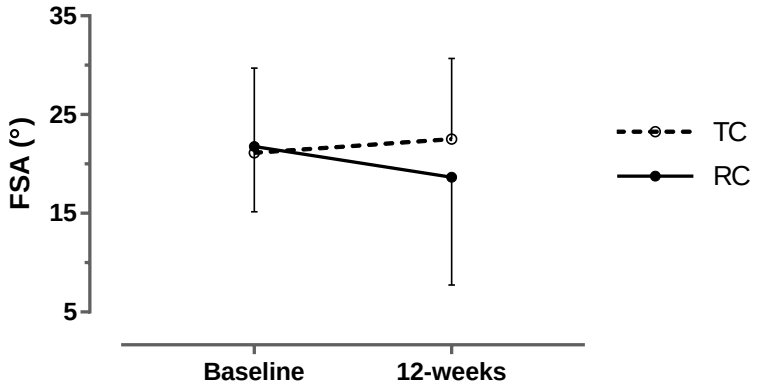


Figure 5.3: Foot strike angle (FSA) at baseline and 12-weeks in the traditionally cushioned (TC) and reduced cushioning (RC) groups.

TC – traditionally cushioned group; RC – reduced cushioned group; FSA – foot strike angle

Table 5.3: Foot-ground interactions of traditionally cushioned (TC) and reduced cushioning (RC) groups.

	TC		**RC**	
	Baseline	12-weeks	Baseline	12-weeks
FSA (º)	21.11 ± 8.59	22.51 ± 8.17	21.76 ± 6.60	18.66 ± 10.94
Spatiotemporal variables				
Stride length (m)	2.22 ± 0.25	2.28 ± 0.21	2.38 ± 0.15	2.39 ± 0.15
Cadence (steps/min)	159.68 ± 12.07	162.44 ± 12.49	162.18 ± 10.68	162.93 ± 11.05
Kinetic variables				
vGRF (BW)	2.36 ± 0.24	2.35 ± 0.22	2.44 ± 0.20	2.37 ± 0.27
ILR (BW/s)	71.45 ± 16.94	78.27 ± 17.30	98.90 ± 33.43	91.34 ± 30.23

TC – traditionally cushioned group; RC – reduced cushioned group; FSA – foot strike angle; vGRF – vertical ground reaction force; ILR – initial loading rate; BW/s – times body weight per second; values presented as mean ± SD.

No differences in foot-ground interaction variables (FSA, stride length, cadence, vGRF and ILR) were found between the RC and TC groups at baseline or 12-weeks (Table 5.3).

No changes in sagittal ankle angle at foot strike over time (baseline vs 12-weeks) were found between the RC and TC groups. The RC group presented with an increase in knee flexion angle at foot strike over time (baseline of 16.10° ± *4.51* to post-intervention of 19.67° ± *3.04*; $p < 0.01$), whereas no changes were found in the TC group (Figure 5.4).

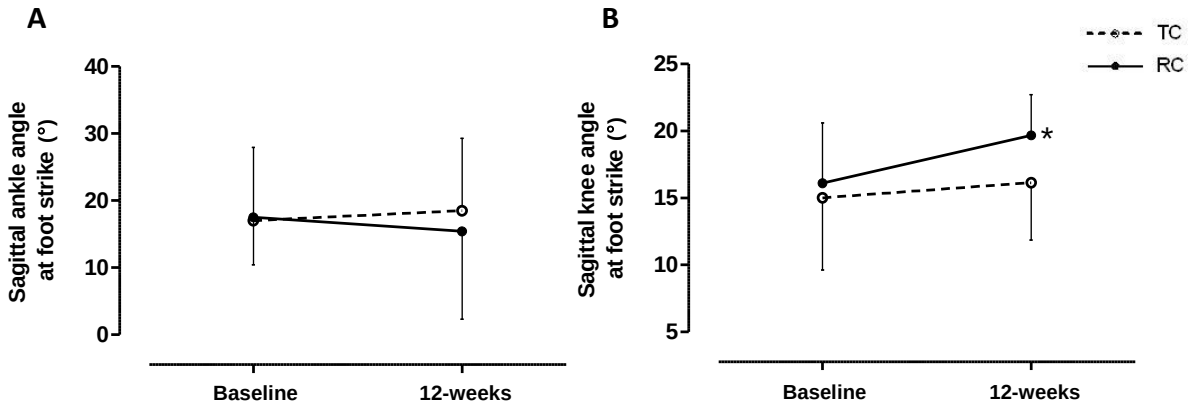


Figure 5.4: Sagittal A) Ankle and B) Knee kinematics at foot strike

TC – traditionally cushioned group; RC – reduced cushioned group; *p < 0.01 indicates a significant increase from baseline to 12-week testing periods on the RC group.

In the RC group, a change in vGRF over time was positively correlated to change in ankle ROM over time ($r = 0.52$, $p < 0.05$) and change in knee ROM during stance over time ($r = 0.48$, $p < 0.05$). No correlations where found between proximal joint ROM during stance phase and changes in vGRF over time in the TC group (Figure 5.5).

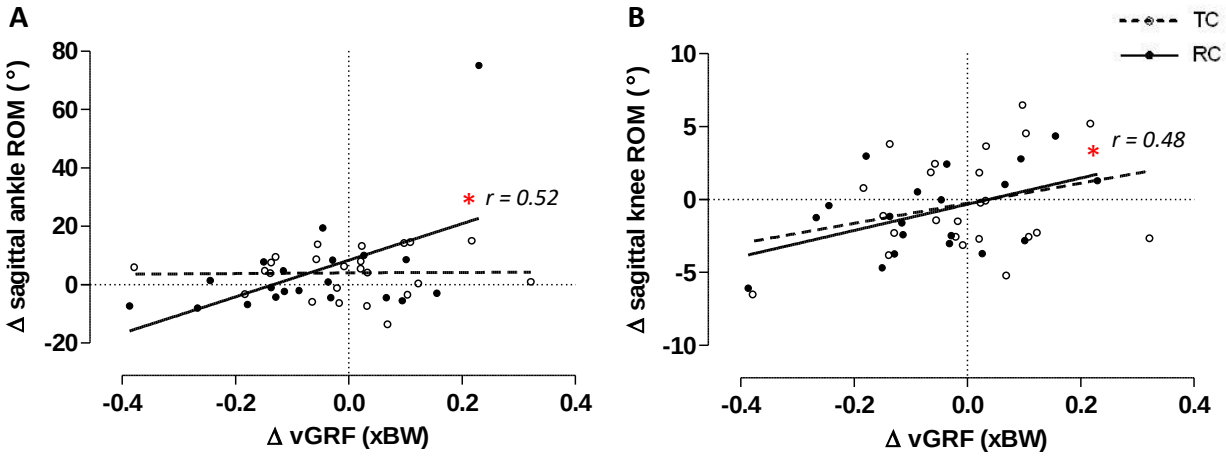


Figure 5.5: Change in sagittal A) Ankle and B) Knee range of motion during stance phase correlated to change vertical ground reaction force in the traditionally cushioned and reduced cushioning groups.

ROM – range of motion; TC – traditionally cushioned group; RC – reduced cushioning group; vGRF – vertical ground reaction force; * indicates a p-value < 0.05.

The TC and RC groups were further split into two sub-groups, namely Increased FSA group (participants that showed an increase in FSA from baseline to 12-weeks) and Decreased FSA group (participants who showed a decrease in FSA from baseline to 12-weeks). Nine (37.5 %) participants in the TC group showed a decreased FSA at 12 weeks compared to baseline, whereas 15 (62.5 % of group) participants presented with an increase in FSA.

The RC group comprised of 14 (70 %) participants who decreased FSA after 12-weeks, and 6 (30 %) participants who increased FSA after 12-weeks. An odds ratio analysis revealed that the RC group were 3.9 times more likely to decrease their FSA after the 12-week running intervention (Table 5.4).

Table 5.4: Odds ratio analysis of participants that either increased or decreased foot strike angle (FSA), in traditional cushioned and reduced cushioned group.

	Increased FSA	Decreased FSA	Total	Odds Ratio
TC	15 (62.5 %)	9 (37.5 %)	24	
RC	6 (30 %)	14 (70 %)	20	3.89; p = 0.035

TC – traditionally cushioned group; RC – reduced cushioned group; FSA – foot strike angle. % of total in the group

When assessing the subgroups, participants in the RC Decreased FSA group landed with a reduced (less dorsiflexed) sagittal ankle angle at foot strike (16.97° ± *8.15* at baseline to 11.99° ± *13.97* post intervention; $p < 0.05$), increased knee flexion (15.00° ± *4.19* at baseline to 20.15° ± *2.65* post intervention; $p < 0.01$) and a reduction in knee ROM during stance phase (34.96° ± *4.28* at baseline to 33.29° ± *5.08* post intervention; $p < 0.05$). Participants in the RC Increased FSA group landed with an increased (more dorsiflexed) sagittal ankle angle at foot strike (18.87° ± *4.12* at baseline to 23.39° ± *5.79* post intervention; $p < 0.05$), however no angle changes were found at the level of the knee. No changes in sagittal ankle or knee angle at foot strike over time were found between participants in the Increased and Decreased FSA subgroups in the TC group.

The participants in the RC Increase FSA group did not present with changes in ILR and vGRF over time (Figure 5.6A and 5.6C respectively), however, those who decreased FSA over time presented with a reduction in vGRF (Figure 5.6C), whilst no change in ILR was found (Figure

5.6A). No changes in ILR and vGRF were found within the either of the TC sub-groups after the intervention (Figure 5.6B and 5.6D).

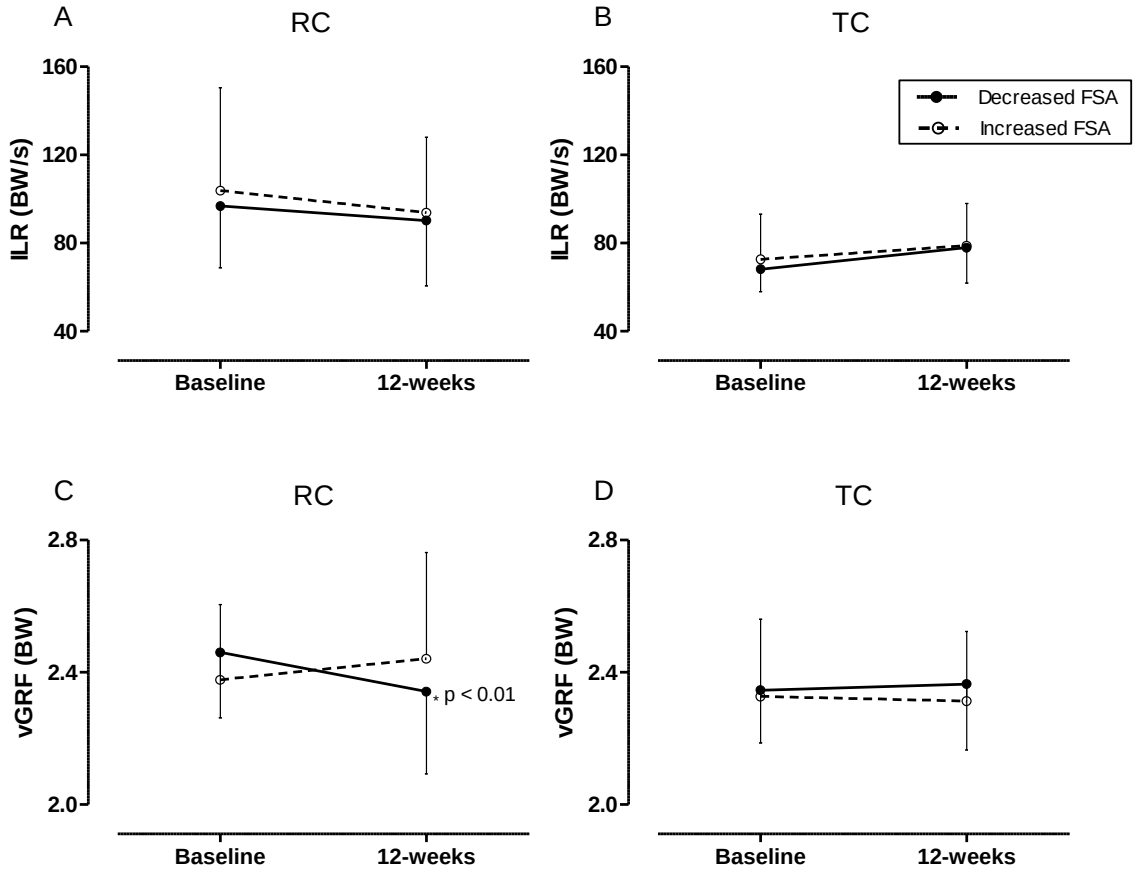


Figure 5.6: Changes in kinetic variables A) Initial loading rates; B) ground reaction forces between participants presenting with an increased or decreased foot strike angle after the intervention, in both reduced cushioning and traditionally cushioned groups.

TC – traditionally cushioned group; RC – reduced cushioned group; FSA – foot strike angle; ILR – initial loading rate; vGRF – vertical ground reaction force; * denotes a significant reduction in vGRF from baseline to 12-weeks.

No changes in stride length or frequency were found in participants within the RC group who showed a reduction in FSA.

To determine whether a change is FSA when wearing footwear with reduced cushioning was as a result of pain or discomfort, a comparison in pain or discomfort scores between RC Increased FSA and RC Decreased FSA was performed. No differences in significant pain or discomfort were found in the RC group, regardless of whether participants increased or decreased FSA (Table 5.5).

Table 5.5: Pain or discomfort scores in the two sub-groups of the reduced cushioned group

RC Group	Increased FSA (n)	Decreased FSA (n)	**RRR:**
Significant pain or discomfort	3	8	**0.88 [0.35-2.20]**
No significant pain or discomfort	3	6	**p=0.78**

n – number of participants; RRR – relative risk ratio.

participants who increased FSA and those who decreased FSA from baseline to 12-weeks testing.

5.6) Discussion

The aim of this study was to determine whether predictors of injury, namely bone oedema and pain or discomfort could be associated with selected biomechanical characteristics. In addition, we aimed to investigate whether running footwear type, specifically the cushioning thickness, influenced foot-ground interactions (FSA, ILR and vGRF) in novice runners. Finally, we sought to determine the implications of proximal joint kinematics on these foot-ground interactions.

This study found that participants who presented with bone oedema (> 1, n = 5) had higher pre- and post-intervention ILR values than those without bone oedema (n = 39). Although this difference of approximately 20 BW/s only approached significance (p = 0.057), this trend suggests a meaningful difference, indicated by the large effect size (ES = 0.93). This difference is further supported by previous findings from Milner et al. (2006) when examining the association between loading rates and stress fractures, whereby they considered “a difference of ≥ 15 % to be clinically relevant” (Milner et al. 2006). The relative difference in the present study was 19 % and 27 % at pre- and post-intervention testing respectively (Table 5.2). Additionally, all five participants with bone oedema had post-intervention ILR values above the 72 BW/s threshold (100 % above the threshold), whilst of the participants who presented with no signs of bone oedema, 27 (69 % above the threshold) were above the threshold and 12 were below. This finding further supports the link between ILR and bone oedema, which is a precursor for stress fractures. As discussed in the previous chapter (Chapter Four), bone oedema may often be asymptomatic, thus not alerting the participants of potential risk of injury whilst running. This may result in the failure to attenuate potentially injurious impact forces by means of kinematic modification.

The lack of association between ILR and pain or discomfort may be the result of the symptomatic nature of pain or discomfort. We hypothesized that the awareness of pain or discomfort may result in the modification of a runner’s kinematics to possibly lessen or alleviate the symptoms by reducing ILR. This was not apparent since no changes in any lower limb

biomechanical variables were found in participants who reported significant pain or discomfort during the 12-week training intervention. Although 42.9 % of participants reported significant pain or discomfort at least once during the 12-week intervention (see Chapter Four), these symptoms mostly resolved by the end of the intervention, resulting in most participants being free of pain or discomfort at the time the post-intervention testing. It is therefore difficult to establish whether differences in biomechanics existed whilst these symptoms are experienced, as has been reported in other studies (Henriksen et al. 2007; Greuel et al. 2019; Seeley et al. 2013). Nevertheless, this finding does suggest that runners reflect similar biomechanics once they are free of pain or discomfort. Since previous injury has been found to be a major predictor of future injury (van der Worp et al. 2015), it remains unclear whether this lack of biomechanical modification as a result of experiencing pain or discomfort may expose these participants to further pain or discomfort. These findings suggest that the link between bone oedema and bone stress injuries is better understood than the link between pain or discomfort and running injury, which is far more complex (Crofford 2015).

The lack of intuitive (without advice to change) foot strike pattern change supports our hypothesis. Only one participant from the RC group transitioned from a RFS to a FFS pattern during the intervention, whereas no foot strike pattern changes occurred within the TC group (Figure 5.2). Despite 18 of the 20 participants in the RC group landing with a RFS pattern after the intervention, no differences in ILR at baseline or 12-weeks were found between footwear groups (Table 5.3). This contradicts previous studies that found landing with a RFS pattern when wearing shoes with reduced cushioning was associated with a significantly greater ILR when compared to running in traditionally cushioned shoes (Willson, Bjorhus, Iii, et al. 2014; Goss et al. 2015; Willy & Davis 2014). This may be the result of impact attenuation strategies adopted by the RC group, who presented with various lower limb kinematic modifications not found in the TC group, which may explain why these participants did not have greater ILR values than the TC group.

These impact attenuation strategies were found at the level of the knee and ankle/foot. At the knee, RC participants landed with increased knee flexion as they habituated to footwear with reduced cushioning over the 12-week running intervention. Additionally, a reduction in knee ROM during stance over time was found to be significantly associated with a reduction in vGRF (Figure 5.5). These kinematic modifications may be linked to foot strike pattern, as landing with a RFS pattern is associated to greater knee joint moments when compared to a FFS pattern (Kulmala et al. 2013; Rooney & Derrick 2013). Since most of the participants presented with a RFS pattern, it can be assumed that knee kinematics may be most influential

in force attenuation. These kinematic modifications support the findings of McMahon et al. (1987), who found that “running with exaggerated knee flexion (Groucho running) reduces the effective vertical stiffness of the lower extremity and causes the runner to attenuate more shock between the shank and the head” (McMahon et al. 1987).

When assessing the ankle and foot, the RC group were more likely to reduce FSA. This coupled with the increased knee flexion at foot strike emulates strategies used to land with a FFS pattern (Tam et al. 2014), which has been linked to a lower ILR values (Breine et al. 2017; Phan et al. 2017). Secondly, a reduction in ankle ROM during stance over time was associated with a reduction in vGRF. Finally, participants who reduced their FSA over time when wearing footwear with reduced cushioning presented with a reduction in vGRF. These changes were only found in the RC group, with no changes in knee, ankle or foot kinematics occurring in the TC group, explaining, in part, the lack of ILR differences between the RC and the TC group. These findings suggest different strategies in force attenuation exist with differing footwear. When running in footwear with reduced cushioning, lower limb joint compliance and control becomes the primary method of force attenuation since ankle and knee kinematics have a direct influence on vGRF. In traditionally cushioned footwear, the lack of association between lower limb kinematics and vGRF suggest that more reliance may be placed on the cushioning properties of the footwear to attenuate forces associated with running.

These force attenuation strategies were not the result of experiencing pain or discomfort, which questions the motive for these biomechanical modifications in novice runners, be it conscious or not. It may be possible that runners wearing footwear with reduced cushioning are able to ‘feel’ or detect excessive impact forces, however they may not be great enough to be considered painful or uncomfortable. Since clinical signs of injury are either predominantly asymptomatic (as seen with bone oedema) or ineffective at promoting long term biomechanical change (pain or discomfort), it is important to determine which factors are responsible for these changes. Due to the reported link between ILR and running injury, this relationship requires further investigation.

Although a direct comparison between foot strike patterns of the same participant was limited due to the lack of foot strike pattern transition, a 50 % reduction in ILR was found in the only participant from the RC group who transitioned from a RFS to a FFS pattern (129.3 vs 60.5 BW/s from baseline to 12-weeks, respectively). This was the greatest change in ILR throughout the study in all participants, supporting previous evidence suggesting that when running in footwear with reduced cushioning, a FFS pattern may be advantageous in reducing ILR.

The clinical significance of a reduction in vGRF found in the RC participants who decreased FSA remains unclear due to the contradictory evidence of vGRF as a risk factor for injury. Several studies have found runners who have a history of stress fractures present with higher vGRF (Grimston et al. 1991; Milner et al. 2006; Ferber et al. 2002), whereas other studies have found either no link between vGRF and injury (Creaby & Dixon 2008; Bennell et al. 2004; Crossley et al. 1999), and even higher vGRF associated with a reduction in injury risk (Queen et al. 2009; Grimston et al. 1994). Three possible explanations for these contradicting results are put forth. Firstly, peak vGRF is comprised of two components, namely passive weight acceptance and active force propulsion. Whilst greater forces during landing may be detrimental for injury risk, greater active propulsive forces may improve running efficiency and may be indicative of a more athletic runner. The differentiation of these two force contributions may provide better insight into the risk of having a high vGRF. Secondly, Nigg et al. (1997) suggested that vGRF are within an acceptable range and thus are not responsible for injury, ultimately negating the importance of vGRF (Nigg 1997). Finally, the disparity in evidence may be the result of compartmentalising the effect of vGRF to each stride. Since many running related injuries are said to be caused by the accumulation of tissue damage over time (Zadpoor & Nikooyan 2011), it is important to assess the effect of accumulative vGRF throughout a run, rather than per step.

Current literature has acknowledged the term ‘accumulative loading’ which not only considers the kinetics of each step, but also the cumulative forces experienced throughout the duration of a run (Mercer et al. 2002). Accumulative load could be determined as the product of cadence and the load per stride (Firminger & Edwards 2016). This term thus explores the inverse relationship between kinetics and cadence. Despite a reduction in vGRF, no spatiotemporal changes were found over time in participants from the RC group who decreased FSA, ultimately representing a reduction in the accumulative load during a run. The absence of spatiotemporal changes may be explained by the lack of foot strike pattern adaptation as only one runner from the RC group transitioned from a RFS to a FFS pattern, since landing with a FFS pattern, or reducing FSA, has been associated with a reduction in stride length and a higher cadence (Allen et al. 2016; Almeida et al. 2015). Reasons as to why a reduction in vGRF was found within the RC group, who decreased FSA without changes in spatiotemporal variables, are not obvious and require further investigation.

Previous studies assessing the efficacy of gait retraining (Crowell et al. 2010; Crowell & Davis 2011b) have reported greater foot strike transition rates and force attenuating strategies when wearing footwear with reduced cushioning when compared to the current study that did not provide any advice on running technique or possible risk factors for injury. This finding emphasises the importance of providing technical advice for runners as exposure to footwear

with reduced cushioning alone does not result in the intuitive transition from a RFS to a FFS pattern, despite a progressive and conservative 12-week habituation phase. (Tam et al. 2017; Crowell et al. 2010).

5.7) Limitations

The implementation of an upper threshold for ILR to determine which participants presented with 'high risk' loading rates represents a simplified approach, despite basing its use on findings from previous research linking running related injuries to ILR (Zadpoor & Nikooyan 2011; Davis et al. 2010; Davis et al. 2016). However, the use of a threshold creates a dichotomy, where in truth, ILR falls on a continuous spectrum. Additionally, the link between ILR and injury remains tenuous. Thus, the findings based on ILR may be a simplification of what appears to be a complex interaction.

The categorization of FSA change, namely 'increased FSA' and 'decreased FSA' again creates a dichotomy for statistical analysis purposes. This grouping method results in participants who decreased FSA by 1°, which carries little clinical significance, with participants who decreased FSA by more than 20°, which may have large effects on ILR and the types of injuries that the participant is exposed to. However, this method was required due to the relatively small subgroup sample size of the study. To mitigate this limitation, future studies should look to increasing sample size, so that changes in FSA can be compared between the following groups:

- Participants who *increased* FSA by *more than* one standard deviation of the entire groups FSA change
- Participants who *increased* FSA by *less than* one standard deviation of the entire groups FSA change
- Participants who *decreased* FSA by *less than* one standard deviation of the entire groups FSA change
- Participants who *decreased* FSA by *more than* one standard deviation of the entire groups FSA change

These groupings would allow for a better understanding of the clinical implications for FSA adaptation.

5.8) Clinical implications

Without gait retraining advice, footwear has limited influence on biomechanical adaptation in novice runners embarking on a 12-week running intervention. This suggests that to promote

clinically significant biomechanical change, footwear should not be prescribed in isolation but rather in combination with running technique advice. Alternatively, more time than 12 weeks may be required, though we cannot offer a reasonable mechanism for why change would be so delayed. It is possible that greater running distances may also prompt changes not seen in this study. The lack of biomechanical adaptation, especially in foot strike pattern transition, supports that footwear should be prescribed based on a runner's current biomechanics, rather than using footwear as a tool to promote biomechanical change.

5.9) Future research

Using a study of similar design, the introduction of a group that receives gait retraining advice to promote a FFS pattern and reduce ILR would allow for a better understanding of the footwear-gait retraining interaction and may result in more personalised injury prevention advice for novice runners. Again, however, the conservative nature of the programme may be obscuring any potential risk of injury, and so while not necessarily ethical, a more aggressive increase in the training volume and intensity may be necessary to create sufficient risk exposure to fully explore the concepts of biomechanics and injury risk.

5.10) Conclusion

Novice runners who present with an ILR of greater than 72 BW/s may be at risk of sustaining bone-related stress injuries. Experiencing pain or discomfort during a 12-week programme does not result in persistent modification of biomechanics (for up to 12 weeks, at least) that may occur to alleviate these symptoms.

Novice runners habituating to footwear with reduced cushioning do not intuitively land with a FFS pattern, however they adopt force attenuation strategies at the knee, ankle and foot. These strategies may accommodate the lack of cushioning to prevent excessive impact forces. These strategies include a more anterior FSA, increased knee flexion when landing and limiting ankle and knee ROM during stance phase.

Additionally, reducing FSA when wearing footwear with reduced cushioning was found to reduce vGRF. This was not coupled with any spatiotemporal changes, suggesting a reduction in accumulative load. Novice runners habituating to footwear with traditional cushioning do not show any changes in kinetic variables, despite limited kinematic adaptation, suggesting that the additional cushioning found within the midsole of the shoe allows for greater biomechanical variability without influencing the kinetic variables associated with running related injury.

Understanding the potential link between running biomechanics and injury is an important step towards the effective implementation of injury risk reducing strategies and allows for better advice to be prescribed by clinicians. The recipient of this advice, the runner, plays a crucial role in the influence of biomechanics on injury risk. The large variation that exists in both running biomechanical data and injury incidence may partly be explained by the wide variety of characteristics that make up a runner. The following chapter will investigate the intrinsic characteristics of novice runners and determine how these variables influence running biomechanics and ultimately injury risk.

Chapter Six

The influence of Body Composition, Strength and Flexibility on Running Biomechanics and Potential Injury Risk?

6.1) Abstract

Describing the causative link between a runner's characteristics and injury is difficult, due to the complex and multifactorial nature of injury. However, the assessment of both intrinsic characteristics of a runner and their biomechanics over time allows for improved understanding of injury mechanism. Therefore, the aim of this study was to determine whether differences in intrinsic characteristics of novice runners, namely body mass, lower limb strength and flexibility were associated with injury and clinical measures of injury such as bone oedema and pain or discomfort. Additionally, this study aimed to determine the influence of running in footwear with reduced cushioning on these intrinsic characteristics and how they changed during a 12-week running intervention.

Fifty-four novice runners were prescribed to the traditionally cushioned footwear group (TC = 32) or the reduced cushioned footwear group (RC = 22). All variables were tested at baseline and post-intervention testing periods. Intrinsic characteristics included anthropometry, strength and flexibility. Anthropometry was assessed using duel energy x-ray absorptiometry and included total mass, fat mass, lean mass, body fat percentage and body mass index (BMI). Lower limb strength was assessed bilaterally using an isokinetic dynamometer. Ankle plantarflexion and dorsiflexion as well as knee flexion and extension were measured concentrically at 60°/s and 180°/s, and eccentric ankle plantarflexion and dorsiflexion was measured at 60°/s only. Lower limb flexibility was measured using the lunge test (calf and Achilles tendon), modified Thomas test (hip flexor and quadriceps) and the active knee extension test (hamstring). Associations between intrinsic characteristics and biomechanical variables were carried out, including initial loading rate (ILR), vertical ground reaction force (vGRF), ankle and knee kinematics at foot strike, peak during stance and range of motion (ROM) during stance phase. Injury outcomes included actual injury, bone oedema and pain or discomfort.

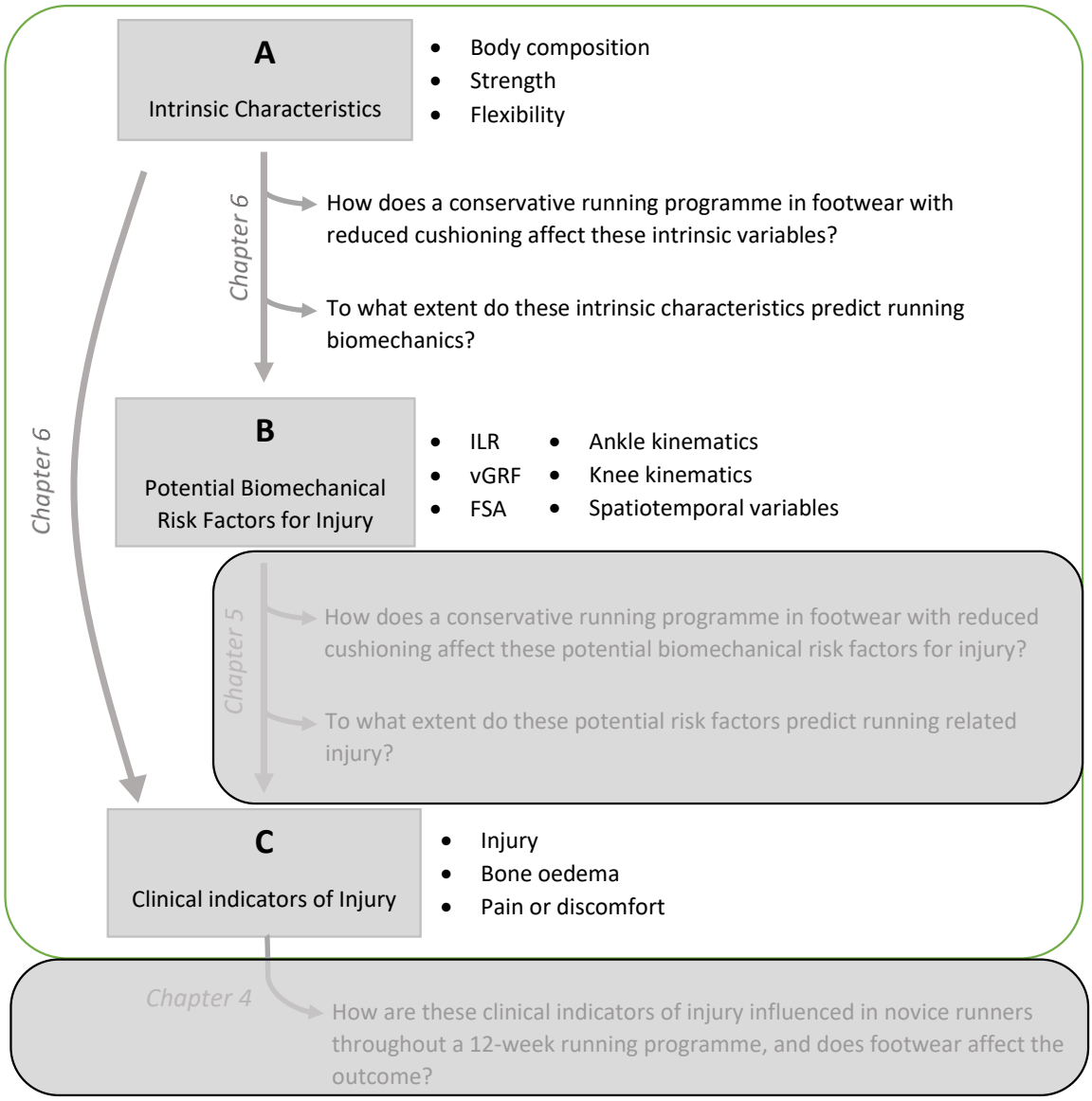
BMI was greater in injured (26.5 kg/m^2) when compared to uninjured (23.3 kg/m^2) participants ($p < 0.05$; ES = 1.11). Additionally, participants who experienced significant pain or discomfort had greater passive quadricep flexibility (51.6° vs no pain or discomfort: 44.9°). No other

differences in any intrinsic characteristics were found between participants who were deemed at risk of injury based on bone oedema, pain or discomfort, ILR and injury itself.

Participants increased passive hip flexor range over time (pre = 18.4º ± 8.8º, post = 20.8º ± 7.2º, – $p < 0.01$), with no effect of footwear. Increases in strength was found predominantly at running specific speeds (180 °/s) in concentric plantarflexion, dorsiflexion and knee extension, with no effect of footwear. Fat mass and body fat percentage were inversely correlated to vGRF, while most mass characteristics were inversely correlated to knee kinematics (greater mass was correlated to greater flexion angles) at foot strike and during stance phase. Lower limb flexibility influences running biomechanics, despite the gait never challenging end range flexibility. Greater hip flexor flexibility was correlated to a greater stride length, whilst greater hamstring flexibility was correlated to a straighter peak knee angle during stance.

Running represents a new and sufficient stimulus to novice runners as increases in ankle and knee strength where found, especially at running specific speeds, suggesting a task-specific strength adaptation. Additionally, greater strength of supporting muscle groups does not result in greater force output, as measured by joint moment, during running, suggesting a more holistic approach should be considered by clinicians when assessing strength and training running specific strength movements. Footwear structure has little effect of intrinsic characteristics. Alternatively, intrinsic characteristics do not necessary determine the success of adapting to footwear without cushioning.

Previous chapters have explored how the act of running, measured in the form of running biomechanics, may influence clinical outcomes during a progressive introduction to running. This chapter focuses on the intrinsic characteristics of a novice runner and assesses the influence that these variables have on running biomechanics, and the risk of sustaining a running related injury. This chapter is important as it provides insight into what variables should be assessed, and whether a novice runner is at heightened risk of injury. This may necessitate changes to the programme and other factors related to the subsequent risk exposure. This chapter therefore focuses on the following sections of the model:



6.2) Introduction

Chapters Four and Five of this dissertation have investigated the biomechanical implications of beginning a structured running programme in novice runners with reduced cushioned footwear, with the aim of improving the understanding of the risks of running related injury.

Whilst running biomechanics play an important role in both injury prevention and injury risk, there are intrinsic characteristics that should be considered in a runner that may provide further insight into risk of future injury. Understanding how potential runners will respond to a given running programme is important as it provides for a screening process that may either reduce the risk of running related injury, or ideally prevent it all together. Intrinsic characteristics that have been considered in the past and have been linked to the risk of running related injury include body mass, strength and flexibility.

The relationship between body mass and injury has garnered the most attention, with most studies finding greater body mass to be a significant risk factor for running related injury (Fuller et al. 2017; Buist et al. 2010; Buist & Bredeweg 2011; Nielsen et al. 2014; Nielsen et al. 2013). Buist & Bredeweg (2011) found that when exposed to running programmes with similar time exposure, novice runners with a BMI greater than 25 kg/m^2 were more prone to injury than novice runners with a BMI of less than 25 kg/m^2 (Buist & Bredeweg 2011).

BMI alone is likely an oversimplification for how mass affects injury risk. This is because body mass is comprised of both fat and lean mass, and these components of mass may exert differences on injury risk through their effects on running biomechanics. For example, lean mass, which is predominantly comprised of muscle, not only produces movement but is also important in attenuating and transitioning impact forces associated with running (Nigg 1997). In contrast, fat mass contributes only to the mass and load that must be moved, distributed and dispersed during locomotion. Little is known about the effects of these body composition variables on injury.

A conservative training structure has been shown to influence the effect that body mass has on running related injury, given that runners with reduced weekly running volume have a lower risk of injury, despite having higher body mass (Malisoux et al. 2015; Taunton 2003). These studies highlight the complexity of body mass, training load and running related injury.

Other intrinsic characteristics have been associated with injury risk, including sub-optimal flexibility and strength. Sub-optimal flexibility of soft tissues has been proposed as a risk factor for many injuries and movement inefficiencies (Hartig & Henderson 1999; Biering-Sorensen 1984; Esola et al. 1996; Witvrouw et al. 2001). With respects to strength, weak hip abduction and hip external rotation strength has been linked to increased running injury risk (Niemuth et

al. 2005; Leetun et al. 2004). Thus, improving lower limb strength may be beneficial in reducing knee pain and potentially injury risk when running (Earl & Hoch 2011). However, the interaction between progressively increasing running volume, lower limb strength and injury risk remains unclear, especially in novice runners with varying footwear.

Whilst there exists a large body of literature investigating the effects of flexibility and strength on running biomechanics and injury, there is scarcity of published research on how running affects these intrinsic characteristics, and how these characteristics ultimately influence injury risk. For example, little agreement exists on whether greater flexibility mitigates the risk of injury, or if reduced flexibility is in fact better. One study found that uninjured runners had less posterior chain flexibility (hamstrings and soleus) when compared to non-runners, suggesting that running results in a reduction in lower limb flexibility (Wang et al. 1993), whilst other studies prescribe stretching interventions to lessen the risk of running related injury (Warne et al. 2014; Mettler et al. 2019). With regards to strength, a study published by Karamanidis and Arampatzis (2005) reported that young male runners had greater isometric ankle plantarflexion strength than young non-runners, which suggests strength benefits associated with running (Karamanidis 2005). Moreover, running biomechanics can influence strength adaptation, since Liebl et al. (2014) found that runners who land with a FFS pattern have greater ankle plantarflexion strength than RFS runners (Liebl et al. 2014). In contrast, other studies have reported that runners have less plantarflexion strength than non-athletic controls (Luna et al. 2012). Regardless of these inconsistencies, it is important to understand the effect that running has on these intrinsic characteristics, as running is often prescribed and practiced for health reasons.

Therefore, the aims of this chapter were to firstly determine whether any differences in intrinsic characteristics in novice runners existed between participants who sustained a running related injury or presented with bone oedema, significant pain or discomfort or initial loading rates greater than 72 BW/s, which has previously been shown to increase injury risk (C). Secondly, this chapter aimed to investigate the influence of intrinsic characteristics on key biomechanical variables (B) including body composition, flexibility and strength for novice runners in differing footwear. Finally, the chapter aimed to determine the influence of a 12-week running intervention on these intrinsic characteristics (A).

We hypothesize that the ‘risk’ group will have greater mass of the body composition variables. Secondly, we hypothesize that intrinsic characteristics, particularly body composition, will influence key running biomechanics. Finally, novice runners partaking in a 12-week training programme will experience a change in body composition, flexibility and strength with little influence from footwear type. Specifically, footwear will not influence body composition or

lower limb flexibility adaptation, however, participants who adopt a forefoot strike pattern will show significant increases in both concentric and eccentric plantarflexion strength.

6.3) Methods

6.3.1. Participant criteria

Refer to Chapter Two, Section Three, Section 2.3.1.

6.3.2. Footwear prescription

Refer to Chapter Two, Section Three, Section 2.3.2.

6.3.3. Overview of testing procedure

Refer to Chapter Two, Section Three, Section 2.3.4.

6.3.4. Training programme

Refer to Chapter Two, Section Three, Section 2.3.5.

6.3.5. Magnetic resonance imaging

Refer to Chapter Two, Section Three, Section 2.3.6.

6.3.6. Injury and pain or discomfort scores

Refer to Chapter Two, Section Three, Section 2.3.7.

6.3.7. Biomechanical analysis

Refer to Chapter Two, Section Three, Section 2.3.8.

6.3.8. Body Composition

Refer to Chapter Two, Section Three, Section 2.3.9.

6.3.9. Flexibility

Refer to Chapter Two, Section Three, Section 2.3.10.

6.3.10. Isometric strength

Refer to Chapter Two, Section Three, Section 2.3.11.

6.4) Statistical analysis

Participants were grouped according to their biomechanical risk factors, previously described, or by the presentation of either an injury or a symptom that might precede injury. Thus, the following groups were created:

1) High initial loading rate (ILR) and Low ILR, with a cut-off ILR greater than or equal to 72 BW/s (Davis, Bowser, & Hamill, 2010; Davis, Bowser, & Mullineaux, 2016; Zadpoor & Nikooyan, 2011).
2) High pain and low pain, with a cut-off of a pain score greater than or equal to 7 at any time during the 12-week programme (Boonstra et al. 2016).
3) Oedema and non-oedema, with the oedema group comprising presenting with bone oedema scores of greater than 1 on the scale used in Chapter Four (Lazzarini et al. 1997).
4) Injured vs uninjured, where injured runners are those who dropped out of the study due to a running related injury that prevented running for one or more weeks.

These groups, once created, were compared for body composition, flexibility and muscle strength according to previously described measures.

Shapiro-Wilks test for normality was conducted on variables of interest. For all statistical comparisons, significance was reported for p-values less than 0.05. Data are presented as mean ± standard deviation (SD). Total body, fat and lean mass data were non-parametric. A Wilcoxon matched pairs test was conducted to analyse changes in total mass and mass characteristics from baseline to 12 weeks.

Comparisons between the previously described groups were made using the Mann-Whitney U test, due to uneven group sizes and the non-parametric nature of the data. Hedge's g effect sizes (ES) were reported for the uneven group sizes. Hedge's g effect size (ES) of 0 - 0.2 = insignificant effect; 0.2 - 0.5 = small effect; 0.5 - 0.8 = moderate effect and > 0.8 = large effect. Strength variable differences between participants in the various groups for ILR were compared using a Mann-Whitney U test. Pearsons correlations were calculated to determine associations between biomechanical variables and mass characteristics, strength and flexibility (n = 54). A Bonferonni adjustment was applied to all correlations since several correlations were tested for a given variable. This adjustment was calculated by dividing the alpha value (0.05) by the number of correlations performed on a variable, to provide a new alpha value. For example, when five correlations were performed on a given variable, the adjusted alpha value was 0.05/5 = 0.01. Correlations would thus only be deemed significant if they adhered to the adjusted alpha value of 0.01 in this example.

Flexibility and strength data were parametric. A repeated-measures ANOVA with a Tukey's LSD post hoc test to determine time by footwear effects was used to determine differences in flexibility and strength variables (n = 44). Comparisons between strength variables and foot strike pattern were conducted between participants who maintained a RFS (n = 41), and the participant who transitioned from a RFS to a FFS (n = 1) using a Mann-Whitney U test.

6.5) Results

6.5.1. Injured versus uninjured runners

Of the 54 participants who took part in the study, 10 participants did not complete the 12-week running intervention due to injury (n = 6), illness (n = 1) or lack of compliance (n = 3).

Table 6.1 categorizes participants into uninjured (those who completed the 12-week intervention) and injured (those who dropped out due to running related injuries; TC = 5, RC = 1). Participants who dropped out due to non-running related injuries and non-compliance were excluded). Subgrouping the injured group into footwear type was not done due to the small number of injured runners. No significant differences were found in participant characteristics between the injured and uninjured participants.

Table 6.1: Participant characteristics between the uninjured groups and injured participants.

Group	Shoe type	N	Male/Female	Age (yrs)	Height (cm)
Uninjured	Combined	44	13/31	29.6 ± 5.2	172.4 ± 8.7
	TC	24	8/16	29.5 ± 6.5	172.1 ± 9.4
	RC	20	5/15	29.7 ± 4.7	170.8 ± 7.5
Injured	Combined	6	4/2	30.0 ± 6.3	173.4 ± 12.1

Combined – all participants of study, regardless of footwear; TC – traditionally cushioned; RC – reduced cushioning.

The model proposed at the outset of this dissertation first addresses the influence of a training intervention in reduced cushioned footwear on intrinsic characteristics. Since training influences global body composition more than footwear structure, we looked at all participants as a single group, rather than in their footwear groups when assessing body composition changes.

Table 6.2: Participant's mass characteristics

		Baseline	12-weeks	% change	*p*
Total mass (kg)	Uninjured	67.4 ± 10.4	66.9 ± 10.3	-0.7	0.26
	Injured	76.0 ± 14.7	-	-	-
BMI (kg/m^2)	Uninjured	23.3 ± 2.8	23.1 ± 2.5	-0.9	0.50
	Injured	26.5 ± 3.2	-	-	-
Fat mass (kg)	Uninjured	19.6 ± 5.7	18.6 ± 5.1	-5.1	0.02*
	Injured	23.3 ± 5.9	-	-	-
Lean mass (kg)	Uninjured	47.8 ± 9.0	48.3 ± 9.2	+1.05	0.23
	Injured	52.7 ± 11.5	-	-	-
Body fat %	Uninjured	29.1 ± 6.7	27.9 ± 6.4	-1.2	0.02*
	Injured	31.7 ± 5.6	-	-	-

Uninjured (n = 44); Injured (n = 6, represents only those participants who dropped out due to running related injury). BMI – body mass index. Differences in time compared using a Wilcoxon matched pairs test; * represents a significant change from baseline to 12-weeks in the uninjured group.

Injured participants had a greater mass than the uninjured participants; 76.0 kg and 67.4 kg respectively, however, this difference most likely stems from a greater number of heavier males than females in the injured group.

Fat mass and body fat percentage both decreased significantly ($p < 0.05$), with no changes in total mass, BMI and lean mass (Table 6.2).

6.5.2. The effects of footwear on flexibility

The effect of footwear was considered when assessing flexibility and strength since footwear companies and previous studies have prescribed exercises to improve the likelihood of a successful transition into footwear with reduced cushioning that focus on strength and flexibility outcomes (Warne et al. 2014).

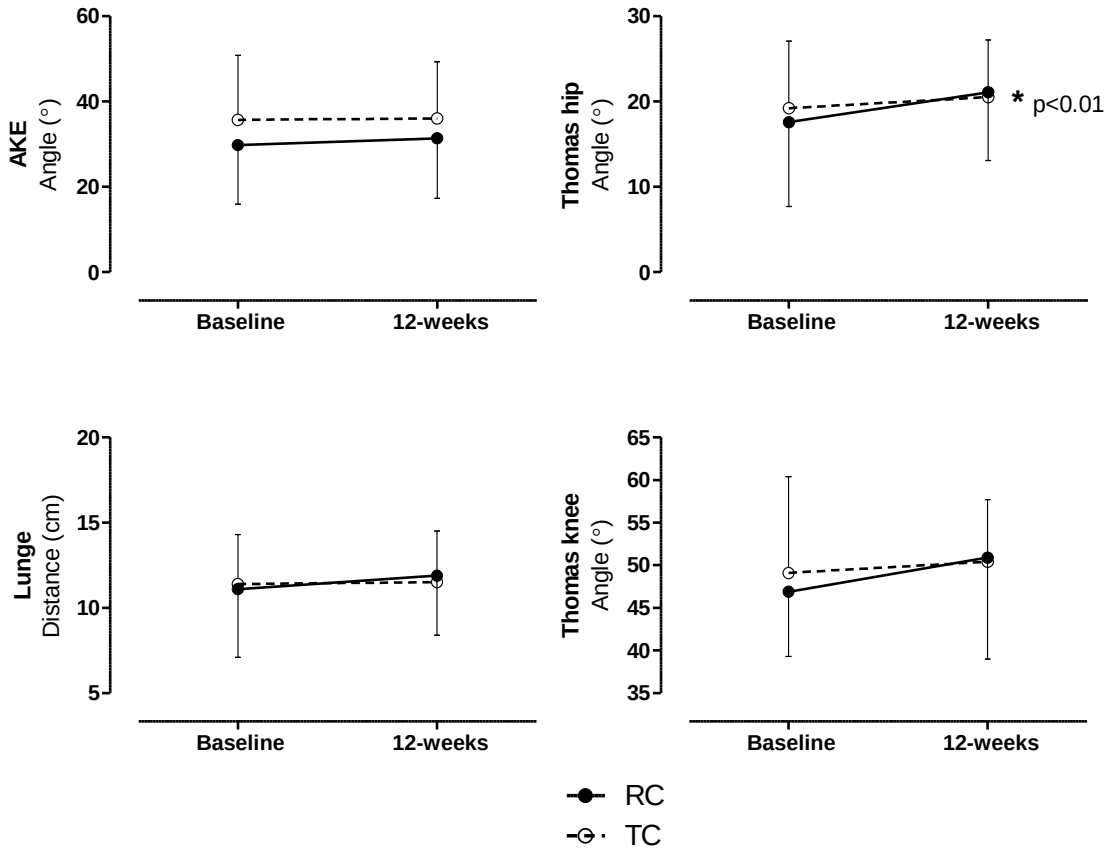


Figure 6.1: The effect of traditionally cushioned and reduced cushioning shoes on lower limb flexibility in novice runners

RC – reduced cushioning group; TC – traditionally cushioned group; AKE – active knee extension test for active hamstring flexibility where a greater angle represents greater knee flexion or a less flexible hamstring group; Thomas hip – Thomas test for passive hip flexor flexibility where a positive angle represents greater hip extension and a negative angle represents greater passive hip flexion (less hip flexor flexibility); Thomas knee – Thomas test for passive quadriceps flexibility where a greater angle represents less knee extension or less quadriceps flexibility; Lunge – lunge test for ankle dorsiflexion flexibility where greater distance represents greater triceps surae and Achilles tendon flexibility.

Differences were analysed using a repeated measures ANOVA test with a Tukeys post hoc. * represents a significant time effect.

Figure 6.1 shows the results from flexibility testing before and after completion of the 12-week programme. A time effect was found for the Thomas test, where participants increased passive hip extension after the 12-week programme [pre = 18.4º ± *8.8º*, post = 20.8º ± *7.2º*, – $p < 0.01$], regardless of shoe type.

Baseline and 12-week comparisons for the AKE, Thomas (knee) and Lunge tests showed no significant changes.

6.5.3. The effects of footwear on strength

Table 6.3A: Changes in concentric ankle strength between groups after 12 weeks running intervention

	Concentric plantarflexion			
	60º/s		180º/s	
	Baseline	12-weeks	Baseline	12-weeks
ALL	48.3 ± 16.2	55.8 ± 17.3*	22.7 ± 7.4	28.0 ± 9.5**
TC	48.4 ± 15.5	51.7 ± 16.8	20.9 ± 6.8	26.6 ± 8.3
RC	48.3 ± 17.4	60.7 ± 17.0	24.8 ± 7.8	29.7 ± 10.8
	Concentric dorsiflexion			
	60º/s		180º/s	
	Baseline	12-weeks	Baseline	12-weeks
ALL	17.7 ± 4.1	19.9 ± 6.8	13.6 ± 2.4	18.5 ± 5.8**
TC	17.6 ± 2.8	20.9 ± 8.9	13.8 ± 2.5	19.5 ± 6.3
RC	17.8 ± 5.2	18.8 ± 2.9	13.5 ± 2.4	17.2 ± 5.1

Data presented as mean average peak torque/body weight (%) ± SD. ALL – all participants from both groups; RC – reduced cushioning group; TC – traditionally cushioned group, º/s – degrees per second (isokinetic speed). Significant differences analysed using a Mann Whitney U test; Significant differences shown by * - $p < 0.05$ and ** - $p < 0.01$.

Table 6.3B: Changes in eccentric ankle strength between groups after 12 weeks running intervention

	Eccentric plantarflexion		**Eccentric dorsiflexion**	
	60º/s		60º/s	
	Baseline	12-weeks	Baseline	12-weeks
ALL	25.7 ±6.8	25.8 ± 6.6	51.2 ± 19.0	51.5 ± 18.9
TC	25.2 ±6.2	25.3 ± 6.1	48.1 ± 16.6	48.4 ± 16.6
RC	26.3 ±7.6	26.4 ± 7.3	55.1 ± 21.5	55.5 ± 21.4

Data presented as mean average peak torque/body weight (%) ± SD. ALL – all participants from both groups; RC – reduced cushioning group; TC – traditionally cushioned group, º/s – degrees per second (isokinetic speed). Significant differences analysed using a Mann Whitney U test; Significant differences shown by * - $p < 0.05$ and ** - $p < 0.01$.

Table 6.3C: Changes in concentric knee extension and flexion strength between groups after 12 weeks running intervention

	Concentric knee extension			
	60º/s		180º/s	
	Baseline	12-weeks	Baseline	12-weeks
ALL	134.3 ± 29.0	123.7 ± 25.7**	76.2 ± 12.5	79.2 ± 15.2*
TC	131.5 ± 34.0	117.7 ± 26.7	75.7 ± 14.2	77.6 ± 17.0
RC	137.4 ± 22.2	130.6 ± 23.2	76.8 ± 10.5	81.0 ± 12.7
	Concentric knee flexion			
	60º/s		180º/s	
	Baseline	12-weeks	Baseline	12-weeks
ALL	63.5 ± 14.6	64.5 ± 13.6	41.7 ± 8.5	43.0 ± 11.8
TC	62.7 ± 17.5	64.9 ± 15.9	41.8 ± 9.1	44.5 ± 13.5
RC	64.5 ± 10.7	64.1 ± 10.8	41.6 ± 8.0	41.2 ± 9.4

Data presented as mean average peak torque/body weight (%) ± SD. ALL – all participants from both groups; RC – reduced cushioning group; TC – traditionally cushioned group, º/s – degrees per second (isokinetic speed). Significant differences analysed using a Mann Whitney U test; Significant differences shown by * - $p < 0.05$ and ** - $p<0.01$.

Table 6.3A-C shows the isokinetic strength at baseline and 12-weeks between footwear groups and as a combine group (both TC and RC).

No footwear effects on any strength variable were found.

Significant time effects were found for 60º/s CON plantarflexion [pre = 48.3 ± 16.2 %, post = 55.8 ± 17.3 %; $p < 0.05$], with CON plantarflexion strength increasing over time. Similarly, significant time effects were also found for 180º/s CON plantarflexion [pre = 22.7 ± 7.4 %, post = 28.0 ± 9.5 %; $p < 0.01$], with CON plantarflexion strength increasing over time. No changes existed over time for 60º/s CON dorsiflexion, however, at 180º/s CON dorsiflexion strength increased over time [pre = 13.6 ± 2.4 %, post = 18.5 ± 5.8 %; $p < 0.01$].

Significant time effects were found for CON knee extension strength where a reduction in strength was found at 60º/s [pre = 134.3 ± 29.0 %, post = 123.7 ± 25.7 %; $p = 0.001$] and an increase in strength was found at 180º/s [pre = 76.2 ± 12.5 %, post = 79.2 ± 15.2 %; $p = 0.044$].

Table 6.4: Correlations between mass characteristics and baseline biomechanical variables

	Correlation statistics	Kinetic variables		Spatiotemporal variables		Foot strike kinematics			Stance phase kinematics			
		ILR	vGRF	Stride length	Cadence	FSA	Ankle angle	Knee angle	Ankle angle	Knee angle	Ankle ROM	Knee ROM
Total mass	r=	-0.18	-0.05	-0.04	-0.07	0.08	-0.25	-0.53*	-0.33	-0.54*	-0.26	-0.24
	p=	0.21	0.75	0.79	0.60	0.59	0.07	0.00	0.02	0.00	0.06	0.08
BMI	r=	-0.17	-0.04	-0.28	0.19	0.02	-0.14	-0.45*	-0.31	-0.43*	-0.15	-0.17
	p=	0.21	0.79	0.04	0.18	0.86	0.33	0.00	0.02	0.00	0.28	0.22
Fat mass	r=	-0.10	-0.42*	-0.26	0.22	-0.03	-0.14	-0.32	-0.26	-0.37*	0.15	-0.08
	p=	0.50	0.00	0.06	0.11	0.86	0.31	0.02	0.06	0.01	0.29	0.55
Lean mass	r=	-0.14	0.18	0.14	-0.21	0.13	-0.20	-0.43*	-0.24	-0.41*	-0.38*	-0.25
	p=	0.31	0.19	0.32	0.14	0.35	0.14	0.00	0.08	0.00	0.01	0.08
Body fat percentage	r=	-0.01	-0.44*	-0.30	0.31	-0.13	-0.02	-0.04	-0.10	-0.10	0.33	0.04
	p=	0.97	0.00	0.03	0.03	0.35	0.89	0.79	0.50	0.47	0.02	0.77

ILR – initial loading rate; vGRF – vertical ground reaction force; FSA – foot strike angle; ROM – range of motion during stance phase. Correlations were calculated using a Pearsons correlation test where * represents a significant correlation. Negative r-values represent inverse relationships. Data used only from participants who completed the intervention (n = 44)

In Table 6.4, both fat mass ($r = -0.42$; $r^2 = 0.17$; $p < 0.01$, moderate relationship) and body fat percentage ($r = -0.44$; $r^2 = 0.19$; $p < 0.01$, moderate relationship) were significantly inversely correlated with vGRF. No significant correlations were found between any of the body composition variables and ILR.

Knee angle at foot strike was inversely correlated to total mass ($r = -0.53$; $r^2 = 0.28$; $p < 0.01$), BMI ($r = -0.45$; $r^2 = 0.20$; $p < 0.01$) and lean mass ($r = -0.43$; $r^2 = 0.18$; $p < 0.01$).

During stance phase, peak knee angle was inversely correlated to total mass ($r = -0.54$; $r^2 = 0.29$; $p = 0.000$), BMI ($r = -0.43$; $r^2 = 0.18$; $p < 0.01$), fat mass ($r = -0.37$; $r^2 = 0.14$; $p < 0.01$) and lean mass ($r = -0.41$; $r^2 = 0.17$; $p < 0.01$). Additionally, ankle ROM was inversely correlated to lean mass ($r = -0.38$; $r^2 = 0.14$; $p < 0.01$).

Table 6.5: Correlations between baseline biomechanical variables and lower limb flexibility

	Correlation statistics	Kinetic variables		Spatiotemporal variables		Foot strike kinematics			Stance phase kinematics			
		ILR	vGRF	Stride length	Cadence	FSA	Ankle angle	Knee angle	Ankle angle	Knee angle	Ankle ROM	Knee ROM
AKE	r=	-0.01	-0.23	-0.26	0.22	-0.12	-0.18	-0.19	-0.21	-0.38*	-0.12	-0.39*
	p=	0.97	0.12	0.08	0.15	0.43	0.22	0.19	0.16	0.01	0.41	0.01
THOM Hip	r=	0.13	-0.03	0.38*	-0.03	0.13	-0.07	0.04	0.15	0.06	0.22	0.16
	p=	0.38	0.85	0.01	0.86	0.37	0.64	0.79	0.31	0.70	0.13	0.28
THOM Knee	r=	-0.12	-0.27	-0.28	0.15	0.11	0.07	-0.25	-0.15	-0.15	0.04	0.01
	p=	0.43	0.07	0.06	0.31	0.46	0.63	0.09	0.33	0.32	0.79	0.96
Lunge distance	r=	-0.03	-0.25	-0.06	0.06	0.23	0.15	0.01	-0.05	-0.03	0.22	-0.09
	p=	0.84	0.09	0.70	0.67	0.11	0.32	0.94	0.72	0.83	0.14	0.56

ILR – initial loading rate; vGRF – vertical ground reaction force; FSA – foot strike angle; ROM – range of motion during stance phase. AKE – Active knee extension test; THOM hip – Thomas test at hip; THOM knee – Thomas test at knee. Correlations were calculated using a Pearsons correlation test where * represents a significant correlation. Negative r-values represent inverse relationships. Data used only from participants who completed the intervention (n = 44)

AKE was inversely correlated to peak knee angle during stance ($r = -0.38$; $r^2 = 0.14$; $p < 0.01$) and knee ROM during stance ($r = -0.39$; $r^2 = 0.15$; $p < 0.01$). THOM hip was positively correlated to stride length ($r = -0.38$; $r^2 = 0.14$; $p < 0.01$).

Table 6.6: Correlations between baseline biomechanical variables and lower limb strength

	Correlation statistics	Kinetic variables		Spatiotemporal variables		Foot strike kinematics			Stance phase kinematics			
		ILR	vGRF	Stride length	Cadence	FSA	Ankle angle	Knee angle	Ankle angle	Knee angle	Ankle ROM	Knee ROM
Ankle CON 60 PF	r=	-0.08	0.13	0.19	0.00	0.10	0.02	0.01	-0.01	-0.04	0.03	-0.23
	p=	0.56	0.35	0.19	0.99	0.51	0.91	0.92	0.96	0.78	0.86	0.10
Ankle CON 60 DF	r=	0.09	0.13	0.09	-0.11	-0.05	-0.08	-0.14	-0.07	-0.19	-0.22	-0.13
	p=	0.52	0.37	0.53	0.45	0.71	0.59	0.31	0.61	0.19	0.13	0.37
Ankle CON 180 PF	r=	0.07	0.09	0.21	-0.11	0.10	-0.09	-0.06	0.02	-0.05	-0.17	-0.12
	p=	0.65	0.55	0.14	0.44	0.49	0.52	0.68	0.87	0.72	0.24	0.41
Ankle CON 180 DF	r=	0.17	0.12	0.06	0.05	-0.23	-0.10	0.13	0.03	0.02	-0.07	-0.15
	p=	0.23	0.41	0.66	0.70	0.11	0.50	0.35	0.83	0.89	0.63	0.29
Ankle ECC 60 PF	r=	-0.02	-0.01	-0.08	-0.02	-0.18	-0.21	-0.08	-0.23	-0.22	-0.22	-0.31
	p=	0.91	0.97	0.59	0.88	0.21	0.14	0.59	0.10	0.12	0.13	0.03
Ankle ECC 60 DF	r=	0.11	-0.17	-0.13	0.35	-0.12	-0.35	-0.10	-0.30	-0.26	-0.02	-0.27
	p=	0.45	0.25	0.38	0.01	0.42	0.01	0.49	0.03	0.07	0.86	0.05
Knee CON 60 Ext	r=	0.12	0.25	0.15	-0.03	-0.02	-0.14	0.09	-0.06	-0.01	-0.32	-0.21
	p=	0.39	0.07	0.31	0.85	0.87	0.33	0.52	0.69	0.96	0.02	0.15
Knee CON 60 Flex	r=	0.01	0.21	0.25	-0.08	0.04	-0.11	0.08	-0.02	-0.03	-0.28	-0.25
	p=	0.93	0.14	0.08	0.60	0.77	0.42	0.56	0.91	0.81	0.05	0.07
Knee CON 180 Ext	r=	-0.14	0.22	0.15	-0.20	0.08	-0.09	-0.01	-0.05	0.01	-0.39	-0.14
	p=	0.34	0.12	0.28	0.16	0.60	0.54	0.96	0.74	0.93	0.01	0.34
Knee CON 180 Flex	r=	-0.11	0.39	0.21	-0.22	-0.06	-0.09	0.07	-0.07	-0.02	-0.31	-0.25
	p=	0.45	0.00*	0.15	0.13	0.68	0.55	0.63	0.64	0.89	0.03	0.08

ILR – initial loading rate; vGRF – vertical ground reaction force; FSA – foot strike angle; ROM – range of motion during stance phase. CON – concentric; ECC – eccentric; PF – plantarflexion; DF – dorsiflexion; Ext – extension; Flex – flexion. Correlations were calculated using a Pearsons correlation test where * represents a significant correlation. Negative r-values represent inverse relationships. Data used only from participants who completed the intervention (n = 44)

CON knee flexion strength at 180 was positively correlated with vGRF ($r = -0.39$; $r^2 = 0.16$; $p < 0.01$). No other strength variables were significantly correlated to biomechanical variables (Table 6.6).

Since significant changes were predominantly found in plantarflexion strength, a further analysis into the effect of foot strike pattern and strength changes was conducted. At baseline and 12-week testing periods, no differences in ECC (60º/s) or CON plantarflexion strength at either speed were found between participants who adopted a FFS and a RFS pattern. However, when assessing the change (delta) from baseline to 12-weeks, large individual variation existed between foot strike patterns, particularly in the participants who adopted a FFS pattern (n = 3) after the intervention. The participant that transitioned from a RFS to a FFS pattern showed the greatest increases in concentric plantarflexion strength at both speeds. Additionally, this participant showed eccentric plantarflexion strength improvements that were greater than all but one other participant.

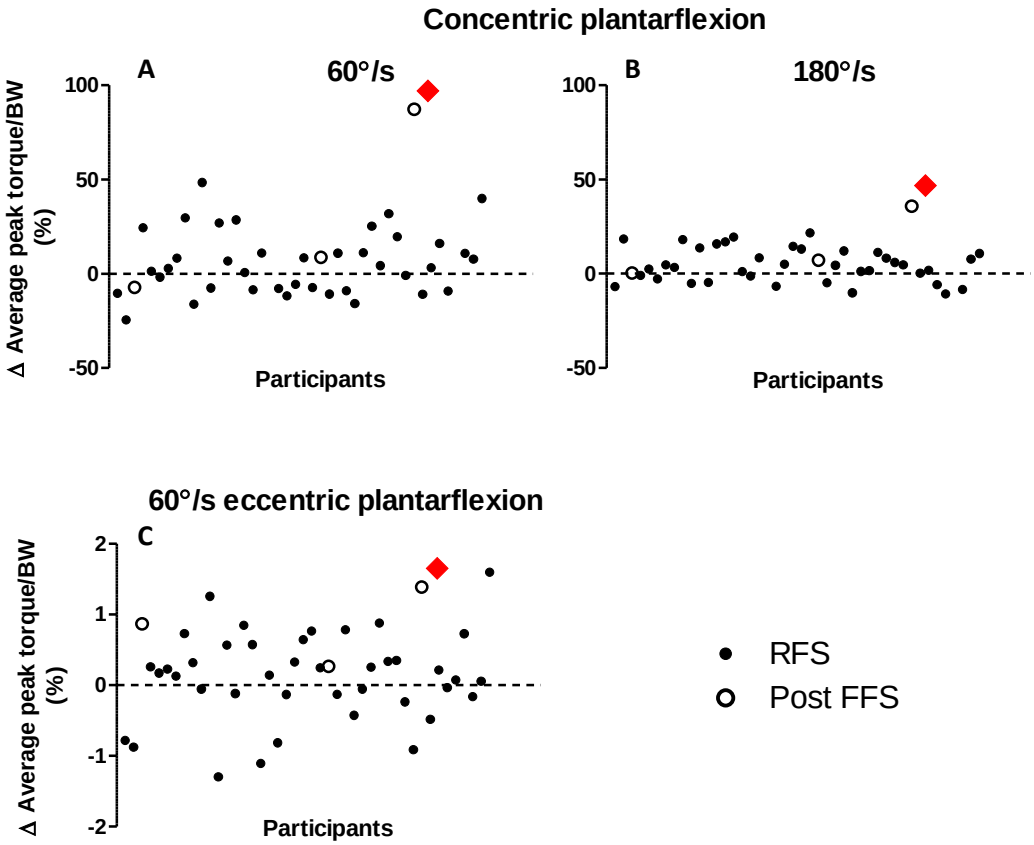


Figure 6.2: The effect of foot strike pattern on changes in strength variables in each participant

A – Δ average peak torque/body weight (%) in 60º/s concentric plantarflexion; B – Δ average peak torque/body weight (%) in 180º/s concentric plantarflexion; C – Δ average peak torque/body weight (%) in 60º/s eccentric plantarflexion. RFS – 12-week rearfoot strike pattern (n = 41); Post FFS – 12-week forefoot strike pattern (n = 3). # denotes the participant who transitioned from a RFS pattern at baseline to a FFS pattern at 12-week testing. A positive Δ represents an increase in average peak torque/BW (%) from baseline to 12-week testing. Individual participants remain in the same horizontal order in all three graphs.

Table 6.7: Relationship between body mass characteristics and risk factors for injury

		Injury	**Oedema**	**Pain or discomfort**	**Baseline ILR**
		Risk = injured; No risk = uninjured	Risk = > 1; No risk = ≤ 1	Risk = ≥ 7; No risk = < 7	Risk = ≥ 72 BW/s; No risk = < 72 BW/s
	N: risk/no risk	6/44	5/39	25/19	27/17
Total mass (kg)	Risk: No risk:	76.0 ± 14.7 67.4 ± 10.4	70.0 ± 17.1 67.0 ± 9.5	68.8 ± 10.1 66.3 ± 10.7	66.7 ± 11.0 68.5 ± 9.7
	p	0.17	0.96	0.60	0.35
	Hedge's g ES	**0.78**	0.28	0.24	-0.18
BMI (kg/m²)	Risk No risk	26.5 ± 3.2 23.3 ± 2.8	23.1 ± 4.6 23.4 ± 2.6	23.7 ± 2.6 23.1 ± 3.0	22.8 ± 3.0 24.1 ± 2.4
	p	**0.049***	0.72	0.52	0.18
	Hedge's g ES	**1.11**	-0.10	0.21	-0.46
Fat mass (kg)	Risk No risk	23.3 ± 5.9 19.6 ± 5.7	21.7 ± 8.3 19.3 ± 5.3	19.4 ± 4.9 19.7 ± 6.3	18.4 ± 5.7 21.4 ± 5.4
	p	0.15	0.67	0.95	0.06
	Hedge's g ES	**0.64**	0.42	-0.05	**-0.53**
Lean mass (kg)	Risk No risk	52.7 ± 11.5 47.8 ± 9.0	48.3 ± 12.3 47.7 ± 8.7	49.4 ± 9.1 46.6 ± 8.9	48.3 ± 9.6 47.1 ± 8.2
	p	0.41	0.78	0.25	0.89
	Hedge's g ES	0.31	0.06	0.31	0.13
Body fat Percentage (%)	Risk No risk	30.8 ± 5.3 29.1 ± 6.7	30.6 ± 6.9 28.9 ± 6.7	28.3 ± 6.2 29.7 ± 7.1	27.6 ± 6.7 31.3 ± 6.3
	p	0.43	0.87	0.28	0.11
	Hedge's g ES	**0.52**	0.25	-0.21	**-0.55**

* represents a significant difference between ‘risk’ and ‘no risk’ groups. Data presented as Mean ± SD.

In Table 6.7, participants who dropped out of the study due to injury had a significantly higher BMI than uninjured participants ($p < 0.05$, ES: 1.11). No other body composition variables differed between participants in any group.

Total mass (ES: 0.78) and fat mass (ES: 0.64) were found to have moderate to strong effect sizes for injury (injured vs uninjured group) (Table 6.7).

Fat mass [18.4 ± 5.7 kg vs 21.4 ± 5.4 kg, $p = 0.06$] and body fat percentage [27.6 ± 6.7 % vs 31.3 ± 6.3 %, $p = 0.11$] showed moderate effect sizes (ES: -0.53 and -0.55, respectively) between ILR groups, with greater fat mass and body fat percentage reported in the low ILR group.

The above analysis was carried out for all flexibility and strength variables. The only significant difference between risk outcome groups was found in the pain or discomfort category, where participants with greater Thomas Knee range in the right leg (more flexible quadriceps) had greater pain or discomfort scores than participants with less range (significant pain or discomfort: 51.6° vs no pain or discomfort: 44.9°). No other risk stratification groups had significant differences in strength or flexibility variables.

6.6) Discussion

This chapter aimed to determine the influence of intrinsic characteristics of novice runners that are often assessed in a clinical setting on risk of sustaining a running related injury. We did this by first assessing the effect that a 12-week running programme in footwear with reduced cushioning had on these intrinsic characteristics. Thereafter, we determined whether these intrinsic characteristics had any effect on key running biomechanics and whether differences in these intrinsic characteristics existed between participants deemed at risk of injury based on injury, clinical and biomechanical outcomes after the intervention.

To better understand how training and footwear structure influence injury risk, we determined how these factors influence the intrinsic characteristics of the runner.

6.6.1. Mass Characteristics

Greater mass in runners is a key risk factor for injury. Whilst this study found that the injured runners had a significantly greater BMI than the uninjured runners, the number of injured runners was limited to six participants which restricted the application of this finding. Moreover, four of the six injured participants were male, thus skewing the data as males weighed more than females. Participants who finished the intervention, thus remaining free of injury, lost significant fat mass and reduced their body fat percentage. A further benefit of these changes may be that the risk factors created by biomechanical factors may be favourably changed by the reduction in mass which may be beneficial in terms of reducing injury risk.

The model proposed throughout this dissertation suggests that intrinsic characteristics such as mass do not directly influence injury risk, but rather influence biomechanical variables. In support, we found several significant correlations between mass characteristics and biomechanical variables. This study found that participants with greater mass characteristics maintained a straighter knee angle at foot strike and peak angle during stance (Table 6.4). This kinematic difference at the knee, rather than the ankle, may be the result of 52 of the 54 participants landing with a RFS at baseline testing, thus making the knee as the primary joint of compliance (Sinclair 2014; Kulmala et al. 2013). These kinematic strategies, which result in a straighter leg throughout stance phase, may reduce the moment arm and thus minimise muscular contribution and joint moments which may, in part, unload the muscular system by placing more responsibility on the skeletal system to absorb impact and attenuate ground reaction forces. This strategy most likely minimises intrinsic forces, rather than extrinsic loads including ILR, since greater mass variables were not significantly correlated to ILR. This lack of correlation may be due to ILR already being normalised to body weight, thus negating any weight related correlations. However, when assessing body composition on the risk of injury, we found that having greater fat mass and body fat percentage were associated with a lower ILR, (less than 72 BW/s), albeit moderate effect sizes. This suggests that the kinematic strategies adopted by participants with greater mass characteristics, especially fat mass and body fat percentage may be effective in mitigating impact loads and extrinsic forces.

Lower vGRF values were correlated to greater fat mass and body fat percentage as well as lower knee flexion strength at 180°/s. From a clinical perspective, higher fat mass and lower strength may be indicative of compromised athletic capabilities and result in lower force outputs during a given task such as running. Since the components of peak vGRF include both passive weight acceptance and active propulsion, having greater fat mass and lower strength at running specific speeds may reduce propulsion forces in runners, results in lower vGRF (Vakula et al., 2019).

6.6.2. Flexibility

The lack of significant correlations found between lower limb flexibility and key biomechanical variables is consistent with previous studies (Mettler et al. 2019; Fukuchi et al. 2016). Additionally, this disconnect may be the result of runners never having to challenge end-range flexibility during their stride, especially at slower speeds such as those assessed here (5 min/km). Rather than a muscle's end range flexibility being a limiting factor, it is more likely that runners aim to keep their muscles in a range that maintains an effective relationship between length and tension, since muscles tend to lose force production properties when stretched or shortened excessively (Gordon et al. 1966). This is evident in the hip, whereby

greater passive hip flexor length was correlated to greater stride length, which has been reported in the literature (Watt et al. 2011). Rather than having greater capacity to extend the hip to its' end range, the optimal length-tension position of the hip flexor more likely occurs at a position of greater hip extension, so that the initiation of the swing phase, which is partly governed by the hip flexors occurs within a range where the hip flexors can produce an appropriate force. This can also be seen at the knee during stance phase where participants with greater hamstring flexibility maintained a straighter peak knee angle and limited knee ROM during stance phase, which requires greater hamstring length given a fixed torso position. Since rear foot striking runners with greater mass characteristics tend to minimise joint moments by maintaining a straighter knee during stance phase, it may be clinically relevant to assess the hamstring flexibility of heavier runners, as greater hamstring flexibility may promote a straighter knee position.

The link between foot strike pattern and lower limb flexibility is unclear. Research by Warne et al. (2014) implemented a conditioning programme to strengthen foot and calf musculature and Achilles tendon flexibility for runners who were transitioning to footwear with reduced cushioning. They reported no injuries amongst the 10 participants over the 4-week transition period inferring that running in footwear with reduced cushioning may require, or even promote increased plantarflexion strength and Achilles tendon flexibility (Warne et al. 2014). Furthermore, these attributes may be protective against injury in runners who run in shoes with reduced cushioning. Whilst our study did not find runners in footwear with reduced cushioning to be at increased risk of injury when compared to those wearing traditionally cushioned footwear, the runners in the RC group were more likely to experience persistence or reoccurrence of pain or discomfort during the intervention when compared to the TC group (Chapter Four, Section 5, Figure 4.3). The lack of changes in Achilles tendon and calf musculature flexibility changes over time may account for the difference in pain or discomfort reported between the groups.

The effect of the increase in passive hip extension flexibility over time on running biomechanics and injury is unclear. A common strategy used by clinicians is to improve hip mobility and flexibility as it is believed to lessen the risk of sustaining a running related injury. However, the mechanisms behind this are unknown, and thus require further research to determine the effect that lower limb flexibility has on running biomechanics and injury.

6.6.3. Strength

Novice runners presented with increases in concentric strength of the ankle, in plantarflexion and dorsiflexion, as well as in knee extension at 180º/s. These findings agree with those published by Karamandis and Arampatzis (2005). However, the strength increases in ankle

dorsiflexion and knee extension may be due to the majority of runners landing with a RFS pattern, which results in the muscle groups controlling these movements (Tibialis Anterior and Quadriceps muscle group) to work eccentrically during the weight acceptance phase. It is hypothesized that running represents a new and sufficient stimulus to novice runners as to promote muscular adaptations. Strength improvements were mainly found at isokinetic speeds that replicate an acceptable running cadence (180º/s equates to between 80 and 90 cycles per minute), suggesting a task specific strength adaptation. Whether these improvements in strength influence injury risk remains unclear since no differences in strength were found between 'risk' and 'no risk' groups. Additionally, we found that greater strength did not influence ILR, suggesting that muscular strength may not be solely responsible for the dampening of extrinsic impact forces (Nigg 1997). Given that ground contact time for these participants was generally less than 250 ms, it is unsurprising to not find differences between the risk groups as the time to peak force production during the isometric testing was often greater than 300 ms. Due to the large variation in strength variables between foot strike patterns (as a result of the low occurrence of FFS patterns), caution was exercised when linking strength variables to foot kinematics. Future studies should categorize participants based on foot strike pattern to better understand the interaction between lower limb strength and foot strike pattern.

The premise of footwear with reduced cushioning was to promote a reduction in FSA, or the adoption of a FFS pattern, which has been found to reduce impact forces by increasing ankle joint plantarflexion moments, thus placing greater workload on the triceps surae (Cauthon et al. 2013; Fuller et al. 2016; Rice & Patel 2017; Lieberman et al. 2010; Rice et al. 2016; Willson, Bjorhus, Williams, et al. 2014). The present study found no differences in strength variables between participants who ran for 12-weeks in footwear with traditional cushioning and those with reduced cushioning. The lack of participants landing with a FFS pattern may account for the similar strength outcomes between footwear groups. Had more runners in the RC group transitioned to a FFS pattern, greater eccentric plantarflexion strength improvements may have been found in the group when compared to the TC group.

The participant in the RC group who transitioned from a RFS to a FFS pattern presented with the greatest increase in CON plantarflexion strength at both speeds as well as an increase in ECC plantarflexion strength that was greater than all but one other participant. Since baseline plantarflexion strength of the participants who either adopted a FFS pattern prior to the intervention, or the participant who transitioned to a FFS pattern were not different to those who maintained a RFS, it is suggested that the transition to a FFS pattern resulted in plantarflexion improvements given that a FFS pattern required greater triceps surae load. Had they not presented with these strength increases, they would either have reverted back to a

RFS pattern or sustained an injury. However, this finding is limited to a single participant, and emphasizes the complex interaction between footwear, strength and flexibility which ultimately requires further research. Since plantarflexion strength is not an effective indicator of foot strike pattern, a key question is “What factors influence the intuitive adoption of or transition to a FFS pattern?”.

Dorn at al. (2012) suggests that the Soleus produces the greatest amount of force during the push-off phase of the gait cycle, inferring that it is influential in imparting propulsive forces and thus contributes to the active peak of vGRF (Dorn et al. 2012). The present study found that participants with greater ankle plantarflexion strength did not have greater vGRF values, suggesting participants did not impart greater propulsion forces at the moment of peak vGRF. This disconnect between strength and key biomechanical variables points towards a more holistic approach to lower limb force production, rather than looking at it in a compartmentalised manner. For example, having greater ankle plantarflexion may not necessarily result in the production of greater ankle plantarflexion moments during running. It is more likely that all the muscle groups of the lower limb act in conjunction with centre of mass distribution to contribute to global lower limb force production during running. In terms of clinical application, this finding points towards the training and strengthening of global, running-specific movements rather than isolating specific muscle groups of the lower limb.

Despite the inconclusive findings between strength and risk of running related injury, we can conclude that novice runners embarking on a running programme do present with task specific improvements in lower limb strength, which may have beneficial implications for injury.

6.7) Limitations

Firstly, as the primary focus of this study was to determine biomechanical changes in novice runners as they embark on a 12-week running programme, the groups were powered according to biomechanical variables, rather than injury. This was because this dissertation aimed to provide an evidence-based link between intrinsic characteristics and injury outcome by mean of assessing and quantifying the biomechanical variables, which represent the mediatory step between intrinsic characteristics and injury. The small sample size of this study warrants caution when determining the influence intrinsic variables and their effect on injury or injury risk outcomes.

Secondly, participants who dropped out because of injury did not undergo post-intervention testing. Therefore, comparisons between injured and non-injured participants could not be conducted with regards to mass and mass characteristics, flexibility or strength variables. Only

risk factors for injury, such as ILR, could be assessed. This leads to interpretations, rather than explicit findings.

Finally, diet or additional physical activity during the 12-week running intervention was not controlled for, although instruction was given to not make any drastic changes in diet and to allow the running to be their primary form of physical activity.

6.8) Clinical implications

Clinicians should be aware of their patient's basic body composition when prescribing running programmes or footwear, as mass and mass characteristics may influence the response to these prescriptions. We recommend runners with greater fat mass and body fat percentage receive advice and instruction (be it in the form of awareness or gait retraining) on reducing knee flexion at foot strike and during stance, as it may have beneficial implications on kinetics. Additionally, runners with greater total mass, BMI and fat mass should approach running with caution, and progress weekly mileage conservatively to reduce the risk of sustaining a running related injury. The speed of running should also be reduced in those runners with higher BMIs, since this will reduce the forces upon landing.

Rather than strengthening specific muscle groups, we recommend runners focus on training compound (many muscle groups), running-specific movements as all the muscles interact in a complex manner, rather than in an isolated form.

6.9) Future research

It is important to better understand the potential link between intrinsic variables, particularly body composition, flexibility or strength and their effect on running biomechanics to 1) determine the likelihood of a novice running succeeding with a training programme in terms of injury prevention and 2) allow for improved gait retraining feedback as intrinsic variables as well as running biomechanics can be assessed and ultimately manipulated to reduce injury risk. More specifically, assessing differences between foot strike patterns may prove insightful, whilst using strength as an indicator for potential gait retraining cues may reduce injury risk. For example, providing cues to transition to a FFS pattern may be better suited to runners who already have good ankle plantarflexion strength.

Studies controlling for intrinsic variables are required as they will shed more light on this scarce yet clinically important topic. This will allow for better understanding of the interaction between

intrinsic variables and running biomechanics and injury, as well as potentially causal relationships.

6.10) Conclusion

Novice runners with greater mass characteristics adopt kinematic strategies, including maintaining a straighter knee during stance phase, which may potentially offset the inherent risk of being heavier as these runners did not present with greater ILR. These strategies were mostly found at the level of the knee, which may be the result of nearly all participants landing with a RFS pattern, rendering the knee the primary joint of impact absorption.

Lower vGRF values were associated with greater fat mass, higher body fat % and lower knee flexion strength. These variables may be indicative of a less athletic person, thus limiting their force production during the propulsion phase of the gait cycle, which may explain the lower vGRF.

Lower limb flexibility influences running biomechanics, despite the gait never challenging end range flexibility. Greater hip flexor flexibility was correlated to a greater stride length, whilst greater hamstring flexibility was correlated to a straighter peak knee angle during stance.

Running represents a new and sufficient stimulus to novice runners as increases in ankle and knee strength were found, especially at running specific speeds, suggesting a task-specific strength adaptation. Additionally, greater strength of supporting muscle groups does not result in greater force output of those muscles, as measured by joint moment, during running, suggesting a more holistic approach should be considered by clinicians when assessing strength and training running specific strength movements.

Chapter Seven

Clinicians Guidelines for Reducing Injury Risk in Novice Runners

7.1) Introduction

As more novice runners start increasing their mileage, it is important to understand what clinicians can do to prevent running related injuries in these runners. In this dissertation we have assessed novice runners embarking on a 12-week running intervention from a clinical perspective, with the aim of identifying measurable and modifiable risk factors for injury. This is an important step towards the application of effective injury prevention strategies, as the detection of early symptoms of running related injury is often inaccessible and costly for novice runners.

Additionally, with running footwear becoming an increasingly popular method of both injury prevention and rehabilitation, this dissertation has focused on the role that footwear plays with regards to modifying potential risk factors for injury.

In this final chapter, we revisit the model from the perspective of the clinician and offer practical advice and the translation of our findings, in the context of the existing literature, for the reduction in injury risk in people who begin running (Questions 1 – 5). Thereafter, we summarize additional key clinical findings from this dissertation into three questions that should be considered by clinicians when prescribing injury prevention advice to novice runners (Questions 6 – 8).

7.2) Model related questions

7.2.1. Question One

What intrinsic characteristics of novice runners are important for clinicians to consider to minimise injury risk, and how does a conservative running programme in footwear with reduced cushioning affect these intrinsic characteristics?

Three key intrinsic characteristics that have been highlighted as potential risk modifiers are:

- body composition
- lower limb strength
- lower limb flexibility.

The results of this study confirmed the literature, where BMI was greater in injured runners than in runners who completed the 12-week intervention without injury. Despite total mass and fat mass also being slightly greater in injured participants, BMI was the only intrinsic variable that we found to be significantly greater between the injured and uninjured participants (Chapter Six), and thus should receive attention from clinicians. Caution should be practiced when using mass derived characteristics to identify injury risk due to the typical difference between males and females, which was a confounder in our study, since our injured cohort was male, and thus naturally had higher mass and BMI.

Strength and flexibility did not directly influence injury risk (Chapter Six), however novice runners with greater quadriceps flexibility may be at risk of experiencing pain or discomfort throughout the intervention. Strength and flexibility can be affected by a 12-week running intervention in novice runners. Increases in ankle dorsiflexion, ankle plantarflexion and knee extension at running specific speeds were noted in novice runners, with footwear having no influence on these strength adaptations. Since most strength improvements were noted at running specific speeds (180°/s), running may represent a new and sufficient stimulus to novice runners, which results in task specific strength adaptation. Additionally, the task of running may potentially increase passive hip flexor flexibility in novice runners, however there is little influence from footwear.

The limited findings linking intrinsic characteristics to injury highlights the complexity of injury mechanism. It is therefore important to better understand the influence of these intrinsic characteristics on running biomechanics, as this forms the link between runner and injury.

7.2.2. Question Two

Do intrinsic characteristics of novice runners influence their running biomechanics?

The field of running biomechanics is highly complex due to, in part, the variability that exists between different runners. This variability may stem from the different intrinsic characteristics of runners, including body composition, strength and flexibility. This study sought to determine the interaction between intrinsic characteristics of novice runners and their running biomechanics.

The majority of participants in this study landed with a rear foot strike (RFS) pattern, which results in the knee being the primary joint of compliance. Novice runners with greater mass characteristics therefore adopted kinematic strategies in the knee to mitigate the potential

increased risk of being heavier. These strategies included maintaining a straighter knee angle at foot strike and during stance phase, which potentially unloads the muscular system by placing increased load on the more passive skeletal system. This may explain why runners with greater initial loading rate (ILR) values had lower fat mass and body fat percentage when compared to participants with lower ILR values.

Lower limb flexibility is important for clinicians to consider when focusing on potential running technique as novice runners with greater passive hip flexor flexibility adopt a greater stride length. Additionally, greater hamstring flexibility may result in a straighter knee angle and limited knee range of motion during stance phase. Whilst end range flexibility is rarely challenged during long distance running in novice runners, it is more likely that greater flexibility shifts the length at which optimal force production is achieved to a position where the muscle is in a longer position. This ultimately results in novice runners adopting positions of greater comfort during the gait cycle. Given the findings between mass, flexibility and force attenuation, it may be of clinical relevance to assess hamstring flexibility in heavier runners as greater hamstring flexibility may promote a straighter knee position during stance which may result in a reduction in vGRF and ILR.

Strength is often cited as an important factor in injury prevention for runners, as poor strength has been found to result in unfavourable biomechanics (Snyder et al. 2009; Earl & Hoch 2011). However, this link is overlooked by many clinicians as they base footwear prescription solely on gait analysis, without the formal assessment of strength. Given the theoretically proposed foot strike pattern differences between traditionally cushioned footwear and footwear with reduced cushioning, it has been hypothesized that running in minimalist footwear requires greater plantarflexion strength due to the increased reliance of the triceps surae to dampen impact forces associated with a forefoot strike pattern (Fuller et al. 2016; Fuller et al. 2015). Whilst increases in plantarflexion strength were found in novice runners after the 12-week running intervention, regardless of footwear and foot strike pattern, we noted that the one participant who did transition from a rear foot strike to a forefoot strike pattern presented with both concentric and eccentric plantarflexion gains that were greater than most other runners who maintained their foot strike patterns. Therefore, the successful transition from a rear foot strike to a forefoot strike pattern may require plantarflexion strength improvement to avoid chronic calf and Achilles tendon injuries.

Whilst strength adaptations may be the result of biomechanical modification, there is little evidence to suggest that strength in indicative of biomechanics. Despite only three participants in this study adopting a forefoot (FFS) pattern, no differences were found in lower limb strength between participants who landed with a FFS pattern and those who landed with a RFS pattern,

suggesting that greater plantarflexion strength may not be an indicator for a FFS pattern. Overall, lower limb strength has little effect on running biomechanics.

No differences in strength changes were noted between novice runners habituating to traditionally cushioned footwear and those wearing reduced cushioned footwear. This suggests that running, rather than footwear structure, may be more effective at promoting task specific strength improvements.

The consideration of lower limb strength may therefore be more applicable for gait retaining rather than footwear prescription alone, since changes in running biomechanics either elicit or require changes in strength, whereas footwear structure has little effect on strength adaptations.

The tenuous link between running biomechanics and lower limb strength in novice runners should guide clinicians towards implementing a more holistic approach to strength interventions, rather than assessing it in a compartmentalised manner. Clinicians should therefore look at training and strengthening of global, running-specific movements rather than isolating specific muscle groups of the lower limb.

7.2.3. Question Three

Do novice runners change their running biomechanics throughout a 12-week running programme, and does footwear influence their biomechanics?

Running is often viewed as a simple activity without many physiological, financial or talent constraints. This oversight of the apparent complexity of running has led to many novice runners progressing their mileage without the awareness of the skills required to run injury-free. Becoming a more trained runner can be assessed by means of improved performance or a reduction in injury risk. This dissertation has focused on the latter and has thus sought to determine whether novice runners present with favourable changes in known injury risk factors as they become more trained.

This dissertation found that novice runners tend to maintain their initially adopted running biomechanics, despite becoming more trained. Additionally, footwear has limited influence on potential biomechanical adaptations. These limited biomechanical adaptations in runners wearing footwear with reduced cushioning included landing with a more flexed knee and an increased likelihood of landing with a reduced foot strike angle (FSA), however, only one runner transitioned to a FFS pattern. Those runners wearing footwear with reduced cushioning

who did reduce their FSA also presented with a reduction in vGRF. Whilst this may be beneficial for accumulative load reduction, there is contrasting evidence to suggest that vGRF is associated with injury risk. Caution should therefore be exercised when relying on changes in vGRF to prescribe advice on injury prevention. Interestingly, no adaptations in key biomechanical variables occurred in novice runners wearing traditionally cushioned footwear, despite becoming more trained. These variables included lower limb kinematics, kinetics and spatiotemporal factors.

Whilst running biomechanics of novice runners may not be drastically influenced as they become more trained, differing force attenuation strategies exist between footwear types. Runners wearing footwear with reduced cushioning rely less on the shock absorbing properties of the midsole of the shoe, and present with lower limb kinematic strategies to compensate for this lack of cushioning. These kinematic strategies were found at the knee and ankle joints, as decreasing knee and ankle joint range of motion during stance phase was positively correlated to a reduction in vGRF. It is suggested that these biomechanical adaptations may be due to heightened sensory feedback offered by the lack of cushioning whist running, resulting in increased biomechanical awareness of the runner. Whereas in traditionally cushioned footwear, the lack of association between lower limb kinematics and vGRF suggest that more reliance in placed into the shoe to attenuate forces.

One key risk factor for running related injury is initial loading rate (ILR), which has been reported extensively in the literature due to growing evidence that it is positively linked to common bone and soft tissue injuries (Milner et al. 2006; Zifchock et al. 2006; Pohl et al. 2009). Moreover, the relatively simple methodology of its assessment has resulted in its inclusion of many running biomechanical studies. In Chapter Five, we measured running kinetics and lower limb kinematics of novice runners and, unsurprisingly, found that the majority of these runners presented with high initial loading rates when first tested. Interestingly, as these novice runners became more trained and experienced, they did not present with any changes in ILR regardless of footwear. Assuming the validity of the link between ILR and running related injury, the risk of injury in these runners remained heightened after the 12-week intervention.

Since running in footwear with varying cushioning properties therefore has either little or no clinically significant influence on ILR, it is important to consider what interventions a clinician may implement to modify ILR to potentially minimise injury risk.

Crowell and Davis examined the efficacy of a gait retraining programme aimed at reducing lower extremity loading during running in trained runners. This programme included real-time visual feedback of ILR, where participants were instructed to “run softer” in an attempt to

reduce tibial acceleration (a proxy for ILR) by 50% of their baseline values. The programme consisted of eight training sessions, where real-time visual feedback was provided for the entirety of the first four sessions, and then gradually reduced over the remaining four sessions. Follow up measurements were taken after the programme and one month after completion of the programme (Crowell & Davis 2011a).

The duration of the intervention, definition of ILR and methodology used to calculate ILR in the Crowell and Davis study was similar to the duration, ILR definition and methodology used in the present study, allowing for comparisons of results. The participants of these two studies differed since the Crowell and Davis study used trained runners who presented with high baseline ILR values, whilst the present study assessed novice runners, regardless of their baseline ILR. Below is a comparison of changes in ILR from baseline to post-intervention, and their effect sizes (ES) between the present study (RC - reduced cushioning; and TC – traditionally cushioned) and the study conducted by Crowell and Davis (GR – gait retraining).

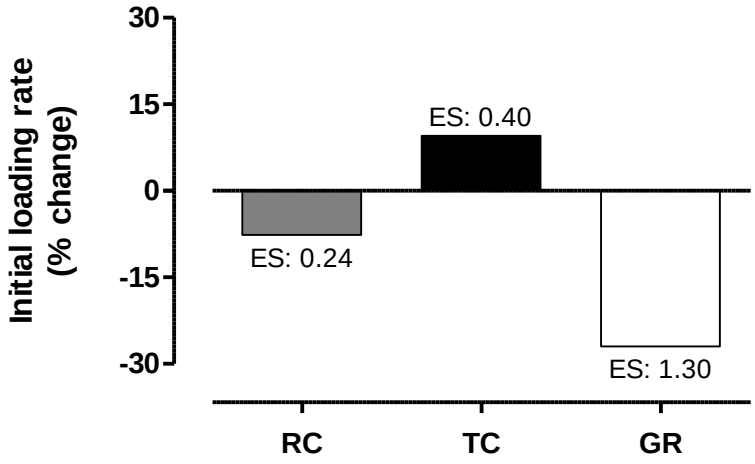


Figure 7.1: Change in initial loading (ILR) rate from baseline to post-intervention between the reduced cushioned (RC) group, traditionally cushioned (TC) group and the participants from the gait retraining (GR) study conducted by Crowell and Davis (Crowell & Davis, 2011). Cohen's effect sizes (ES) are reported for the change in ILR in each group. A negative value represents a reduction in ILR.

The efficacy of targeted gait retraining far exceeds that of footwear habituation alone (Figure 7.1), as the gait retraining intervention implemented by Crowell and Davis (2011) resulted in a 27% reduction in ILR after a one month follow-up, compared to the very small changes found in the present study that were achieved by means of footwear modification (RC = 7.6% reduction and TC = 9.6% increase). A study conducted by Tam et al. (2016) found that runners habituating to barefoot running over 8-weeks without gait advice presented with an 8% reduction in ILR (N. Tam et al. 2016). This is very similar to the reduction in ILR found within

the RC group in the present study, suggesting that footwear, or lack thereof, has limited potential to influence ILR. This finding emphasizes the importance of running technique, rather than the reliance of external factors such as footwear to optimize running biomechanics and other variables related to injury risk.

A recent study found that verbal instruction on running technique, regardless of footwear specifications, was equally effective at promoting lower limb kinematics associated with a FFS pattern when compared to running in footwear with reduced cushioning without verbal instruction (Barcellona et al. 2017). This suggests that although biomechanical adaptation is possible with the use of footwear alone, it may also be achieved without the reliance of varying footwear specifications. Another study combined both gait retraining and footwear modification, and found that when used together, runners were able to reduce ILR to a greater extent than with gait retraining alone (Warne et al. 2016).

Based on these findings, it appears that more time should be spent focusing on improving running technique, which represents a more intrinsic form of adaptation, as it eliminates the reliance of specific footwear to determine running biomechanics. Unfortunately, gait retraining is often an inaccessible and costly endeavour, which is why the use of footwear has gained popularity. This is not to say that footwear specifications should be ignored. Injury risk factors may be reduced to a greater extent when footwear modifications and gait retraining are implemented together, when compared to gait retraining alone.

7.2.4. Question Four

Are running biomechanics associated with injury outcomes, and what variables should clinicians be assessing?

The costly process of imaging and clinical diagnosis of injury presents two issues. Firstly, this is only implemented once injury has occurred, resulting in a runner having to take time off running. Secondly, it is often expensive which leads to many injured runners not receiving a formal diagnosis and subsequent rehabilitation advice, leaving them at heightened risk for future injury. This has prompted the need to better understand the interaction between measurable running biomechanical variables and the onset of injury, so that runners can be assessed and provided with running technique advice in the hope to prevent injury prior to its onset.

Two key biomechanical variables have been reported to have an evidence-based link to injury. These are foot strike pattern and initial loading rate. Although both these variables have not been found to be causative of injury, their association to injury allows for clinical insight and the potential prevention of future injury, especially in novice runners. In general, greater ILR values are linked to an increased risk in running related injury, particularly bone stress injuries. Foot strike pattern, however, represents a more categorical interaction where a RFS pattern has been associated with greater risk of knee and impact related injuries and a FFS pattern with calf strains, Achilles tendinopathies and metatarsal stress fractures.

This study found that greater ILR values were associated with a greater risk of bone oedema. Moreover, runners who landed with a RFS pattern, despite having limited cushioning properties in their shoes, did not present with ILR values that were greater than runners who landed with a FFS pattern. This contradicts previous literature, however, these runners presented with lower limb kinematic strategies that potentially countered the impact forces associated with landing with a RFS pattern with limited cushioning.

The lack of runners who adopted a FFS pattern limited analysis of biomechanical variables and injury outcomes between foot strike patterns. However, runners wearing footwear with reduced cushioning who reduced their FSA, despite still landing with a RFS pattern, presented with a reduction in vGRF. This may represent a reduction in accumulative load, given the unchanged spatiotemporal variables amongst these runners.

Overall, running biomechanical variables have little predictive value for predicting injury outcome. The highly individual response of novice runners to a 12-week running intervention, coupled with the effects of wearing footwear with differing cushioning properties suggests that each runner should be assessed individually, and injury prevention and biomechanical advice should be prescribed based on the merits of each case.

7.2.5. Question Five

Is a conservative and progressive running programme effective at reducing injury risk in novice runners, and how does footwear influence this risk?

The 12-week running programme used in this dissertation yielded a running injury prevalence of 11.1 %, with the incidence of injury (5.6 injuries/1000 hours) that was three to five fold lower than a previously published meta-analysis (Videbæk et al. 2015) and a studies of similar design (Buist et al. 2008; Kluitenberg et al. 2015), respectively. Reasons for successful

outcome of this programme may be due to the time spent running in the first week, which suggests that the more conservative the programme in the first week, the more successful the programme. Additionally, the limitation of BMI to less than 27 kg/m^2 may have resulted in lower injury rates.

No differences in injury incidence was found between runners wearing footwear with reduced cushioning and those wearing traditionally cushioned footwear. Moreover, the conservative and progressive running programme was effective at preventing any incidences of bone stress fractures, which is a common injury, especially in runners wearing footwear with reduced cushioning (Ridge et al., 2013).

Prevalence of significant pain or discomfort was similar between the reduced cushioning and traditionally cushioned groups, with nearly half of all novice runners experiencing pain or discomfort at least once during the 12-week intervention. However, runners wearing footwear with reduced cushioning were likely to experience pain or discomfort more frequently or for longer periods of duration, which might limit adherence to running. These findings hold important clinical implications, as pain or discomfort is likely to be experienced in novice runners, and clinicians should manage the expectations of novice runners as they increase their load. Additionally, clinicians should advise their patients to acknowledge any pain or discomfort as these symptoms are likely, however, these symptoms are not always indicative of injury and may be alleviated by reducing training load.

7.3) Additional Questions

7.3.1. Question Six

What structural specifications are important to consider when prescribing footwear?

Runners are often influenced by footwear aesthetics, rather that structural specifications. Whilst footwear specialists and clinicians consider structural specifications when prescribing footwear, the effect of these specifications on a specific runner's biomechanics is often unknown. The primary purpose of offering footwear choices with varying specifications is to:

- promote comfort
- reduce injury risk
- improve performance
- or a combination of the three

Whilst the subjective nature of comfort renders it a simple yet key factor, structural specifications that influence injury risk and performance require evidence of favourable

biomechanical or physiological adaptations to support their prescription, respectively. Since the focus of this dissertation is on injury prevention and running biomechanics, the effect of various structural specifications on biomechanical outcomes has been assessed. Only structural specifications that are easily accessible to footwear specialists, clinicians and runners were considered. More importantly, for the purpose of biomechanical comparison, only neutral footwear was considered since they often comprise of continuous structural specifications, rather than the categorical nature of stability footwear. For example, mass of a shoe represents continuous data, whereas a stability shoe either has motion control devices or it does not.

Based on these criteria, we found that shoe mass, heel-toe differential and heel stack height are important factors to consider when prescribing footwear as they potentially influence both biomechanics and risk of injury. Further, these specifications are commonly reported by footwear manufacturers and easily understood by runners. More specifically, we noted that both heel-toe differential and heel stack height are positively correlated to foot strike angle (FSA). Although flexibility is also reported to be an important specification, its measurement is complex and is rarely reported by manufactures. In addition, there is limited research studying the biomechanical effects of footwear flexibility, thus making it difficult to incorporate in our biomechanical outcome-based findings.

A better understanding of the effects of structural specifications of footwear on biomechanics and injury risk has resulted in the categorization of footwear. Marketed categories include:

- minimalist shoes
- traditionally cushioned shoes
- racing flats
- maximalist shoes

This dissertation aimed to determine the influence of footwear with reduced cushioning, or minimalist footwear, on running biomechanics and injury risk. However, the lack of an objective definition for minimalist shoes resulted in large discrepancies of conclusions in the literature regarding the biomechanical implications of minimalist footwear. Therefore, prior to conducting the studies of this dissertation, we needed to objectively define minimalist footwear using a biomechanical outcome-based approach (Chapter Three: Part One). We concluded that a shoe may only be considered minimalist if it contains a highly flexible sole and upper that weighs 200g or less, has a heel stack height of 20 mm or less and a heel-toe differential of 7 mm or less.

We then integrated this new objective definition with an already established Minimalist Index, which allows for the comparison of different footwear by rating their degree of minimalism on a scale of 0 – 100 (with 100 being a shoe that highly minimalist). We concluded that a shoe may be categorized as minimalist if it scores a rating of 72 or greater on the minimalist index (Chapter Three: Part Two).

7.3.2. Question Seven

What factors should a clinician consider when prescribing injury prevention advice to novice runners?

Previous injury has been suggested as a common risk factor for future injuries, highlighting the need to promote injury prevention, rather than injury rehabilitation (Hespanhol Junior et al. 2013; Nielsen et al. 2013). Whilst clinically relevant, this approach is often impractical since many runners only seek clinical advice after the onset of injury. The aim of this dissertation was to assess the clinical and biomechanical adaptations that occur in a group of novice runners as they embark on a 12-week running programme. Additionally, the effect of footwear, with focus on minimalist footwear, was assessed. The intention was to highlight key clinical and biomechanical factors that account for the high prevalence of injury in novice runners.

Based on the findings of this dissertation, we propose a hierarchy of clinical intervention importance whereby clinicians can assess certain variables and prescribe information based on the efficacy of running injury prevention modalities. The order of importance of broad categories that we propose clinicians to consider when prescribing injury prevention advice to novice runners is shown below, from most important/influential to least important/influential:

Training structure → running biomechanics → footwear prescription

Whilst all these categories play an important role in injury prevention, there may be benefit in initially assessing and effecting change in training structure, rather than only relying on footwear prescription. Reasons for this are further explained, using findings from this dissertation and other literature.

7.3.2.1. Training Structure

The prevalence of running injury in novice runners following the conservative and supervised 12-week running intervention used in this study was 11.1%, whilst the incidence of injury was 5.6 injuries per 1000 hours of running. These values are two to three-fold lower than what has

been reported in studies of similar design (Kluitenberg et al. 2015; Buist et al. 2008). The use of a run/walk system coupled with good supervision and a very conservative and progressive training structure when prescribing training programmes to novice runners may account for these positive results.

Clinicians must also be made aware that pain or discomfort is likely to be experienced by almost half (43 %) of all novice runners as they progress their mileage, however, these symptoms are unlikely to result in a running related injury if a well-structured and conservative training programme is followed.

7.3.2.2. Running Biomechanics

The identification of risk factors for injury, prior to the onset of injury remains an important process of reducing the high incidence of running related injuries, especially in novice runners. However, the complex and multifactorial nature of injury renders this process difficult. With this in mind, this study found that an initial loading rate of 72 BW/s or greater was associated with an increased likelihood of developing bone oedema in the distal tibia, fibula, ankle and foot. No other biomechanical factors were found to be significantly linked to running related injury.

Interestingly, pain or discomfort whilst running does not result in long-term biomechanical modifications suggesting that runners with these symptoms either do not modify their gait to alleviate the pain or discomfort, or that they revert to pre-symptom biomechanics once the pain or discomfort subsides. Given the causative association between gait and injury, this lack of biomechanical modification supports the link between previous injury and risk of future injury.

The variable effects of running biomechanics on injury risk make definitive conclusions difficult. However, this study found evidence to suggest that anthropometrical testing in novice runners prior to the initiation of a running programme is important since BMI was found to be positively correlated to running injury. Additionally, novice runners with greater fat mass and body fat percentage may require running technique advice in the form of increasing cadence, which was found to have beneficial implications on both ILR and vGRF.

7.3.2.3. Footwear Prescription

Finding the right shoes is often viewed as the first and most important step for novice runners as they start running. This is, in part, due to marketing strategies and the over-simplification of the effects of running footwear. Both cushioning, and lack thereof have been touted as effective strategies to prevent impact-related injuries in runners, such as bone oedema, which is a precursor for stress fractures. Whilst this study reported that 11.4 % of novice runners

who completed the 12-week running intervention showed signs of bone oedema, no differences were noted between runners wearing traditionally cushioned footwear and those wearing footwear with reduced cushioning.

Although biomechanical and clinical differences between runners wearing traditionally cushioned and those wearing reduced cushioned footwear were minimal, some differences were noted which may have important clinical significance. When running in footwear with reduced cushioning, ankle and knee kinematics have a direct influence on vGRF, suggesting that the lack of cushioning requires force attenuation strategies to be governed by lower limb joint compliance and control. In contrast, running in traditionally cushioned footwear allows for greater lower limb joint kinematic variation, without affecting vGRF, suggesting that the cushioning provided by the midsole allows for greater biomechanical variability without negative kinetic implications.

Additionally, this study found that reducing FSA whilst habituating to footwear with reduced cushioning resulted in a reduction in vGRF without spatiotemporal adaptations, thus lessening accumulative load. These findings highlight the importance of gait adaptation for minimalist footwear to be effective.

Based on these findings and the proposed hierarchy of clinical intervention importance, clinicians should prioritise training structure with the goal to prescribe a conservative training programme which allows novice runners to habituate to the unfamiliar and repetitive forces of running. Given a well-structed training programme, the assessment and modification of running biomechanics in the form of gait training or retraining may be an effective method of injury prevention. Only once training structure and running biomechanics have been assessed and optimized, should specific running footwear be prescribed to minimise injury risk. Specific footwear should be prescribed to complement the runner's current biomechanics, rather than attempting to change these biomechanics as footwear has little effect of biomechanical modification without the input of gait retraining.

The clinical application of this proposed hierarchy of clinical intervention importance suggests that improving training structure may be the most effective method of preventing injury in novice runners. Only once training structure has been assessed and improved, should running biomechanics be assessed and modified with the final step being footwear prescription based on these running biomechanics. Results from this dissertation, in combination with current literature, advocate for this order of importance since footwear has little influence on running biomechanics, whereas gait retraining proves to be more effective. Furthermore, whilst poor biomechanics have been linked to running related injury, the implementation of a structured, conservative and supervised training programme may mitigate the influence of poor

biomechanics or incorrect footwear prescription as it allows novice runners to become accustomed to the repetitive forces associated with running.

7.3.3. Question Eight

Should minimalist shoes be prescribed to prevent injury?

The popularity of minimalist shoes surged due to manufacturers' claims that they are effective at reducing the risk of sustaining a running related injury. This statement, however, originated from inconclusive and tenuous scientific findings (Goss & Gross 2012; Willy & Davis 2014). The lack of supporting evidence for the use of these shoes resulted in many runners experiencing injuries related to the minimal support and cushioning offered by minimalist footwear (Cauthon et al. 2013).

The premise of minimalist footwear is to promote biomechanics similar to that of running barefoot, whist still offering enough plantar protection. Some of these proposed biomechanical changes include the adoption of a forefoot strike pattern, or at least a reduction in foot strike angle, increased lower limb compliance and an increase in cadence, with the overall effect of reducing ILR which has been linked to several running related injuries.

This study found that habituating to footwear with reduced cushioning does not result in the adoption of a forefoot strike pattern. In fact, only one of the 20 participants presented with a transition from a rearfoot strike to a forefoot strike pattern. Although this complete foot strike pattern transition was uncommon, participants wearing footwear with reduced cushioning were four times more likely to reduce their foot strike angle when compared to participants wearing traditionally cushioned footwear. This had important biomechanical implications, as runners wearing footwear with reduced cushioning who reduced their FSA, despite still landing with a RFS pattern, presented with a significant reduction in vGRF. Moreover, these runners did not present with any spatiotemporal variable changes, suggesting an overall reduction in accumulative load. Interestingly, this reduction in FSA only occurred in 70 % of runners wearing footwear with reduced cushioning, thus highlighting the biomechanical variability between individuals. A similar, but inverse pattern was noted in runners wearing traditionally cushioned footwear, where 62.5 % increased FSA over the 12-week intervention, however no kinetic changes were found. The isolation of this reduction in vGRF to only a portion of the reduced cushioned group suggests that it is the runner, rather than the footwear that is more likely to influence running biomechanics.

This study also found no differences in the number of participants reporting pain of discomfort between the two footwear groups. However, participants wearing footwear with reduced cushioning reported pain or discomfort more often than those wearing traditionally cushioned shoes. This was in part due to the proportion of participants wearing reduced cushioned footwear who presented with a rear foot strike pattern.

Limited biomechanical changes found within the runners wearing footwear with reduced cushioning, coupled with the previous findings whereby gait retraining was more effective than footwear habituation in affecting running biomechanics promote a holistic approach to footwear prescription. That is, the prescription of minimalist footwear may be an effective tool to promote biomechanical change, albeit subtle, however it must not be prescribed in isolation. Running technique advice must accompany minimalist footwear prescription to fully benefit the runner.

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The prescription of minimalist footwear therefore warrants caution since footwear with reduced cushioning is associated with frequent pain or discomfort and may only be beneficial given specific running biomechanics that are more likely to be achieved through gait retraining and not by the shoes themselves. Additionally, the lack of foot strike pattern transition in the runners wearing reduced cushioned footwear suggests that clinicians should first look at their patients' current running biomechanics and prescribe a shoe that best suits their needs. If biomechanical modification is required, the prescription of minimalist footwear should be used as a tool to promote change, alongside gait retraining.

Chapter Eight

Limitations and Future Studies

The design and complexity of this prospective study was important in determining key measurable and modifiable risk factors for injury in novice runners. Furthermore, the length of the study allowed for the better understanding of pain or discomfort experienced by novice runners and the progression of these symptoms to either biomechanical modification or running related injury.

8.1) Limitations

This study assessed various biomechanical and clinical variables as indicators of injury and was powered to find differences in these variables. The injury component, however, is underpowered, largely as a result of the success of the conservative 12-week programme, which only yielded 6 injuries (11.1 % of participants). As a result, the model we proposed can be assessed with sufficient power for the risk factor differences between groups, but not for the association between those risk factors and actual, real-world injury. Therefore, injury prevalence, incidence and other inferences between any variable and actual injury must be considered with caution, and instead the potential risk must be weighted more heavily in our theoretical model.

Secondly, the runners who dropped out of the 12-week intervention did not undergo post-intervention testing. This means that we were unable to determine whether these injured participants presented with bone oedema prior to dropping out. However, ILR and pain or discomfort measurements were known. This limitation allows only for the assumption that measured clinical and biomechanical variables were responsible or played a role in the onset of injury.

Finally, this dissertation referred to minimalist footwear as footwear with reduced cushioning. Reasons for this arise from logistical issues. At the time of the study design, adidas agreed to provide the participants in the reduced cushioned group with adidas Gazelles, their version of a minimalist shoe. The first intake of participants (n = 6) received these shoes, however, prior to the initiation of the intervention for the second intake, adidas announced that they had discontinued this shoe. Participants in the reduced cushioned group for the second and third intake were given either adidas Gazelles (which we sourced from local running stores) or adidas Adizero Feather Prime (provided by adidas). Fortunately, the structural specifications of these shoes were very similar (see methods in Chapter Two), and both shoes were considered as minimalist based on the objective definition offered in Chapter Three: Part One.

Additionally, footwear groups were not matched for gender. This was due to limited availability of shoe sizes provided by adidas.

8.2) Future studies

Although studies have been published on the comparison between gait retraining and footwear habituation, there is still a need for long-term prospective studies. Ideally, a study that follows the design of this 12-week intervention comprising of groups including traditionally cushioned and reduced cushioned footwear without gait advice, and traditionally cushioned and reduced cushioned with gait advice. Additionally, the inclusion of frontal plane kinematics as well as antero-posterior kinetics would provide further insight. This will allow for a better understanding of the effects and interaction between footwear habituation and gait retraining.

Considering the hierarchy of clinical intervention importance proposed in the previous chapter (Chapter Seven), studies should aim to assess the effect of these three categories on injury risk, as well as the interaction between these categories. However, this study design would be highly complex and would need to recruit many participants due to the number of variables.

The variability of running biomechanics continues to limit research and findings. The grouping of participants into biomechanical categories such as foot strike pattern, low and high cadence or low and high initial loading rates could improve the applicability of findings.

Whilst the complexity and multifactorial nature of running related injury requires study designs that are equally complex, but with highly controlled variables, this study both answers important questions about the topic, and raises new questions that could further improve our understanding of how novice runners learn to run and the effect that footwear has in the process.

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