Barefoot vs Running shoes – Comparing 20m sprint performance, spatiotemporal variables and foot strike patterns in schoolchildren in the Western Cape

by

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DECLARATION

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SUMMARY

A short anaerobic sprint test such as a 20m sprint test forms part of many fitness test batteries used by sports teams and in schools during physical education classes for fitness testing. Some of these short sprint tests are done on a hard running surface and some of the protocols do not specify or standardise the type of footwear that should be worn and participants have a choice to sprint either barefoot (BF) or in running shoes. Similarly, many children and adolescents in South African schools participate in athletics competitions that are sometimes held on synthetic athletics tracks and since most children and adolescents do not own spikes, they have to choose between competing BF or in their running shoes. In some countries such as South Africa, which has a BF culture, sprinting BF is common. Currently, there is limited research available to answer whether it is faster to sprint BF or shod.

The aim of the current study was to determine the acute effects of sprinting BF and in running shoes on 10m and 20m sprint performance, spatiotemporal variables and foot strike pattern (FSP). 115 Girls and 161 boys (N=276) aged 8-19 years from randomly selected schools in the Western Cape Province were recruited for the study. Children performed two 20m maximal effort sprints from a standing start on a hard running surface in both a BF and running shoes condition in random order. For each sprint, 10m and 20m sprint times, step frequency (StepF), stride length (SL), flight time (FT), ground contact time (GCT) and swing time (SwT) were measured and FSP was determined. Sprint times were measured with electronic photocells (Brower Timing Systems, Salt Lake City, UT) and spatiotemporal variables were measured with the OptoGait system (Microgate S.r.I, Bolzano, Italy). High-speed video footage was taken with a GoPro camera (GoPro HD Hero 4, GoPro Inc., San Mateo, California, USA) at 240Hz and was analysed with video analysis software (Kinovea 0.8.15) to determine FSPs. The data of the fastest sprint in each footwear condition was used for further statistical analysis.

Statistically significant differences as well as small to medium practically significant differences were found between the BF and shod conditions for children and adolescents' 10m and 20m sprint performance and all the measured spatiotemporal variables. When BF, children and adolescents' 10m and 20m sprint performances

were significantly faster (p<0.001) but with only small effect sizes (d=0.24 and d=0.25 respectively). The faster sprint performances when BF were due to a significantly higher StepF (p<0.001) with a medium effect size (d=0.42) despite being accompanied by a significantly shorter SL (p<0.001) with a medium effect size (d=0.73). The significantly higher StepF when BF was due to a significantly shorter FT (p=0.022) with a small effect size (d=0.16), a significantly shorter GCT (p<0.001) with a medium effect size (d=0.69) and a significantly shorter SwT (p<0.001) with a medium effect size (d=0.56). All differences in sprint performance and spatiotemporal variables were due to the shoe mass effect and not due to FSP differences caused by the footwear effect. Changing from the shod to the BF condition caused a significant decrease in the occurrence of a rearfoot strike (RFS) from 57% to 27% and a significant increase in the occurrence of a forefoot-/midfoot strike (FFS/MFS) from 43% to 73% (p<0.001). The shod condition, therefore, encouraged a significantly higher rate of RFS and the BF condition a significantly higher rate of FFS/MFS.

In conclusion, changing from running shoes to BF has a significant acute effect on short anaerobic sprint performance, spatiotemporal variables and FSPs of school-aged children. Sprinting BF is only marginally faster than sprinting in running shoes over 10m and 20m but this may potentially only be applicable to habitually BF children and adolescents. Sprinting BF or in running shoes is, therefore, almost the same speed and children and adolescents can choose either footwear condition for sprint tests of fitness batteries and for athletics competitions held on synthetic athletics tracks. Caution should be taken when acutely changing to sprinting BF since it increases the risk of plantar surface injuries.

Key words: Barefoot, sprint performance, spatiotemporal variables, foot strike pattern, kinematics, children, adolescent, pre-adolescent, biomechanics, gait.

OPSOMMING

‘n Kort anaërobiese naellooptoets soos die 20m naellooptoets vorm deel van baie toetsbatterye wat vir fiksheid gedurende liggaamlike opvoedingsklasse en by sportspanne gedoen word. Sommige van hierdie naellooptoetse word op harde oppervlaktes gedoen. Sommige protokolle spesifiseer of standaardiseer nie met watter tipe skoene gehardloop moet word nie en het deelnemers die keuse om kaalvoet of met skoene te hardloop. Baie kinders en adolessente in Suid Afrikaanse skole neem deel aan atletiekkompetisies wat dikwels op sintetiese bane gehou word. Aangesien die meeste kinders en adolessente nie hul eie spykerskoene het nie, moet hulle kies om kaalvoet of in hul eie hardloopskoene te hardloop. In sommige lande soos Suid Afrika, wat ‘n kaalvoetkultuur het, is naellope kaalvoet algemeen. Daar is tans beperkte navorsing beskikbaar om aan te dui of dit vinniger is om kaalvoet of in hardloopskoene te nael.

Die doel van die huidige studie was om te bepaal wat die akute effek van ‘n naelloop kaalvoet (KV) en met sportskoene op 10m en 20m naellooprestasie, tyd-ruimtelike veranderlikes en voetneersitpatrone was. 115 Meisies en 161 seuns (N=276) tussen die ouderdom 8 tot 19 jaar is genader uit lukraak verkose skole in die Wes-Kaap Provinsie. Kinders het twee 20m maksimale naellope vanuit ‘n staande wegspring op ‘n harde oppervlakte gehardloop, in beide die KV en skoenkondisie. Vir elke naelloop is die tye oor 10m en 20m geneem, en treefrekwensie (TF), treelengte (TL), vlugtyd (VT), grondkontaktyd (GKT) en swaaityd (ST) gemeet en is die voetneersitpatrone bepaal. Naellooptye is bepaal met gebruik van elektroniese spoedselle (Brower Timing Systems, Salt Lake City, UT). Tyd-ruimtelike veranderlikes is met behulp van die OptoGait sisteem gemeet (Microgate S.r.I, Bolzano, Italië). Hoë spoed videomateriaal was teen 240Hz geneem met ‘n GoPro kamera (GoPro HD Hero 4, GoPro Inc., San Mateo, Kalifornië, VSA) en is ontleed met video analise sagteware (Kinovea 0.8.15) om die voetneersitpatrone te bepaal. Die data van die vinnigste naellooptyd vir kaalvoet en met skoene is gebruik vir verdere statistiese analise.

Statisties beduidende verskille, asook klein tot medium prakties beduidende verskille, is gevind tussen die KV en skoenkondisies vir kinders en adolessente se 10m en 20m naellooptye en al die tyd-ruimtelike veranderlikes. Wanneer kaalvoet, het die kinders en adolessente beduidend vinniger ($p<0.001$) in die 10m en 20m gehardloop, maar met slegs 'n klein effekgrootte ($d=0.24$ en $d=0.25$ onderskeidelik). Dit was as gevolg van 'n beduidend hoër TF ($p<0.001$) en medium effekgrootte ($d=0.42$) ten spyte van 'n beduidend ($p<0.001$) en medium effekgrootte ($d=0.73$) korter TL in die kaalvoetkondisie. Die beduidend hoër TF wanneer kaalvoet was as gevolg van beduidend korter VT ($p=0.022$) en klein effekgrootte ($d=0.16$), 'n beduidend korter GKT ($p<0.001$) en medium effekgrootte ($d=0.69$) en 'n beduidend korter ST ($p<0.001$) (medium effekgrootte, $d=0.56$). Alle verskille in naellooprestasie en tyd-ruimtelike veranderlikes was as gevolg van die massa van die skoene en nie as gevolg van veranderings in VSP wat deur die skoenkondisies veroorsaak is nie. Verandering van skoene na KV het 'n beduidende laer voorkoms van hakslag hardlooppatrone meegebring vanaf 57% tot 27% en 'n beduidende toename in die voorkoms van voorvoet-/middelvoet voetslag (VV/MV) van 43% na 73% ($p<0.001$). Die skoenkondisie het dus 'n beduidende hoër voorkoms van agtervoetneersit tot gevolg gehad en die KV kondisie 'n beduidende hoër voorkoms van voorvoet/midvoetneersit gehad.

Skoene het 'n beduidende akute effek op kort anaërobiese naellooprestasie, tyd-ruimtelike veranderlikes en voetneersitpatrone by skoolkinders. Kaalvoetnaellope is effens vinniger as skoene oor 10m en 20m, maar dit kan potensieel net van toepassing wees op kinders en adolessente wat gewoond is aan kaalvoet loop. Om KV of in hardloopskoene te nael is bykans dieselfde en kan kinders kies waarmee hulle getoets wil word of hardloop op sintetiese oppervlaktes. Versigtigheid moet aan die dag gelê word by akute oorskakeling van skoene na KV aangesien die risiko van beserings aan die plantaaroppervlaktes kan verhoog.

Sleutelwoorde: kaalvoet, naellooprestasie, tyd-ruimtelike veranderlikes, voetneersitpatrone, kinematika, kinders, adolossente, biomeganika, loopgang

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Proverbs 3:5-6 "Trust in the LORD with all your heart, and do not lean on your own understanding. In all your ways acknowledge him, and he will make straight your paths."

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KEY TERMS

Footwear – A person's footwear condition. Can refer to a barefoot or shod condition**.**

Barefoot – Wearing no shoes, flip-flops or socks.

Sports shoes – Any shoe primarily designed for sports or other forms of physical exercise and is appropriate to use on a hard running surface. Includes regular running shoes, trail running shoes, tennis shoes and indoor sports shoes such as indoor soccer shoes.

Children – Boys and girls aged 1-9 years old. This age range for children was chosen based on the cut-offs of the World Health Organisation (WHO).

Adolescents – Boys and girls aged 10-19. This age range for adolescents was chosen based on the cut-offs of the World Health Organisation (WHO).

Running – Sub-maximal running like jogging.

Sprinting – Running at maximal effort and includes both the acceleration and top speed periods of a sprint.

Good back side mechanics – A sprinting technique where the knee and the hip joints of the swing leg flex together soon after toe-off to bring the heel close to the gluteus maximus as the swing leg is swung forwards.

Poor back side mechanics – A sprinting technique where flexion in the knee joint of the swing leg is initially delayed after toe-off resulting in the heel swinging back high behind the body, following a large circular path as the swing leg is swung forward during the swing phase.

Recovery phase – The period of the swing phase when the swing leg is swung forwards, stretching from toe-off until peak hip flexion is reached.

Scissors like motion of the legs – When a sprinter's knees are moving towards one another in the sagittal plane.

Landing energy – The kinetic and potential energy of the body at foot strike.

Kinematic parameters of running:

Foot strike patterns were divided into three categories as done by Lieberman *et al*. (2010).

Rearfoot strike (RFS) – When the heel of the foot makes first contact with the ground.

Midfoot strike (MFS) – When the heel and the ball of the foot make contact with the ground at the same time.

Forefoot strike (FFS) – When the ball of the foot makes first contact with the ground.

Spatiotemporal variables of running:

Step frequency (StepF) – Number of steps per second where a step is the distance between the front most part of the foot (toe) of two subsequent feet (Microgate S.r.l., n.d.).

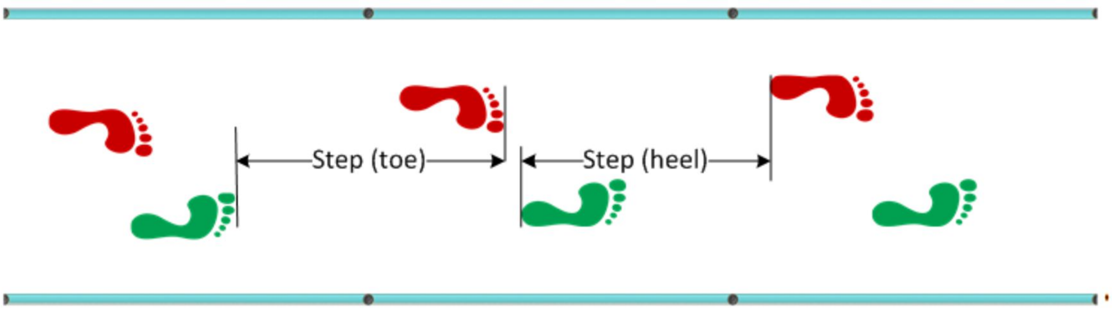

Figure 1.1. Illustration of step length (Microgate S.r.l., n.d.)

Stride length (SL) – Distance between the front most part of the foot (toe) of two subsequent steps of the same foot (Microgate S.r.l., n.d.).

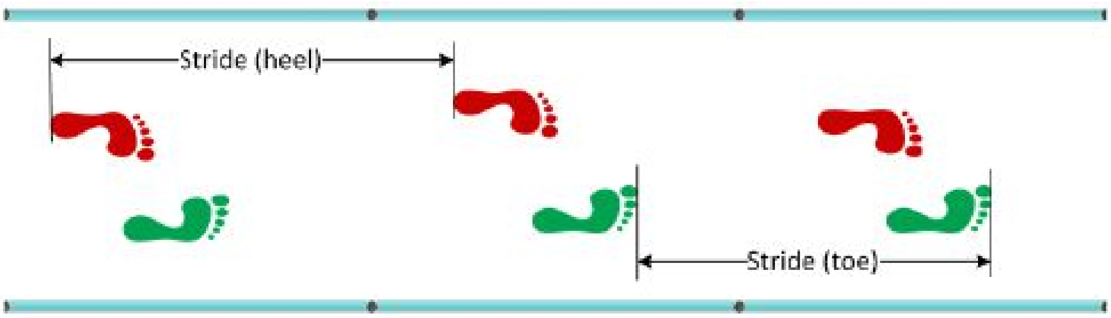

Figure 1.2. Illustration of stride length (Microgate S.r.l., n.d.)

LIST OF ABBREVIATIONS

α	Angular acceleration
BF	Barefoot
CoM	Centre of mass
COP	Centre of pressure
FFS	Forefoot strike
FSP	Foot strike pattern
FT	Flight time
GAS	Gastrocnemius
GCT	Ground contact time
GLU	Gluteus maximus
GRF	Ground reaction force
GRI	Ground reaction impulse
HAM	Hamstrings
I	Moment of inertia
k	Radius of gyration
m	Mass
MFS	Midfoot strike
REC	Rectus femoris
RFS	Rearfoot strike
ROM	Range of motion
SF	Stride frequency
SL	Stride length
StepF	Step frequency
StR	Stance phase reversal
SwT	Swing time
τ	Torque

CHAPTER ONE

INTRODUCTION

1.1. OVERVIEW OF LITERATURE

Many schoolchildren around the world participate in team sports such as rugby, soccer, field hockey, netball and basketball where running speed, and more specifically, acceleration is an important motor skill for performance. Maximal effort sprints in rugby union, Australian football and soccer often last 2s or less which equates to about 10m (Lockie *et al*., 2013b), highlighting the importance of acceleration in these sports. Agility is also an important skill in these sports and agility is dependent on acceleration since an athlete must be able to accelerate away from opponents to out manoeuvre them. Many schoolchildren around the world also participate in athletics where most of the events are either pure sprint events, such as the 100m-400m sprint and hurdle events, or events that largely rely on an athlete's sprinting ability, such as long jump, triple jump and pole vault. The acceleration period forms a significant part of a 100m race. Untrained and low level sprinters accelerating between 30-40m before reaching top speed (Delecluse *et al*., 1995 cited in Maćkała *et al*., 2015) and elite sprinters accelerating even longer, between 50-70m, before reaching top speed (Ae *et al*., 1992; Gajer *et al*., 1999, Morin *et al*., 2013). During long jump, triple jump and pole vault run-ups are usually less than 45m for senior athletes (Boland Athletics, n.d.:122,137,167) and, therefore, even shorter for children and adolescents. Running speed and more specifically, acceleration, is, therefore, also an important motor skill in many athletics events.

A short anaerobic sprint test such as a 20m sprint test forms part of many fitness test batteries used by sports teams and in schools during physical education classes for fitness testing (Safrit, 1995; Kremer *et al*., 2001; Whaley *et al*., 2006; Miller, 2012). Some of these short sprint tests are done on a hard running surface such as a handball court (Kremer *et al*., 2001) and some of the protocols do not specify or standardise the type of footwear that should be worn (Miller, 2012). When these tests are performed on a hard running surface, participants have a choice to sprint either barefoot or in running shoes since spikes cannot be used on these surfaces. Similarly, many children and adolescents in South African schools participate in athletics competitions (such as inter-house and inter-school competitions) that are sometimes held on synthetic athletics tracks and since most children and adolescents do not own spikes, they have to choose between competing barefoot or in their running shoes. In some countries, sprinting barefoot might not even be considered but in countries such as South Africa, which has a barefoot culture, sprinting barefoot is common.

Running shoes may be more comfortable to sprint in due to their cushioned heel which protects the foot from painful foot strikes on a hard running surface and may offer a performance advantage by potentially offering more traction, but on the other hand, they also add extra mass to the feet which could decrease sprint performance. Research has shown that running barefoot could potentially offer performance advantages to long distance running because a barefoot condition has no added mass to the feet (Frederick, 1984; Burkett *et al*., 1985; Divert *et al*., 2008; Squadrone & Gallozzi, 2009; Hanson *et al*., 2011) but limited research exist to illuminate whether sprinting barefoot might also offer a performance advantage. Only one study was found testing short anaerobic sprint performance in a barefoot and shod condition but their sample size was relatively small (Theophilos *et al*., 2014). The researchers reported no significant difference in 30m sprint performance of 33 adolescent athletes between a barefoot, running shoes and spikes condition. Besides (Theophilos *et al*., 2014), other studies have also investigated if added mass to the feet has a significant effect on short anaerobic sprinting performance (Bennett *et al*., 2009; Sterzing *et al*., 2009; Worobets *et al*., 2015). Worobets *et al*. (2015) found no significant difference in the 10m sprint performance of 20 recreational basketball players between an unweighted (331g/shoe) and a weighted (497g/shoe) basketball shoe condition (with a mass difference of 166g/shoe). Similarly, Sterzing *et al*. (2009) found no significant decrease in the time taken to complete a 26m running/cutting Slalom course when 20 adult amateur to sub-elite soccer players sprinted with a 70g rubber insole placed in a 200g Nike Mercurial Vapor II FG soccer boot. The differences in additional mass to the feet, however, might have been too small to see a significant difference in these studies. The difference in mass between a barefoot and running shoes condition would be a lot more (about 250g/foot) compared to the mass differences in the aforementioned studies. In contrast, Bennett *et al*. (2009) found significantly slower 40m sprint times when mass was added to the lower limbs. Added mass was 10% of individual segment mass and was evenly distributed about the radius of gyration of the thigh and shank of eight national representative adult male beach sprinters. The significant decrease in sprint performance was accompanied by an insignificant decrease in both stride length and stride frequency and an insignificant increase in both flight time and ground contact time.

Spatiotemporal variables may be used to explain any potential differences in sprinting performance between sprinting barefoot and sprinting in running shoes. Although spatiotemporal variables have extensively been studied while sprinting (Moravec *et al.*, 1988; Mero *et al.*, 1992; Ae *et al.*, 1992; Ito *et al.*, 2006; Mackala, 2007; Schache *et al.*, 2011; Dorn *et al.*, 2012; Krzysztof & Mero, 2013; Nagahara *et al.*, 2014), no existing research was found on the acute effects of changing from running shoes to barefoot on spatiotemporal variables while sprinting. However, many studies have measured the acute effects of changing from running shoes to barefoot on spatiotemporal variables while running. These are the only studies available to provide insight to what the possible acute effects of changing from running shoes to barefoot on spatiotemporal variables might be while sprinting. When runners run in a barefoot condition they tend to adapt a higher stride frequency and shorter stride length compared to a shod condition (de Wit *et al.*, 2000; Divert *et al.*, 2005; Squadrone & Gallozzi, 2009; Bonacci *et al.*, 2013; Mullen & Toby, 2013; Hollander *et al.*, 2014; Squadrone *et al.*, 2015). It is believed that this adaptation is made to prevent a painful foot strike since larger stride lengths have been shown to have larger impact forces (Thompson *et al.*, 2014). Furthermore, research has also examined the acute effects of changing from running shoes to barefoot on flight time and ground contact time, however, the findings on these two variables have been inconsistent (de Wit *et al.*, 2000; Divert *et al.*, 2005; Squadrone & Gallozzi, 2009; Squadrone *et al.*, 2015). Most of these studies done on running were done in adults with only a couple being done in children and adolescents (Mullen & Toby, 2013a; Hollander *et al.*, 2014).

Research has shown that changing from running shoes to barefoot has an acute effect on foot strike patterns during running. Modern running shoes have been shown to encourage a greater tendency to rearfoot strike and a barefoot condition has been shown to encourage a greater tendency to forefoot strike/midfoot strike (de Wit *et al.*, 2000; Squadrone & Gallozzi, 2009; Lieberman *et al.*, 2010; Hamill *et al.*, 2011; Mullen & Toby, 2013; Hollander *et al.*, 2014; Squadrone *et al.*, 2015). Only one study was found determining the acute effects of changing from running shoes to barefoot on foot strike patterns when sprinting. Theophilos *et al*. (2014) found that all 33 adolescent athletes used a forefoot strike when sprinting 30m in both a barefoot and running shoes condition.

The foot strike pattern used while sprinting could potentially influence sprinting performance and since shoes affect foot strike pattern, shoes could potentially have an acute effect on sprinting performance due to their acute effect on foot strike patterns. A forefoot strike might be a more efficient foot strike pattern for sprinting than a rearfoot strike since elite sprinters almost always use a forefoot strike when sprinting (Krell & Stefanyshyn, 2006; Toon *et al.*, 2009; Hébert-Losier *et al.*, 2015). On the other hand, the reason why elite sprinters usually forefoot strike could simply be due to their high running speed, since higher running speeds have been shown to be associated with a forefoot strike/midfoot strike. Mullen and Toby (2013) showed that participants were more likely to forefoot strike/midfoot strike when running at higher running speeds and to rearfoot strike at lower running speeds. Running shoes may also encourage a greater tendency to rearfoot strike when sprinting as seen when running and, therefore, could potentially be disadvantageous for sprinting performance.

Concerning the aforementioned literature, it is clear that there is currently a gap in existing literature concerning various aspects relating to the acute effects of changing from running shoes to barefoot while sprinting in children and adolescents. There is currently uncertainty about whether it is faster to sprint barefoot or in running shoes. Knowing which footwear condition is faster to sprint in would be useful information for the many children and adolescents around the world participating in sprint tests done on a hard surface where participants can choose to either sprint barefoot or in running shoes. This information would also be useful to children and adolescents who do not own spikes and compete in athletics competitions held on synthetic athletics tracks. Furthermore, the existing research on the acute effects of shoe mass on sprinting performance has mostly been done in adults and sample sizes have always been small ($N \leq 33$). There are also gaps in the research concerning the acute effects of changing from running shoes to barefoot on spatiotemporal variables and foot strike patterns while sprinting in children and adolescents.

1.2. AIMS OF THE STUDY

The primary aim of the current study was to determine the acute effects of changing from running shoes to barefoot on 10m and 20m sprint performance and spatiotemporal variables in schoolchildren in the Western Cape. The secondary aim was to determine the acute effects of changing from running shoes to barefoot on foot strike pattern during sprinting in schoolchildren in the Western Cape.

1.3. OBJECTIVES

The objectives of the current study were to:

1. Determine whether children and adolescents sprint faster when barefoot or in sports shoes.
2. Compare the following spatiotemporal variables between sprinting barefoot and in sports shoes: stride length (m), step frequency (Hz), ground contact time (s), flight time (s) and swing time (s).
3. Determine if a child or adolescent's shoe mass explains any possible differences in sprinting performance or spatiotemporal variables between sprinting barefoot and in sports shoes.
4. Determine the acute effects of changing from sports shoes to barefoot on the foot strike pattern distribution during the acceleration period of a maximal effort sprint.
5. Determine if a child or adolescent's foot strike pattern explains any possible differences in sprinting performance or spatiotemporal variables between sprinting barefoot and in sports shoes.

1.4. HYPOTHESES

The researchers hypothesised that:

1. There would be no significant difference in children and adolescents' sprinting performance between sprinting BF or in sports shoes.
2. Children and adolescents will have a significantly shorter SL, GCT, FT and SwT and a significantly higher StepF when sprinting barefoot compared to sprinting in sports shoes.
3. The mass of shoes would have no significant effect on children and adolescents' sprinting performance.
4. All participants would use a forefoot strike/midfoot strike when sprinting barefoot or in sports shoes.
5. Children and adolescents' foot strike pattern would not explain any possible differences in sprinting performance or spatiotemporal variables between sprinting barefoot and in sports shoes.

Although the hypotheses are listed here, they will be mentioned again throughout the theoretical background. This will be done to provide context to explain why these hypotheses were made.

1.5. VARIABLES

Dependent variables

Spatiotemporal variables: 10m and 20m sprint time (s), average speed over last 10m (m/s), stride length (m), step frequency (steps/s), ground contact time (s), flight time (s) and swing time (s).

Kinematic parameters: Foot strike pattern.

Independent variables

Type of footwear (barefoot/sports shoes), standing height, body mass, shoes mass.

1.6. OUTLINE OF THE THESIS

Chapter Two consists of the theoretical context for the current study and reviews literature, and related studies on the acute effects of barefoot vs running shoes on sprint performance, spatiotemporal variables and foot strike patterns in school aged children and adolescents. Furthermore, it provides insight into whether the mass of shoes and a child’s foot strike pattern might have a significant influence on sprinting performance. In Chapter Three, the specific methods for data collection are discussed. The results are presented in Chapter Four. Chapter Five contains a discussion of the main findings, as well as a conclusion to the current study, limitations of the study, and recommendations for future research.

The referencing style used in the current study is the “Harvard – Stellenbosch University” style from Mendeley Desktop’s reference library.

CHAPTER TWO

THEORETICAL BACKGROUND

2.1. INTRODUCTION

In this chapter, a biomechanical foundation to understand the fundamentals of sprinting will first be laid. Factors such as the different phases of the sprinting cycle and the link between the sprinting cycle and spatiotemporal variables will be explained. Furthermore, key biomechanical principles of angular kinetics of sprinting will be looked at. This will provide a platform to understand the biomechanics of sprinting before considering how changing from running shoes to barefoot (BF) might affect children and adolescents' sprinting performance.

Secondly, the potential acute effects of changing from running shoes to BF on sprinting performance, spatiotemporal variables and foot strike pattern (FSP) will be discussed. Furthermore, the potential acute effects of shoe mass and FSP on sprinting performance will be looked at.

In the following section, a biomechanical foundation will be laid to help understand sprinting mechanics. First, the different phases of the sprinting cycle will be looked at, followed by spatiotemporal variables often analysed in research. Furthermore, the close link between the sprinting cycle and spatiotemporal variables will be highlighted and lastly, key biomechanical principles of angular kinetics of sprinting will be discussed.

2.2. THE SPRINTING CYCLE

In this section, the sprinting cycle will be discussed in detail. The different phases that make up the sprinting cycle will be highlighted and explained to provide reference points of the sprinting cycle that will be referred to when the sprinting technique is discussed in a later section.

Sprinting is a cyclical movement where one cycle of the sprinting motion is known as a stride. A stride lasts from the moment the foot of the relevant leg initially touches the floor until the same foot touches the floor again. Figure 2.1 illustrates one full stride.

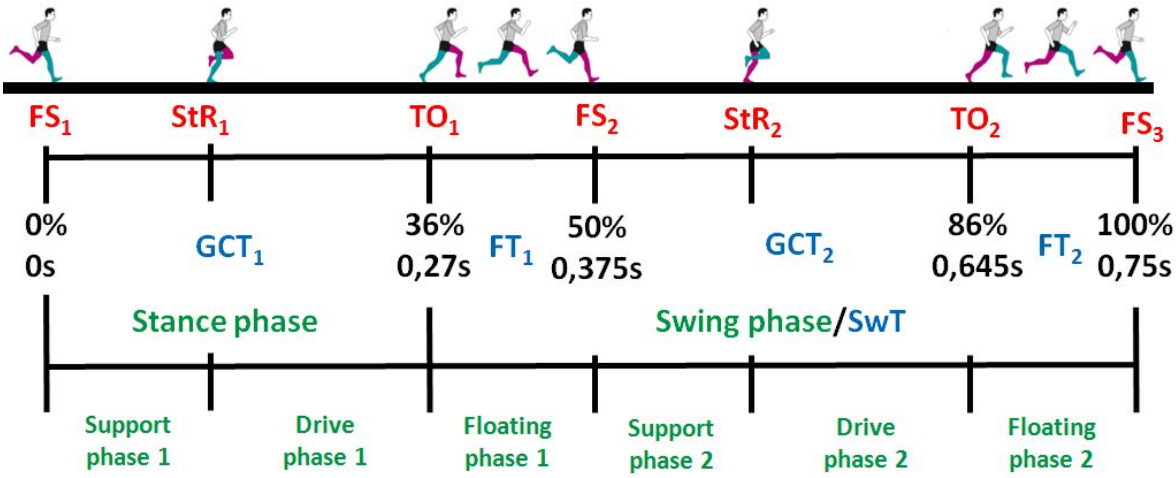

Figure 2.1. Illustration of a single stride in the sprint cycle, adapted from Figure 3 in Novacheck (1998) and Microgate S.r.l. (n.d.). The times and percentages were acquired by Novacheck (1998) from the Motion Analysis Lab at Gillette Children's Specialty Healthcare and the sprinting speed was 3.9m/s. The green text represents phases of the sprint cycle, the red text represents the reference points of the stance phase and the blue text represents spatiotemporal variables. The position of StR might not be accurate. Its approximate position is based on Figure 2d in Novacheck (1998). FS= Foot strike, StR= Stance phase reversal, TO= Toe-off, GCT= Ground contact time, FT= Flight time and SwT= Swing time.

The movement of a single leg can be divided into a stance and swing phase. During the stance phase the leg is in contact with the ground, and during the swing phase, the relevant leg is airborne and is moved forward to anticipate the next stance phase (Novacheck, 1998; Bosch & Klomp, 2005:122-123; Brown *et al*., 2012).

The stance phase may further be divided into the support phase and the drive phase (Novacheck, 1998; Fletcher, 2009). Fletcher (2009:20) defines the support and drive phase as follows:

> *"The Support Phase can be defined as the horizontal distance that the toe of the lead foot is forward of the Centre of Gravity (CoG), at the instant the sprinter lands; the Drive Phase is defined as the horizontal distance that the CoG is forward of the take off foot, at the instant the latter leaves the ground"*

Important reference points in the stance phase are foot strike (the point when first ground contact is made), stance phase reversal (StR) (the transition between the support phase and the drive phase), and toe-off (when the foot leaves the ground).

During the support phase, also known as stance phase absorption, the shock of impact is absorbed and the horizontal speed of the body’s centre of mass (CoM) decreases due to braking forces (Novacheck, 1998). During the drive phase, also known as stance phase generation, horizontal speed of the body's CoM increase as the body is propelled forward and upward and the body’s kinetic and potential energy is increased (Novacheck, 1998).

At toe-off, the sprinter’s relevant leg enters the swing phase, which lasts from toe-off until foot strike of that same leg. Each swing phase starts and ends with a floating phase (Bosch & Klomp, 2005:122-123) and has a stance phase of the contralateral leg in between the two floating phases (Weyand *et al.*, 2010). A floating/flight phase is defined as the phase when neither foot is in contact with the ground or the horizontal distance the body’s CoM travels while the runner is in the air (Fletcher, 2009).

The first floating phase immediately after toe-off concerns the motion of the relevant leg when it is the trailing leg and the second floating phase when it is the leading leg. In this paper the motion of the trailing leg as it is brought forward after toe-off, will be referred to as the recovery phase and lasts until peak hip flexion is reached. The recovery phase, therefore, lasts longer than the first floating phase. The second floating phase, which considers the motion of the swing leg when it is the leading leg, may be divided into two parts. During the first part, the tibia swings out as the knee extends and during the second part, the leg is brought down forcefully to the ground and the legs perform a scissors like motion.

Breaking the sprint cycle into different phases as shown above makes it easier to analyse the sprinting technique. Having different phases and reference points provides a framework to refer to when considering the motion at joints and the associated muscle contractions.

2.3. SPATIOTEMPORAL VARIABLES OF THE SPRINTING CYCLE

In this section, spatiotemporal variables often analysed in research will be explained along with their close link to the sprinting cycle.

Typical spatiotemporal variables in research are stride length (SL), stride frequency (SF), ground contact time (GCT), flight time (FT) and swing time (SwT). A SL is the distance from foot strike of one leg to a subsequent foot strike of that same leg and, therefore, involves both the stance and swing phase of that leg. SF is the amount of strides per second and depends on how fast the sprinting cycle is executed. GCT is the duration of the stance phase from foot strike to toe-off. FT is the duration of the floating phase from toe-off of one leg until the foot strike of the other leg (Hunter *et al*., 2004a) and represents the time it takes to reposition the leg in the air for the next step. SwT is the duration of the swing phase from toe-off until foot strike of the same leg and represents the time it takes to reposition the swing leg for the next stride. SwT is the sum of two FTs and one GCT. SL and SF has been of particular importance in research since they can be placed into a sprint formula where average speed (m/s) = SL (m/stride) x SF (strides/s) (Mero *et al*., 1992; Zatsiorsky, 2000; Hunter *et al*., 2004a; Fletcher, 2009). Therefore, differences in spatiotemporal can be used to explain differences in sprinting performance.

In summary, spatiotemporal variables have a close link with the sprinting cycle. Typical spatiotemporal variables in research are SL, SF, GCT, FT and SwT and differences in these variables can be used to explain differences in sprinting performance.

2.4. ANGULAR KINETICS OF SPRINTING

Understanding angular kinetics is a prerequisite to understand sprinting mechanics. In this section, key biomechanical principles such as torque, moment of inertia and angular acceleration will be looked at to help understand how the mass of running shoes might affect sprinting performance.

2.4.1. TORQUE

The human body has many joints around which movement takes place. Human movement occurs through muscles acting around these joints to produce torque. Torque is the angular equivalent to linear force and, therefore, may be thought of as a force that produces rotation (Hall, 2007:424). Torque (τ) is the product of force (F) and the force's moment arm ($d_\perp$), where the moment arm is the perpendicular distance from the axis of rotation to the force's line of action (Hall, 2007:424). The formula for toque is thus ($\tau = Fd_\perp$). Figure 2.2 illustrates how the main hip flexors (Iliopsoas) produce torque around the hip joint.

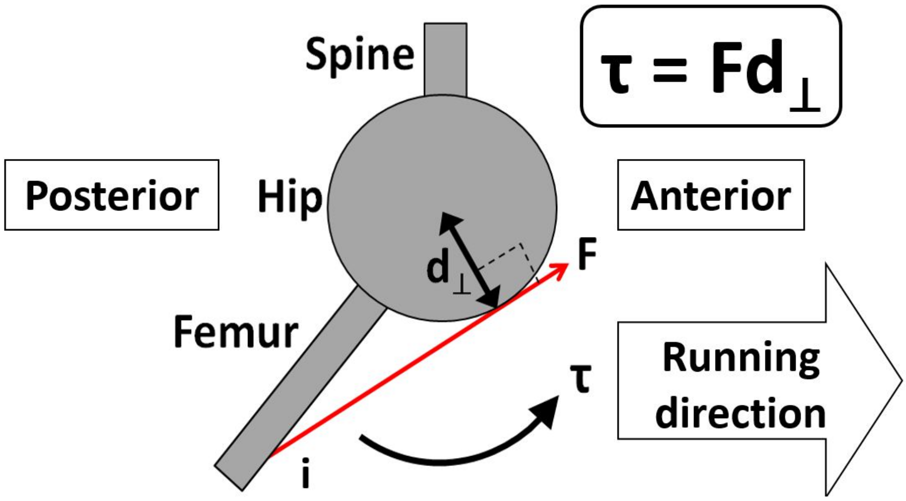

Figure 2.2. Illustration of how the Iliopsoas produces torque around the hip joint when the hip is extended. $d_\perp$ is the perpendicular distance from the axis of rotation to the line of action of the force F produced by the Iliopsoas. τ represents the resulting torque produced.

The Iliopsoas muscle group inserts on the femur at point i, shown in Figure 2.2 and pulls on the femur at an angle in the direction illustrated by F. The moment arm ($d_\perp$) is the perpendicular distance from the centre of the axis of rotation (the hip joint) to the line of action of the force. Similarly, Figure 2.3 represents the knee joint and illustrates how the knee extensors (F_1) and knee flexors (F_2) act around the knee joint.

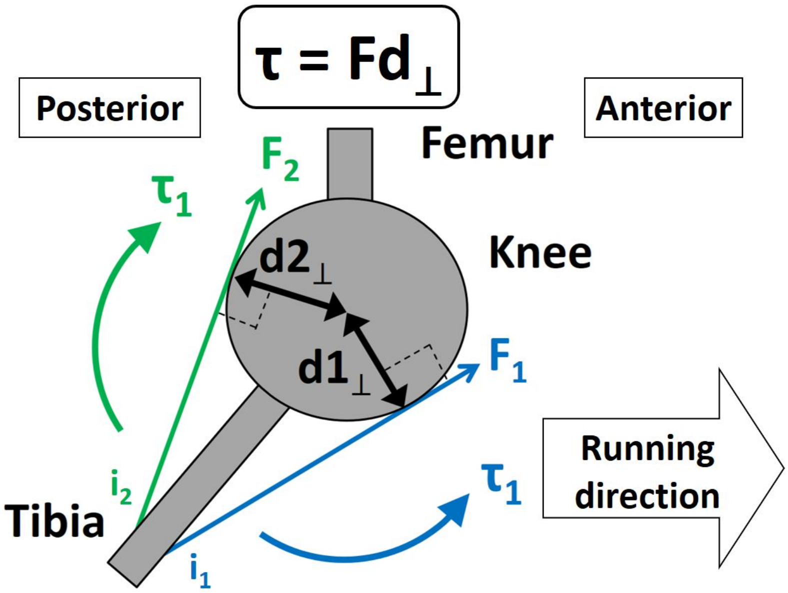

Figure 2.3. Illustration of how the knee flexors (green) and extensors (blue) can produce torque around the knee joint when the knee is flexed. $d1_{\perp}$ and $d2_{\perp}$ are the perpendicular distances from the axis of rotation (knee joint) to the lines of action of the forces F_1 and F_2 produced by the knee extensors and flexors respectively. τ_1 and τ_2 represent the resulting torques produced.

2.4.2. MOMENT OF INERTIA

When considering linear motion, inertia is the tendency of a body to resist acceleration. According to Newton's second law of motion, the greater an object's mass the greater its resistance to acceleration. Inertia of an object is, therefore, directly proportional to its mass (Hall, 2007:460).

When it comes to angular motion, the angular equivalent to inertia is the moment of inertia. Moment of inertia (I) may, therefore, be defined as the tendency of a body to resist angular acceleration (Hall, 2007:460). The formula for moment of inertia (I) = mass of the rotating body (m) x the radius of gyration squared (k^2) or ($I=mk^2$). Similar to inertia in linear motion, I is also directly proportional to m. k concerns the distribution of mass with respect to the axis of rotation. Hall (2007:462) defines k as "the distance from the axis of rotation to a point where the body's mass could be concentrated without altering its rotational characteristics".

Examples of how m and k affect I will now be looked at. Compare bat A and B in Figure 2.4. Both bats have the exact same dimensions but bat B has a larger mass than bat A. Since the dimensions of the bats are the same, the distribution of mass and, therefore, k is also the same. Looking at the formula $I=mk^2$, if m is greater I will be greater when k is constant. Bat B will, therefore, be more difficult to swing due to its higher mass and higher I.

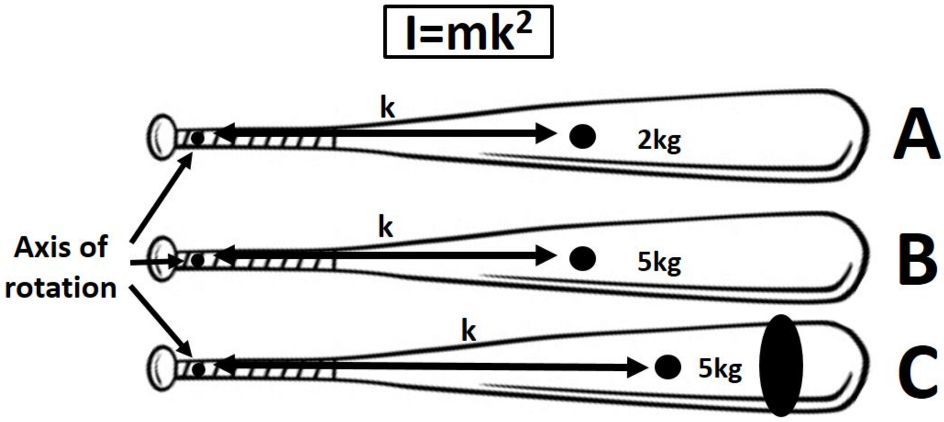

Figure 2.4. Three baseball bats are shown with equal dimensions but different masses. Bat A has a mass of 2kg and bat B a mass of 5kg. Bat C has a weight ring near the end of the bat and the combined mass of bat C and the weight ring is 5kg. As illustrated, the radius of gyration (k) is shifted further away from the axis of rotation in bat C.

To highlight the effect of k on I, bat B and C will be compared in Figure 2.4. The total mass of the rotating body (m) in these two bats are equal but k of bat C is longer than that of bat B. This is caused by the added weight ring that causes the distribution of mass to be further from the axis of rotation. Since k is squared, a small increase in k will result in a large increase in I. Bat C will, therefore, be more difficult to swing than bat B despite them being the same weight.

In Figure 2.4, the baseball bat is only one segment rotating around an axis of rotation but later in the theoretical background how the three leg segments (thigh, lower leg and foot) rotate around the hip and knee joints will be looked at. This concept of k increasing when mass is added near the end of the rotating segment will then be applied when looking at the effect shoe mass has on the moment of inertia of the leg during the swing leg.

2.4.3. ANGULAR ACCELERATION

In this section, how increasing the speed of the swing phase can increase sprinting performance will be discussed, followed by how the mass of running shoes could potentially affect sprinting performance.

During the swing phase of sprinting a sprinter should aim to bring the swing leg forward as fast as possible since a faster swing phase allows the sprinter to sprint faster. To achieve this, the sprinter needs to increase the angular acceleration (α) around the hip as much as possible. α Is proportional to the net torque (τ) around the joint and inversely proportional to the moment of inertia of the leg (I). Therefore, ($\alpha \propto \tau / I$). α Can be increased if τ is increased or I is decreased (Blazevich, 2007:71-87).

Figure 2.2 will be used as a visual illustration for the following explanation. During the recovery phase, hip flexion occurs due to τ produced by the iliopsoas muscles around the hip joint. To increase τ either F or $d_{\perp}$ needs to be increased. $d_{\perp}$ cannot be changed due to anatomical reasons and F cannot be further increased since it is assumed that muscles are already contracting with maximal force during maximal effort sprinting. It is, therefore, not possible to increase α by increasing τ during maximal effort sprinting.

However, α can be increased by decreasing I with good sprinting mechanics. The human leg consists of three segments rotating around the hip as its axis of rotation. The three segments are the thigh, lower leg (shank) and foot. The three segments all have different m-values and Figure 2.5 illustrates how they also have different k-values. The resultant I around the hip is the sum of the three segments' moments of inertia ($I=\sum mk^2$). A small decrease in the k values will result in a large decrease in I and, therefore, a large increase in α because k is squared.

During the recovery phase, a sprinter can largely and rapidly decrease the k values by simultaneously flexing the hip and knee joints to bring the heel as close to the gluteus maximus (GLU) as possible. Compare the lengths of k_1, k_2 and k_3 when the leg is straight (Figure 2.5 B) to when it is bent (Figure 2.5 A). Elite sprinters minimise their k values during the recovery phase by bringing the heel as close to the GLU as possible, enabling them to have a rapid recovery and swing phase. The faster swing phase allows a higher SF and a better sprinting performance. This sprinting technique, where the heel is brought close to the GLU will be referred to as good back side mechanics and is explained in more detail in appendix eleven (11.4.2.1).

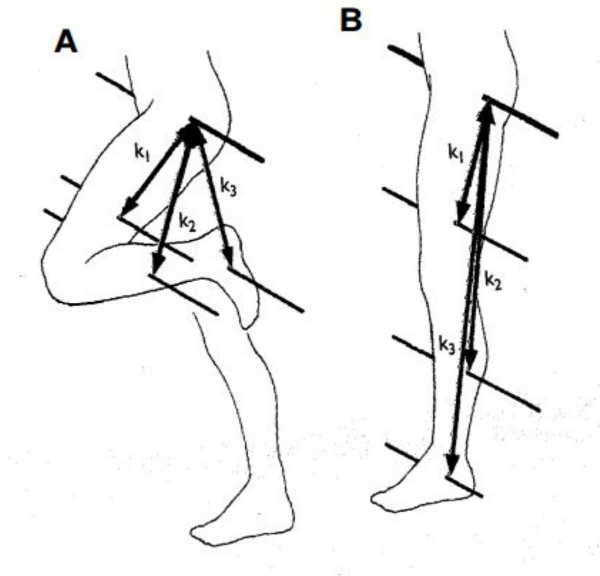

Figure 2.5. Illustration of how the moment of inertia of the leg can be decreased by bringing the heel to the gluteus maximus. A) Decreased moment of inertia. B) Increased moment of inertia. (Fletcher n.d.).

The mass of running shoes could potentially affect sprinting performance. Wearing running shoes may significantly decrease the speed of the entire swing phase. Wearing running shoes add mass to the feet and increases the moment of inertia (I) of the leg in two ways. Firstly, added mass to the feet would increase m in the formula $I=mk^2$. Secondly, the leg is a very long moment arm and wearing running shoes result in added mass to the very end of this moment arm. This will result in the distribution of mass to be further away from the hip and knee joints and, therefore, increase k as illustrated in Figure 2.6. Figure 2.6 illustrates how k-values about the hip and knee joint increase when running shoes are worn (compared to a BF condition). Since k is squared, a small increase will largely increase I and, therefore, largely decrease α around the hip and knee joints.

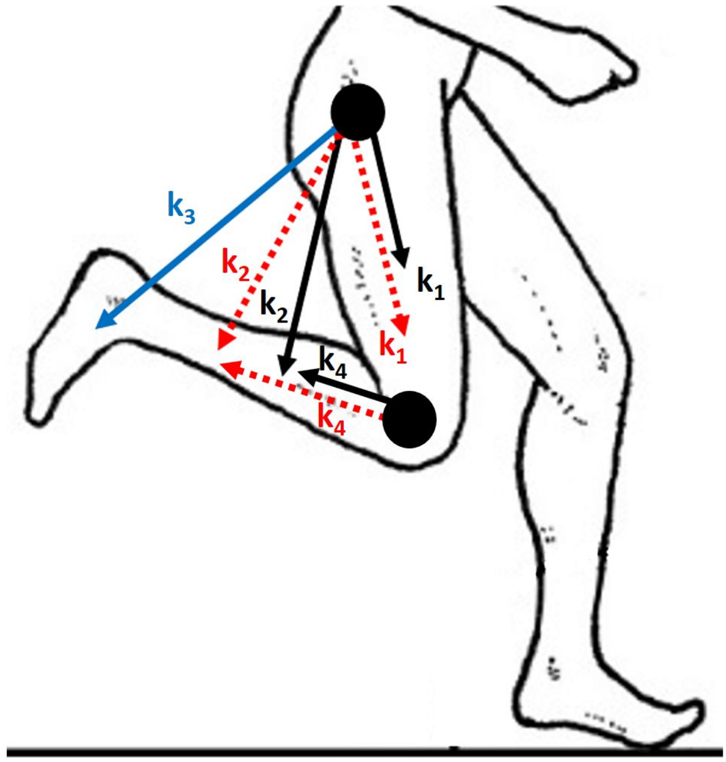

Figure 2.6. Radii of gyration about the hip and knee joints when barefoot (black) and when running shoes are worn (red). The moment arm from the hip joint to the foot is about the same when barefoot or when running shoes are worn and is, therefore, represented as one value (k_3). When wearing running shoes (red) the values of k_1, k_2 and k_4 are larger than when barefoot (black). Another moment of gyration from the knee joint to the foot has been left out to not clutter this figure but take not that the foot segment also has a moment of gyration about the knee joint. This moment of gyration would be about the same when barefoot or in running shoes.

After toe-off, knee flexion occurs and the increased I caused by the mass of shoes places a larger strain on the knee flexors. Since the knee flexors are assumed to be contracting at maximum intensity already, knee flexion occurs slower. Similarly, when the swing leg is brought in front of the body, knee extension occurs and as with knee flexion, the added mass of shoes decrease the speed of knee extension. Hip and knee flexion and extension are, therefore, slowed down with added mass to the feet and could potentially significantly slow down the swing phase. A slower swing phase will result in a longer swing time and a lower SF since SF is the inverse of stride time (SF=1/stride time) and stride time = GCT+SwT. Therefore, SF can also be written as SF = 1/(GCT+SwT) showing that a longer SwT would, decrease SF if GCT remains unchanged. If SL remains unchanged, a lower SF will result in a slower sprinting performance. Wearing running shoes could, therefore, potentially decrease sprinting performance by decreasing the speed of the swing phase.

The extra mass running shoes add to the feet will affect those with poor back side mechanics (i.e. those who do not bring their heel close to their GLU during the recovery phase) more than those with good back side mechanics. In those who use poor back side mechanics, the mass of running shoes would cause a greater increase in the moment of inertia (I) than it would if good back side mechanics were used (see Figure 11.7). When poor back side mechanics are used the k^2 part in the formula $I=mk^2$ is much larger and acts as a large multiplier of any increase in m. Therefore, the same increase in m (such as wearing running shoes) will then cause a much larger increase in I. Therefore, the mass of shoes will have a larger effect on inexperienced sprinters.

In summary, using good sprinting mechanics where the heel is brought close to the GLU as the leg is swung forward, decreases the moment of inertia of the swing leg allowing a higher angular acceleration and, therefore, the leg can be swung forward faster. This will allow a higher SF and a faster sprinting performance. Wearing running shoes could potentially decrease sprinting performance due to the mass they add to the feet. The mass running shoes add to the feet, increases the moment of inertia of the leg and results in a slower angular acceleration of the swing leg. This could significantly slow down the swing phase, decreasing SF and result in a decrease in sprinting performance. The same increase in mass (such as wearing running shoes) will cause a much larger increase in I in those who use poor back side mechanics (such as inexperienced sprinters) and will slow them down more than those who use good back side mechanics.

2.5. POTENTIAL ACUTE EFFECTS OF CHANGING FROM RUNNING SHOES TO BAREFOOT ON FOOT STRIKE PATTERN, SPATIOTEMPORAL VARIABLES AND SPRINTING PERFORMANCE

In this section, the potential acute effects of changing from running shoes to BF on FSP, spatiotemporal variables and sprinting performance will be discussed. First, the potential acute effects of changing from running shoes to BF on FSP will be looked at followed by the potential acute effects on spatiotemporal variables and lastly the potential acute effects on sprinting performance will be discussed along with the potential effects of shoe mass and FSP on sprinting performance.

2.5.1. POTENTIAL ACUTE EFFECTS OF CHANGING FROM RUNNING SHOES TO BAREFOOT ON FOOT STRIKE PATTERN DURING SPRINTING

Research has shown that changing from running shoes to BF has a significant effect on kinetics and kinematics of runners. Some of the kinetic and kinematic differences between a BF and running shoes condition are mentioned below. Compared to running in running shoes, running BF has shown the following acute changes in kinetics and kinematics.

- Higher external vertical loading rate in a barefoot rearfoot strike (RFS) than a shod RFS (de Wit *et al*., 2000; Lieberman *et al*., 2010).
- Earlier impact peak in a barefoot RFS than a shod RFS (de Wit *et al*., 2000, Lieberman *et al*., 2010).
- Lower impact ground reaction force (Hollander *et al*., 2014; Thompson *et al*., 2014).
- Lower maximum ground reaction force (Hollander *et al*., 2014).
- More plantarflexed ankle angle at foot strike (de Wit *et al*., 2000; Lieberman *et al*., 2010; Hollander *et al*., 2014; Thompson *et al*., 2014).
- Smaller peak knee flexion during stance (Bonacci *et al*., 2013).
- No difference in knee angle at foot strike (Hollander *et al*., 2014) or larger knee flexion at foot strike (de Wit *et al*., 2000).
- More vertical position of shank at foot strike (de Wit *et al*., 2000).
- Decreased peak knee extension and abduction moments (Bonacci *et al*., 2013).
- Smaller initial ankle eversion at impact (de Wit *et al*., 2000).
- Lower heel height during swing (Mullen & Toby, 2013).

Although many studies have investigated the acute effects of changing from running shoes to BF on kinetics and kinematics while running, very limited research in this area has been done while sprinting. Changing from running shoes to BF may potentially affect a sprinter’s FSP when sprinting and may potentially also affect spatiotemporal variables producing a specific sprinting performance. Therefore, the effect of changing from running shoes to BF on FSP could potentially be the first link in a chain of events affecting sprinting performance.

Existing literature (reported on in the following section) has shown that the following factors affect FSP; 1) changing from running shoes to BF, 2) running speed, 3) whether a runner is accelerating or running at a constant speed, 4) being habitually BF vs habitually shod and 5) hardness of the running surface. The current study's main interest lies in the first point mentioned but these other factors will also be discussed to better understand the FSP distributions that will be determined.

2.5.1.1. The effect of changing from running shoes to barefoot on foot strike pattern

In this section, studies done while participants performed maximal effort sprints will first be looked at. However, limited research has been done in this area during sprints and in children and adolescents. Most studies were done while running and in adults. Secondly, for this reason, studies on running and running at higher speeds will also be looked at. Thirdly, a summary will be given on the existing research on sprinting and running and lastly, the reason why running shoes and BF encourage a particular FSP will be discussed.

Theophilos *et al*. (2014) was the only study found assessing FSP in adolescents when sprinting. They tested 30m sprint performance on a synthetic athletics track in 33 adolescent athletics athletes (14 girls and 19 boys) sprinting in running shoes, spikes and when BF. Participants were aged 11.9±1.1 years with a training experience of 2.3±1 years in athletics and trained at least four times per week. They reported that only forefoot strikes (FFSs) were used in all footwear conditions and, therefore, changing from running shoes to BF had no acute effect on FSP.

Three other studies, which were done in adults, also reported FSPs when sprinting and had similar findings to Theophilos *et al*. (2014). Hébert-Losier *et al*. (2015) examined 14 adult male orienteers (seven elite and seven amateur) performing a 20m sprint in shoes with a 5m flying start. However, they only reported the average ankle angles per group, which were all plantarflexed, indicating the use of a FFS in both groups. The footwear used in this study was not specified but the researchers believe that regular running shoes or trail running shoes were used because participants sprinted on a road, a path, and a forest runway. Krell and Stefanyshyn (2006) determined FSPs of

76 elite adult sprinters (33 female and 43 male) at the 60m mark of a 100m sprint done in spikes on a synthetic track. They found that all foot strikes were FFS except for two, which were midfoot strike (MFS). Toon *et al*. (2009) determined the FSPs of four adult national level sprinters (two female and two male) at the 10m and 50m mark during a maximal effort sprint on an indoor synthetic track. All participants used a FFS at the 10m and 50m marks in both a BF and sprint spikes condition.

From the study by Theophilos *et al*. (2014) and the three studies done on adults while sprinting we see that a FFS/MFS was always used when sprinting in running shoes (Theophilos *et al*., 2014; Hébert-Losier *et al.*, 2015), spikes (Krell & Stefanyshyn, 2006; Theophilos *et al*., 2014) or BF (Toon *et al.*, 2009; Theophilos *et al*., 2014) and this occurred in adolescents and in adults. Adolescents and adults, therefore, seem to display the same FSP distribution when sprinting BF or in running shoes.

In contrast, previous studies on running have shown mixed findings concerning FSP distributions when changing from running shoes to BF. Three studies done on children and adolescents were found comparing FSP distributions while running in running shoes and a summary of their findings is shown in Table 2.1. These three studies found very similar results. All three studies found a decrease in the occurrence of a RFS when changing from running shoes to BF and all three studies found that a RFS occurred >50% of the time in running shoes (Lieberman *et al.*, 2010; Mullen & Toby, 2013b; Hollander *et al.*, 2014). Two of the three studies found that a RFS also occurred >50% of the time when BF (Lieberman *et al.*, 2010; Hollander *et al.*, 2014) but Mullen and Toby (2013) found that a FFS/MFS occurred >50% of the time when BF.

Many studies in this area have also been done in adults but only five will be discussed in this section. A summary of their findings is shown in Table 2.2. Three of the five studies on adults determined the occurrence of a RFS in running shoes and when BF (Lieberman *et al.*, 2010; Hamill *et al.*, 2011; Squadrone *et al*., 2015). As in the three studies on children and adolescents, two of these three studies on adults found a decrease in the occurrence of a RFS when changing from running shoes to BF (Lieberman *et al.*, 2010; Hamill *et al.*, 2011). In contrast, Squadron *et al*. (2015) found no change with all participants using a RFS in running shoes and when BF. The other two studies on adults only determined the mean FSP in each footwear condition. de Wit *et al*. (2000) found that the mean FSP was a RFS in running shoes and when BF and Squadrone and Gallozzi (2009) found that the mean FSP was a MFS in both footwear conditions.

The findings of studies done on children, adolescents and adults while running are quite similar with most studies finding a decrease in the occurrence of a RFS when changing from running shoes to BF and most studies finding a RFS occuring >50% of the time in running shoes and when BF. However, the FSP distributions seen while running is very different to that seen while sprinting and studies on running can, therefore, not be used to predict FSP distributions while sprinting.

From the one study done in adolescents sprinting BF and in running shoes and the three studies done on adults while sprinting the researchers hypothesise that all participants (children, adolescents and adults) in the current study would only use a FFS/MFS while sprinting BF or in running shoes. However, the researchers acknowledge that there is limited literature to support this hypothesis since only one study had thus far been done in adolescents while sprinting BF and in running shoes, none has been done in children and only one has been done in adults while sprinting BF but not also in running shoes.

Running with a RFS when barefoot could result in painful heel collisions with the floor. It is suggested that the use of a FFS/MFS during barefoot running could be a strategy to avoid that painful impact due to limited padding under the heel (de Wit *et al.*, 2000; Mullen & Toby, 2013a; Squadrone *et al.*, 2015). Lieberman *et al*. (2010) found that peak vertical impact forces were approximately three times higher in a barefoot and cushioned running shoe RFS compared to a barefoot FFS. Using a FFS instead of a RFS, therefore, results in a large decrease in vertical impact forces. Also, when barefoot, the average loading rate was seven times higher in a RFS compared to a FFS over the same percentage of stance (Lieberman *et al.*, 2010). The lower impact forces and much lower loading rates in a FFS are possible since the triceps surae eccentrically controls the loading. This eccentric loading increases the time component of the foot strike impulse and, therefore, a lower impact force is experienced.

Table 2.1. Summary of studies done on children and adolescents investigating the acute effect of changing from running shoes to barefoot.

Reference	Sample size and ages	Details of Participants	Running surface and Speeds	Method of determining FSP	Acute effects of changing from running shoes to BF
Hollander *et al.* (2014)	N=36 (22 girls, 14 boys) 6-9 years (mean age 7.42±1.05 years).	The children were recruited from sports teams and, on average, participated in sports for 4.8±1.6 hours/week	Instrumented treadmill 8 and 10kim/h	A RFS was identified by using the presence of an additional peak in the ground reaction force curve (impact transient) during the contact period on the instrumented treadmill.	Significant decrease in mean rate of RFS at (8km/h / 10km/h) from (75.8%/78.5%) to (54.5%/60.0%). RFS occurred >50% of the time in both the running shoes and BF conditions.
Lieberman *et al*. (2010)	N=17 (7 girls, 10 boys) 11-16 years (mean age 15.0±0.8 years)	All adolescents habitually shod since childhood	Hard dirt road Self selected pace of 17.6-18.4km/h	Two -dimensional visual method using a 500Hz video camera and markers on anatomical landmarks.	Decrease in occurrence of RFS from 97% to 62%. RFS occurred >50% of the time in both the running shoes and BF conditions.
Mullen and Toby (2013)	N=12 (6 girls, 6 boys) 13-18 (mean age 16 years)	All track and cross-country athletes	Treadmill 4 Speeds ranging from 9.6-19.3km/h	12-Camera, marker-based motion capture system	Decrease in occurrence of RFS from 70% to 28%. RFS occurred >50% of the time in running shoes. FFS/MFS occurred >50% of the time when BF.

Table 2.2. Summary of studies done on adults investigating the acute effect of changing from running shoes to barefoot.

Reference	Sample size and ages	Details of Participants	Running surface and Speeds	Method of determining FSP	Acute effects of changing from running shoes to BF
Lieberman *et al.* (2010)	<u>3 Groups of adults</u> 1) N=8 (2 females and 6 males aged 19.1±0.4 years) 2) N=14 (1 female and 13 males aged 23.1±3.5 years) 3) N=8 (1 female and 7 males aged 38.3±8.9 years)	All ran a minimum of 20km/week. 1) Habitually shod amateur and collegiate athletes from USA. 2) Recently shod athletes from the Rift Valley Province of Kenya, all training for competition but were previously habitually BF. 3) Ran habitually BF/minimalists but grew up habitually shod from the USA.	USA participants ran on synthetic indoor track and Kenyan participants ran on a hard dirt road 14.4 - 21.2km/h	Two-dimensional visual method using a 500Hz video camera and markers on anatomical landmarks.	1) Decrease in occurrence of RFS from 100% to 83%. 2) Decrease in occurrence of RFS from 29% to 9%. 3) Decrease in occurrence of RFS from 50% to 25%. Group 1 had a RFS >50% of the time in running shoes and when BF. Groups 2 and 3 had a FFS/MFS ≥50% of the time in running shoes and when BF.
Hamill *et al.* (2011)	N=10 (5 females aged 27.4±3.7 years and 5 males aged 29.6±2.9 years)	All regular runners who ran at least 15km/week and all normally used a RFS.	Overground over a force plate along runway (Surface not specified) Preferred running speed of 12.85 ± 1.48km/h and at a fixed speed of 14.40km/h± 5%	Strike index calculated from force plate data	Decrease in occurrence of RFS from 100% to 0%. All participants changed to MFS when BF, based on strike index.
de Wit *et al.* (2000)	N=9 9 males aged 27±9 years	All trained long distance runners running 30-40km/week.	Treadmill 12.6, 16.2 and 19.8km/h	Two-dimensional visual method using a 500Hz video camera and markers on anatomical landmarks.	Mean FSP was a RFS in running shoes and BF and at all speeds.
Squadrone and Gallozzi (2009)	N=8 8 males aged 32±5 years	All were runners with a long training experience in BF running and three had even run a marathon while BF. Average 10kim race time was 40.3±4 min.	Instrumented treadmill 12km/h	Strike index using instrumented treadmill	Mean FSP was a MFS in running shoes and when BF.
Squadrone *et al.* (2015)	N=14 14 males aged 30±6 years	All experienced recreational runners with a 10km race time of 43±6 min. All were used to running >45km/week and had a training experience in wearing minimalist shoes (at least 50% of their training volume) for an average of 2.8 years before the test.	Instrumented treadmill 12km/h	Strike index using instrumented treadmill	100% Occurrence of RFS in running shoes and when BF.

A MFS will allow a flatter foot placement and thereby increase the surface area at impact. This will decrease the pressure experienced under the heel. Flatter foot placement in (Squadrone & Gallozzi, 2009; Mullen & Toby, 2013a) resulted in lower plantar heel pressures and Mullen and Toby (2013) found a strong correlation between these two variables. Flatter foot placement and lower peak pressures had a correlation of ($r = -0.7$, $p<0.05$). Nigg (2010) cited in (Lieberman, 2012) stated that habitually shod runners when barefoot are more likely to RFS on soft surfaces like grass and to FFS/MFS on hard surfaces. This adds to the argument that a FFS/MFS might be a strategy to avoid a painful RFS.

Running shoes encourage a RFS due to a cushioned and elevated heel (Lieberman *et al.*, 2010). Squadrone *et al*. (2015) found that shoes with more heel cushioning had better shock absorption qualities and Mullen and Toby (2013) found that heel cushioning in running shoes decreases the rate of body weight loading allowing a RFS to feel comfortable. The elevation of the heels forces the foot into a more plantar flexed position. Mullen and Toby (2013:456) stated:

> *"We believe that the large heels in cushioned trainers nearly preclude runners from forefoot striking because of the added 1 to 3 cm beneath the heel and the increased plantar flexion built into the shoe".*

If a runner is used to landing with a MFS during barefoot running and keeps running with that same ankle angle but now wears running shoes with an elevated heel the same ankle angle would result in a RFS due to the heel to toe offset. Both elevation and the cushioning in running shoes, therefore, promote a RFS.

In summary, running in a barefoot condition encourages a FFS/MFS to avoid a painful RFS and running shoes encourage a RFS due to their cushioned and elevated heels.

2.5.1.2. The effect of running speed on foot strike pattern

In this section, the acute effects of running speed on FSPs will be discussed. In a study on 12 adolescent competitive track and cross-country athletes (six girls and six boys aged 13-18 years with a mean age of 16 years), speed changes showed that at the two slower speeds for boys/girls (2.68/2.68 and 3.58/3.13m/s), adolescents were more likely to RFS regardless of shoe type (BF, track flat, trainer). At faster speeds

(4.47/3.58 and 5.36/4.02 m/s) adolescents were more likely to FFS/MFS in the BF and flat conditions, but not in the trainer (Mullen & Toby, 2013a).

Furthermore, important differences in the distribution of foot strike have been found between elite and recreational runners. de Almeida *et al.* (2015) found that 95% of recreational runners RFS running at an average pace of 12.2km/h, Larson *et al*. (2011) found that 88% of runners running at an average pace of 11km/h RFS and Hasegawe *et al*. (2007) observed that 75% of elite marathon runners running 17.7-19.6km/h RFS. All these studies were conducted during a competitive race. Runners at different levels use different FSPs (de Almeida *et al*., 2015) and this difference in distribution may at least in part be due to the fact that runners at different levels run at different speeds. A higher proportion of elite runners, who run at a higher average speed, FFS/MFS compared to recreational runners. Kasmer *et al*. (2013) confirmed this by finding that more elite marathon runners were significantly less likely to RFS.

In contrast, de Wit *et al*. (2000) analysed nine trained adult long distance runners running BF and in running shoes at 3.5, 4.5 and 5.5m/s (12.6, 16.2 and 19.8km/h). No significant running speed effect on sole angle and, therefore, FSP was seen. The acute effect of running speed on FSP is, therefore, unclear since there are mixed findings in existing research.

As opposed to running, all existing research determining FSP while sprinting in both adolescents and adults found that only a FFS/MFS was used when sprinting BF, in running shoes or in spikes (Krell & Stefanyshyn, 2006; Toon *et al.*, 2009; Theophilos *et al*., 2014; Hébert-Losier *et al.*, 2015). Faster speeds seem to be associated with a FFS/MFS and slower speeds with a RFS. A possible reason for this could be that as running speed increases, SL and SF both increase and as SL increases, impact experienced at foot strike also increases (Thompson *et al.*, 2014). At lower speeds it might still be comfortable to RFS even when BF but at higher speeds a FFS/MFS occurs more often to avoid a painful heel strike. At high enough speeds, it might even become painful to RFS in cushioned shoes and a shift to a FFS/MFS is expected.

In summary, faster speeds are associated with a FFS/MFS and slower speeds with a RFS. A possible reason for the use of a FFS/MFS at higher running speeds could be to avoid a painful heel strike.

2.5.1.3. The effect of accelerating vs running at a constant speed on foot strike pattern

The acceleration period is expected to encourage a FFS due to the forward body lean. Theophilos *et al*. (2014) found that only FFSs were used during a short 30m sprint from a block start. Similarly, Toon *et al*. (2009) also found that only FFSs were used at the 10m mark during a 100m sprint from a block start. Furthermore, all elite sprinters accelerate from the blocks using FFSs. This was noted when looking at videos of elite sprinters starting from a block start. Similarly, all research that recorded FSPs while sprinting at or near constant speed (Krell & Stefanyshyn, 2006; Toon *et al*., 2009) also found only FFSs being used, except for the two MFSs seen in (Krell & Stefanyshyn, 2006). When one is sprinting at maximal effort, whether one is accelerating or sprinting at a constant speed seems to have no significant effect on one's FSP. In both situations, only a FFS/MFS is expected.

2.5.1.4. The effect of being habitually barefoot vs habitually shod on foot strike pattern

Footwear may also have a chronic effect on a child's FSP. Habitually shod runners mostly RFS when shod or running BF, whilst habitually BF runners generally FFS/MFS in both shod and BF conditions (Lieberman *et al.*, 2010). Whether a sample of participants are habitually BF or habitually shod will, therefore, affect their FSP distributions. The acute effects of changing from running shoes to BF on FSP can be better understood by keeping in mind that being habitually BF or shod affects the FSP distributions seen. Habitually wearing shoes could potentially teach children and adolescents bad habits for effective sprinting since shoes encourage a RFS and it is expected that a FFS is better for sprinting. The reason why a FFS is expected to be a better FSP for sprinting performance is discussed later on in (2.5.3.2). However, research has no yet investigated whether being habitually shod encourages sprinting with a RFS.

2.5.2. POTENTIAL ACUTE EFFECTS OF CHANGING FROM RUNNING SHOES TO BAREFOOT ON SPATIOTEMPORAL VARIABLES

In this section, the acute effects of changing from running shoes to BF on spatiotemporal variables will be discussed. Spatiotemporal variables have been studied extensively while sprinting but no research was found on the acute effects of changing from running shoes to BF on spatiotemporal variables while sprinting. Research in this area has been focussed on running. Therefore, existing research on running will be looked at to help predict what the potential acute effects of changing from running shoes to BF might be on spatiotemporal variables during sprinting.

Several studies on running have found significantly lower SLs and higher SFs when BF compared to running in running shoes (de Wit *et al.*, 2000; Divert *et al.*, 2005; Squadrone & Gallozzi, 2009; Bonacci *et al.*, 2013; Mullen & Toby, 2013a; Hollander *et al.*, 2014; Squadrone *et al.*, 2015). The effects on GCT and FT were, however, inconsistent. Table 2.3 shows the findings of several studies that evaluated the acute effect of running in a BF condition on GCT and FT compared to running in a shod condition. No research was found assessing SwT in a BF and shod condition.

Table 2.3. Research findings on acute effect of running in a BF condition on GCT and FT compared to running in a shod condition.

	FT	GCT
Shorter	(Divert *et al.*, 2005)	(de Wit *et al.*, 2000)
Longer	(Squadrone & Gallozzi, 2009)	(Divert *et al.*, 2005; Squadrone *et al.*, 2015)
Unaffected	(de Wit *et al.*, 2000)	(Squadrone & Gallozzi, 2009)

de Wit *et al*. (2000) analysed spatiotemporal variables of nine trained adult male long distance runners (age: 27±9 years) running in a BF and running shoes condition at 3.5, 4.5 and 5.5m/s (12.6, 16.2 and 19.8km/h) on a treadmill. Participants ran between 30-40km/week. A significantly shorter SL, higher SF and shorter GCT were found in the BF condition compared to the running shoes condition and FT was unaffected. de Wit *et al*. (2000) suggested that the acute spatiotemporal changes they observed were primarily due to acute kinematic changes at foot strike. Although runners used a RFS in both the BF and shod conditions, in the BF condition, runners adapted a much flatter more plantar flexed foot and a more flexed knee at foot strike. Due to these kinematic changes, when running BF, runners touched the heel down closer to the vertical projection of the hip resulting in a reduced SL. The higher SF was a result of the reduced SL since runners ran at constant speeds and, therefore, had to adopt a higher SF. Since runners touched the heel down closer to the vertical projection of the hip in the BF condition, the support phase was shorter and, therefore, braking forces were also less compared to the running shoes condition.

The reason for the flatter foot placement and the shorter SL in the BF condition could have been to avoid a painful RFS. Flatter foot placement in Mullen and Toby (2013) resulted in lower plantar heel pressures and these two variables were strongly correlated. Flatter foot placement and peak pressures had a correlation of ($R = -0.7$, $p<0.05$). The flatter, more plantar flexed foot in the BF condition in de Wit *et al.* (2000) could have resulted in lower plantar heel pressures and a less painful heel strike.

Thompson *et al*. (2014) independently evaluated the effect of changing from running shoes to BF and SL on lower leg kinetics to determine what the origin of kinematic and kinetic changes are when running in shoes compared to running BF. When participants ran at identical SLs there was no difference between BF and shod running kinetics. However, when running with larger stride lengths, GRFs were higher overall including at impact. Shorter SLs, therefore, had reduced impact GRFs (Thompson *et al.*, 2014) and have been shown to increase shock attenuation (Mercer *et al*., 2002). The shorter SL seen in de Wit *et al.* (2000) when running BF could, therefore, also have been an adaptive response to avoid painful foot strikes.

Based on the acute effects of changing from running shoes to BF on spatiotemporal variables while running, sprinting BF might also result in shorter SLs and higher SFs compared to sprinting in running shoes. If foot strikes are also closer to the vertical projection of the hip while sprinting BF, sprinting BF could offer a potential benefit to sprinting performance since the braking forces will then also be less.

In summary, research has shown that footwear has an acute effect on spatiotemporal variables while running with a BF condition showing significantly shorter SLs and significantly higher SFs than a shod condition. Changing from running shoes to BF has also been shown to have an acute effect on FT and GCT while running but research findings have been inconsistent on these two variables. Changing from running shoes to BF could potentially have the same acute effects on spatiotemporal variables while sprinting but no research has yet been done to assess this possibility. For the current study, the researchers hypothesise that children and adolescents will have a significantly shorter SL, GCT, FT and SwT and a significantly higher StepF when sprinting BF compared to sprinting shod.

2.5.3. POTENTIAL ACUTE EFFECTS OF CHANGING FROM RUNNING SHOES TO BAREFOOT ON SPRINTING PERFORMANCE

Sprinting in shoes might significantly affect sprinting performance compared to sprinting BF and the potential difference in sprinting performance might be due to various qualities of shoes. The two main qualities relating to the current study are 1) shoe mass and 2) shoe design. Other qualities mentioned in the literature are 3) traction, 4) midsole bending stiffness and 5) shoe's effect on proprioception. In the first part of this section, the potential acute effects of shoe mass and shoe design on sprinting performance will be discussed. After that, a short summary will be given to highlight where in the sprinting cycle shoe mass and shoe design might affect sprinting performance. Lastly, the acute effects that the other footwear qualities mentioned has on sprinting performance will also briefly be looked at.

2.5.3.1. Acute effects of shoe mass on sprinting performance

The potential acute effects shoe mass might have on sprinting performance has been described in detail in (2.4.3). Compared to a BF condition, any shod condition has added mass to the feet, which increases the moment of inertia (I) of the leg. The increased moment of inertia could, significantly slow down the swing phase and SF. Next, the available research on the acute effect added mass to the lower limbs has on sprinting performance will be looked at to better predict whether a shoe mass effect on sprinting performance is expected.

Bennett *et al*. (2009) tested 40m sprint performance in eight highly trained (national representative) male beach sprinters (aged 27±7.3 years) under a resisted condition, where mass was added to the lower extremities (thigh and shank), and under normal conditions with no added mass. Bennett *et al*. (2009) did not report the specific added mass in the resisted condition but reported the added mass to be approximately 10% of individual segment mass placed evenly distributed about the radius of gyration of the thigh and shank. Participants had an average personal best in the 100m sprint of 11.10s. The article did not state which running surface participants sprinted on or the footwear condition used. Bennett *et al*. (2009) found that sprinting with added mass to the lower extremities resulted in a significantly slower average running velocity, significantly slower 10-20m, 30-40m and total 40m sprint performance ($p \leq 0.02$). Furthermore, they found a small but insignificant increase in total stride time, FT and GCT. SL and SF were also slightly but insignificantly decreased.

In contrast, Theophilos *et al*. (2014) did not find a significant effect on sprinting performance due to shoe mass. They measured 30m sprint performance of 33 adolescents (14 girls aged 12.3±0.4 years and 19 boys aged 11.6±0.8 years) in three footwear conditions on a synthetic indoor running track. All participants were athletes with a training experience of 2.3±1 years in athletics and trained at least four times per week. The footwear conditions were BF (no added mass to the foot), spikes (441g) and running shoes (507g). There were no significant differences in performance between the BF (5.31±0.5s), running shoes (5.30±0.5s) and spikes (5.28±0.4s) conditions. The effect of shoe mass might not have been seen due to the mass differences being too small and the distance sprinted (30m) being too short for a significant effect (Theophilos *et al.*, 2014). The mass effect of shoes will have a bigger impact over larger distances. Another possible reason is that the running shoes and spikes conditions may have had better traction compared to the BF condition. The added traction might have balanced out any potential negative effect shoe mass might have had on sprinting performance.

Similarly, no significant performance decreases were seen with added mass to the feet in Sterzing *et al.* (2009) and Worobets and Wannop (2015). Worobets and Wannop (2015) tested 10m sprint performance of 20 active recreational basketball players in basketball shoes of three different masses namely, 0.414kg (the reference condition), 0.331kg (the −20% condition), and 0.497kg (the +20% condition). Despite increasing the mass of the shoe from 0.331 to 0.497kg (an increase of 0.166kg or 50%), the basketball players suffered no decrease in 10m sprint time on a hardwood floor of a gymnasium. The age and sex of the participants is uncertain since the only recruitment criteria was that players had to properly fit into the men's size 10 US test shoe and be active recreational basketball players free from injury.

A similar result was found by Sterzing *et al.* (2009). When testing various soccer shoes, an addition of 0.070 kg (an increase of 35%) to a soccer shoe had no negative effect on the performance during a 26m running/cutting Slalom course. Participants were 20 adult amateur to sub-elite soccer players with a minimum of five years soccer experience. The mean age was not reported for these 20 players since they were merely one of the groups involved in the study and mean age was only reported when all the participants were grouped together. 52 Players participated in the study overall and had a mean age of 24.5±4.2 years.

The mass differences between shoe conditions in Worobets and Wannop (2015) and Sterzing *et al.* (2009) were quite small. The lack of significant differences in sprinting performance might have been due to the mass differences being too small and the distance sprinted being too short to see a significant effect.

In summary shoe mass seems to have no significant effect on short anaerobic sprint performance. This could be due to the distance being too short to see a significant effect and modern day sports shoes being light enough to have no significant effect. Therefore, the researchers hypothesise that the mass of shoes would have no significant effect on children and adolescents' sprinting performance. Furthermore, the researchers hypothesise that there would be no significant difference in children and adolescents' sprinting performance between sprinting BF or in sports shoes.

2.5.3.2. Acute effects of shoe design on sprinting performance

Shoe design might potentially influence sprinting performance due to its effect on FSP. Running in running shoes encourages a greater tendency to RFS while running BF encourages a greater tendency to FFS/MFS (de Wit *et al.*, 2000; Squadrone & Gallozzi, 2009; Lieberman *et al.*, 2010; Hamill *et al.*, 2011; Mullen & Toby, 2013a; Hollander *et al.*, 2014; Squadrone *et al.*, 2015).

Very limited research has been done determining FSPs while sprinting in running shoes. Theophilos *et al*. (2014) stated that only a FFS was used during a 30m sprint in running shoes, however they did not mention using any equipment such as high-speed video footage or force plates to determine FSPs. Therefore, it is assumed that they subjectively judged FSPs with the naked eye. Their statement that only FFSs were used might potentially be inaccurate since it is sometimes even difficult to determine FSPs while analysing high-speed video footage when the FSP is close to a MFS. The FSP distribution while sprinting in running shoes by Theophilos *et al*. (2014) is, therefore, not reliable. Hébert-Losier *et al*. (2015) also determined FSP while sprinting in running shoes. Some participants could potentially have sprinted with a RFS but this is uncertain since only the average ankle angle was reported and this was a plantarflexed angle indicating that on average a FFS was used. The existing literature, therefore, do not clearly indicate what the expected FSP distributions will be when sprinting in running shoes. Sprinting in running shoes may potentially also encourage a greater tendency to RFS as seen in running and could potentially be an ineffective FSP for sprinting. A FFS might offer various mechanical advantages for sprinting. Potential advantages of a FFS to sprinting will now be discussed.

Footwear affects the centre of pressure (COP) at foot strike. Running shoes, which encourage a RFS, will cause the COP to be in the posterior third of the foot at foot strike. In contrast, a BF condition, which encourages a greater tendency to FFS, encourages the COP to be in the anterior third. If the COP is more anterior, the length of the lever arm about the ankle joint would increase and greater moments acting around the ankle joint would need to be countered by the ankle plantar flexors. If a sprinter has enough strength to overcome the greater moments, it will provide a potential mechanical advantage to propel the body forward (Stefanyshyn & Fusco, 2004).

Furthermore, one of the critical factors affecting sprint performance is the ability for sprinters to absorb and generate large amounts of mechanical energy during each ground contact. With a FFS the foot is in a better position at foot strike for elastic components in the lower limb to be stretched and store energy (Fletcher, 2009). As mentioned before, by landing with a FFS the lever arm producing torque around the ankle joint is greater since the COP is further from the pivot (the ankle joint). This increased torque around the ankle will allow landing energy, from the body's CoM dropping down, to be stored and re-used by the elastic components in the lower limbs (Novacheck, 1998; Lieberman *et al.*, 2010). Therefore, a FFS could potentially allow better utilisation of the elastic components in the lower extremities. At higher running speeds, GCT is short and it becomes difficult to increase force production against the ground. Better utilising the elastic components in the legs would allow rapid load and recoil of elastic components making it possible to exert large forces against the ground even though GCT is short (11.4.1.2). Therefore, sprinting with a FFS could potentially allow quicker GCTs, a higher SF and a faster sprinting performance.

Another potential performance enhancement is that a FFS is also used to keep the body's CoM high. During sprinting, a sprinter should aim to move the body's CoM from point A to B in as short a distance as possible. This can be achieved by reducing up and down undulation of the body's CoM at each step by using a FFS. Elite sprinters almost always FFS making use of this benefit (Krell & Stefanyshyn, 2006; Toon *et al.*, 2009; Hébert-Losier *et al.*, 2015).

Research found that running with a RFS results in a great deal of the initial strike energy being lost (Lieberman *et al.*, 2010). Theophilos *et al*. (2014) stated that cushioned running shoes probably compromise the lower limb's ability to act like a spring, affecting the running technique in short (30-60m) or longer (80-200m) sprints. Therefore, shoes might negatively affect sprinting performance since they encourage a RFS. For the current study, the researchers hypothesise that children and adolescents' FSP will have a significant effect on their sprinting performance with a FFS/MFS being faster than a RFS.

Shoes may also negatively influence sprinting performance due to the mechanical work needed to deform the shoe. According to the researchers' knowledge, no studies have yet been done on the mechanical work needed to deform running shoes during a sprint. Such studies have, however, been done while running. According to Webb *et al*. (1988), up to 13% of work done during shod walking goes into compressing and flexing the sole and in rotating the sole against the ground.

In summary, sprinting BF potentially offers the following acute advantages during the stance phase to improve sprinting performance: 1) decreases braking forces, 2) encourages a FFS that may be better for sprinting performance and 3) extra energy is not needed to deform the shoe and rotate it against the ground. During the swing phase, sprinting with running shoes will increase the moment of inertia of the leg and may significantly slow down the swing phase. A significantly slower swing phase could potentially also significantly decrease SF that will decrease sprinting performance if SL remains unchanged.

2.5.3.3. Other qualities of shoes which influences sprinting performance

Besides the mass and the design of shoes, literature has also shown that other qualities of shoes affect sprinting performance namely: traction, midsole bending stiffness and the shoe's effect on proprioception. These three factors will only briefly be discussed since they are not the main focus of the current study.

2.5.3.3.i. Effect of traction on sprinting performance

Of all the shoe qualities mentioned, traction plays the largest role on sprinting performance and many sports shoes use studs or spikes to improve traction. Worobets and Wannop (2015) tested the effect of altering traction, forefoot bending stiffness and the mass of basketball shoes on 10m sprint performance on a hardwood floor of a gymnasium in 20 recreational basketball players. Traction had the most significant effect on 10m sprint performance followed by forefoot bending stiffness and basketball shoe mass had no effect. Decreasing the traction by 20% resulted in an 11% ($p<0.01$) slower 10m sprint. Increasing traction of a reference shoe by 20% resulted in a 4% increase in performance in a cutting drill but not in the 10m sprint. Luo and Stefanyshyn (2011) found that increasing traction of shoes has a beneficial influence on sprinting performance, but only up until a certain threshold value after which further increases in traction does not result in a further increase in performance.

Similarly results from Sterzing *et al.* (2009) showed that increasing traction of soccer boots resulted in improved performance in a 6m acceleration test (14.62% $p<0.01$) and a Slalom agility test (26.34% $p<0.01$). Participants were 20 adult amateur to sub-elite soccer players with a minimum of five years soccer experience and tests were performed on either natural grass or FIFA 2-Star artificial turf. The 20 participants that performed the 6m acceleration test and Slalom agility test in different traction conditions were only one of the many groups involved in the study but their mean age was not mentioned. Sterzing *et al*. (2009) tested 52 players in total, with a mean age of 24.5±4.2 years.

In contrast, no significant differences in 30m sprint performance were found between sprinting in spikes, running shoes or BF in Theophilos *et al.* (2014). All three footwear conditions might have had traction values at or above the threshold value suggested by Luo and Stefanyshyn (2011). It is expected that the spikes condition, and maybe also the running shoes condition, had better traction than the BF condition. Another possible reason why no significant difference was seen could be that the added traction in the shod conditions might have balanced out any potential negative effect shoe mass could have had on sprinting performance.

If shoes offer better traction than a BF condition, sprinting with shoes might offer a potential performance advantage over a BF condition. However, this is expected to only be true if the traction is high enough to provide a larger performance advantage than the potential negative effect shoe mass has on performance.

2.5.3.3.ii. Effect of midsole bending stiffness on sprinting performance

Optimising midsole bending stiffness has been shown to improve sprinting performance with stiffer midsoles generally resulting in better sprint performance. In Worobets and Wannop (2015), increasing bending stiffness from 0.22 Nm/˚ to 0.33 Nm/˚ resulted in a 1% increase in 10m sprint performance ($p = 0.013$) on a hardwood floor of a gymnasium. In Stefanyshyn and Fusco (2004) 34 university track and field athletes who specialised in sprint, long jump, hurdle or decathlon events (30 males and four females) performed maximal effort 40 m sprints from a standing start and their sprint times were recorded from 20 to 40m. The mean age of participants was not reported. Increasing the bending stiffness of sprinting shoes on average resulted in an increase in sprinting performance, however, there was no consistent trend among athletes and the optimal bending stiffness might be specific to each athlete. Sprint performance was significantly increased by 1.2% ($p<0.001$) with the best midsole stiffness condition compared to the standard shoe. If shoes have an optimal or near optimal bending stiffness it could potentially offer a performance advantage over sprinting BF.

2.5.3.3.iii. Shoes' effect on proprioception and how this may affect sprinting performance.

The soles of the shoes offer a barrier between the plantar surface of the feet and the ground which limits proprioception (sensory feedback) on the soles of the feet (Lieberman, 2012). According to Jenkins and Cauthon (2010) cited in Lieberman (2012) plantar proprioception activates reflexes during running and helps the central nervous system to make the right decisions in maintaining stability, avoiding painful impacts and adjusting leg stiffness. Shoes could potentially decrease stability and could decrease the efficiency of movement during sprinting. Decreased stability might increase energy spent on rotational movements such as swinging the arms more across the body in order to help stabalise the body instead of it being used to propel the body forwards. Sprinting BF might also result in more syncronised muscle contractions due to better feedback to the central nervouse system, potentially resulting in better sprinting performance.

On the other hand, sprinting BF on hard surfaces, might be painful, especially to habitually shod populations who's feet have not adapted. Running at higher velocities results in larger SLs and higher impact forces on the feet (Thompson *et al.*, 2014). If people are not used to sprinting BF they may reduce their SLs to sub-optimal SLs for sprinting in order to reduce the impact experienced on the feet. Sprinting BF may then result in a decrease in sprinting performance. In situations like this, shoes, which help cushion the foot at impact. This may provide children and adolescents with added confidence while sprinting to strike the floor with more force and sprint at optimal SLs. The added impact attenuation offered by shoes may potentially help improve sprint performance to those with 'soft feet'. BF training could help condition children and adolescents' feet for BF running/sprinting. BF training produces calluses on the soles of the feet making them 'harder' and more adapted to run on hard surfaces (Lieberman, 2012). If a child or adolescent's feet are adapted to sprint BF he/she could sprint with optimal SLs, utilise the benefits of unhindered proprioception and have the benefit of no added mass on the feet. These benefits could potentially improve sprinting performance.

SUMMARY

There is a gap in the existing research concerning the acute effects of changing from running shoes to BF on short anaerobic sprint performance in children and adolescents. There are also gaps in the research concerning the acute effects of changing from running shoes to BF on spatiotemporal variables and FSPs while sprinting in children and adolescents. Furthermore, most studies relevant to the current study have been done in adults and sample sizes were usually small.

The only study found assessing the acute effects of changing from running shoes to BF on FSP while sprinting found that footwear has no effect on FSP since all participants used a FFS in both the BF and running shoes condition. In contrast, the majority of research on running showed that running shoes encourage a higher rate of RFS due to their cushioned and elevated heels and a barefoot condition encourages a higher rate of FFS/MFS to avoid a painful RFS.

No research was found on the acute effects of changing from running shoes to BF on spatiotemporal variables while sprinting. However, studies on running showed significantly shorter SLs and significantly higher SFs in a BF condition compared to a shod condition. Research has also shown that changing from running shoes to BF has an acute effect on FT and GCT while running but research findings have been inconsistent on these two variables. Changing from running shoes to BF could potentially have the same acute effects on spatiotemporal variables while sprinting.

Sprinting BF could potentially offer performance advantages over sprinting shod during both the swing phase and the stance phase. During the swing phase, sprinting shod increases the moment of inertia of the swing leg due to the extra mass shoes add to the feet, and could potentially result in a significantly slower swing phase, lower SF and decreased sprinting performance. However, existing research show that shoe mass has no significant effect on sprinting performance. All but one of the existing studies, however, compared different shod conditions of varying mass and mass differences were smaller than it would have been if a BF and shod condition were compared. The one study that did compare sprinting performance in a BF and shod condition had a relatively small sample size. Changing from running shoes to BF might also affect sprinting performance in the stance phase, through its effect on FSP. Sprinting with a FFS is expected to be faster than sprinting with a RFS and since a BF condition encourages a higher rate of FFS/MFS, sprinting BF might also offer a performance advantage during the stance phase. However, no research has yet been done to investigate whether a sprinter’s FSP has a significant effect on sprinting performance.

CHAPTER THREE

METHODOLOGY

3.1. INTRODUCTION

In this chapter, the specific methods used to determine the aims and objectives of the current study will be explained. It explains the study design, how the specific population was selected and recruited, the testing protocol and the statistical methods used to determine the results.

The current study formed part of a much larger cross-sectional, binational study comparing the performance of children and adolescents aged 6-18 from South Africa and Germany in multiple fitness tests done in a barefoot (BF), school shoes and sports shoes condition (Hollander *et al*., 2016). Due to this, the same protocol that was used in the larger study also had to be used in the current study. The larger study involved seven testing stations (anthropometric measurements, 20m sprint test and five other stations). Due to all the testing stations that needed to be completed by participants within a single physical education lesson of 45-50min, time limitations lead to certain decisions that will be described later in the methodology.

3.2. STUDY DESIGN

This field based study can be typified as a cross-sectional study with a quasi-experimental design in which quantitative data were used. Qualitative data were also collected for one of the variables. A randomized stratified sample was used to recruit a variety of schools from the five different regions in the Western Cape. Random sampling was done to identify the five towns and six schools where data were collected. At the schools the classes, age groups and number of boys and girls tested were selected according to convenience. The footwear condition in which children and adolescents first sprinted was also randomised.

A pilot study (Appendix Ten) was done at one school before the data collection period to test the protocol and the necessary adjustments were made. Children and adolescents who participated in the pilot study did not participate in the rest of the study.

3.3. PARTICIPANTS

115 Girls and 161 boys (N=276) aged 8-19 years from six randomly selected schools in the Western Cape Province were recruited to volunteer for the study. Only children and adolescents registered at the selected schools between the ages 8-19 (born 1996-2007) were tested. Children and adolescents were excluded if they did not hand in a completed assent and consent form or if they had any injury/illness that prevented them from performing to the best of their ability. Children and adolescents were also excluded if they did not bring their own sports shoes to the testing.

The reason why school going children and adolescents were chosen as the study sample is that the results of the current study could be of particular importance to them. School going children and adolescents annually participate in fitness test batteries in Life Orientation/Physical education classes that typically include a short anaerobic sprint. The sprint test is sometimes done on a hard running surface (where spikes cannot be used) and children and adolescents have the choice to sprint either BF or in running shoes. Furthermore, many South African children and adolescents participate in athletics competitions that are sometimes held on synthetic athletics tracks and most children and adolescents do not own spikes. They then have to choose whether they will sprint BF or in their running shoes but there is uncertainty on which footwear condition is faster. The results of the current study will enable them to make an informed decision on whether it is faster to sprint BF or in running shoes during fitness tests and athletics competitions.

3.4. PLACE OF STUDY

Testing was done at the selected schools in the Western Cape on an appropriate hard flat surface such as a smoothed cement floor, a gravel road, or a netball court. Testing was done either during physical education lessons or after school.

3.5. DURATION OF THE STUDY

Data were collected over a period of two months, from the beginning of August 2015 until end September 2015.

3.6. DELIMITATIONS

Only children and adolescents aged 8-19 from the randomly selected schools in the Western Cape were tested and all children and adolescents were only tested on one occasion.

3.7. ASSUMPTIONS

It was assumed that children and adolescents were honest concerning the inclusion and exclusion criteria. That children and adolescents took part out of their own free will and not as a result of any form of pressure. That all children and adolescents were motivated to perform to the best of their ability and that children and adolescents adhered to the rule of not borrowing someone else's shoes.

3.8. ETHICAL ASPECTS

The current study formed part of a larger study "Moving Feet – A Comparative Study between Habitually Barefoot and Shod School-Aged Children" which also formed part of the large binational research project (Hollander, *et al*., 2016) and ethical approval was received under that study. The study protocol was approved by the Departmental Ethics Committee (DESC) at Stellenbosch University and the Research Ethics Committee: Human Research (Humanities) (Proposal number HS1153/2014) (Appendix One). Permission to perform the study was also obtained from the Western Cape Education Department (Appendix Two) and the principals of the selected schools. Informed consent forms were given to children and adolescents to take to their parents/guardians and assent forms were given to the children and adolescents to fill in if they wanted to volunteer for the study (Appendix Three-Eight). All participation was voluntary and no remuneration was given. Each participant, however, received a small thank you gift after being tested such as a small ruler, tennis ball or a Steri Stumpie. Children and adolescents were not informed about the gift before they decided to volunteer. Children and adolescents were informed that they could withdraw from the testing procedure at any time without any negative consequences and all tests had standardized protocols and were safe. Children and adolescents' names were not recorded. Instead, each child and adolescent received a participant number to maintain his or her anonymity. Data were kept on a personal laptop safe guarded by a password. The hard copies of the recording sheets and ethical forms were kept in a locked room protected by an alarm system at the department of Sports Science at Stellenbosch University.

3.9. EXPERIMENTAL PROCEDURES

CLOTHING

Children and adolescents were tested in light exercise clothing or in their school shirt and exercise shorts, provided by the researchers, if they did not have light exercise clothing. Some of the children and adolescents from one primary school sprinted in a sports shirt and tracksuit pants since the exercise shorts of appropriate size was not available during that testing occasion for them to borrow. Children and adolescents sprinted in the shoes they usually do sport or physical activity in on a hard surface. Therefore, the type of shoe used was not the same for all participants. This was decided because it was expected that not all children and adolescents would own the same type of shoe such as regular running shoes for example. The researchers decided to not buy new standardised shoes for participants to sprint in because according to Nyska *et al*. (1996), running patterns may be altered and unnatural when first performing in new shoes. The shod condition will from now on also be referred to as sports shoes. Researchers used their own discretion to decide whether shoes were appropriate sports shoes or not. Appropriate shoes included regular running shoes, trail running shoes, tennis shoes, squash shoes, netball shoes, CrossFit shoes, indoor soccer shoes and indoor hockey shoes. The researchers did not consider any of the following factors of the shoe when deciding whether shoes were appropriate or not and no measures were made of the following: age of shoes, midsole bending stiffness, degree of traction of sole, flaring of the shoe. Children and adolescents were excluded if their shoes were not appropriate and they were not allowed to borrow each other's shoes. This was monitored as well as possible by the researchers. The researchers suspected that some children and adolescents would not bring appropriate exercise clothes with them; therefore, researchers took exercise shorts of varying sizes to the testing for children and adolescents to use.

RECRUITMENT OF CHILDREN AND ADOLESCENTS AT SCHOOLS

Printed copies of the informed assent and consent forms were given to teachers to hand out to the children and adolescents during school. An explanation on the relevance and procedures of the study was given to the teachers and they were asked to ask the children and adolescents if they would like to volunteer. Only a limited amount of students could be tested per lesson and volunteers were recruited on a first-come, first-served basis. Table 3.1 illustrates the order in which testing procedures occurred on testing days.

BLINDING

It was impossible to blind the children and adolescents; however, children and adolescents were not informed of the true aim of the study to avoid potential bias from their preconceived ideas on which footwear condition should be faster.

Table 3.1. The order in which testing procedures occurred on testing days.

#	Test/Measurement
1	Pre-test administration.
2	Anthropometric measurements and measuring shoe mass.
3	20m Sprint test (the footwear condition in which participants sprinted first was randomised)

PRE-TEST ADMINISTRATION

Before testing, children and adolescents handed in their signed assent and consent forms and were asked if they had any injury/illness/condition that could prevent a maximal performance. Children and adolescents then received a recording sheet (Appendix Nine) with their participant number on. Participant numbers were also written on children and adolescents' hands to help them remember their number and make responses quicker when their number was called out to sprint. Children and adolescents were asked to carry their recording sheet with them to all the testing stations and to hand it in after their testing.

3.10. TESTS AND MEASUREMENTS

3.10.1. ANTHROPOMETRIC ASSESSMENT AND MEASURING SHOE MASS

Body mass

Children and adolescents were weighed BF in light sports clothes or school shirt and exercise shorts. Some of the children and adolescents from one primary school were weighed in a sports shirt and tracksuit pants because of the aforementioned reasons. Body mass was measured on a digital scale (A&D Personal Precision Scale UC-321, Milpitas, CA, USA). Children and adolescents were asked to remove anything from their pockets that would add extra mass. The scale could accurately measure to the nearest 0.05kg. The A&D Personal Scale UC-321 had face validity and was assumed to be a valid measuring instrument for body mass. Each day before testing the scale was calibrated with a 2.5kg weight.

Standing height

Height was measured with a portable stadiometer (Charder HM-200P Portstad, Charder Electronic Co Ltd, Taichung City, Taiwan) while BF with children and adolescents' heads in the Frankfurt plane. The stadiometer measured to the nearest 1cm. Children and adolescents were asked to take in a deep breath, to then relax and gently exhale while maintaining an upright position. Height was measured at the end of exhalation. The portable stadiometer had face validity and was assumed to be a reliable measuring instrument.

3.10.2. SHOE MASS

The left shoe of each child was weighed with a kitchen scale (MAINSTAYS ™ Digital Kitchen Scale) weighing accurate to 1g. The value was multiplied by two to give the weight of the pair of shoes. The scale had face validity for measuring mass.

3.10.3. SPRINT TEST (20M)

The 20m sprint test was chosen since it is an established fitness test used in the Eurofit protocol to assess schoolchildren in Europe (Kremer *et al*., 2001). The chosen distance is also very relevant to the study population since it tests acceleration and acceleration is a very relevant motor skill to the study population in the current study as described in (1.1).

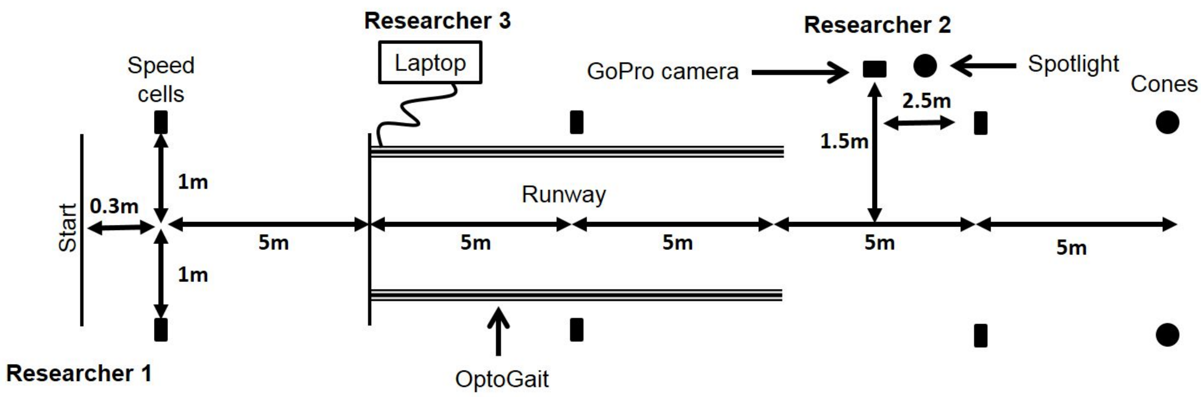

Figure 3.1. Set-up for the 20m sprint test.

Figure 3.1 shows how the 20m sprint test was set-up. A 2m starting line was marked and photocells (Brower Timing Systems speed gates, Salt Lake City, UT, USA) with an accuracy of 0.01s were set up 0.3m, 10.3m and 20.3m from the starting line. The Brower timing system has previously been shown to be valid and reliable to measure 10m and 20m sprint times (Shalfawi *et* al., 2010; Shalfawi *et* al., 2012). The reason that the starting line was 0.3m from the first photocell was to prevent children and adolescents from accidently setting it off prematurely. Photocells were placed 2m apart, perpendicular to the runway, each being 1m from the centre of the runway. The height of the photocells varied at different testing locations. Photocells were made about waist height to measure the displacement of the centre of mass (CoM) throughout the sprints. Heights were, therefore, higher when testing adolescents in high school compared to when testing primary school children and adolescents. Two cones were placed at the 25m mark (5m beyond the finish line) and children and adolescents were instructed to sprint past the cones before slowing down. This was done to encourage children to not slow down before reaching the finish line. A wide-angle high-speed camera (GoPro HD Hero 4, GoPro Inc., San Mateo, California, USA) was placed on the ground (to minimise the top-down view effect) perpendicular to the runway at the 17.5m mark and 1.5m from the centre of the runway. The GoPro was placed on the side of the runway so that the sun was behind the GoPro. The side varied at different testing opportunities. A spotlight (Godox LED308 Video Light, Fuyong Town, Baoan District, Shenzhen, China) with a strength of 5600K was used to shine onto the area where foot strikes were videoed when ambient lighting was not enough. The spot light was placed immediately to the side of the camera so that no light shined directly into the GoPro camera's lens. A smartphone with the GoPro app was used to check if the video image was clear before testing.

Masking tape was used to mark a line 5m from the first photocells to act as the starting point for the OptoGait photoelectric cell system (Microgate S.r.I, Bolzano, Italy) with optical sensors working at a frequency of 1000 Hz at an accuracy of 1 cm. The OptoGait was set up from the 5-15m marks just inside the legs of the photocell tripods. Researcher 1 stood at the starting line to explain the procedures to the children and adolescents, to make sure they started at the right place, to set them off, to remotely operate the photocells and to record their times on the recording sheets. Researcher 2 was situated behind the GoPro camera to operate it and to show little cards to the camera with appropriate participant numbers on before each trial. Researcher 3 operated the OptoGait on a laptop.

Before testing, children and adolescents were informed of the procedures. Children and adolescents performed two maximal effort sprint trials in a BF and sports shoe condition. Only two trials were done in each footwear condition as this was prescribed in the Eurofit protocol for the 20m sprint test and this protocol was used for the bi-national study (Kremer *et al*., 2001). The researchers believe that two trials were enough to get repeatable results since the 10m and 20m sprint test has previously been shown to be highly reproducible without need for familiarization. The 10m sprint was shows to have a coefficient of variance (CV) of 2.0% and an intraclass correlation coefficient (ICC) of 0.93 and the 20m sprint has been shown to have a CV of 1.0% and an ICC of 0.91 (Moir *et al*., 2004).

All trials were done from a standing start position with both feet behind the starting line. Children and adolescents could place their feet as they liked behind the line. Most, if not all, the children and adolescents started from a staggered stance. After the signal was given, children and adolescents started whenever they were ready. The footwear condition in which children and adolescents performed their first two sprints was randomised. Children and adolescents were informed to slowly walk back to the starting line after each sprint and a rest period of at least two minutes was given between sprinting trials. The fastest sprint time in each footwear condition was taken as their score. Further statistical analysis for relevant data such as their 10m and 20m sprint times, spatiotemporal gait parameters and foot strike pattern (FSP) was only done for their fastest sprint in each footwear condition. If the researchers perceived that a maximal attempt was not given children and adolescents were asked to redo that trial after a rest period of at least two minutes. The criteria used to judge if participants sprinted maximally was to observe if they decelerated before crossing the finish line and to subjectively judge if the participant's effort was maximal.

3.10.4. MEASURING SPATIOTEMPORAL GAIT PARAMETERS

The OptoGait photoelectric cell system (Microgate S.r.I, Bolzano, Italy) with optical sensors working at a frequency of 1000 Hz at an accuracy of 1 cm was used to measure the following spatiotemporal gait parameters: stride length (m), stride frequency (strides/s), ground contact time (s) and flight time (s). Lee *et al*. (2014) found that the OptoGait has strong concurrent validity along with relative and absolute test-retest reliabilities. They calculated intra-class correlation coefficient values (ICC) and coefficients of variation of method error (CV_{ME}) between the Optogait and the Gaitrite electronic walkway (CIR System Inc., Clifton, NJ, USA). They found high test retest reliability with ICC values of (0.929-0.988) for stride length, stride frequency, flight time and ground contact time. They also found that CV_{ME} values were relatively small (0.32-1.37%) for stride frequency and stride length and (3.37-4.07%) for contact time and flight time. For all these parameters SEM between two sessions were low (2.17−5.96%) indicating strong and absolute reliability. Minimum detectable changes (MDC95) at a confidence level of 95% were calculated and indicated a low level of variation between the two sessions with values ranging from 6.01−16.52%. They concluded that the OptoGait can be used for clinical assessments or research purposes as an objective means of assessing gait and similar results were found by Lienhard *et al*. (2013).

3.10.5. DETERMINING FOOT STRIKE PATTERN

Videos were taken with a wide-angle high-speed camera (GoPro HD Hero 4, GoPro Inc., San Mateo, California, USA). The camera was set to record at a frequency of 240Hz, resolution was WVGA = 848x480 pixels (16:9), and an ultra-wide angle setting was used. The camera was placed on the floor to minimise the top down view effect in order to determine foot strike patterns more accurately. This allowed the foot strike to occur as close to the middle of the camera's view as possible where the fish eye effect caused by the camera was the least. A GoPro HD Hero 4 camera was chosen instead of a standard video camera for four reasons namely: 1) because the GoPro allows an ultra-wide angle view. We wanted a camera with such a feature to increase the probability that a foot strike would fall in the camera's view. Using this setting allowed the researchers to place the camera as close as 1.5m from the centre of the runway and still acquire at least two steps for all participants. 2) The GoPro was also chosen because of its high frequency of 240Hz which is similar to the 250Hz used by de Almeida *et al*. (2015) and higher than the frequency used in previous studies such as Kerr, *et al*. (1983) cited in de Almeida *et al*. (2015) who used 60Hz and Hasegawa *et al*. (2007) who used 120Hz. 3) The GoPro is very small and this allowed the lens to be very close to ground level which minimised the top-down view effect. 4) Lastly the GoPro was a cost effective option.

Video analysis software (Kinovea 0.8.15) was used to view the high-speed videos frame by frame and to determine FSP. The Kinovea software has a function to zoom in up to x2.5 and this zoom function was used to make the classification process more accurate. Foot strike was taken when the foot initially made contact with the ground. This was determined by playing the video forward and backward frame by frame to see at which point the part of the foot that initially touches the ground does not further move down. This was often easier to determine while playing the video backwards and seeing when the foot leaves the ground. Another method that has been used is to classify foot strike patterns at the first sign of weight bearing which can be seen by deformation of the fat pad on the sole of the foot or deformation of the sole of the sole of the shoe. The researchers did not choose this method because they believe that if a certain part of the foot initially touches the ground then that part of the foot is also the part that first begins to bear weight.

FSPs were determined subjectively with a visual method as done by de Almeida *et al*. (2015). This method was chosen because no markers were placed/made on anatomical landmarks of the foot or lower leg due to time constraints when testing. The researchers acknowledge that more objective methods to determine FSP with video analysis exist such as using software to calculate posterior sole angle at touch down and correcting for this angle during normal stance but these methods require that markers be placed on participants (Lieberman *et* al., 2010; Altman & Davis, 2012).

FSPs were divided into three categories as done by Lieberman *et al.* (2010). The three categories are rearfoot strike (RFS), where the heel of the foot makes first contact with the ground, midfoot strike (MFS), where the heel and the ball of the foot makes contact with the ground at the same time and forefoot strike (FFS) where the ball of the foot makes first contact with the ground.

Since only the video of the fastest sprint in each footwear condition was analysed, only one foot strike was analysed for each child in each footwear condition. The fastest BF sprinting trials were analysed first for each child and the foot strike that occurred closest to the centre of the camera's view was analysed whether it was from a medial or lateral view. The same foot was then analysed in the shod condition for that child to eliminate FSP differences between feet.

403 FSPs were determined from the high-speed videos. 50 BF and 50 shod randomly selected foot strikes were re-assessed three weeks after the first assessment and only four of the 100 FSPs were not classified the same as the first assessment. Therefore, 25% (100/403 x 100=25%) of the total number of foot strikes were re-assessed. Testing for intrarater reliability gave the following kappa coefficient of conformance: kappa=0.94 with a 95% confidence interval of 0.89-0.98.

The images in Figure 3.2 in the top row of images, starting from the left, we see a barefoot RFS on a netball court, a barefoot MFS on smoothed cement and a barefoot FFS on gravel. In the second row of images, starting from the left, we see a shod MFS on gravel, a shod FFS on a netball court and a shod RFS on smoothed cement.

Figure 3.2. Actual footage of foot strikes showing a rearfoot strike, midfoot strike and forefoot strike in both a barefoot and running shoes condition on the three different surfaces used in the current study.

3.11. STATISTICAL ANALYSES

All statistical analysis was done with Statistica (13.2.92.1 64-bit). Descriptive statistics of children and adolescents' physical characteristics as well as shoe mass and mean running speeds over the last 10m were determined as mean±SD. The range of average running speeds over the last 10m was also determined. Preceding further analyses, tests for interactions between participants' footwear condition with participants' sex, age and running surface were done for all dependent variables. Participants would be divided into groups based on sex, age or running surface if the tests for interactions produced statistically significant values.

A mixed model linear regression was used to assess the differences between sprinting BF or shod in 10m and 20m sprint time and spatiotemporal variables. To take account of the repeated measure of the assessment, the participant was added as a random effect and footwear condition was added as a fixed effect. FSP and shoe weight were added as covariates to test if they explained the differences in 10m and 20m sprint performance and spatiotemporal variables between the BF and shod conditions. A McNemar Chi-squared test was done to compare FSP distributions between the BF and shod conditions. Statistical significance was taken at ($p<0.05$) for all analyses. Cohen's d values were calculated to determine practical significance and were interpreted as follows: $d<0.20$ negligible, $d=0.20$ small, $d=0.50$ moderate and $d=0.80$ large effect size.

CHAPTER FOUR

RESULTS

4.1. INTRODUCTION

The primary aim of the current study was to determine the acute effects of changing from running shoes to barefoot (BF) on 10m and 20m sprint performance and spatiotemporal variables in schoolchildren in the Western Cape. The secondary aim was to determine the acute effects of changing from running shoes to BF on foot strike pattern (FSP) during sprinting in schoolchildren in the Western Cape. The results will be reported according to the objectives set out for the current study

4.2. GROUPING OF PARTICIPANTS

Not all children and adolescents had full data sets, therefore, the number of children and adolescents reported for different variables throughout the results are different.

Table 4.1 shows the p-values where participants' footwear condition was added as a main effect for all dependent variables as well as tests for interactions of participants' footwear condition with sex, age and running surface for all dependent variables. All spatiotemporal variables were only assessed on a netball court, therefore, "NA" was inserted in Table 4.1 for the tests for interaction between participants' footwear condition with the running surface.

Table 4.1. Outcomes expressed in p-values where participants' footwear condition was added as a main effect for all dependent variables as well as tests for interactions of participants' footwear condition with sex, age and running surface for all dependent variables.

Dependent variable	Footwear	Footwear with sex and age	Footwear with sex	Footwear with age	Footwear with surface
10m sprint time	0.000***	0.59	0.759	0.772	0.225
20m sprint time	0.000***	0.95	0.529	0.444	0.151
Stride length	0.000***	0.731	0.592	0.811	NA
Step frequency	0.000***	0.256	0.173	0.169	NA
Flight time	0.022*	0.131	0.504	0.44	NA
Ground contact time	0.000***	0.719	0.286	0.79	NA
Swing time	0.000***	0.119	0.247	0.323	NA
Foot strike pattern	0.000***	0.842	0.604	0.381	0.472

*Significantly different from sprinting barefoot ($p \leq 0.05$).
**Significantly different from sprinting barefoot ($p \leq 0.01$).
***Significantly different from sprinting barefoot ($p \leq 0.001$).

Table 4.1 shows that the footwear main effect was significant across all the dependent variables. This means that changing from running shoes to BF significantly changed all dependent variables and that further analysis can be done to see how the variables were changed. Furthermore, Table 4.1 shows that all interactions between participants' footwear condition with sex, gender and running surface were not statistically significant. This means that participants' sex, age and running surface had no significant effect on the difference between BF and shod conditions across all dependent variables. In other words, the same footwear effect was seen in both sexes, across all ages and on all running surfaces for all dependent variables. These results show that all children and adolescents can be grouped together in further analysis to investigate the acute effects of participants' footwear condition on all dependent variables. Subdividing participants into different sexes, age groups or groups based on running surface would increase the chance of false findings. Therefore, all further analysis done to investigate the acute effects of changing from running shoes to BF on all dependent variables will be done by grouping all participants together.

4.3. PARTICIPANT CHARACTERISTICS

Table 4.2 displays the physical characteristics and the average shoe mass with standard deviations (SD) with all participants grouped together. Shoe mass data were not always collected. As mentioned before in the methodology, the current study formed part of a larger study where multiple tests were done within one testing occasion. At some testing occasions there was a shortage of researchers and not all participants' shoe mass could then be measured due to time constraints of physical education lessons in which data were collected.

Table 4.2. Physical characteristics and information on shoe mass of all participants expressed in mean±SD.

Age		Height (cm)		Body mass (kg)		Shoe mass (g)	
n	mean±SD	n	mean±SD	n	mean±SD	n	mean±SD
276	13.6±2.7	275	160±17	275	55.30±16.80	169	557±110

4.3. SPRINT PERFORMANCE AND SPATIOTEMPORAL VARIABLES

Table 4.3 shows the mean values of participants' 10m and 20m sprint times and spatiotemporal variables in the BF and shod condition along with 95% confidence intervals (95% CI), the difference in means between footwear conditions, mean percentage change, p-values and Cohen's d-values. Mean percentage change was determined by dividing the difference in means by the mean value of the shod condition and multiplied by 100. For example the mean percentage change in 10m sprint time was calculated as 0.03÷2.14x100=1.40% and flight time (FT) was calculated as 0.002÷0.099x100=2.02%.

Statistically significant differences as well as small to medium practically significant differences were found between the BF and shod conditions for participants' 10m and 20m sprinting performance and all the measured spatiotemporal variables. In the BF condition the following was found: Participants' 10m sprint performance was 0.03s (1.40%) faster (p≤0.001) with a d-value of 0.24, indicating a small practical significant difference. 20m Sprint performance was 0.07s (1.86%) faster (p≤0.001) with a d-value of 0.25, indicating a small practical significant difference. Stride length (SL) was 10cm (3.43%) shorter (p≤0.001) with a d-value of 0.42, indicating a medium practical significant difference. StepF was 0.216Hz (5.61%) higher (p≤0.001) with a d-value of 0.73, indicating a medium practical significant difference. FT was 0.002s (2.02%)

shorter ($p \leq 0.05$) with a d-value of 0.16, indicating a small practical significant difference. Ground contact time (GCT) was 0.012s (7.41%) shorter ($p \leq 0.001$) with a d-value of 0.69, indicating a medium practical significant difference. Swing time (SwT) was 0.017s (4.72%) shorter ($p \leq 0.001$) than the shod condition with a d-value of 0.56, indicating a medium practical significant difference. Figures 4.1-4.6 graphically illustrates the differences found between the BF and shod conditions for 10m and 20m sprint performances and all spatiotemporal variables.

The results for the crude models in Table 4.3 and 4.4 are identical. Table 4.4 shows adjustments for FSP and shoe mass as confounders. All the significant differences between the shod and BF condition remained when adjusting for FSP. Therefore, the reason for the difference in sprinting performance and spatiotemporal variables is not due to differences in FSP caused by the footwear effect. When adjusting for shoe mass, however, all the significant differences disappeared. Therefore, shoe mass explained the significant differences in 10m and 20m sprint performance and all spatiotemporal variables between the running shoes and BF condition.

Table 4.3. The influence of sprinting barefoot or shod on sprint performance and spatiotemporal variables. The p-values represent statistical significance and Cohen's d-values represent practical significance.

		Crude[a]			Difference in means	Mean % change	p	d
		n	mean	(95% CI)				
10m sprint (s)	barefoot	274	2.11	2.08-2.14	0.03	1.40	0.000***	0.24(small) †
	shod	199	2.14	2.12-2.17				
20m sprint (s)	barefoot	276	3.69	3.64-3.74	0.07	1.86	0.000***	0.25(small) †
	shod	201	3.76	3.71-3.81				
Step frequency (Hz)	barefoot	106	4.069	4.014-4.124	0.216	5.61	0.000***	0.42(medium) ††
	shod	109	3.853	3.798-3.908				
Stride length (cm)	barefoot	106	282	277-286	10	3.42	0.000***	0.73(medium) ††
	shod	109	292	287-297				
Flight time (s)	barefoot	106	0.097	0.094-0.099	0.002	2.02	0.022*	0.16(small) †
	shod	109	0.099	0.097-0.102				
Ground contact time (s)	barefoot	106	0.150	0.147-0.153	0.012	7.41	0.000***	0.69(medium) ††
	shod	109	0.162	0.158-0.165				
Swing time (s)	barefoot	106	0.343	0.338-0.349	0.017	4.72	0.000***	0.56(medium) ††
	shod	109	0.360	0.354-0.366				

*Significantly different from sprinting barefoot (p≤0.05).
**Significantly different from sprinting barefoot (p≤0.01).
***Significantly different from sprinting barefoot (p≤0.001).

†Small effect (d<0.20)
††Medium effect (d<0.50)
†††Large effect (d<0.80)

Table 4.4. The influence of sprinting barefoot or shod on sprint performance and spatiotemporal variables with adjustments for FSP and shoe mass. FSP=foot strike pattern.

		Crude[a]				Adjusted for FSP[c]				Adjusted for shoe mass[d]			
		n	mean	(95% CI)	p	n	mean	(95% CI)	p	n	mean	(95% CI)	p
10m sprint (s)	barefoot	274	2.11	2.08-2.14	0.000***	237	2.08	2.06-2.11	0.003**	167	2.15	2.10-2.20	0.882
	shod	199	2.14	2.12-2.17		163	2.11	2.08-2.13		162	2.15	2.11-2.20	
20m sprint (s)	barefoot	276	3.69	3.64-3.74	0.000***	238	3.63	3.59-3.68	0.000***	168	3.79	3.71-3.87	0.804
	shod	201	3.76	3.71-3.81		164	3.68	3.63-3.73		163	3.77	3.70-3.85	
Step frequency (Hz)	barefoot	106	4.069	4.014-4.124	0.000***	106	4.075	4.005-4.145	0.000***	89	3.982	3.879-4.085	0.551
	shod	109	3.853	3.798-3.908		108	3.877	3.803-3.951		90	3.931	3.828-4.034	
Stride length (cm)	barefoot	106	282	277-286	0.000***	106	282	277-287	0.000***	89	280	273-288	0.090
	shod	109	292	287-297		108	292	287-297		90	291	283-299	
Flight time (s)	barefoot	106	0.097	0.094-0.099	0.022*	106	4.075	4.005-4.145	0.000***	89	0.098	0.093-0.103	0.946
	shod	109	0.099	0.097-0.102		108	3.877	3.803-3.951		90	0.098	0.092-0.103	
Ground contact time (s)	barefoot	106	0.150	0.147-0.153	0.000***	106	0.150	0.146-0.153	0.000***	89	0.159	0.153-0.165	0.262
	shod	109	0.162	0.158-0.165		108	0.160	0.156-0.164		90	0.153	0.147-0.159	
Swing time (s)	barefoot	106	0.343	0.338-0.349	0.000***	106	0.343	0.334-0.352	0.000***	89	0.355	0.344-0.366	0.495
	shod	109	0.360	0.354-0.366		108	0.359	0.349-0.368		90	0.348	0.338-0.359	

[a]Crude; crude model without adjusting for confounders. [c]Adjusted for FSP; the same model as the crude model but adjusted for FSP. [d]Adjusted for shoe mass; the same model as the crude model but adjusted for shoe mass.
*Significantly different from sprinting barefoot (p≤0.05).
**Significantly different from sprinting barefoot (p≤0.01).
***Significantly different from sprinting barefoot (p≤0.001).
[1]Adjusted models not different (>10%) from crude model.

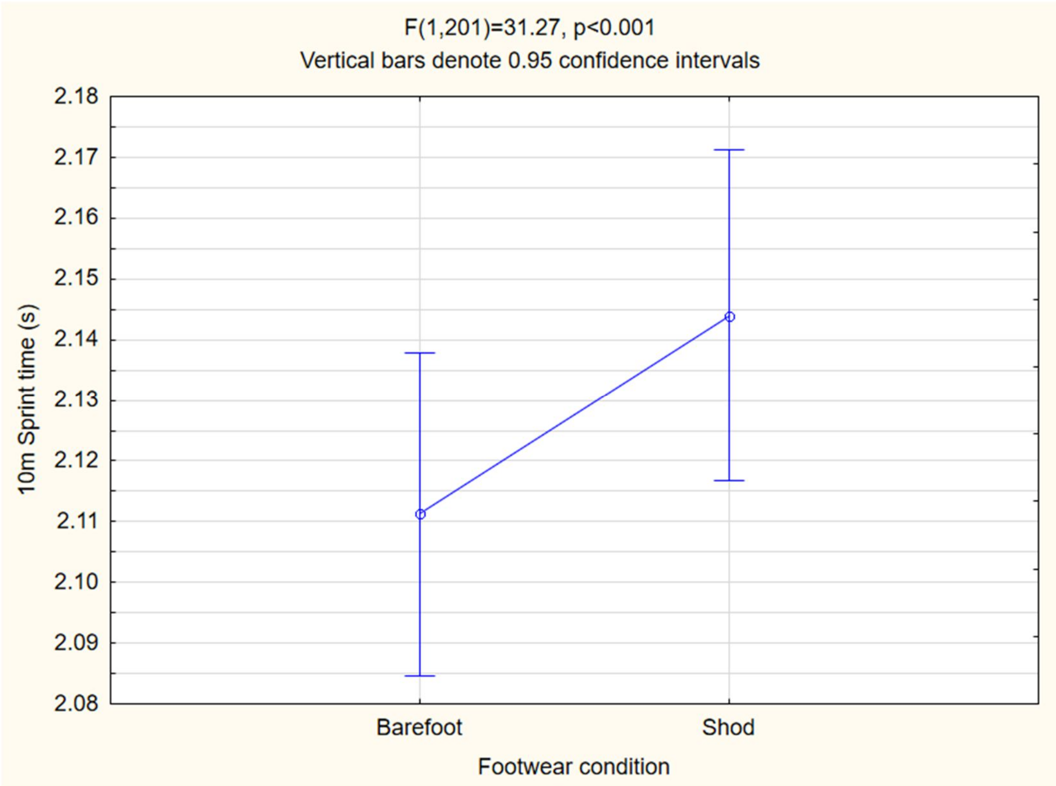

Figure 4.1. Mean differences in 10m sprinting performance between the barefoot and shod conditions.

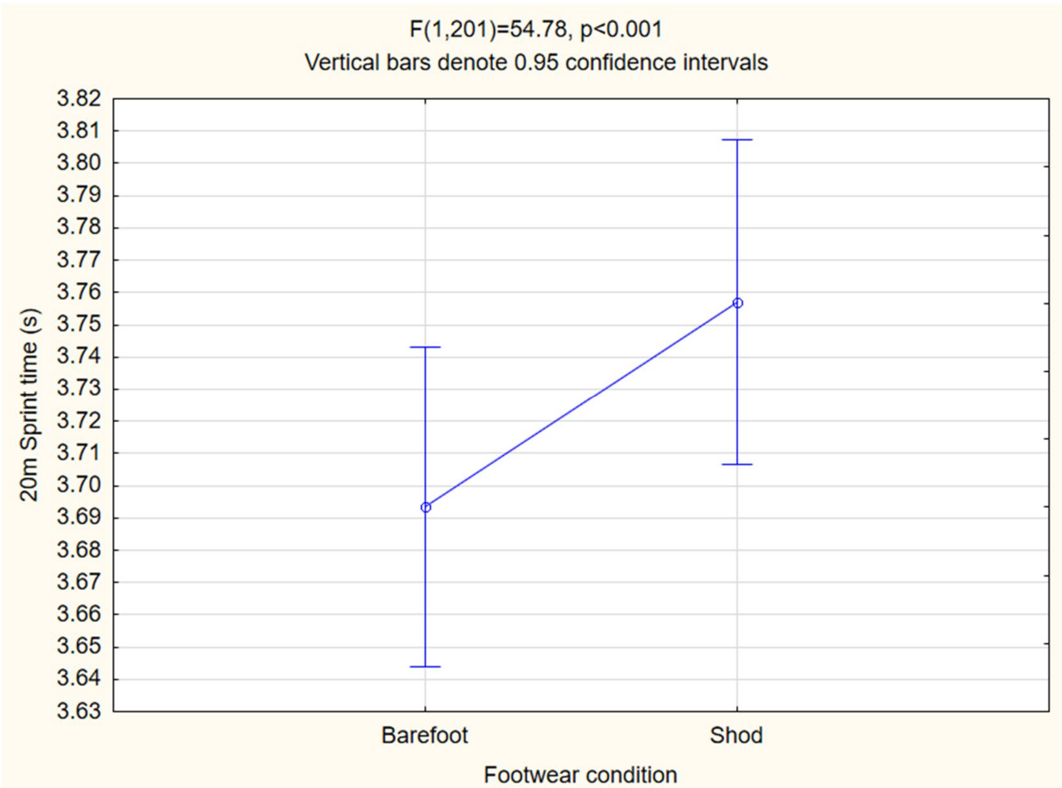

Figure 4.2. Mean differences in 20m sprinting performance between the barefoot and shod conditions.

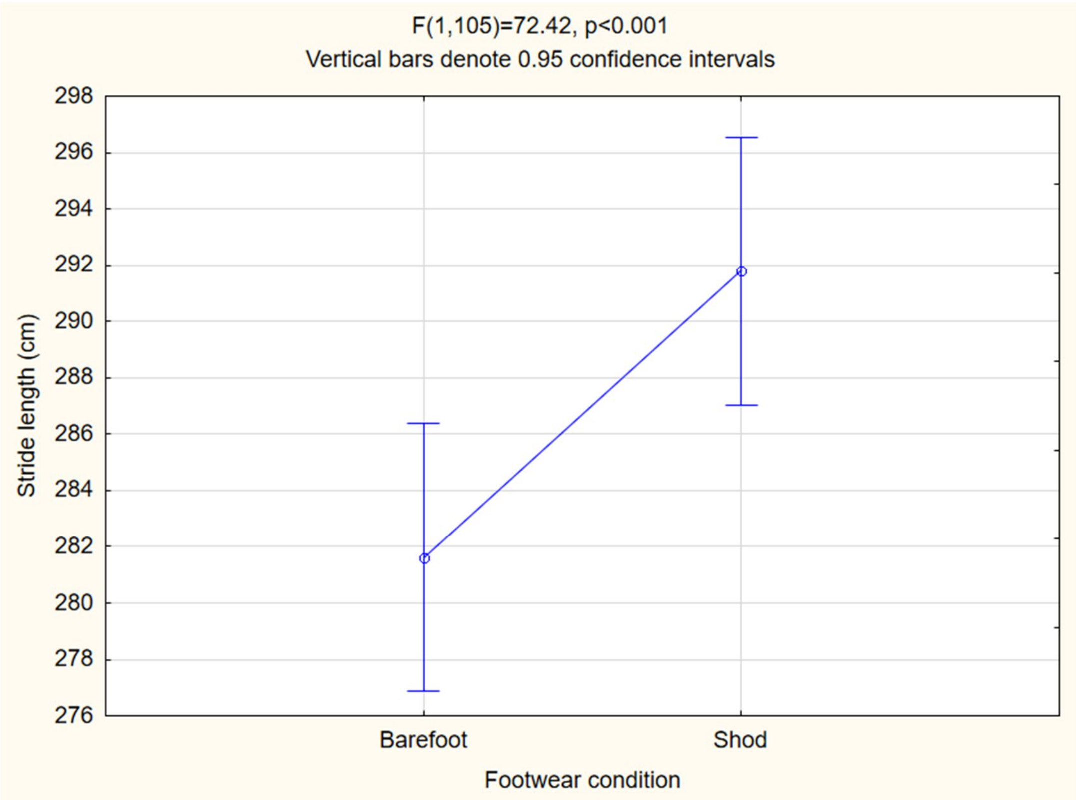

Figure 4.3. Mean differences in stride length between the barefoot and shod conditions.

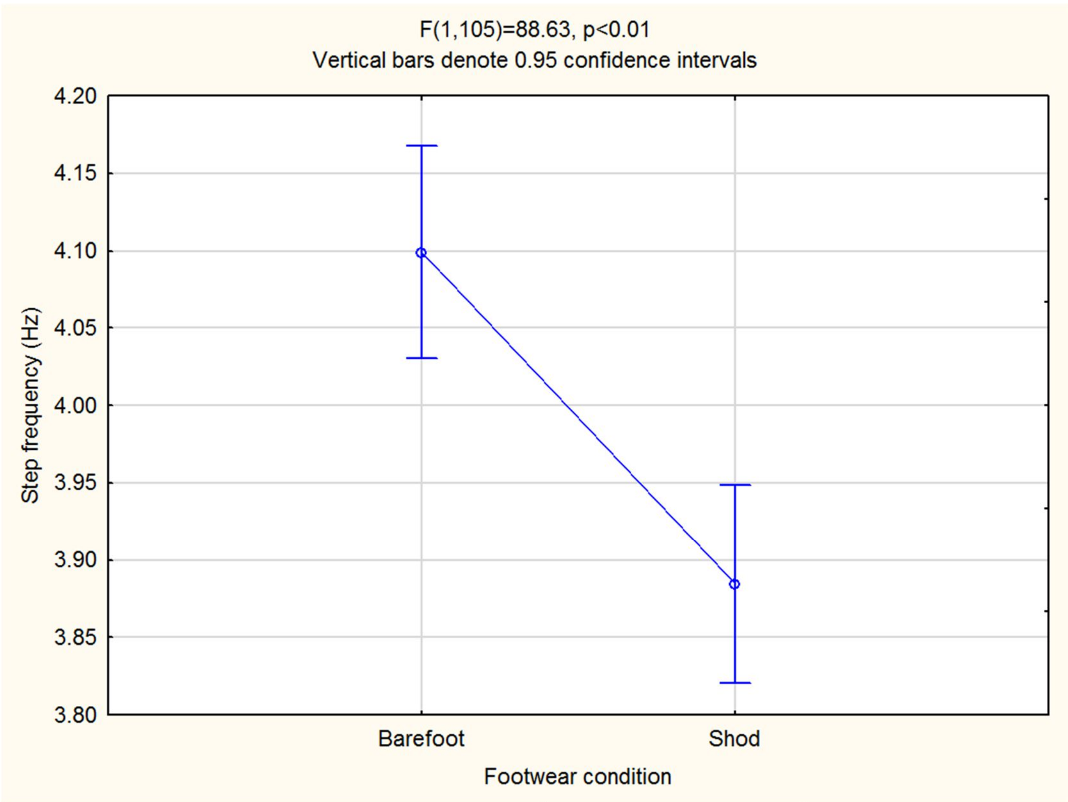

Figure 4.4. Mean differences in stride frequency between the barefoot and shod conditions.

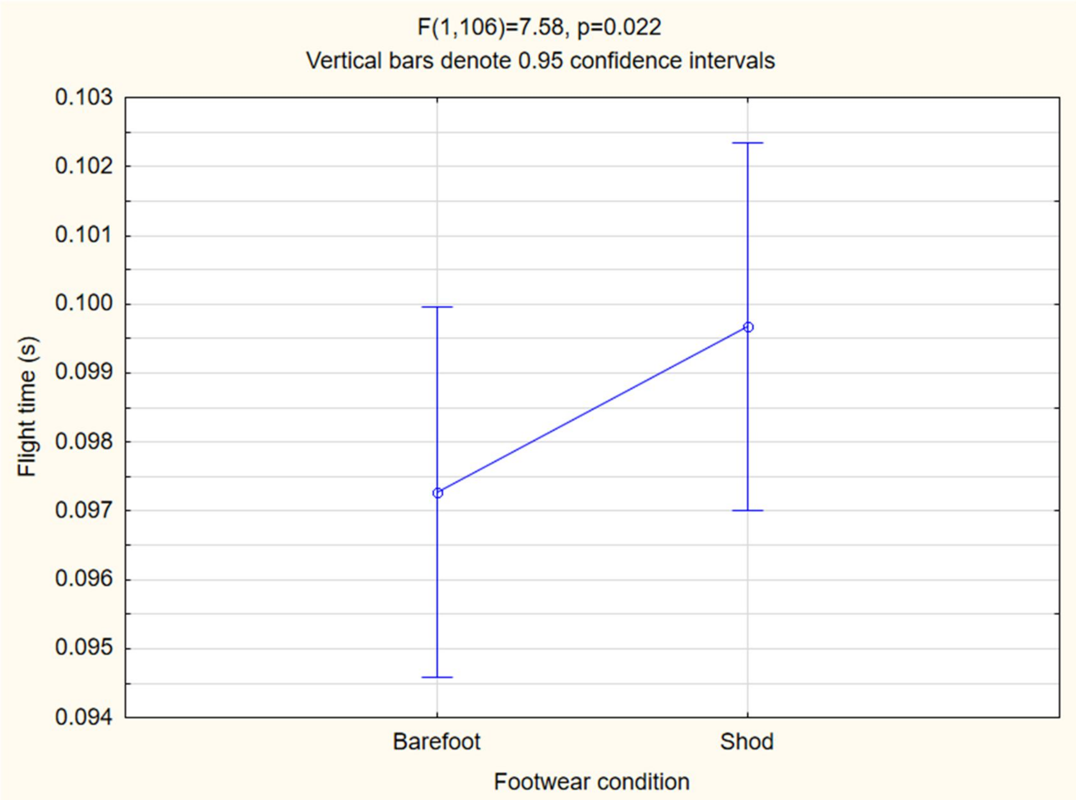

Figure 4.5. Mean differences in flight time between the barefoot and shod conditions.

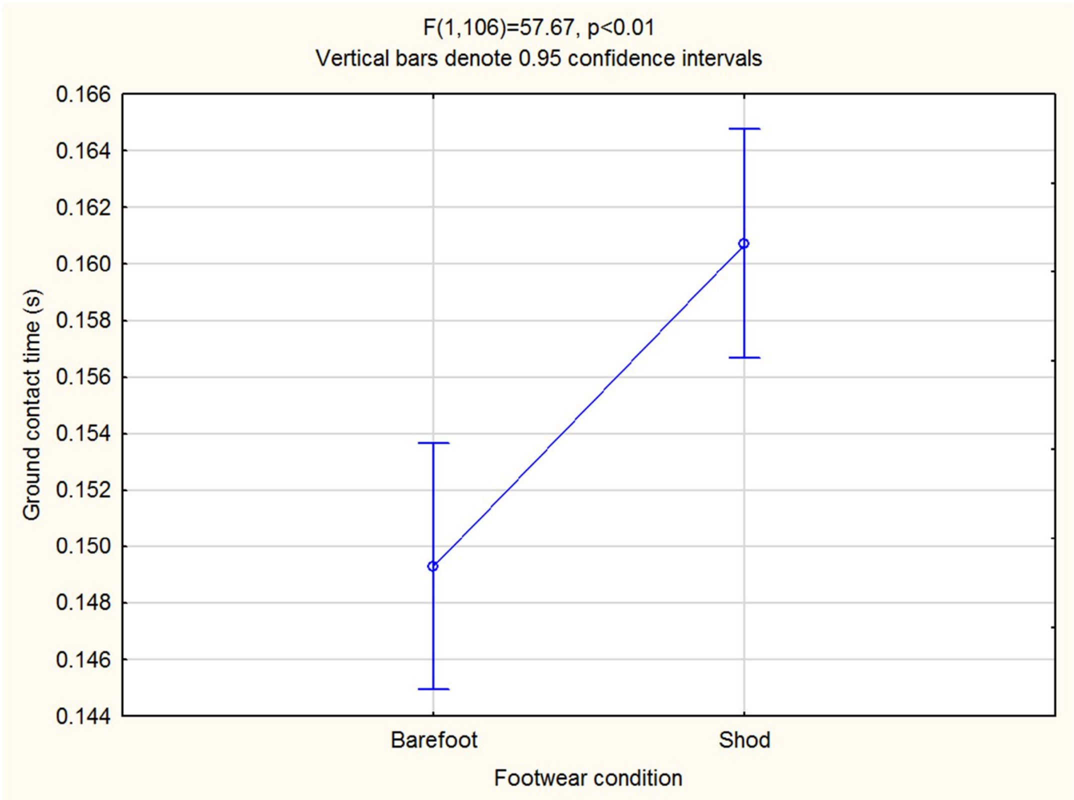

Figure 4.6. Mean differences in ground contact time between the barefoot and shod conditions.

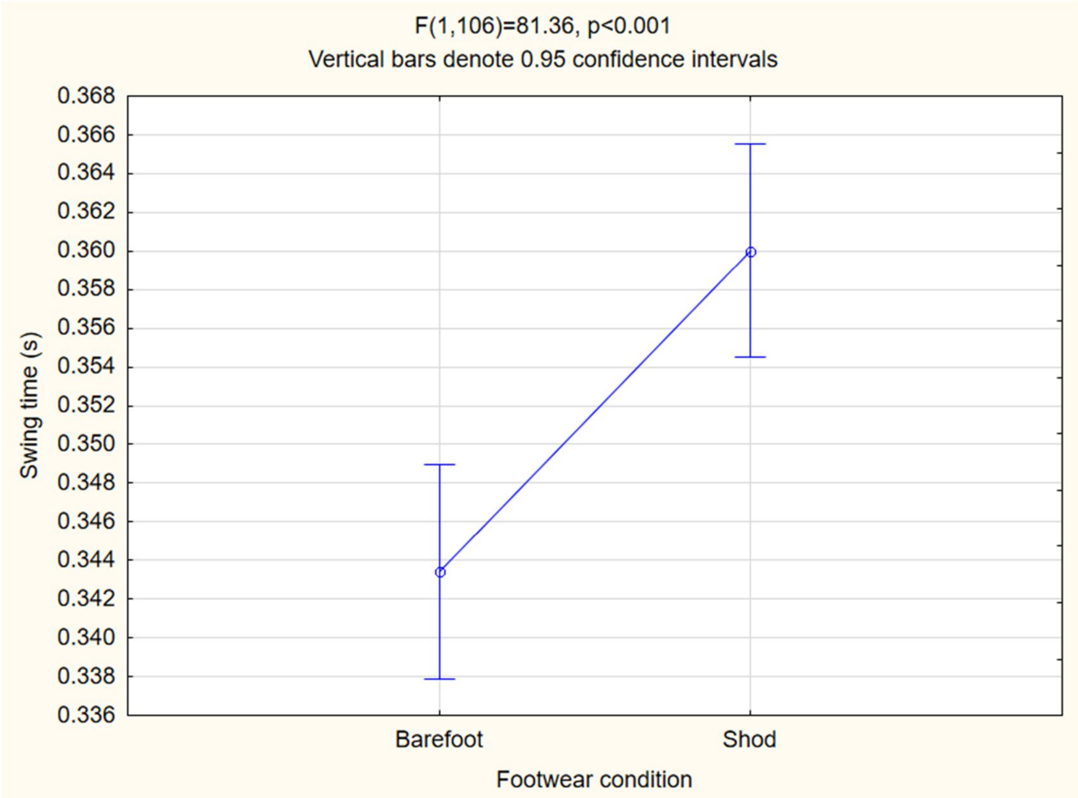

Figure 4.7. Mean differences in swing time between the barefoot and shod conditions.

4.4. FOOT STRIKE PATTERNS

Table 4.5 shows that FSPs were determined for 164 children and adolescents in the BF and shod condition. Although any appropriate type of sports shoe was allowed in the study, 161 (98%) of the 164 children and adolescents sprinted in running shoes (the vast majority in regular running shoes and a few in trail running shoes) and the other three participants sprinted in indoor soccer shoes. Therefore, these results should be very similar to that if only running shoes were used. Throughout the rest of the thesis, the shod condition will be referred to as running shoes since only three participants did not sprint in running shoes.

When sprinting in running shoes, 57% of children and adolescents used a rearfoot strike (RFS) and only 43% used a forefoot-/midfoot strike (FFS/MFS). The FSP distribution shifted significantly more towards a FFS/MFS when sprinting barefoot ($p<0.001$) with 73% using a FFS/MFS and only 27% using a RFS in the barefoot condition. The shod condition, therefore, encouraged a significantly higher rate of RFS and the barefoot condition encouraged a significantly higher rate of FFS/MFS.

Table 4.5. Foot strike pattern distributions in the barefoot and shod conditions when all participants were grouped together. RFS=Rearfoot strike, MFS=Midfoot strike and FFS=Forefoot strike.

	RFS (Frequency)	MFS/FFS (Frequency)	%RFS	%MFS/FFS	p
Barefoot	44	120	27	73	0.000***
Shod	94	70	57	43	

*Significantly different from sprinting barefoot (p≤0.05).
**Significantly different from sprinting barefoot (p≤0.01).
***Significantly different from sprinting barefoot (p≤0.001).

Figure 4.8 shows the FSP distributions in the BF and shod conditions. Figure 4.9 shows the probability of a RFS with 95% CI in the BF and running shoes condition and how the probability of a RFS significantly decreased when changing from running shoes to BF (p<0.001).

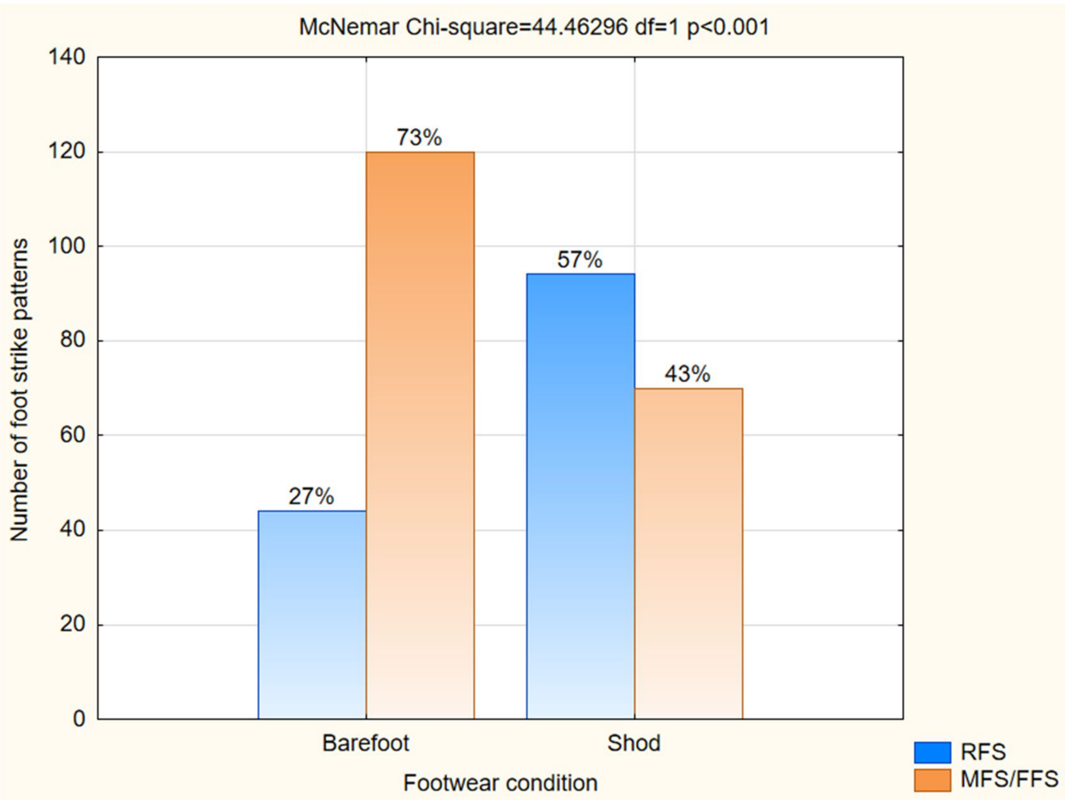

Figure 4.8. Foot strike pattern distributions in the barefoot and shod conditions.

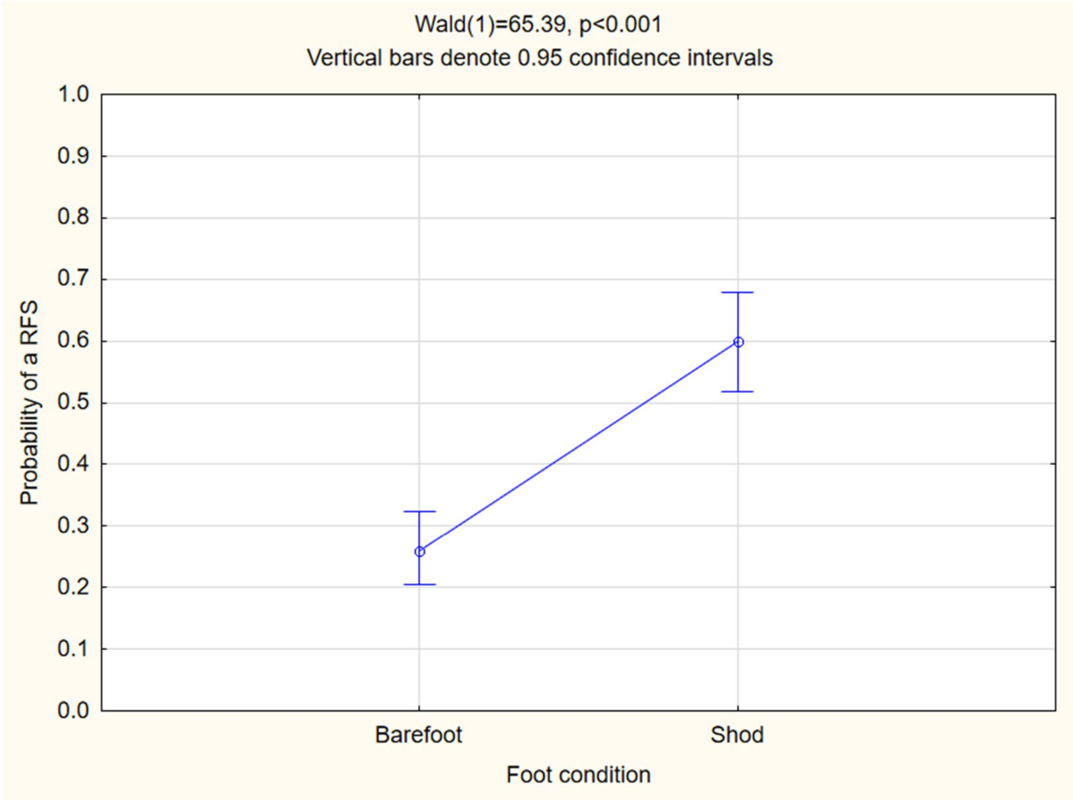

Figure 4.9. Probability of a rearfoot strike in the barefoot and shod conditions.

Table 4.6 shows the mean running speeds (m/s) over the last 10m when FSPs were determined along with standard deviation (SD) and the range. This is shown because previous research has shown that running speed affects FSP (Mullen & Toby, 2013). Table 4.6 will, therefore, allow average running speed to be taken into account when comparisons of FSP distributions are made with other studies.

Table 4.6. The mean running speeds (m/s) over the last 10m when foot strike patterns were measured along with standard deviation (SD) and the range.

	n	mean	± SD	Range	
BF	276	6.42	±0.93	2.69	-8.91
Shod	201	6.20	±0.91	2.57	-8.26

Further results of participants' physical characteristics along with mean shoe mass, all dependent variables and average running speeds over the last 10m when FSP was determined of girls and boys subdivided into three different age groups (<13, 13-15 and >15 years) in both the BF and running shoes conditions may be found in Appendix

Twelve. The reason for adding these results as an appendix is simply to provide comparable data to the body of literature.

4.5. SUMMARY

Statistically significant differences as well as small to medium practically significant differences were found between the BF and shod conditions for children and adolescents' 10m and 20m sprinting performance and all the measured spatiotemporal variables. When BF, children and adolescents' 10m and 20m sprint performances were significantly faster ($p<0.001$) but with only small effect sizes ($d=0.24$ and $d=0.25$ respectively). The faster sprinting performances when BF were due to a significantly higher StepF ($p<0.001$) with a medium effect size ($d=0.42$) despite being accompanied by a significantly shorter SL ($p<0.001$) with a medium effect size ($d=0.73$). The significantly higher StepF when BF was due to a significantly shorter FT ($p=0.022$) with a small effect size ($d=0.16$), a significantly shorter GCT ($p<0.001$) with a medium effect size ($d=0.69$) and a significantly shorter SwT ($p<0.001$) with a medium effect size ($d=0.56$). All differences in sprinting performance and spatiotemporal variables were due to the shoe mass effect and not due to FSP differences caused by the footwear effect. Changing from the shod to the BF condition caused a significant decrease in the occurrence of a RFS from 57% to 27% and a significant increase in FFS/MFS from 43% to 73% ($p<0.001$). The shod condition, therefore, encouraged a significantly higher rate of RFS and the BF condition a significantly higher rate of FFS/MFS.

CHAPTER FIVE

DISCUSSION

INTRODUCTION

The primary aim of the current study was to determine the acute effects of changing from running shoes to barefoot (BF) on 10m and 20m sprint performance and spatiotemporal variables in schoolchildren in the Western Cape. The secondary aim was to determine the acute effects of changing from running shoes to BF on foot strike pattern (FSP) during sprinting in schoolchildren in the Western Cape.

MAIN FINDINGS

The results showed that children and adolescents (boys and girls of all ages) sprinted marginally faster over 10m and 20m when BF than in running shoes. The average 10m sprint time was 0.03s (1.40%) faster when BF (2.11s) than in running shoes (2.14s) and the average 20m sprint time was 0.07s (1.86%) faster when BF (3.69s) than in running shoes (3.76s). Both the 10m and 20m sprint times were significantly faster when BF ($p<0.001$) but with only small effect sizes ($d=0.24$ and $d=0.25$ respectively).

The results of the spatiotemporal variables showed that the BF condition was marginally faster due to a significantly higher step frequency (StepF) despite being accompanied by a significantly shorter stride length (SL). Average StepF was 0.216Hz (5.61%) higher when BF (4.069Hz) than in running shoes (3.853Hz). This difference was statistically significant ($p<0.001$) and had a medium effect size ($d=0.42$). Average SL was 10cm (3.43%) shorter when BF (282cm) than in running shoes (292cm). This difference was also statistically significant ($p<0.001$) and had a medium effect size ($d=0.73$). Considering the sprint formula where average velocity (m/s) = stride length (m/stride) x stride frequency (strides/s) (Mero *et al.*, 1992; Zatsiorsky, 2000; Hunter *et al.*, 2004a; Fletcher, 2009), the shorter SL is disadvantageous to a faster sprinting performance if SF remains unchanged. The higher

StepF when BF, therefore, more than made up for the shorter SL. The higher StepF when BF was due to a significantly shorter flight time (FT) ($p=0.022$), ground contact time (GCT) ($p<0.001$) and swing time (SwT) ($p<0.001$). Average FT was 0.002s (2.02%) shorter when BF (0.097s) than in running shoes (0.099s) with only a small effect size ($d=0.16$). Average GCT was 0.012s (7.30%) shorter when BF (0.150s) than in running shoes (0.162s) with a medium effect size ($d=0.69$). Average SwT was 0.017s (4.72%) shorter when BF (0.343s) than in running shoes (0.360s) and had a medium effect size ($d=0.56$).

The small p-values found for 10m and 20m sprint times and all spatiotemporal variables indicate that differences definitely existed between the BF and running shoes condition for these variables and that these differences were not merely due to chance. However, the effect sizes indicate that the sizes of these differences were only either small or medium.

The results also showed that when adjusting for FSP all statistically significant differences between the BF and running shoes conditions for 10m and 20m sprint time and all spatiotemporal variables remained indicating that these differences were not due to FSP differences caused by the footwear effect. In contrast, when adjusting for shoe mass, all differences between the BF and running shoes conditions for 10m and 20m sprint times as well as for all spatiotemporal variables were insignificant. This showed that these differences were caused by the extra mass shoes add to the feet. Therefore, shoe mass has a significant effect on short anaerobic sprinting performance but the size of the effect is only small for both 10m and 20m sprinting performance.

Concerning FSP distributions, when sprinting in running shoes, 57% of children and adolescents used a rearfoot strike (RFS) and only 43% used a forefoot-/midfoot strike (FFS/MFS). The FSP distribution shifted significantly more towards a FFS/MFS when sprinting BF ($p<0.001$) with 73% using a FFS/MFS and only 27% using a RFS. Therefore, the shod condition encouraged a significantly higher rate of RFS and the barefoot condition encouraged a significantly higher rate of FFS/MFS while sprinting. The results of the current study were all contrary to the hypotheses except for the hypothesis that children and adolescents will have a significantly shorter SL, GCT, FT and SwT and a significantly higher StepF when sprinting BF compared to sprinting in sports shoes.

In the current study the additional mass running shoes added to the feet resulted in an increase in the moment of inertia of the leg and, therefore, decreased the speed at which the leg could be swung forward. As a result, more time was needed to reposition the leg for the next stride, explaining the significantly longer SwTs in running shoes. The increased moment of inertia in the running shoes condition also explains the significantly longer FT, since FT represents the time needed to reposition the leg for the next step (Weyand *et al.*, 2000). The longer FTs would have required a larger vertical ground reaction impulse (GRI) in order to project the body's centre of mass (CoM) higher. A possible way in which children and adolescents could have achieved this is to produce a resultant GRI that is angled more vertically. A resultant GRI refers to the result of the horizontal and vertical GRI components. When children and adolescents perform a maximal effort sprint it is assumed that their rate of force production against the ground and, therefore, the resultant GRI is at the maximal level that still allows an efficient sprinting technique. The resultant GRI during jumping for example would be higher than when sprinting but producing GRIs that are that high does not allow an efficient sprinting technique. In Figure 5.1, an arbitrary value of 1000N is used to illustrate the maximum resultant GRI when sprinting as an example. Angling the resultant GRI more vertically causes an increase in the vertical component and a decrease in the horizontal component. The increased vertical component will cause a higher vertical projection of the body's COM, allowing longer FTs, and the smaller horizontal component would decrease the forward running speed resulting in longer GCTs since GCT has been shown to be inversely proportional to the running speed (Moravec *et al.*, 1988; Fletcher, 2009; Hobara *et al.*, 2010; Nagahara *et al.*, 2014).

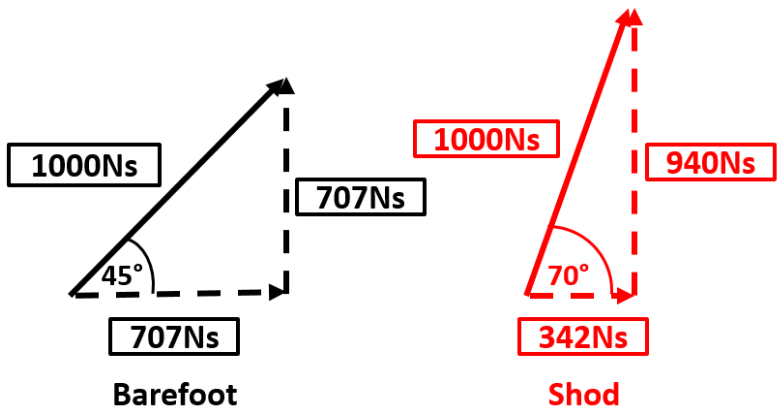

Figure 5.1. How the resultant ground reaction impulse, with an arbitrary value of 1000N in this figure, might be angled more vertical in the shod condition. The change in angle is exaggerated to emphasise the point the researchers are making. Potential changes in the angle that could actually occur are expected to be much less than illustrated.

The finding that there was a significant decrease in the rate of a RFS when changing from running shoes to BF could be due to children and adolescents changing their FSP from a RFS when shod to a FFS/MFS when BF to avoid painful heel collisions with the floor. The finding that sprinting in running shoes encouraged a greater occurrence of a RFS could be due to their cushioned and elevated heel. The reason why a BF condition encourages a greater occurrence of a FFS/MFS and running shoes encourage a greater occurrence of a RFS is explained in further detail in (2.5.1.1).

COMPARING FINDINGS TO EXISTING LITERATURE

The results of the current study will now be compared to relevant literature structured in accordance with the objectives of the current study. The specific objectives of the current study were to:

1. Determine whether children and adolescents sprint faster when barefoot or in sports shoes.
2. Compare the following spatiotemporal variables between sprinting barefoot and in sports shoes: stride length (m), step frequency (Hz), ground contact time (s), flight time (s) and swing time (s).
3. Determine if a child or adolescent's shoe mass explains any possible differences in sprinting performance or spatiotemporal variables between sprinting barefoot and in sports shoes.
4. Determine the acute effects of changing from sports shoes to barefoot on the foot strike pattern distribution during the acceleration period of a maximal effort sprint.
5. Determine if a child or adolescent's foot strike pattern explains any possible differences in sprinting performance or spatiotemporal variables between sprinting barefoot and in sports shoes.

Objective One: To determine whether children and adolescents sprint faster when barefoot or in sports shoes

The finding that the BF condition was significantly (statistically and practically) faster when BF is in contrast to the findings of Theophilos *et al.* (2014) which was the only other study found comparing sprinting performance between a BF and running shoes condition. Theophilos *et al*. (2014) found no significant differences in 30m sprint performance between a BF (5.31±0.5s) and running shoes condition (5.30±0.5s) for either adolescent girls or boys.

The reason for the different findings could be due to the methodological differences between the current study and Theophilos *et al*. (2014). The reason why Theophilos *et al*. (2014) did not find statistically significant differences could have been due to them having a much smaller sample size. Another possible reason could be that all the adolescents in Theophilos *et al*. (2014) were trained athletics athletes where the current study included non-athletes. Research has shown that non-athletes have smaller and weaker hip flexors, knee flexors and knee extensors than athletes (Baechle & Roger, 2008:100; Hoshikawa *et al*., 2011). The reasons why children and adolescents with weaker hip flexors would be affected more by wearing running shoes will further be discussed under objective three.

Objective Two: To compare the measured spatiotemporal variables between sprinting barefoot and in sports shoes

No research was found where spatiotemporal variables and sprinting performance were both measured in a BF and running shoes condition. Comparisons to previous research are, therefore, limited to studies on running. The findings of the current study are in agreement with previous studies on running which showed that running BF results in a significantly shorter SL and higher SF (de Wit *et al.*, 2000; Divert *et al.*, 2005; Squadrone & Gallozzi, 2009; Bonacci *et al.*, 2013; Squadrone *et al.*, 2015). Therefore, compared to the BF condition, the same acute effect of running shoes on SL and SF is seen when running and sprinting.

Previous research on running has shown mixed results regarding the acute effects of changing from running shoes to BF on FT and GCT. These findings are shown in Table 2.3. The finding in the current study of a shorter FT in the BF condition is in agreement with the study by Divert *et al.* (2005) but in contrast to de Wit *et al.* (2000) and Squadrone and Gallozzi (2009). The finding in the current study of a shorter GCT in the BF condition is in agreement with de Wit *et al.* (2000) but in contrast to Squadrone and Gallozzi (2009), Divert *et al.* (2005) and Squadrone *et al.* (2015).

Objective Three: To determine if a child or adolescent's shoe mass explains any possible differences in sprinting performance or spatiotemporal variables between sprinting barefoot and in sports shoes.

The finding that show mass had a significant effect on sprinting performance in the current study is similar to the findings of Bennett *et al.* (2009) who found a significant decrease in 40m sprinting time when mass was added to the legs. Added mas was 10% of individual segment mass placed evenly distributed about the radius of gyration of the thigh and shank. However, this finding is in contrast to the findings of all previous research found investigating the effect of shoe mass on sprinting performance. As mentioned before, Theophilos *et al. (*2014) found no significant difference in sprinting performance between sprinting BF and in running shoes where the average mass of shoes were 505g for girls and 508g for boys. These masses were relatively similar to the average shoe mass in the current study (577±110g). Similarly, Worobets and Wannop (2015) and Sterzing *et al*. (2009) found no significant differences in 10m sprint performance and the time taken to complete a 26m running/cutting Slalom course when differences in shoe mass were 166g and 70g respectively. A possible reason why Worobets and Wannop (2015) and Sterzing *et al*. (2009) found no significant differences could that the mass differences were too small. Another possible reason why these studies did not find a significant shoe mass effect could be that the sample sizes in Sterzing *et al.* (2009), Theophilos *et al.* (2014) and Worobets and Wannop (2015) were 20, 33, and 20, respectively, and might have been too small to show significant differences.

Lastly, a possible reason why Theophilos *et al*. (2014) and Sterzing *et al*. (2009) did not find a significant shoe mass effect is that all their participants were athletes where the current study also included non-athletes. Theophilos *et al*. (2014) only used athletics athletes and they had an average training experience of 2.3±1 years. Sterzing *et al*. (2009) only included amateur to sub-elite soccer players with a minimum of five years soccer experience. As mentioned before, non-athletes have been shown to have smaller and, therefore, probably also weaker hip flexors, knee flexors and knee extensors than athletes do. Hoshikawa *et al*. (2011) found that the cross sectional area of the hip flexors, knee flexors and knee extensors in track and field athletes aged 16-18 years are much larger than that of non-athletes and the cross sectional area of muscles has been shown to be proportional to their strength

(Baechle & Roger, 2008:100). The added mass of shoes would cause a smaller relative increase in strain in athletes due to them having stronger leg muscles. The stronger leg muscles in athletes could potentially have enabled them to overcome the additional mass easier and, therefore, not experience a significant decrease in sprint performance. This possible reason is, however, speculative since research has not yet shown that those with stronger hip flexors are affected less by the same increase in mass added to the feet. Furthermore, since the current study did not record physical activity questionnaire data there is no evidence to comment on the average level of athleticism of the current study's participants.

Objective Four: To determine the acute effects of changing from sports shoes to barefoot on foot strike pattern distribution during the acceleration period of a maximal effort sprint

In this section, the FSP distributions seen in the current study will firstly be compared to those in previous research on sprinting and running. Secondly, the shift that occurs when changing from running shoes to BF will also be discussed.

Limited research in children and adolescents have been done on the acute effects of changing from running shoes to BF on FSP during sprinting. Most studies in this area were done on adults and sample sizes were always relatively small. Contrary to the findings of the current study, which found all three FSPs represented in the BF and shod conditions, all previous research in both adolescents and adults found that only a FFS/MFS was used when sprinting BF or in running shoes (Krell & Stefanyshyn, 2006; Toon *et al.*, 2009; Theophilos *et al.*, 2014; Hébert-Losier *et al.*, 2015). Theophilos *et al*. (2014) was the only other study found assessing FSP in adolescents when sprinting and reported that all adolescents used a FFS when sprinting BF or in running shoes. Similarly, three other studies done in adults which also reported FSPs when sprinting found that a FFS was always used except for the two MFSs found by Krell and Stefanyshyn (2006) (Krell & Stefanyshyn, 2006; Toon *et al.*, 2009; Hébert-Losier *et al.*, 2015).

Potential reasons for the current study's findings being different to previous research lie in methodological differences. It is expected that Theophilos *et al*. (2014) determined FSP merely by looking at participants during the sprints since no mention was made on how FSP was determined and no equipment, such as video footage or the use of a force plate, was used which would indicate otherwise. Their method of determining FSP could have been inaccurate. They also did not indicate where during the 30m sprint they determined FSP. Therefore, it is assumed that all participants used a FFS throughout their entire 30m sprints. However, it is possible that some participants might have used other FSPs, especially a MFS, since it is sometimes difficult to distinguish between a FFS and MFS even when analysing high-speed video footage. Another reason for the current study's different findings could be that FSP was determined at the 50m and 60m mark in Toon *et al. (*2009) and Krell and Stefanyshyn (2006) and participants were probably at or very close to top speed. It has been shown that faster speeds are associated with a FFS/MFS and slower speeds with a RFS (see 2.5.1.2). Furthermore, participants in Theophilos *et al*. (2014) and Toon *et al*. (2009) started from a crouched start where in the current study a standing start was used. Starting from a crouched start could have caused participants to still have had a forward body lean at the 10m mark in Toon *et al*. (2009) and throughout the 30m sprint in Theophilos *et al*. (2014), encouraging the use of a FFS. Lastly, another possible reason why only FFS/MFSs were seen in previous studies (Krell & Stefanyshyn, 2006; Toon *et al.*, 2009; Theophilos *et al.*, 2014; Hébert-Losier *et al.*, 2015) could be that only elite or amateur athletes were used. All the athletes were either elite sprinters (Krell & Stefanyshyn, 2006; Toon *et al.*, 2009) or athletes competing in sports where high-speed running or sprinting is a requirement (Theophilos *et al.*, 2014; Hébert-Losier *et al.*, 2015). In contrast, not all children and adolescents in the current study were athletes. A lower occurrence of a RFS is expected in athletes, especially sprint athletes who might be trained to not sprint with a RFS, than in non-athletes.

The FSP distribution during sprinting found in the existing study will now be compared to FSP distributions in previous studies done on running. Many studies have determined FSP during running but only some of the studies will be used for comparisons in this section since running was not the focus of the current study.

Previous studies done on running have reported that, when running in running shoes, the occurrence of a RFS in children and adolescents ranged from 46%-97% (Lieberman *et al.*, 2010; Mullen & Toby, 2013a; Hollander *et al.*, 2014) and in adults from 29%-100% (Hasegawa, 2007; Lieberman *et al.*, 2010; Larson *et al.*, 2011; Altman & Davis, 2012; de Almeida *et al.*, 2015). The current study found that the occurrence of a RFS was 57% when sprinting in running shoes. The occurrence of a RFS, therefore, falls in the ranges previously seen in children, adolescents and adults while running. Research on BF running showed that the occurrence of a RFS ranged from 12%-62% in children and adolescents (Lieberman *et al.*, 2010; Mullen & Toby, 2013a; Hollander *et al.*, 2014) and 0%-83% in adults (Lieberman *et al.*, 2010; Altman & Davis, 2012). The current study found that the occurrence of a RFS was 27% when sprinting BF. The occurrence of a RFS in the BF condition, therefore, also falls in the ranges previously seen in children, adolescents and adults while running.

It is interesting to note that the occurrence of a RFS in the current study was not lower than the lowest occurrence of a RFS seen while running. This was true when comparing the current study's findings to children, adolescents or adults in both the shod and BF condition. It was expected that the occurrence of a RFS would have been lower when sprinting compared to running since all previous studies determining FSP while sprinting have found that the occurrence of a RFS was always 0% (Krell & Stefanyshyn, 2006; Toon *et al.*, 2009; Theophilos *et al.*, 2014; Hébert-Losier *et al.*, 2015). Furthermore, higher running speeds are expected to be associated with a lower occurrence of a RFS (see 2.5.1.2).

The lowest occurrence of a RFS in children and adolescents, from previous research, when running in running shoes (46%) was found in adolescent athletes running at fairly high constant speeds on a treadmill (4.02m/s for girls and 5.36m/s for boys) (Mullen & Toby, 2013). It is uncertain why the rate of RFS was lower in Mullen and Toby (2013) than in the current study. A possible reason could be that all the participants were competitive athletes recruited from track and cross-country teams. As mentioned before, the current study included non-athletes and a greater occurrence of a RFS is expected in non-athletes than athletes since athletes, especially track athletes, might be trained to not run with a RFS. This possible reason is however merely speculative.

The lowest occurrence of RFS in children and adolescents, from previous research, running in a BF condition (12%) was seen in two groups; 1) adolescent athletes running at fairly high constant speeds on a treadmill (4.02m/s for girls and 5.36m/s for boys) and 2) in habitually BF adolescents who have never worn shoes before, also running at fairly high constant speeds (5.5m/s) (Lieberman, *et* al., 2010; Mullen & Toby, 2013). The reason why the occurrence of a RFS in Lieberman *et* al. (2010) was lower than in the current study could be due to the fact that the adolescents were habitually BF. Similarly the reason why previous research in adults found the occurrence of a RFS to be lower than the current study while running in running shoes and BF (29% and 9% respectively) could be that the participants were previously habitually BF and, at the time of the study, have only recently been training in running shoes (Lieberman *et al*., 2010). Being habitually BF has been shown to encourage a FFS/MFS (Lieberman *et al*., 2010).

The current study's finding that the FSP distribution shifted more towards a FFS/MFS when changing from shod to BF is in contrast to Theophilos *et al*. (2014). However, the current study's finding is in agreement with previous studies done on running (Lieberman *et al.*, 2010; Hamill *et al.*, 2011; Mullen & Toby, 2013a; Hollander *et al.*, 2014).

Objective Five: To determine if a child or adolescent's foot strike pattern explains any possible differences in sprinting performance or spatiotemporal variables between sprinting barefoot and in sports shoes

According to the knowledge of the researchers, no previous research has investigated whether the footwear effect on FSP explains differences in sprinting/running performance between different footwear conditions.

IMPLICATIONS OF FINDINGS

Although the results showed that there was a statistically and practically significant difference in 10m and 20m sprint time between the BF and running shoes condition, the size of the differences were small (0.03s and 0.07s respectively). One of the implications of the findings of the current study is to give advice to children and adolescents on whether it is faster to sprint BF or in running shoes on a hard running surface. This would be useful information to children and adolescents who can choose whether to sprint BF or in running shoes in short anaerobic sprint tests where the protocol does not prescribe a specific footwear condition. It would also be useful information to the many children and adolescents who do not own spikes and participate in athletics competitions held on synthetic tracks. These children also have the choice to sprint either BF or in running shoes.

Sprint times during these fitness test batteries and in many inter-house and inter-school athletics competitions are often measured with handheld stopwatches. Mean absolute error of hand held stop watches compared to single split and multiple split electronic timers was found to be 0.15±0.20s and 0.16±0.19s respectively (Hetzler *et al*., 2008). Therefore, hand held stopwatches would not be able to pick up differences as small as 0.03s and 0.07s. When sprint time is measured with hand held stopwatches sprinting BF or in running shoes are practically the same speed and children can choose either footwear condition. When more reliable time measuring devices are used such as photocells the small differences of 0.03s and 0.07s for the 10m and 20m sprint would be detectable. Choosing to sprint BF would be a faster option but would not make a large difference. Therefore, even when reliable time measuring devices such as photocells are used, sprinting BF or in running shoes are almost the same speed and children and adolescents can choose either footwear condition. Sprinting BF might also only be faster to children and adolescents who do not suffer discomfort while sprinting BF and are truly able to sprint maximally while BF. As mentioned before, South Africa has a BF culture. Thus, sprinting BF might only be faster, and only marginally so, to children and adolescents in South Africa and other countries with a BF culture.

It is also important to mention that not all participants in the current study sprinted faster when BF. Possible reasons why some children and adolescents sprinted faster in running shoes could be that they might not have been accustomed to sprinting BF and could potentially have experienced pain while sprinting BF on a hard surface. Habitually shod children and adolescents could have fallen into this category. These children and adolescents might potentially have adopted shorter, sub-optimal SLs in an attempt to decrease the impact forces experienced during foot strikes. Shorter SLs have been shown to have reduced impact GRFs (Thompson *et al.*, 2014) and to increase shock attenuation (Mercer *et al*., 2002). Another possible reason could be that these children and adolescents were wearing running shoes with higher traction than those who sprinted faster BF since traction was not controlled in the current study. Research has shown that traction has a significant effect on sprinting performance (Luo, 2012, Worobets *et* al., 2014; Worobets & Wannop, 2015). These possibilities are merely speculative since no information was recorded on whether participants were habitually BF or shod and no measurements on traction were made in the current study.

The results of the current study also have potential implications for the protocols of short anaerobic sprint tests. When hand held stop watches are used in these tests there is no need to standardise participants' footwear condition since the small differences are not detectable. However, when more reliable measuring devices are used, such as photocells, these small differences are detectable.

Fitness tests often aim to test if there has been an improvement due to training and if the type of footwear is not standardised it could make it more difficult to see true improvements in sprinting performance due to the training itself. For example, if the effectiveness of a particular intervention to improve sprinting performance wants to be tested, a participant might sprint in running shoes during baseline testing. If the same participant then chooses to sprint BF on the follow up testing, a marginal improvement in sprinting performance might be seen. This improvement could falsely be attributed to a successful intervention to improve sprinting performance but the actual reason for the improvement could be due the acute change in footwear. Protocols might want to consider standardising the type of footwear used for each individual so that the same child or adolescent is always tested in the same footwear condition. Logistically, it might be more convenient to simply standardise the footwear condition for all participants so that all participants either sprint BF or in running shoes. This would eliminate the possibility of accidently testing participants in different footwear conditions on different testing occasions. As mentioned before, this might potentially only be applicable to habitually BF populations. The researchers want to make it clear that they are not stating that all sprint test protocols should definitely standardise the type of footwear used but that they should consider the points mentioned.

Choosing to sprint either BF or in running shoes might have potential health implications. Acutely performing two 20m sprints during a fitness test, as done in the Eurofit test battery, in either a BF or running shoe condition is not expected to cause any injury in healthy children and adolescents. However, if children and adolescents acutely change to a BF condition when competing in athletics competitions held on synthetic running tracks and then compete in multiple events that involve running or sprinting, they could potentially suffer abrasive injuries to the plantar surface of the foot. Habitually being BF leads to certain adaptations such as the development of calluses on the plantar surface of the feet that makes the foot more resistant to abrasive injuries (Lieberman, 2012).

Furthermore, if children and adolescents for example decide that they want to compete either BF or in running shoes in athletics competitions held on synthetic running tracks, they might also choose to chronically train sprints in that particular footwear condition. This could potentially place them at higher risk for injuries seen in habitually BF or minimalist runners or those seen in habitually shod runners. The type of injuries they might potentially be at higher risk of depends on the presence or lack of a protective layer between the foot and running surface, the presence or lack of cushioning under the foot as well as the type of FSP used.

When running BF there is no protective layer between the foot and running surface. Plantar surface injuries have been found to be significantly higher in BF runners than shod runners (Altman & Davis, 2016). Concerning the cushioning under the foot, habitually BF and minimalist runners have been shown to be at a higher risk to develop injuries such as metatarsal stress fractures and bone marrow edema. This is because of the lack of cushioning under the foot to protect it from hard collisions with a hard running surface such as a tar road (Cauthon *et al*., 2013; Ridge *et al*., 2013). When suddenly changing from running in running shoes to exclusively run BF or in minimalist shoes bones in the feet are not allowed to gradually adapt to the increased impacts during foot strikes.

Concerning the FSP used, habitually BF and minimalist runners who run with a FFS/MFS are at increased risk to develop injuries such as calf muscle strains and Achilles tendinopathy (Cauthon *et al*., 2013; Altman & Davis, 2016). These types of injuries are linked to the fact that they run with a FFS/MFS and not to the lack of cushioning under the foot. A habitually shod runner who runs with a FFS/MFS will also be at higher risk for these types of injuries. Habitually running with a RFS places runners at increased risk for different types of injuries. The vast majority of habitually shod runners RFS and because they RFS they are at higher risk to develop injuries such as plantar fasciitis, and hip and knee injuries such as Iliotibial band syndrome, tibial stress syndrome/fractures and gluteal strains/tendinitis (Taunton *et al*., 2002; Altman & Davis, 2016). The injuries related to running might be closely linked to the repetitive nature of running where hundreds to thousands of foot strikes occur within a single long distance training session or race. During sprint training, the number of foot strikes are a lot less than during running and those who train sprints could potentially be at lower risk for the aforementioned injuries than runners are. On the other hand, impacts at foot strikes are a lot more forceful during sprinting compared to running and these heavier impacts could potentially accelerate the development of the aforementioned injuries. According to the researchers' knowledge, there is currently no existing literature about how one's footwear influences the development of injuries during long-term sprint training.

CONCLUSION

According to the researchers' knowledge, the current study was the first study to determine the acute effects of changing from sprinting in running shoes to sprinting barefoot (BF) on spatiotemporal variables and to determine whether foot strike pattern (FSP) has a significant effect on sprinting performance. Furthermore, the current study was only the second study to investigate whether it is faster to sprint BF or in running shoes, to determine the acute effects of sprinting BF and in running shoes on FSP and to determine whether the mass of shoes significantly affect sprinting performance in children and adolescents. For all the objectives researched in the current study, the current study was the first study to do so with a relatively large sample size.

The primary finding of the current study is that it was significantly (statistically and practically) faster for children and adolescents to sprint BF than in running shoes but only marginally so with small effect sizes for 10m and 20m sprint performance. The reason for this was that running shoes added additional mass to the feet that increased the moment of inertia of the leg and resulted in significantly more time needed to reposition the leg for the next stride. In the running shoes condition flight time (FT), swing time (SwT) and ground contact time (GCT) were significantly longer and resulted in a significantly lower step frequency (StepF). Furthermore, stride length (SL) was significantly longer when sprinting in running shoes. Sprinting BF or in running shoes is, therefore, almost the same speed and children and adolescents can choose either footwear condition for sprint tests of fitness batteries and for athletics competitions held on synthetic athletics tracks.

If children and adolescents decide to compete in athletics competitions held on synthetic running tracks in a BF or running shoes condition they may also decide to chronically train sprints in that footwear condition. Choosing to chronically train sprints in either footwear condition may place children and adolescents at higher risk for certain types of injuries related to their footwear condition. However, there is currently uncertainty about how one's footwear influences the development of injuries during long-term sprint training.

The current study also found that changing from running shoes to BF has an acute effect on children and adolescents' FSP distributions while sprinting. Changing from running shoes to barefoot caused a significant decrease in the occurrence of a rearfoot strike (RFS) from 57%-27% and, therefore, a significant increase in the occurrence of a forefoot-/midfoot strike

(FFS/MFS) from 43%-73%. Furthermore, the results of the current study showed that the acute effect footwear had on children and adolescents' FSP had no significant effect on their sprinting performance.

LIMITATIONS

The type of shoes used by participants was not standardised in the current study. Therefore, there could have been a lot of variability between shod conditions concerning shoe qualities that have been shown to significantly affect sprinting performance such as traction, midsole bending stiffness and shoe mass. The current study did not determine whether participants were habitually BF or shod. This information would have been useful to help explain why some participants sprinted faster in running shoes. Physical activity questionnaire data was not determined from participants. This would have helped in comparing the current study's results with others.

The gold standard for measuring spatiotemporal variables and FSP is pressure plate/mat data. In the current study, the OptoGait was used to determine spatiotemporal variables and video analysis of high-speed videos was used to determine FSP. Since field-testing was done on a large amount of children and adolescents, the chosen methods were more feasible for the current study. The visual method used in the current study only subjectively classified FSPs into three discrete categories and was not sensitive to small changes that potentially occurred. The visual method has a limited ability to accurately classify participants with a MFS (Altman & Davis, 2012). No markers were used on children and adolescents due to time constraints. Adding markers to anatomical landmarks would have allowed a more objective method to determine FSP and would have allowed small changes in posterior sole angle to be measured. Only a single foot strike was analysed in each footwear condition per participant. When only assessing one step, there is a possibility that the step analysed is different from the participant's normal gait. However, the current study used a large sample size that allowed reliable determination of FSP distributions.

The frequency (240Hz) of the camera used in the current study to determine FSPs while sprinting was low. This frequency was chosen because it was similar to that used by de Almeida (2015) to determine FSPs while running. With lower frequencies, there is a chance that the actual moment of foot strike occurs between two frames. It has been shown that the accuracy of foot strike classification is directly related to the frequency of the video camera used (Fellin *et al*. 2010). Future research can aim to use a camera with a frequency of at least 400Hz for kinematic measurements during sprinting. The GoPro camera's only resolution option at 240Hz was low (WVGA = 848x480 pixels) which made it slightly more difficult to analyse FSPs accurately. A higher resolution would have made the video footage less pixelated and the boundaries between the foot and the ground more distinct. At one school, testing was done indoors and the ambient lighting was low, making it more difficult to determine FSP. A 500W spot light was used to help illuminate the foot strike area but despite that, the combination of low resolution and relatively low lighting made it more challenging to accurately analyse foot strike patterns that were close to a MFS at that school. Future studies that aim to determine FSPs with low ambient lighting should use more additional light than the 500W spot light used in the current study. Furthermore, if a higher frequency camera is used, more additional lighting will be needed than that used in the current study.

FUTURE RESEARCH

Future studies should aim to gather more background information about participants such as whether participants are habitually BF/shod and physical activity questionnaire data. The shoe used in future studies could be standardised in order to control for shoe qualities such as traction, midsole bending stiffness and shoe mass which have been shown to significantly influence sprinting performance. Participants should then be given time to become accustomed to the new shoes before testing is done. Measurements of shoe-surface and barefoot-surface traction could also be made. Future studies on sprinting may want to use a camera with a frequency of at least 400Hz and a higher resolution than that used in the current study. Studies should make sure additional lighting is enough for clear images. Anatomical markers should be used if kinematic measurements are to be made from two-dimensional video analysis. Future studies could compare sprinting BF and in running shoes under laboratory conditions. Using a motorised instrumented treadmill as done by Morin *et al.* (2015) will allow gold-standard measurements of FSP and spatiotemporal variables throughout an entire maximal effort sprint. Adding measurements of three-dimensional kinematics (e.g. using the Vicon system) and EMG measurements will give more insight on the acute effects of footwear on sprinting performance. Future studies could investigate if sprinting BF is also faster over longer distances such as over a 100-400m sprint and if the shoe mass effect is larger over longer distances. Future studies may want to use more homogenous groups and could investigate whether a significant shoe mass effect is also seen in a sample including only track sprint athletes and investigate whether minimalist spikes has a significant advantage over regular spikes. Future research could investigate whether one's FSP significantly affects one's sprinting performance regardless of the footwear effect. Longitudinal studies could also be done to investigate the development of injuries related to long-term sprint training in running shoes or BF. The FSP used in either footwear condition should then also be taken into consideration.

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APPENDIX ONE

UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
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Approval Notice

Stipulated documents/requirements

18-Feb-2015
De Villiers, Johanna JE

Proposal #: HS1153/2014

Title: **Moving Feet – A Comparative Study between Habitually Barefoot And Shod School-Aged Children.**

Dear Ms. Johanna De Villiers,

Your **Stipulated documents/requirements** received on **18-Feb-2015**, was reviewed by members of the **Research Ethics Committee: Human Research (Humanities)** via Expedited review procedures on **17-Feb-2015** and was approved.
Sincerely,

Clarissa Graham
REC Coordinator
Research Ethics Committee: Human Research (Humanities)

Investigator Responsibilities

Protection of Human Research Participants

Some of the general responsibilities investigators have when conducting research involving human participants are listed below:

1.Conducting the Research. You are responsible for making sure that the research is conducted according to the REC approved research protocol. You are also responsible for the actions of all your co-investigators and research staff involved with this research. You must also ensure that the research is conducted within the standards of your field of research.

2.Participant Enrollment. You may not recruit or enroll participants prior to the REC approval date or after the expiration date of REC approval. All recruitment materials for any form of media must be approved by the REC prior to their use. If you need to recruit more participants than was noted in your REC approval letter, you must submit an amendment requesting an increase in the number of participants.

3.Informed Consent. You are responsible for obtaining and documenting effective informed consent using **only** the REC-approved consent documents, and for ensuring that no human participants are involved in research prior to obtaining their informed consent. Please give all participants copies of the signed informed consent documents. Keep the originals in your secured research files for at least five (5) years.

4.Continuing Review. The REC must review and approve all REC-approved research proposals at intervals appropriate to the degree of risk but not less than once per year. There is **no grace period.** Prior to the date on which the REC approval of the research expires, **it is your responsibility to submit the continuing review report in a timely fashion to ensure a lapse in REC approval does not occur.** If REC approval of your research lapses, you must stop new participant enrollment, and contact the REC office immediately.

5.Amendments and Changes. If you wish to amend or change any aspect of your research (such as research design, interventions or procedures, number of participants, participant population, informed consent document, instruments, surveys or recruiting material), you must submit the amendment to the REC for review using the current Amendment Form. You **may not initiate** any amendments or changes to your research without first obtaining written REC review and approval. The **only exception** is when it is necessary to eliminate apparent immediate hazards to participants and the REC should be immediately informed of this necessity.

6.Adverse or Unanticipated Events. Any serious adverse events, participant complaints, and all unanticipated problems that involve risks to participants or others, as well as any research related injuries, occurring at this institution or at other performance sites must be reported to Malene Fouch within **five (5) days** of discovery of the incident. You must also report any instances of serious or continuing problems, or non-compliance with the RECs requirements for protecting human research participants. The only exception to this policy is that the death of a research participant must be reported in accordance with the Stellenbosch Universtiy Research Ethics Committee Standard Operating Procedures. All reportable events should be submitted to the REC using the Serious Adverse Event Report Form.

7.Research Record Keeping. You must keep the following research related records, at a minimum, in a secure location for a minimum of five years: the REC approved research proposal and all amendments; all informed consent documents; recruiting materials; continuing review reports; adverse or unanticipated events; and all correspondence from the REC

8.Provision of Counselling or emergency support. When a dedicated counsellor or psychologist provides support to a participant without prior REC review and approval, to the extent permitted by law, such activities will not be recognised as research nor the data used in support of research. Such cases should be indicated in the progress report or final report.

9.Final reports. When you have completed (no further participant enrollment, interactions, interventions or data analysis) or stopped work on your research, you must submit a Final Report to the REC.

10.On-Site Evaluations, Inspections, or Audits. If you are notified that your research will be reviewed or audited by the sponsor or any other external agency or any internal group, you must inform the REC immediately of the impending audit/evaluation.

APPENDIX TWO

Western Cape Government
Education

Directorate: Research
Audrey.wyngaard@westerncape.gov.za
tel: +27 021 467 9272
Fax: 0865902282
Private Bag x9114, Cape Town, 8000
wced.wcape.gov.za

REFERENCE: 20141023-38716
ENQUIRIES: Dr A T Wyngaard

Mrs Johanna
De Villiers PO
Box 1551
Stellenbosch
7599

Dear Mrs Johanna De Villiers

RESEARCH PROPOSAL: MOVING FEET – A COMPARATIVE STUDY BETWEEN HABITUALLY BAREFOOT AND SHOD SCHOOL-AGED CHILDREN

Your application to conduct the above-mentioned research in schools in the Western Cape has been approved subject to the following conditions:

1. Principals, educators and learners are under no obligation to assist you in your investigation.
2. Principals, educators, learners and schools should not be identifiable in any way from the results of the investigation.
3. You make all the arrangements concerning your investigation.
4. Educators' programmes are not to be interrupted.
5. The Study is to be conducted from **02 February 2015 till 30 September 2015**
6. No research can be conducted during the fourth term as schools are preparing and finalizing syllabi for examinations (October to December).
7. Should you wish to extend the period of your survey, please contact Dr A.T Wyngaard at the contact numbers above quoting the reference number?
8. A photocopy of this letter is submitted to the principal where the intended research is to be conducted.
9. Your research will be limited to the list of schools as forwarded to the Western Cape Education Department.
10. A brief summary of the content, findings and recommendations is provided to the Director: Research Services.
11. The Department receives a copy of the completed report/dissertation/thesis addressed to:

    The Director: Research
    Services Western Cape
    Education Department
    Private Bag X9114
    CAPE TOWN 8000

We wish you success in your research.

Kind regards.
Signed: Dr Audrey T Wyngaard
Directorate: Research
DATE: 24 October 2014

Lower Parliament Street, Cape Town, 8001
tel: +27 21 467 9272 fax: 0865902282 Safe Schools: 0800 45 46 47

Private Bag X9114, Cape Town, 8000
Employment and salary enquiries: 0861 92 33 22
www.westerncape.gov.za

APPENDIX THREE

STELLENBOSCH UNIVERSITY

PARTICIPANT INFORMATION LEAFLET AND ASSENT FORM

TITLE OF THE RESEARCH PROJECT:
Moving Feet – A Study where we compare school-aged children who normally walk barefoot to those who normally wear shoes.

RESEARCHER'S NAME: Elbé de Villiers

ADDRESS: Department of Sport Science, Stellenbosch University

CONTACT NUMBER: 021 808 4735 / 021 808 4735

What is RESEARCH?
Research is something we do to find **NEW KNOWLEDGE** about the way things (and people) work. We use research projects or studies to help us find out more about children and teenagers and the things that affect their lives, their schools, their families and their health. We do this to try and make the world a better place!

What is this research project all about?
During this project we want to see what effect your everyday shoes have on:
The way you walk
The shape of your feet
Your balance
The distance that you can jump

Why have I been invited to take part in this research project?
You were invited because you are a pupil in one of the schools that was chosen for the study. You are healthy, do not have an injury and you are the right age.

Who is doing the research?
My name is Elbé de Villiers. I am a Biokineticist working at Stellenbosch University. My job is to help people get better after they had an injury, where in an accident or where very ill. We help them by doing specific exercises.

What will happen to me in this study?
During the study we will do a few tests.
First of all, we will measure your height and weight.
Then we will do a warm-up (light jogging and stretches) to get you ready for the other tests.
We will ask you to walk a few metres over a platform. We will take measurements of your foot while you are standing and sitting
The balance test is next. You will need to walk backwards on three different sized plank, 3 times.
You will be asked to jump forward as far as you can 3 times and jump sideways as many times as possible in 15 seconds. You will do this twice.
Next you will jog and run 20 metres while being recorded by a video camera. We want to see how you put your foot down while running. Only the running will be done twice and the time it takes you to complete this will be taken.
Lastly we will measure your hand grip strength.

Can anything bad happen to me?
Nothing bad can happen to you during the study. You will only run short distances and jump three times. The only thing that might happen is that your muscles might feel uncomfortable.
We will show you how to do everything.

Will anyone know I am in the study?
Nobody have to know that you are part of the study. Your specific results will only be known by Elbé.

Who can I talk to about the study?
If you have questions or want to speak to someone about the study you can contact: Elbé de Villiers (cell phone: 084 515 7642; email: edup@sun.ac.za) or Dr Ranel Venter (cell phone: 083 309 2894; email: rev@sun.ac.za).

What if I do not want to do this?
No one can force you to be part of the study. If you do not want to do this, you do not have to. Even if your parents allowed you and signed the form, you still do not have to do it. If you said that you want to be part of the study and decide later on that you do not want to do it anymore, nothing will happen to you and you can just stop being part of it.

Do you understand this research study and are you willing to take part in it?

YES NO

Has the researcher answered all your questions?

YES NO

Do you understand that you can STOP being in the study at any time?

YES NO

________________________ Date ________________________

Signature of Child

VERY IMPORTANT: **Please bring the following to the testing**

1. **Shoes you do sport in (e.g Takkies)**
2. **School shoes**
3. **Socks**
4. **Exercise shorts**
5. **The two completed forms signed by the participant and parents**

APPENDIX FOUR

UNIVERSITEIT•STELLENBOSCH•UNIVERSITY
jou kennisvennoot • your knowledge partner

STELLENBOSCH UNIVERSITY
CONSENT TO PARTICIPATE IN RESEARCH

Moving feet – a comparative study of school children who normally wear shoes and those who normally walk barefoot

I am Elbé de Villiers (a PhD student in Sport Science) of the Department of Sport Science at Stellenbosch University. I would like to invite your child to participate in my research study. The results of the study will form part of the thesis for my doctoral degree in Sport Science. Your child has been chosen as a possible participant in the study because he/she is in one of the participant schools and also is of the right age.

1. PURPOSE OF THE STUDY

The main purpose of this study is to determine the effect that shoes have on the developing foot. I will also determine whether shoes influence children's ability to move.

2. PROCEDURES

If you agree that your child may take part in this study, your child will have to undergo the following tests and measurements:

Anthropometric measurement: Your child's length and weight will be measured.

Complete a questionnaire on physical activity: This is done to determine how active your child is.

Jogging and running for 20 metres: While your child runs, he/she will be recorded on a video camera. The child will be asked to do this three times with and without shoes. The video is just to determine how your child lands with his feet while running.

Balance tests: Your child will be asked to walk backwards on three different sized bars. This will be done twice on each bar with and without shoes.

Jumps: Your child will be asked to jump as far as he/she can with both feet together. The distance will be measured. Your child will do this jump three times with and without shoes.
Next your child will be asked to jump sideways as many times as possible in 15 seconds. They will do it twice with and without shoes.

Foot shape: Your child will be asked to walk over a platform with a pressure plate embedded in it. They will also have to stand on a foot measuring platform, which then will determine the child's foot length and breadth as well as the height of his/her foot bridge while standing and seated.

Grip strength: Your child's grip strength will be determined by using a hand grip calliper.

3. POTENTIAL RISKS AND DISCOMFORT

Although some of the tests might be unknown to your child, they are simple tests. They should not make your child exceptionally tired or cause any discomfort.

4. POTENTIAL BENEFITS FOR STUDY PARTICIPANTS AND/OR SOCIETY

Your child will gain no direct benefit from the study.

The study does hold benefits for knowledge in the field of sport science, however, and specifically on the effect of shoes on children's feet and their ability to move. The results could possibly also provide shoe manufacturers with the necessary knowledge in the future to design shoes that are beneficial for the development of children's feet.

5. REMUNERATION FOR PARTICIPATION

Your child will not be paid for participation in this study.

6. CONFIDENTIALITY

Any information that is obtained in connection with this study and that could reveal your child's identity will remain confidential and will only be revealed with your consent or if required by law. Confidentiality will be maintained by storing the data on a personal computer with a password. Only the researcher and the supervisor will be able to look at the data. The data will be dealt with anonymously at all times.

If the research should be published, the data will be discussed in general – in other words for the group as a whole.

7. PARTICIPATION AND WITHDRAWAL

You can decide whether or not your child may participate in this study. If you offer that your child may participate, you may still withdraw him/her from the study at any stage without this holding any negative consequences for your child. The researcher could also decide to remove your child from the study should circumstances require this.

8. DETAILS OF RESEARCHERS

If you have any questions on the research or if anything about it bothers you, you are welcome to contact us:

Elbé de Villiers (cell phone 084 515 7642; e-mail edup@sun.ac.za) or Dr Ranel Venter (cell phone 083 309 2894; e-mail rev@sun.ac.za)

9. RIGHTS OF RESEARCH PARTICIPANTS

You may withdraw your consent at any stage and discontinue your child's participation, without any negative consequences. Your child will not waive any legal claims or rights by taking part in this research study. For any questions about your child's rights as a study participant, contact Ms Maléne Fouché at the Stellenbosch University Division for Research Development [mfouche@sun.ac.za; 021 808 4622].

SIGNATURE OF PARENT / GUARDIAN

I was given a copy of the letter with information.
I was given the opportunity to ask questions, and they were answered satisfactorily.

I consent that ______________________________ may participate in this study. I have received a copy of this form.

____
Name of parent/guardian

______________________________ ______________
Signature of parent/guardian **Date**

<u>Physical Address:</u>
Street number and name: ______________________________
Area / Suburb: ______________________________
Town / City: ______________________________

<u>VERY IMPORTANT:</u> Could you please remind your child to bring the following to the testing

1. **Shoes he/she does sport in (e.g Takkies)**
2. **School shoes**
3. **Socks**
4. **Exercise shorts**
5. **The two completed forms signed by the participant and parent**

APPENDIX FIVE

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jou kennisvennoot • your knowledge partner

STELLENBOSCH UNIVERSITY
CONSENT TO PARTICIPATE IN RESEARCH

Moving feet – a comparative study of school children who normally wear shoes and those who normally walk barefoot

I am Elbé de Villiers (a PhD student in Sport Science) of the Department of Sport Science at Stellenbosch University. I would like to invite you to participate in my research study. The results of the study will form part of the thesis for my doctoral degree in Sport Science. You have been chosen as a possible participant in the study because you are in one of the participant schools and also are of the right age.

1. PURPOSE OF THE STUDY

The main purpose of this study is to determine the effect that shoes have on the developing foot. I will also determine whether shoes influence children's ability to move.

2. PROCEDURES

If you agree to take part in this study, you will have to undergo the following tests and measurements:

Anthropometric measurement: Your length and weight will be measured.

Complete a questionnaire on physical activity: This is done to determine how active you are.

Questionnaire on being barefoot: This will be done to determine how often you are barefoot.

Jogging and running for 20 metres: First you will jog and then sprint for 20 metres. While doing this, you will be recorded on a video camera. You will be asked to do the sprinting twice with and without shoes. The video is just to determine how you land with your feet while running.

Balance tests: You will be asked to walk backwards on three different sized bars. This will be done twice on each bar with and without shoes.

Jumping: You will be asked to jump as far as you can with both feet together. The distance will be measured. You will do this jump three times with and without shoes.
With the next jump, you will have to jump sideways as many times as possible in 15 seconds. The jumps will be counted and you will do it twice with and without shoes.

Foot shape: You will be asked to walk over a platform with a pressure plate embedded in it.
You would also have to stand with both legs on a foot measuring platform and your arch height, foot length and foot width will be measured by a calliper while you are standing and being seated.

Grip strength: Your grip strength will be determined by using a hand grip calliper.

3. POTENTIAL RISKS AND DISCOMFORT

Although some of the tests might be unknown to you, they are simple tests. They should not make you exceptionally tired or cause any discomfort.

4. POTENTIAL BENEFITS FOR STUDY PARTICIPANTS AND/OR SOCIETY

You will gain no direct benefit from the study.

The study does hold benefits for knowledge in the field of sport science, however, and specifically on the effect of shoes on children's feet and their ability to move. The results could possibly also provide shoe manufacturers with the necessary knowledge in the future to design shoes that are beneficial for the development of children's feet.

5. REMUNERATION FOR PARTICIPATION

You will not be paid for participation in this study.

6. CONFIDENTIALITY

Any information that is obtained in connection with this study and that could reveal your identity will remain confidential and will only be revealed with your consent or if required by law. Confidentiality will be maintained by storing the data on a personal computer with a password. Only the researcher and the supervisor will be able to look at the data. The data will be dealt with anonymously at all times.

If the research should be published, the data will be discussed in general – in other words for the group as a whole.

7. PARTICIPATION AND WITHDRAWAL

You can decide whether or not you want to participate in this study. If you offer that you will participate, you may still withdraw from the study at any stage without this holding any negative consequences for you. The researcher could also decide to remove you from the study should circumstances require this.

8. DETAILS OF RESEARCHERS

If you have any questions on the research or if anything about it bothers you, you are welcome to contact us:

Elbé de Villiers (cell phone 084 515 7642; e-mail edup@sun.ac.za) or Dr Ranel Venter (cell phone 083 309 2894; e-mail rev@sun.ac.za)

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SIGNATURE OF PARTICIPANT

I was given a copy of the letter with information.
I was given the opportunity to ask questions, and they were answered satisfactorily.

I consent that I, ________________________________ will participate in this study. I have received a copy of this form.

____
Name of participant

____ ________________
Signature of participant **Date**

<u>VERY IMPORTANT:</u> Please bring the following to the testing

1. **Shoes you do sport in (e.g. Takkies)**
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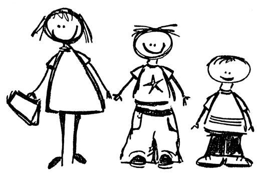
APPENDIX SIX

UNIVERSITEIT STELLENBOSCH

INLIGTINGSTUK EN TOESTEMMINGSVORM VIR DEELNEMERS



NAAM VAN DIE NAVORSINGSPROJEK: Bewegende voete – 'n studie waar ons skoolkinders wat gewoonlik skoene dra vergelyk met dié wat gewoonlik kaalvoet loop

NAVORSER(S) SE NAAM: Elbé de Villiers

ADRES: Departement Sportwetenskap, Universiteit Stellenbosch

KONTAKNOMMER: 021 808 4735 / 084 515 7642

Wat is NAVORSING?
Navorsing is iets wat ons doen om MEER TE LEER oor hoe dinge (en mense) werk. Ons gebruik navorsingsprojekte of -ondersoeke om meer uit te vind oor kinders en tieners en die dinge wat hulle lewe beïnvloed, soos hulle skool, hulle gesin en hulle gesondheid. Ons doen dit omdat ons die wêreld 'n beter plek probeer maak.

Waaroor gaan hierdie navorsingsprojek?
Met hierdie navorsing wil ons kyk of die skoene wat jy dra, die volgende doen:
Die manier waarop jy loop verander
Die vorm van jou voet verander
Jou balans beter maak
Jou verder laat spring

Hoekom vra julle my om aan hierdie navorsingsprojek deel te neem?
Ons wil graag hê dat jy moet deelneem aan die projek, omdat jy in die skool is wat ons gekies het om deel te wees, jy gesond is, jy nie enige beserings het nie, en jy die regte ouderdom is.

Wie doen die navorsing?
My naam is Elbé de Villiers en ek werk by die Universiteit Stellenbosch. Ek is ’n Biokinetikus. Ek gebruik oefening om mense sterker te maak nadat hulle seergekry het of as hulle baie siek was.

Wat sal ek moet doen as ek aan die studie deelneem?
Ons gaan eers kyk hoe lank en hoe swaar jy is.
Daarna gaan ons jou laat opwarm deur liggies te draf en bietjie strekke te doen om jou reg te kry vir die toetse.
Jy gaan 20 meter moet hardloop terwyl jy met ’n videokamera afgeneem word en jou tyd geneem word.
Dan gaan jy ’n op ’n meetapparaat moet staan vir ’n paar sekondes, sodat ons jou voet kan meet.
Ons gaan ook jou balans toets. Jy sal agteruit moet loop op drie verskillende plankies. Dit gaan jy twee keer moet doen.
Volgende gaan ons kyk hoe ver jy met altwee bene gelyktydig kan spring.
Daarna gaan ons kyk hoeveel keer jy sywaarts kan spring in 15 sekondes. Dit moet ook twee keer gedoen word.
Laastens gaan ons ook kyk hoe sterk jou handgreep is.

Is daar enigiets wat kan verkeerd gaan?
Jy gaan kort ente hardloop en driekeer spring en jou spiere kan dalk vreemd voel, maar niks kan jou seermaak of niks kan verkeerd gaan nie.
Ons sal ook vir jou mooi wys hoe om alles te doen.

Sal ander mense weet ek neem aan die projek deel?
Niemand hoef te weet dat jy aan die studie deelneem nie en niemand anders, behalwe Elbé, sal weet hoe jy met die toetse gevaar het nie.

Met wie kan ek oor die projek gesels?
As jy enige vrae het oor die projek of as jy met iemand wil gesels kan jy vir Elbé de Villiers (selfoon: 084 515 7642; e-pos: edup@sun.ac.za) of Dr Ranel Venter (selfoon: 083 309 2894; e-pos: rev@sun.ac.za) kontak.

Wat gebeur as ek nie wil deelneem nie?
Jy hoef net deel te neem aan die projek as jy wil. Jy gaan nie gedwing word nie en dit maak nie saak as jou ouers gesê het jy mag nie, en as jy nie wil nie, hoef jy nie.

As jy wel gesê het jy wil deelneem en jy sien later jy is nie lus nie, kan jy enige tyd vir my sê en dan kan jy ophou deelneem aan die projek.

Verstaan jy waaroor hierdie navorsing gaan, en sal jy aan die projek deelneem?

JA	NEE

Het die navorser ál jou vrae beantwoord?

JA	NEE

Verstaan jy dat jy kan OPHOU deelneem net wanneer jy wil?

JA	NEE

_______________________ _______________________

Kind se handtekening Datum

BAIE BELANGRIK: Bring asseblief die volgende saam na die toetsing

1. **Skoene waar in jy sport doen (bv. Tekkies)**
2. **Skool skoene**
3. **Kouse**
4. **Kort oeven broek**
5. **Die twee ingevulde vorms getek deur die deelnemer en ouer**

APPENDIX SEVEN

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TOESTEMMING TOT DEELNAME AAN NAVORSING

Bewegende voete – 'n vergelykende studie van skoolkinders wat gewoonlik skoene dra teenoor dié wat gewoonlik kaalvoet loop

Ek is Elbé de Villiers ('n PhD-student in Sportwetenskap) van die Departement Sportwetenskap aan die Universiteit Stellenbosch. Ek nooi u kind om deel te neem aan my navorsingstudie. Die resultate van die studie sal deel uitmaak van die tesis vir my doktorsgraad in Sportwetenskap. U kind is as 'n moontlike studiedeelnemer gekies omdat hy/sy in een van die deelnemerskole is en ook die regte ouderdom is.

1. DOEL VAN DIE STUDIE

Die hoofdoel van hierdie studie is om te bepaal watter effek skoene op die ontwikkelende voet het. Ek sal ook vasstel of skoene kinders se bewegingsvermoë beïnvloed.

2. PROSEDURES

Indien u instem dat u kind aan hierdie studie kan deelneem, sal u kind die volgende toetse en metings ondergaan:

Antropometriese meting: U kind se lengte en gewig sal gemeet word.

Invul van 'n vraelys oor fisiese aktiwiteit: Dít word gedoen om te bepaal hoe aktief u kind is.

Invul van 'n vraelys oor kaalvoetgewoontes: Hiermee wil ons agterkom hoe gereeld u kind kaalvoet is.

Draf en hardloop oor 20 meter: Terwyl u kind draf en hardloop sal hy/sy met 'n videokamera afgeneem word. Die video word geneem om te kyk hoe u kind se voet neergesit word tydens die verskillende situasies. Die tyd wat dit u kind neem om die 20 meter te hardloop sal geneem word en hy/sy sal gevra word om dit twee keer te doen met en sonder skoene.

Balanstoetse: Die kind sal gevra word om agteruit te loop op drie verskillende plankies, elkeen met 'n ander breedte. Dit moet twee keer elk gedoen word met en sonder skoene.

Spronge: U kind sal gevra word om so ver as moontlik met albei voete tegelyk te spring. Die afstand sal gemeet word. U kind sal die sprong drie keer doen, met en sonder skoene.
Na die verspring sal u kind gevra word om so veel keer as moontlik in 15 sekondes sywaarts te spring. Dit sal twee keer herhaal word en die beste een sal gebruik word, met en sonder skoene.

Handgreep: Die krag van albei u kind se hande sal gemeet word met 'n handgreepkaliper.

Voetvorm: U kind sal gevra word om kaalvoet op 'n voetmetingsapparaat te staan waar u kind se voetlengte en -breedte sowel as die hoogte van sy/haar voetbrug bepaal sal word.

3. MOONTLIKE RISIKO'S EN ONGEMAK

Hoewel van die toetse dalk onbekend sal wees vir u kind, is dit eenvoudige toetse. Dit behoort nie u kind buitengewoon moeg te maak of ongemak te veroorsaak nie.

4. MOONTLIKE VOORDELE VIR STUDIEDEELNEMERS EN/OF DIE SAMELEWING

U kind sal geen direkte voordeel uit die studie trek nie.

Die studie hou egter wel voordele in vir kennis op die gebied van sportwetenskap en veral oor die uitwerking van skoene op kinders se voete en bewegingsvermoë. Die resultate kan skoenvervaardigers ook moontlik in die toekoms die nodige kennis gee om skoene te ontwerp wat voordelig is vir die ontwikkeling van kinders se voete.

5. VERGOEDING VIR DEELNAME

U kind sal nie vir deelname aan hierdie studie betaal word nie.

6. VERTROULIKHEID

Enige inligting wat in verband met hierdie studie bekom word en u kind se identiteit verklap, sal vertroulik bly en slegs met u toestemming of ingevolge wetsvereistes bekend gemaak word. Vertroulikheid sal gehandhaaf word deur die data op 'n persoonlike rekenaar met 'n wagwoord te berg. Slegs die navorser en die studieleier sal na die data kan kyk. Die data sal te alle tye anoniem hanteer word.

Indien die navorsing gepubliseer word, sal die data in die algemeen – met ander woorde vir die groep in die geheel – bespreek word.

7. DEELNAME EN ONTTREKKING

U kan kies of u kind aan hierdie studie mag deelneem of nie. Indien u aanbied dat u kind kan deelneem, kan u hom/haar steeds in enige stadium onttrek sonder dat dit enige gevolge vir u kind sal inhou. Die navorser kan ook besluit om u kind aan die studie te onttrek indien omstandighede dit vereis.

8. BESONDERHEDE VAN NAVORSERS

As u enige vrae oor die navorsing het of as enigiets daarvan u pla, kontak ons gerus:

Elbé de Villiers (selfoon 084 515 7642; e-pos edup@sun.ac.za) of dr Ranel Venter (selfoon 083 309 2894; e-pos rev@sun.ac.za)

9. REGTE VAN NAVORSINGSDEELNEMERS

U kan in enige stadium u toestemming terugtrek en u kind se deelname staak, sonder enige nadelige gevolge. U kind doen nie afstand van enige wettige aansprake of regte deur aan hierdie navorsingstudie deel te neem nie. Vir enige vrae oor u kind se regte as studiedeelnemer, skakel met me Maléne Fouché in die Universiteit Stellenbosch se Afdeling Navorsingsontwikkeling [mfouche@sun.ac.za; 021 808 4622].

HANDTEKENING VAN OUER / VOOG

Ek het geleentheid gekry om vrae te vra, en dit is bevredigend beantwoord.

Ek stem in dat ________________________________ aan hierdie studie kan deelneem. Ek het 'n afskrif van hierdie vorm ontvang.

____

Naam van ouer/voog

____ ________________

Handtekening van ouer/voog **Datum**

Woonadres:

Straatnaam en nommer: ____

Voorstad / area: ____

Stad / Dorp: ____

BAIE BELANGRIK: Sal u asseblief u kind herinner om die volgende saam toetsing toe te bring

1. **Skoene waar in hy/sy sport doen (bv. Tekkies)**
2. **Skool skoene**
3. **Kouse**
4. **Kort oeven broek**
5. **Die twee ingevulde vorms getek deur die deelnemer en ouer**

APPENDIX EIGHT

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UNIVERSITEIT STELLENBOSCH
TOESTEMMING TOT DEELNAME AAN NAVORSING

Bewegende voete – 'n vergelykende studie van skoolkinders wat gewoonlik skoene dra teenoor dié wat gewoonlik kaalvoet loop

Ek is Elbé de Villiers ('n PhD-student in Sportwetenskap) van die Departement Sportwetenskap aan die Universiteit Stellenbosch. Ek nooi jou om deel te neem aan my navorsingstudie. Die resultate van die studie sal deel uitmaak van die tesis vir my doktorsgraad in Sportwetenskap. Jy is as 'n moontlike studiedeelnemer gekies omdat jy in een van die deelnemerskole is en ook die regte ouderdom is.

1. DOEL VAN DIE STUDIE

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2. PROSEDURES

Indien jy instem om aan hierdie studie deel te neem, sal jy die volgende toetse en metings ondergaan:

Antropometriese meting: Jou lengte en gewig sal gemeet word.

Invul van 'n vraelys oor fisiese aktiwiteit: Dít word gedoen om te bepaal hoe aktief jy is.

Invul van 'n vraelys oor kaalvoetgewoontes: Hiermee wil ons agterkom hoe gereeld jy kaalvoet is.

Draf en hardloop oor 20 meter: Terwyl jy draf en hardloop sal jy met 'n videokamera afgeneem word. Die video word geneem om te kyk hoe jy jou voet neersit tydens die verskillende situasies. Die tyd wat dit jou neem om die 20 meter te hardloop sal geneem word en jy sal gevra word om dit twee keer te doen, met en sonder skoene.

Balanstoetse: Jy sal gevra word om agteruit te loop op drie verskillende plankies, elkeen met 'n ander breedte. Dit moet ook twee keer elk gedoen word, met en sonder skoene.

Spronge: Jy sal so ver as moontlik met albei voete tegelyk probeer spring. Die afstand sal gemeet word. Jy sal die sprong drie keer doen, met en sonder skoene.
Na die verspring sal jy gevra word om so veel keer as moontlik in 15 sekondes sywaarts te spring. Dit sal twee keer herhaal word en die beste een van die twee sal gebruik word, met en sonder skoene.

Handgreep: Die krag van albei jou hande sal gemeet word met 'n handgreepkaliper.

Voetvorm: Jy sal gevra word om kaalvoet op 'n voetmetingsapparaat te staan terwyl jou voetlengte en -breedte sowel as die hoogte van jou voetbrug bepaal sal word.

3. MOONTLIKE RISIKO'S EN ONGEMAK

Hoewel van die toetse dalk onbekend sal wees vir jou, is dit eenvoudige toetse. Dit behoort jou nie buitengewoon moeg te maak of ongemak te veroorsaak nie.

4. MOONTLIKE VOORDELE VIR STUDIEDEELNEMERS EN/OF DIE SAMELEWING

Jy sal geen direkte voordeel uit die studie trek nie.

Die studie hou egter wel voordele in vir kennis op die gebied van sportwetenskap en veral oor die uitwerking van skoene op kinders se voete en bewegingsvermoë. Die resultate kan skoenvervaardigers ook moontlik in die toekoms die nodige kennis gee om skoene te ontwerp wat voordelig is vir die ontwikkeling van kinders se voete.

5. VERGOEDING VIR DEELNAME

Jy sal nie vir deelname aan hierdie studie betaal word nie.

6. VERTROULIKHEID

Enige inligting wat in verband met hierdie studie bekom word en jou identiteit kan verklap, sal vertroulik bly en slegs met jou toestemming of ingevolge wetsvereistes bekend gemaak word. Vertroulikheid sal gehandhaaf word deur die data op 'n persoonlike rekenaar met 'n wagwoord te berg. Slegs die navorser en die studieleier sal na die data kan kyk. Die data sal te alle tye anoniem hanteer word.

Indien die navorsing gepubliseer word, sal die data in die algemeen – met ander woorde vir die groep in die geheel – bespreek word.

7. DEELNAME EN ONTTREKKING

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8. BESONDERHEDE VAN NAVORSERS

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HANDTEKENING VAN DEELNEMER

Ek het geleentheid gekry om vrae te vra, en dit is bevredigend beantwoord.

Ek ______________________________stem in om aan hierdie studie deel te neem. Ek het 'n afskrif van hierdie vorm ontvang.

____

Naam van deelnemer

____ ________________

Handtekening van deelnemer **Datum**

<u>BAIE BELANGRIK:</u> Bring asseblief die volgende saam na die toetsing

1. **Skoene waar in jy sport doen (bv. Tekkies)**
2. **Skool skoene**
3. **Kouse**
4. **Kort oeven broek**
5. **Die twee ingevulde vorms getek deur die deelnemer en ouer**

APPENDIX NINE

Recording sheet

Name: ________________________ Date:_____________

Participant number: ____________

Anthropometric measurements

Boy ☐ **Girl** ☐

Age	
Date of birth (day/month/year)	
Height (cm):	
Body mass (kg)	
Shoe mass of left shoe (g)	

20m Sprint test

Footwear condition to start with (Circle): BF / Shod			
Trial	Split	**BF**	**Shod**
Trial 1	10m split time		
	20m split time		
Trial 2	10m split time		
	20m split time		

APPENDIX TEN

PILOT STUDY

As mentioned in the methodology the current study formed part of a much larger binational study (Hollander *et al*., 2016) which included seven testing stations of which the 20m sprint was only one. During the pilot study, many changes were made to the original protocol of the larger study. The most important change that occurred was that initially, the researchers tried to test many participants in a single lesson but after many adjustments, no more than seven participants could be tested in a single lesson to acquire full data sets. This appendix will only discuss the changes that were made to the 20m sprint test.

During the pilot study, the researchers added markers to anatomical landmarks of the foot and ankle. This was done because initially the researchers wanted to use the method used by (Altman & Davis, 2012) to determine foot strike pattern (FSP). However, due to time constraints it was decided to not add markers to the participants.

During the pilot study, the researchers initially only wanted to determine FSPs from a lateral view to avoid any potential differences that may exist between classifying FSPs from a medial and lateral view. For example, the researchers did not know if there was a higher probability to classify a foot strike as a MFS from a lateral view than from a medial view. When viewing the FSPs on the high-speed video footage the researchers saw that the fish-eye effect of the GoPro's ultra-wide view increased the further away you went from the centre of the camera's view. Foot strikes that occurred exactly at the centre of the camera's view were least affected but the further away foot strikes occurred from the centre the greater the fish-eye effect was on them. Due to this observation, the researchers decided that it was better to rather determine FSP of the foot that was closest to the centre of the camera's view. Some children used different FSPs with different feet (left or right foot). Therefore, the researchers decided to first determine the FSP that was closest to the centre of the camera's view for the fastest barefoot (BF) sprint and then to determine the FSP of the same foot (left or right) in the shod condition even if it was not the closest to the centre. For most children and adolescents, the same foot was closest to the centre of the camera's view when BF and shod.

Initially the researchers wanted to standardise the side of the runway the GoPro camera was placed. However, when testing outside, it was important to place the GoPro with the lens facing away from the sun. Therefore, the researchers decided that the side the camera would be placed would not be standardised but that the camera would be placed with the lens always facing away from the sun.

At the first school data was collected from during the pilot study, participants performed their 20m sprints in an indoor school hall. The ambient lighting was limited due to the lighting of the hall and made it difficult to accurately determine FSPs. Therefore, the researchers decided to purchase a spotlight (Godox LED308 Video Light, Fuyong Town, Baoan District, Shenzhen, China) to light up the area where foot strike was determined. When testing was performed outside, the ambient lighting was sufficient and no additional lighting was used.

APPENDIX ELEVEN

SPRINTING TECHNIQUE

INDEX OF SPRINTING TECHNIQUE SECTION

11.1. INTRODUCTION

A 100m sprint can be divided into three sections namely the acceleration, speed maintenance/constant speed and the deceleration periods. Research has shown that top speed during a 100m sprint is only reached after 50-80m in elite sprinters (Ae *et al.*, 1992; Gajer *et al.*, 1999) and between 30-40m in untrained and low level sprinters (Delecluse *et al.*, 1995 cited in Maćkała *et al.*, 2015). After top speed is reached, it is maintained for a short duration during the constant speed period before deceleration occurs.

The sprinting distance in the current study will only be 20m and the deceleration phase is, therefore, not relevant. The distance might be too short for older adolescents to reach top speed but younger children might reach the speed maintenance phase before the end of the 20m sprint. Sprinting biomechanics in both the acceleration and constant speed periods are, therefore, relevant for the current study and both will be discussed in detail. Moreover, during the transition from initial acceleration to top speed the sprinting technique gradually changes to that seen at top speed. To understand what happens in between these periods, biomechanics at both sides of the spectrum need to be considered.

In this section, changes in spatiotemporal variables during a sprint and the strategies the body applies to increase running speed during initial acceleration and near top speed will firstly be described. Secondly, the sprinting biomechanics in both the acceleration period and the high-speed running period (at or near top speed) will be discussed. For both periods, the different phases of the sprinting cycle will be looked at in depth. The motion in the hip, knee and ankle joints, the muscles involved and the sprinting technique will be described for the different phases of a sprinting stride. How athletes should sprint and some common errors in less experienced sprinters will also be explained since the majority of the participants in the current study are inexperienced sprinters. Furthermore, reference will be made to when muscles are active. Figure 11.1 shows typical EMG activity while running but will still be useful to help understand sprinting biomechanics. As running speed increases, such as when sprinting, muscles become active earlier in the running cycle and tend to be active for a greater portion of the cycle (Bosch & Klomp, 2005:127). To help interpret Figure 11.1, Novacheck (1998) stated that there is a delay of about 50ms between the start of EMG activity and the start of force production (Sherif *et al*., 1983 cited in Novacheck, 1998) and that muscle force continues even after EMG activity has ended. Therefore, the early end of activity should not be mistaken with the end of force production. The following references, (Bosch & Klomp, 2005) and (Novacheck, 1998), are comprehensive research on the biomechanics of sprinting and will be referred to often throughout this section.

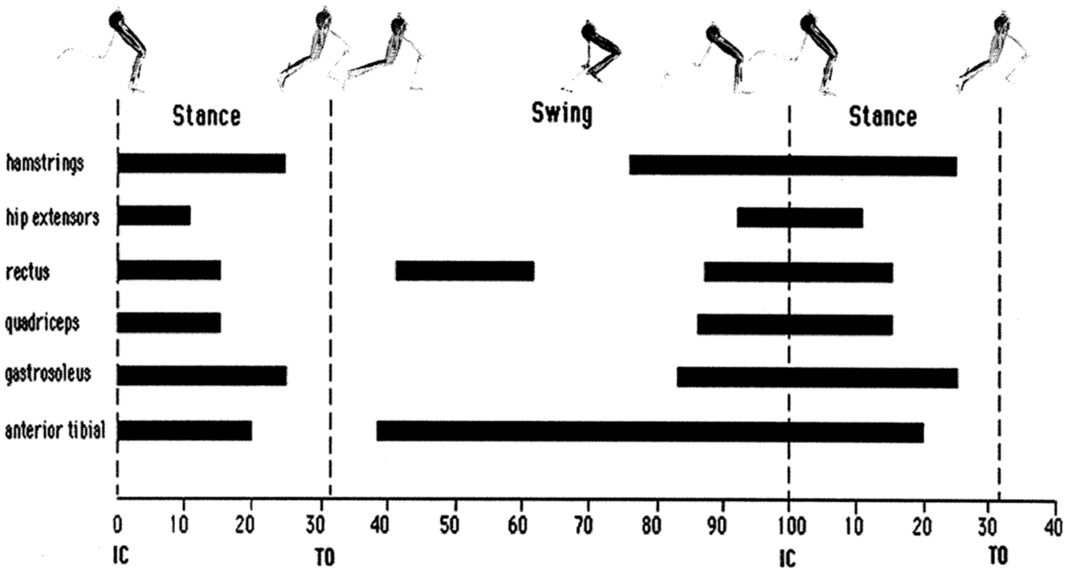

Figure 11.1. EMG of major leg muscles while running. The solid bars represent muscle activity. The quadriceps refer to the vastus muscle group. The scale on the x-axis going from 1-100 represents percentage of the gait cycle. This figure was adapted from Mann and Hagy (1980) cited in Novacheck (1998). More than one gait cycle was shown to better show the continuous nature of the running cycle. Novacheck (1998) stated that the large number of active muscle groups around the time of initial contact (IC) and the lack of active muscle at the time of toe off (TO) should be noted.

11.2. CHANGES IN SPATIOTEMPORAL VARIABLES DURING ACCELERATION

Before looking at the acceleration and high-speed running periods of sprinting, how spatiotemporal variables change during acceleration to top speed of a maximal effort sprint will first be looked at. The strategies the body uses to increase running speed during initial acceleration and closer to top speed will also specifically be looked at.

As a sprinter accelerates to top speed, SL and SF increase (Moravec *et al.*, 1988; Ae *et al.*, 1992; Mero *et al.*, 1992; Ito *et al.*, 2006; Mackala, 2007; Schache *et al.*, 2011; Dorn *et al.*, 2012; Krzysztof & Mero, 2013; Nagahara *et al.*, 2014). FT also increases and GCT decreases (Moravec *et al.*, 1988; Hobara *et al*., 2010; Lockie *et al*., 2013a; Nagahara *et al.*, 2014). Initially both SL and SF rapidly increase (Figure 11.2 C, E, F and G) but SF reaches a plateau within the first 15m of maximal effort acceleration. Research shows mixed results concerning the distance at which SF plateaus. Figure 11.2 C shows that in 12 adult male sprinters SF, on average, reached a plateau at the fourth step (4.7 ± 0.3m from the start line) during a 60m maximal effort sprint (Nagahara *et al.*, 2014). Figure 11.2 E, F and G show that during a 100m sprint of three elite male sprinters, SF only reached a plateau somewhere between the first 10m to 15m. SL, however, continues to increase to top speed (Moravec *et al.*, 1988; Ae *et al.*, 1992; Mero *et al.*, 1992; Ito *et al.*, 2006; Mackala, 2007; Schache *et al.*, 2011; Dorn *et al.*, 2012; Krzysztof & Mero, 2013; Nagahara *et al.*, 2014). Therefore, the body's strategy to increase running speed during initial acceleration (up to 5m or 15m) is to rapidly increase both SL and SF after which the strategy changes to only further increase SL. During acceleration, the body's CoM also gradually rises (Figure 11.2 D). To give a visual illustration of how the kinematics change during a sprint, the stick figures in Figure 11.2 also illustrate how the positions of body segments change at foot strike and take-off throughout an entire acceleration to top speed. Illustrations are given from the first to the 25th step, during a 60m sprint.

In summary, the body uses different strategies to increase running speed during a maximal effort sprint to top speed. During initial acceleration (up to 5m or 15m), the strategy to increase running speed is to rapidly increase both SL and SF after which the strategy changes to only further increase SL.

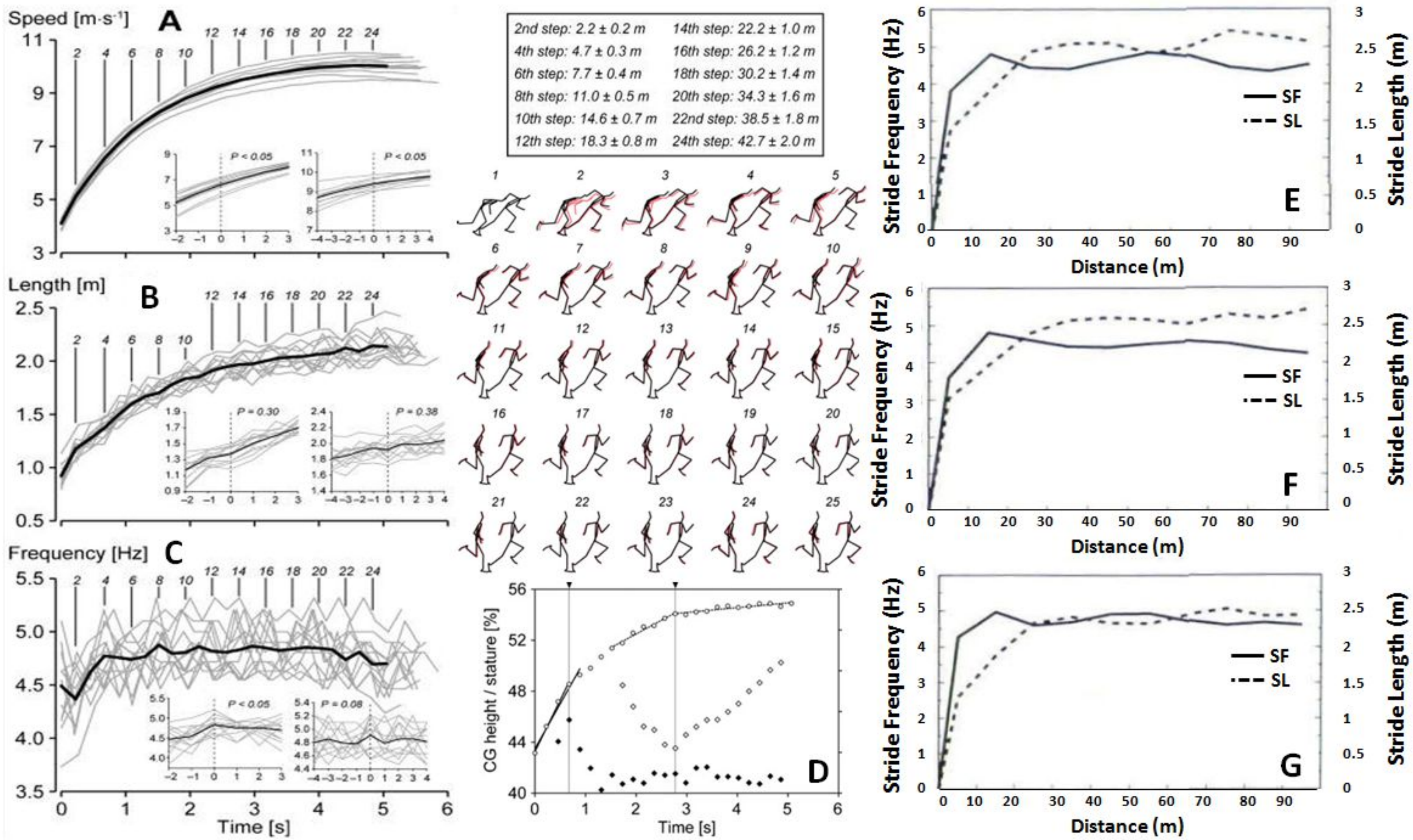

Figure 11.2. A, B, C and D are adjusted from Nagahara *et al.* (2014) and respectively indicate the average running speed, step length, step frequency and how the body's centre of gravity (CG) rises during a 60m sprint. The vertical solid lines with numbers in A, B and C indicate the number of steps. The open circles in D represent the mean height of the centre of gravity at each step. The vertical lines, closed and open diamonds in D may be ignored. The box above the stick figures indicates the average distances from the start line to the respective steps (mid-position of a step). E, F and G are adjusted from (Ae *et al.*, 1992) and indicate how stride length and stride frequency change during the 100m sprints of Carl Lewis, Leroy Burrell and Dennis Mitchell respectively.

11.3. ACCELERATION PERIOD

In this section, the sprinting mechanics of the acceleration period, which are quite different to high-speed running, will be discussed in detail. Firstly, general aspects of the acceleration period will be discussed. Secondly, the stance phase will be discussed in detail and thirdly, the swing phase will also be discussed in detail. Lastly, a summary will be given of the acceleration period.

During the start of a sprint, whether it is from a standing start or from a block start, the body leans forward and if the lean is large enough the body's CoM will be ahead of the point of foot strike (Jacobs & van Ingen Schenau, 1992; Mero *et al.*, 1992; Novacheck, 1998; Nagahara *et al.*, 2014). The forward body lean allows a larger horizontal component of the ground reaction force (GRF) which is useful to accelerate the body forwards. The aim in this phase is to exert as much horizontal force as possible. Large extensions occur in joints of the legs as the sprinter aims to exert force against the ground for as long as possible. Large movements also occur in the arms to counterbalance the large extensions in the legs. Two distinctive characteristics of the start and initial acceleration period are the longer GCT and the use of explosive concentric muscle action.

Longer ground contact time (GCT)

The horizontal speed of the body is slow at the start and, therefore, GCT is longer than at high-speed running (0.12-0.18s at the start compared to 0.07-0.10s at top speed for elite sprinters) (Mero *et al*., 1992; Bosch & Klomp, 2005:169). Due to the forward body lean, a forward moment develops around the transverse axis that needs to be countered. The longer GCT allows enough time to counter this moment. As sprinting speed increases, GCT shortens resulting in less time to counter this moment and the body position gradually becomes more upright (Mero *et al*., 1992; Nagahara *et al*., 2014; Novacheck, 1998; Bosch & Klomp, 2005:169-180).

Explosive concentric muscle action

At the start, and during acceleration, sprinting is reliant on powerful concentric muscle actions as opposed to a large reliance on the use of elastic components seen at high-speed running. Two aspects allow favourable conditions for strong concentric muscle action to produce large amounts of force during this phase; 1) Large flexion is seen in the hip, knee and ankle joints at foot strike along with large extensions in these joints at toe-off. The joints, therefore, move through large ranges of motion over which concentric contractions can act. 2) GCT is long and the speed at which muscles need to contract is, therefore, not as high compared to high-speed running. Therefore, large forces can be produced through concentric contractions considering the force-velocity relationship.

11.3.1. STANCE PHASE OF ACCELERATION PERIOD

In this section, the stance phase during the acceleration period will be discussed in detail. Firstly, general aspects of the stance phase during the acceleration period will be discussed. Secondly, the support phase and lastly the drive phase will be discussed in depth. The discussions of the support and drive phase will be structured in two sections. In the first section, general aspects of the respective phase will be discussed. In the second section, detailed discussions will be made of the motion in the hip joint followed by the motion in the knee joint and lastly the motion in the ankle joint.

During initial acceleration, GCT lasts longer than FT. Furthermore, GCTs are at their longest and FTs at their shortest which is beneficial for acceleration (Moravec *et al.*, 1988; Hobara *et al.*, 2010; Lockie *et al.*, 2013a; Nagahara *et al.*, 2014). The longer GCT increases the durations of force production and, since a sprinter can only accelerate when force is exerted against the ground, the short FT decreases the waiting periods between periods of force production.

Figure 11.3 shows how the hip, knee and ankle joints of the stance leg flex and extend throughout the stance phase. The stance phase was analysed at the 16m mark of a 25m maximal effort sprint from a standing start. There are similarities in methodology between (Hunter *et al.*, 2004b) from which Figure 11.3 was taken and the current study. In the current study, maximal 20m sprints will be performed, also from a standing start, and FSP will be determined around the 17.5m mark. Therefore, Figure 11.3 shows very relevant information to the current study.

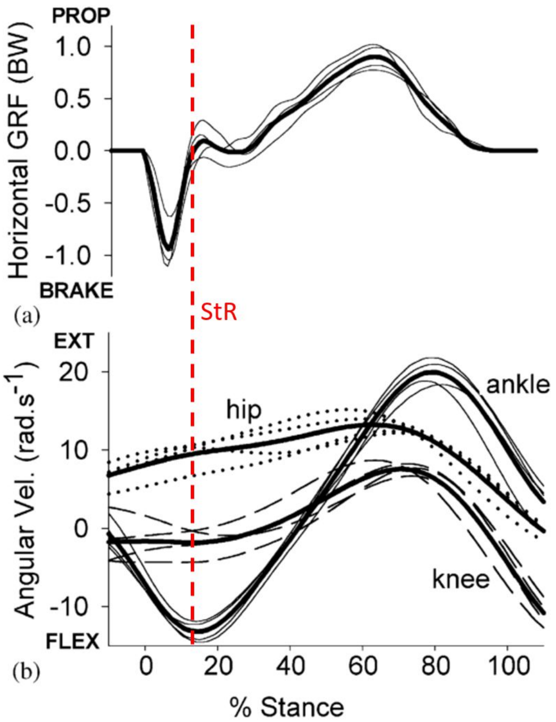

Figure 11.3. The angular velocities of the hip, knee and ankle joints during the stance phase which occurred at the 16m mark of a 25m maximal effort sprint from a standing start. The thick lines represent the mean and the thin lines the individual results for the four adult male track and field athletes in the original study. The athletes' personal-best times for the 100m ranged from 10.60 to 10.97s and their mean age was 21±3 years. EXT= extension, FLEX= flexion and StR= stance phase reversal (end of the support phase) indicated by the red line. Adapted from Hunter *et al.* (2004b).

11.3.1.1. Support phase of acceleration period

During the support phase, the horizontal speed of the body decreases slightly due to horizontal forces opposite to the running direction (i.e. braking forces), even if the body's CoM is ahead of the point of foot strike (Mero *et al.*, 1992). During initial acceleration the support phase only makes up a small proportion of the stance phase and average braking forces are small (Mero *et al.*, 1992). Therefore, the decrease in speed is the smallest during initial acceleration. As speed increases, there is an increase in the proportion that the support phase makes up of the stance phase and an increase in average braking forces resulting in a greater decrease in speed (Mero *et al.*, 1992).

Besides the forward body lean, there are other kinematic differences between initial acceleration and high-speed running. At foot strike, there is large flexion in the hip and knee joints and the ankle joint is largely dorsiflexed (Jacobs & van Ingen Schenau, 1992). The large flexion seen in the joints allows the extensor muscles to produce large amounts of force concentrically over large ranges of motion. Next, the motions in the hip, knee and ankle joints will be looked at along with the muscle actions to produce those motions.

Hip joint

Hip extension occurs throughout the entire support phase and the rest of the stance phase (Figure 11.3). The hip extensors, gluteus maximus (GLU) and hamstrings (HAM), are very active during the first half of the stance phase to rotate the leg backwards in hip extension (Novacheck, 1998).

Knee joint

During initial acceleration, there is no extension in the knee joint during the support phase (Figure 11.3). Knee extension is initially delayed until the body is in a position where knee extension would favourably contribute to propelling the body horizontally forwards. If knee extension occurs too early, the projection of the body will be too vertical (Jacobs & van Ingen Schenau, 1992; Nagahara *et al.*, 2014). It can be said that the body first rotates forward around the hip joint before knee extension occurs. The GLU and HAM work together to achieve this motion (Figure 11.4) (Jacobs & van Ingen Schenau, 1992). When the GLU acts to extend the hip it has an indirect effect on extending the knee since the foot is fixed on the ground (Bosch & Klomp, 2005:56-57). The HAM resists this knee extension to allow hip extension alone.

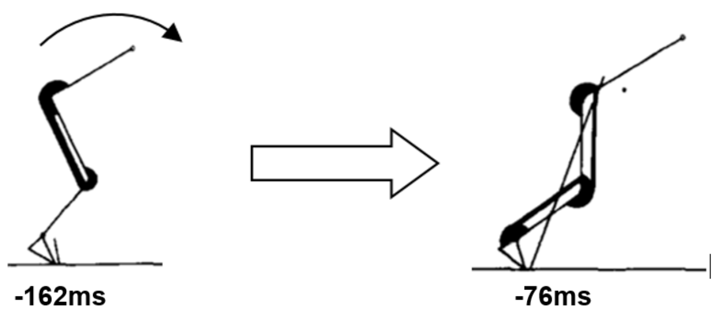

Figure 11.4. Illustration of how hip extension initially occurs without much knee extension causing the body to rotate around the hip joint before knee extension occurs. The level of activity is depicted by the thickness of the muscle line. Time is expressed relative to the instant of toe-off. Adapted from (Jacobs & van Ingen Schenau, 1992).

Jacobs and van Ingen Schenau (1992) found that, the EMG activity of the GLU and HAM and relatively low activity of the rectus femoris (REC) explain the hip extensor moment from foot strike until about 100ms before toe-off (43% of stance). This was during the second stance phase after starting from starting blocks. Figure 11.5 shows the kinematics of the support leg from foot strike until toe-off during the second stance phase (Jacobs & van Ingen Schenau, 1992).

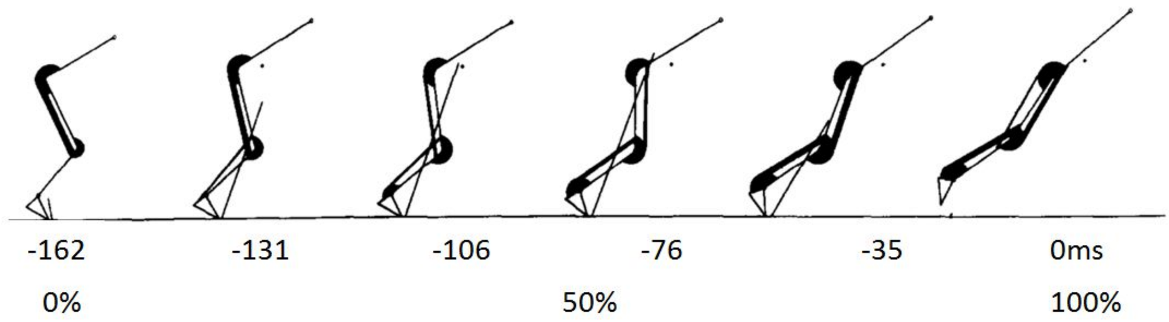

Figure 11.5. Stick figures showing the positions of the trunk and stance leg, together with the actions of the muscles at different time samples during the second stance phase after starting from starting blocks. The level of activity is depicted by the thickness of the muscle line. Time is expressed relative to the instant of toe-off and percentages show the percentage of the stance phase. Foot strike started 175.2ms before toe-off. Adapted from (Jacobs & van Ingen Schenau, 1992).

Ankle joint

The degree of ankle dorsiflexion increases as the body's weight is transferred to the stance leg (Figure 11.3). The plantarflexors, GAS and soleus, eccentrically control the rate of dorsiflexion during the support phase (Brown *et al.*, 2012; Perl *et al.*, 2012). Despite a dorsiflexed ankle joint, a forefoot strike (FFS) will still occur due to the forward body lean.

11.3.1.2. Drive phase of acceleration period

During the drive phase the kinetic and potential energy of the body is increased as the body is propelled upward and forward (Novacheck, 1998). During initial acceleration, the aim is to exert as much force for as long as possible especially towards the end of the drive phase when the horizontal component of the GRF is at its largest (Bosch & Klomp, 2005:174; Jacobs & van Ingen Schenau 1992). Through the horizontal component of the GRF, the horizontal speed of the body's CoM increases as the body is propelled forwards. Next, the motions in the hip, knee and ankle joints will be looked at along with the muscle actions to produce those motions.

Hip joint

Figure 11.3 shows that hip extension continues throughout the drive phase until toe-off (Jacobs & van Ingen Schenau, 1992; Novacheck, 1998; Dorn *et al.*, 2012). During the first half of the stance phase the GLU and the HAM work together to cause hip extension and EMG activity in both muscles are high (Jacobs & van Ingen Schenau, 1992; Novacheck, 1998). During the second half of the stance phase, HAM activity rapidly decreases but GLU activity remains high until toe-off (Jacobs & van Ingen Schenau, 1992; Dorn *et al.*, 2012). The GLU, therefore, extends the hip joint without the aid of the HAM during the second half of stance.

The speed of hip extension increases from StR until about 60% of stance (Figure 11.3). Hip extension then begins to decelerate in preparation for the swing phase as the hip flexors become dominant over the hip extensors (Novacheck, 1998). Deceleration of leg segments is important to prevent hyperextension or hyperflexion, which could damage joints (Jacobs & van Ingen Schenau, 1992). A decrease in the hip extension moment was found by Jacobs and van Ingen Schenau (1992) around 100ms before toe-off (43% of stance). This was due to decreased HAM activity and increased activity of the REC, which acted as a hip flexor. Other hip flexors like the iliopsoas also play a role to decelerate the hip joint. During the second half of the stance phase, when the hip joint is still extending and the iliopsoas is active, the tendon of the psoas major (part of the iliopsoas) is stretched and the absorbed energy is released at toe-off for hip flexion (Novacheck, 1998).

Knee joint

As previously described, during the support phase knee extension is delayed as the body is first rotated around the hip (Jacobs & van Ingen Schenau, 1992). Only after this rotation, is the knee extended in the drive phase. Jacobs and van Ingen Schenau (1992) found an increase in knee extensor moment from 100ms before toe-off (43%

of stance) which was due to decreased HAM activity and increasing activity of the quadriceps.

The biarticular REC plays an important role in transferring energy from the hip to the knee joint. Some of the energy produced during hip extension by the powerful GLU muscle is used to extend the knee through energy transfer by the REC (Jacobs & van Ingen Schenau, 1992; Novacheck, 1998; Prilutsky & Zatsiorsky, 1994; Bosch & Klomp, 2005:54). The monoarticular vastus group also plays a very important role in the drive phase to powerfully extend the knee joint.

The REC and the HAM work reciprocally. When the one plays a predominant role during propulsion the other one is either working only slightly or not at all (Jacobs & van Ingen Schenau, 1992). During the initial acceleration period, the REC plays a dominant role over the HAM (Bosch & Klomp, 2005:173) but as speed increases, the knee is less flexed at foot strike and the HAM progressively becomes more dominant.

Ankle joint

Powerful plantarflexion occurs at the end of the drive phase and the body is propelled upwards and forwards (Novacheck, 1998). The energy for plantarflexion derives from contraction of the GAS and soleus muscles, recoil of the elastic components in the lower leg and energy transfer from knee extension by the GAS (van Ingen Schenau & Cavanagh, 1990; Jacobs & van Ingen Schenau, 1992; Prilutsky & Zatsiorsky, 1994; Novacheck, 1998). At some point during knee extension, the biarticular GAS begins to act to decelerate knee extension and cause powerful plantarflexion. Jacobs and van Ingen Schenau (1992) found a decreasing knee extension- and increased plantar flexion moment at the ankle joint from 88ms before toe-off (50% of stance). This was due to increased activity of the GAS, a decreasing moment arm of knee extensors and increasing shortening velocity of the knee extensors. The biarticular GAS plays an important role in transferring energy from knee extension to the ankle joint for powerful plantarflexion and in this way supports the work done by the soleus muscle (van Ingen Schenau & Cavanagh, 1990; Jacobs & van Ingen Schenau, 1992; Prilutsky & Zatsiorsky, 1994; Novacheck, 1998).

Stefanyshyn and Nigg (1997) calculated energy absorption and production in the joints of the lower limb during the stance phase of an acceleration period and found the ankle joint to be the largest energy absorber and producer. The ankle joint absorbed and produced even more energy than the knee and hip joints. Data were collected from five competitive adult male sprinters (aged 22.2±2.2 years) after they had accelerated approximately 15m at maximal effort and continued accelerating through the data collection area. Data were collected over a 1.93m distance. Average speeds when data were collected ranged from 7.1-8.4m/s (Stefanyshyn & Nigg, 1997). The ankle joint, therefore, plays an important role in accelerating the body during the acceleration period.

The stance leg is extended almost completely during the drive phase with maximum hip and knee extension reached at toe-off. The knee of the swing leg remains swung forward, bent at least 90°, until the knee of the stance leg is maximally extended. The pelvis is tilted forwards to allow an increased hip extension, the trunk is held erect and the arms are swung high to assist with counterbalancing the large movements of the legs (Bosch & Klomp, 2005:174). During the acceleration period, the CoM's trajectory is more horizontal and relatively low compared to high-speed running (Novacheck, 1998; Bosch & Klomp, 2005:174).

11.3.2. SWING PHASE OF ACCELERATION PERIOD

In this section, the swing phase during the acceleration period will be discussed in detail. Firstly, general aspects of the swing phase during the acceleration period will be discussed. Secondly, the motion of the swing leg when it is the trailing leg and lastly the motion of the swing leg when it is the leading leg will be discussed in detail. The discussions of the motion of the swing leg when it is the trailing leg and when it is the leading leg will be structured by firstly discussing the motion in the hip joint followed by the motion in the knee joint and lastly the motion in the ankle joint in detail.

The swing phase lasts from toe-off until foot strike of the same leg. There are two floating phases during a single swing phase with a stance phase of the contralateral leg in between the two floating phases (Novacheck, 1998). The first floating phase immediately after toe-off concerns the motion of the relevant leg when it is the trailing leg and the second floating phase when it is the leading leg.

During initial acceleration, the projection of the body is relatively low at toe-off and the horizontal and vertical components of the GRF are proportionally larger and smaller, respectively, compared to high-speed running. Due to the low body projection, the floating phases are short and FT is shorter than GCT. The motion of the leg in the two floating phases will now be looked at focussing on the motions in the hip, knee and ankle joints along with the muscle actions involved to produce those motions.

11.3.2.1. Motion of swing leg when it is the trailing leg

Hip joint

After toe-off, hip flexion occurs to swing the leg forwards during the recovery phase. As mentioned before, in this paper the recovery phase lasts from toe-off until peak hip flexion is reached. Concerning moments, the hip flexors are dominant over the hip extensors during the first half of the swing phase (Novacheck, 1998). The main hip flexors, the iliopsoas muscles, and the REC act to flex the hip joint during the swing phase (Novacheck, 1998; Morin *et al.*, 2015).

Knee joint

The knee also flexes after toe-off and hip and knee flexion should be done simultaneously. The posterior swing of the tibia during knee flexion is controlled by the REC that is the only active quadriceps muscle during this time (Novacheck, 1998). During initial acceleration, the knee is not flexed very much during the swing phase and the foot of the swing leg remains relatively close to the ground so that it can quickly be placed on the ground again for the next step. Knee flexion increases as running speed increases and the motion of the swing leg gradually becomes more cyclical. During initial acceleration, the motion of the swing leg is quite linear and can be likened to a piston action instead of the cyclical action seen at high-speed running.

Ankle joint

The ankle is plantarflexed after toe-off and is dorsiflexed as the leg is swung forwards in preparation for foot strike. The tibialis anterior acts to dorsiflex the ankle joint.

11.3.2.2. Motion of swing leg when it is the leading leg

Hip joint

During the second half of the sing phase, hip flexion decelerates until peak hip flexion is reached. This is due to the hip extensors becoming dominant over the hip flexors and act to slow down hip flexion (Novacheck, 1998). The hip extensors are dominant over the hip flexors during the second half of the swing phase and the first half of stance (Novacheck, 1998). After peak hip flexion has been reached, the GLU and HAM muscles extend the hip to prepare the leg for foot strike. This is sometimes referred to as a scissors like motion (Novacheck, 1998).

Knee joint

During initial acceleration when the tibia of the swing leg swings out during knee extension, the knee is not extended as much as during high-speed running and results in a more flexed knee joint at foot strike. Before foot strike, the quadriceps contract to develop pre-tension in anticipation of impact in order to absorb the shock at impact (Novacheck, 1998; Morin *et al.*, 2015). As running speed increases and impact forces become higher, their shock absorbing role becomes more important (Novacheck, 1998).

Ankle joint

During initial acceleration, the ankle is pre-tensed in a dorsiflexed position in preparation for foot strike. As running speed increases, the ankle joint may become more plantarflexed at foot strike since a FFS is often used at high-speed running (Novacheck, 1998; Krell & Stefanyshyn, 2006; Toon *et al.*, 2009; Theophilos *et al.*, 2014; Hébert-Losier *et al.*, 2015).

11.3.3. SUMMARY OF ACCELERATION PERIOD

During the start and initial acceleration period, the strategy to increase speed is to rapidly increase both SL and SF. The body is leaned far forwards to increase the backward force applied by the leg and, therefore, the horizontal component of the GRF. A lot of force is exerted at the end of push-off when the horizontal component of the GRF is at its greatest and large extensions occur in the legs that are counterbalanced by large movements of the arms. Since the horizontal speed is relatively low, the GCT is long allowing enough time to counterbalance the forward body lean. The motion of the swing leg is a lot more linear and can be likened to a piston action as opposed to a cyclic motion. At foot strike, the knee and hip are a lot more flexed compared to high-speed running and this phase is reliant on powerful concentric muscle actions. The strength of the GLU and quadriceps can be better utilised during acceleration due to the large ROM over which they can produce force against the ground and the relatively slow speed of contraction.

11.4. HIGH-SPEED RUNNING PERIOD

In this section, the sprinting mechanics of the high-speed running period (near and during top speed sprinting) will be discussed. The sprinting mechanics are quite different to that of the acceleration period discussed prior to this section. Firstly, general aspects of the high-speed running period will be discussed. Secondly, the stance phase and thirdly, the swing phase will be discussed in detail. Lastly, a summary will be given of the high-speed running period.

During high-speed running, the body is a lot more upright and the hip and knee joints are a lot less flexed at foot strike. A FFS is most often used with a plantarflexed ankle (Novacheck, 1998; Krell & Stefanyshyn, 2006; Toon *et al.*, 2009; Theophilos *et al.*, 2014; Hébert-Losier *et al.*, 2015). Compared to the acceleration period, smaller extensions occur in the leg joints and smaller movements in the arms are needed to counterbalance the motion of the legs.

During top speed running, the aim is simply to maintain and not to further increase running speed. SL and SF are both at maximum values during top speed sprinting and due to the high running speed the GCT is very short with FT lasting longer than GCT. Due to the shorter GCT, the body needs to be held upright since there is not enough time to counterbalance a large forward lean (Bosch & Klomp, 2005:169-180).

11.4.1. STANCE PHASE OF HIGH-SPEED RUNNING PERIOD

In this section, the stance phase during the high-speed running period will be discussed in detail. Firstly, general aspects of the stance phase during the high-speed running period will be discussed. Secondly, the support phase and lastly, the drive phase will be discussed in detail. The discussions of the support and drive phase will be structured in two sections. In the first section, general aspects of the respective phase will be discussed. In the second section, detailed discussions will be made of the motion in the hip joint followed by the motion in the knee joint and lastly the motion in the ankle joint.

During high-speed running, FTs are at their longest and GCTs at their shortest (Moravec *et al*., 1988; Hobara *et al*., 2010; Nagahara *et al*., 2014). The short GCT means that there is limited time for force production against the ground. The longer FTs indicate that the vertical displacement of the body's CoM is higher during high-speed running compared to the initial acceleration period. Due to the high running speed and high vertical displacement, the body's kinetic and potential energy is highest during top speed running. Landing energy is, therefore, also highest during top speed running and this energy can be absorbed and re-used by the elastic components of the legs. High-speed running is more reliant on the use of elastic energy than the initial acceleration phase.

Figure 11.6 shows how the hip, knee and ankle joints of the stance leg flex and extend throughout the stance phase of top speed sprinting.

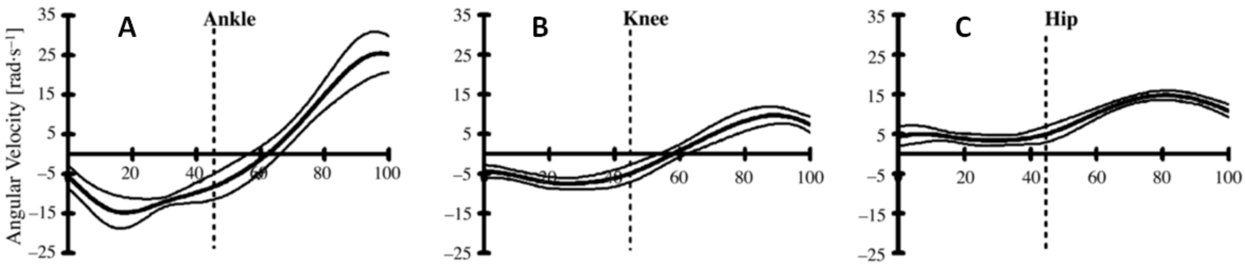

Figure 11.6. Angular velocities of the hip knee and ankle joints during the stance phase of sprinting at top speed. The thick line represents the mean for the four athletes and the thin lines represent the standard deviation. The vertical dotted lines represent stance phase reversal. Positive values for the ankle joint represent plantarflexion. Positive values for the knee and hip joints represent extension. Participants were four well-trained male sprinters. The ages of the participants were not reported but it is expected that all participants were adults. Adapted from Bezodis *et al.* (2008).

11.4.1.1. Support phase of high-speed running period

During the support phase, the horizontal speed of the body's CoM decreases due to braking forces (Mero *et al*., 1992). The main reason for the decreased horizontal speed during the support phase is the distance that foot strike is ahead of the body's CoM (Deshon & Nelson, 1964 and Kunz & Kaufman, 1981 cited in Mero *et al*., 1992). Therefore, foot strike should be directly under or only slightly in front of the body's CoM to make the support phase as short as possible and minimise braking forces.

During this phase, the shock of landing is absorbed especially at the ankle joint. Muscle activity is highest in anticipation of and just after foot strike (Deshon & Nelson, 1964 and Kunz & Kaufman, 1981 cited in Mero *et al*., 1992; Novacheck, 1998). Due to the high vertical displacement during high-speed running, the sprinter's body ''falls' from a higher height and there is more momentum directed vertically downward which can be absorbed and re-used during push-off. Due to the high forward running speed and the inevitable braking forces, some of the momentum directed horizontal forward is also absorbed and can be re-used during push-off. At foot strike, impact forces act to further flex the hip, knee and ankle joints making pre-tension very important in the extensor muscles (Mero *et al*., 1992). Next, the motion in the hip, knee and ankle joints will be looked at along with the muscle actions to produce those motions.

Hip joint

At foot strike, the hip joint is a lot less flexed compared to the acceleration period due to the upright body position. Hip extension occurs during the support- and the rest of the stance phase (Figure 11.6). The hip extensors, GLU and HAM, are very active in the second half of the swing phase and the first half of the stance phase as they extend the hip (Novacheck, 1998).

Knee joint

The knee joint is also less flexed at foot strike compared to initial acceleration (Nagahara *et al.*, 2014). The support phase is short, leg stiffness is high and the knee does not flex as much during the support phase compared to running (Novacheck, 1998). The quadriceps are active from late swing to StR. During late swing, they prepare the leg to counter the large flexion moment the GRF will have around the knee joint and during the support phase shock is absorbed as they act to counter the moment the GRF causes (Novacheck, 1998).

An indication of good sprinting technique is that the knee of the swing leg should not be behind the knee of the stance leg at StR where the body's total weight is on the stance leg. If the swing leg's knee is behind the stance leg's knee at this point, it indicates a slow recovery phase. When sprinting technique is good, the knees should be side by side. In this position, the body is in a better position to absorb shock (Bosch & Klomp, 2005:134-136).

Ankle joint

A plantarflexed FFS is often used during high-speed running and ankle dorsiflexion occurs as the weight of the body is transferred to the stance leg (Figure 11.6 A) (Novacheck, 1998; Krell & Stefanyshyn, 2006; Toon *et al.*, 2009; Theophilos *et al.*, 2014; Hébert-Losier *et al.*, 2015). During dorsiflexion, the plantarflexors eccentrically control loading and absorb shock. Landing energy from the drop of the body's CoM can be stored as elastic energy in the leg's elastic components (Bobbert *et al.*, 1986; Alexander, 1989; Mero *et al.*, 1992; Novacheck, 1998).

During high-speed running, the foot is swung to the ground at a very high speed. Pretension in the ankle joint before impact is very important to rapidly transfer force to the ground and to effectively use the elastic components of the lower leg (Bosch & Klomp, 2005:123; Brown *et al*., 2012). Using a pre-tensed FFS helps to keep the body's CoM high. Pretension helps to minimise the degree of dorsiflexion and the negative vertical displacement of the body's CoM. Larger negative vertical displacement requires more energy to lift the body's CoM again during the drive phase and decreases performance (Brown *et al*., 2012).

11.4.1.2. Drive phase of high-speed running period

During high-speed running, GCT is short (about 0.08-0.10s at top speed for elite sprinters) (Mero *et al*., 1992) and, therefore, time for force production is also short. The use of elastic components to store and utilise elastic energy becomes very important since there is only limited time for concentric contractions to produce propulsive force. Elastic components can recoil much faster than muscle fibres can contract and are, therefore, able to effectively produce force against the ground when GCTs are short (Alexander, 2002). At foot strike the velocity of the stance leg's foot becomes zero but the forward speed of the hips are still high in relation to the ground. The foot, therefore, gets rapidly 'dragged' behind the body and an 'automatic' hip extension occurs (Blazevich, 2007:53-55). The speed of hip extension, therefore, largely depends on the speed the hips are travelling. For this reason, GCT largely depends on running speed. For the GLU to exert additional force it must contract faster than the leg is 'pulled' back. Due to the need for such a high speed of contraction, the magnitude of force produced by the GLU is relatively small because of the force-velocity relationship (Bosch & Klomp, 2005:19). Next, the motion in the hip, knee and ankle joints will be looked at along with the muscle actions to produce those motions.

Hip joint

As in the drive phase during acceleration, hip extension continues until toe-off (Figure 11.6 C) (Novacheck, 1998). The GLU and the HAM work together to extend the hip during stance. GLU EMG activity remains high until toe-off (Jacobs & van Ingen Schenau, 1992; Dorn *et al*., 2012) but HAMs primarily only work during the first half of the stance phase (Novacheck, 1998; Bosch & Klomp, 2005:46,59). During the last part of the drive phase, when the hip is extended, the HAMs are very inefficient at contributing to hip extension due to them having a small moment arm with the hip in that position (Bosch & Klomp, 2005:43, 58). EMG data also show that they are not very active during this time (Jacobs & van Ingen Schenau, 1992). In contrast to the acceleration period, the HAM play a dominant role over the REC in propulsion during high-speed running.

The velocity of hip extension increases from StR to about 80% of stance during top speed sprinting (Figure 11.6). Hip extension then decelerates as the hip flexor moment becomes dominant over the hip extension moment (Novacheck, 1998). Hip flexors such as the Iliopsoas and REC act to decelerate the hip in preparation for the swing phase (Novacheck, 1998; Hunter *et al*., 2004b). As mentioned before, the tendon of the psoas (part of the iliopsoas muscle group) is stretched as the hip continues extension while the psoas is actively contracting. This develops tension, which is then released at toe-off for hip flexion (Novacheck, 1998).

Keeping the trunk upright during high-speed running allows early pre-tension to develop in the abdominal and iliopsoas when the hip extends (Bosch & Klomp, 2006). Developing early pre-tension will enable them to perform rapid hip flexion and a faster recovery phase is then possible. Inexperienced sprinters may keep their trunk bent forward during high-speed running to avoid the eccentric strain placed on the abdominals as the hip extends (Bosch & Klomp, 2005:40-42). The forward lean will result in a slower recovery phase since their iliopsoas and abdominal muscles will not be aided with early development of pre-tension.

Knee joint

During high-speed running, the stance leg is not completely extended during the drive phase which is in contrast to the acceleration period. Elite sprinters clearly still have the knee bent at toe-off with peak knee extensions of about 20° during sprinting (Novacheck, 1998). This allows the foot to come off the ground earlier and the leg to recover to the front sooner.

Compared to the acceleration period, the knee joint's ROM is smaller during high-speed running (Novacheck, 1998). According to Novacheck (1998), elite athletes do not even extend their stance leg knee during the drive phase (Novacheck, 1998). In less experienced sprinters, however, minor knee extension occurs and the quadriceps then contract concentrically. Knee extension during high-speed running is only minor due to two reasons; 1) Knee joint stiffness is high, therefore, the knee joint does not flex much during the support phase (Novacheck, 1998) and 2) The knee joint is still flexed at toe-off meaning there is little room for knee extension to occur. Due to the small ROM at the knee joint, the quadriceps do not contribute much to propulsion during high-speed running and mainly play a role in absorbing shock during landing (Jacobs & van Ingen Schenau, 1992; Novacheck, 1998; Bosch & Klomp, 2005:173).

Ankle joint

Powerful plantarflexion occurs at the end of the drive phase and the body is propelled upwards and forwards (Figure 11.6 A) (Novacheck, 1998). The energy for plantarflexion derives from contraction of the GAS and soleus muscles, recoil of the elastic components in the lower leg and some energy might be transferred from knee extension through energy transfer by the GAS (van Ingen Schenau & Cavanagh, 1990; Jacobs & van Ingen Schenau, 1992; Prilutsky & Zatsiorsky, 1994; Novacheck, 1998).

The GAS and soleus produced higher vertical and horizontal GRFs than the vastus and rectus femoris during constant speed running and sprinting at 3.49 ±0.12m/s, 5.17±0.13m/s, 6.96±0.13m/s and 8.99±0.67m/s (Schache *et al.*, 2011). Running and sprinting at a constant speed, therefore, seems to show the same trends concerning the contributions of the different muscles to the GRF. Furthermore, the ankle joint was shown to be the largest energy absorber and producer in the lower limb during the stance phase, even higher than the hip joint, while seven adult athletic participants ran at a constant speed of 3.5m/s (12.6km/h) (Schache *et al.*, 2011). Since the same trends were seen in the contributions of different muscles to the horizontal and vertical GRFs during running and sprinting, the ankle joint might also be the highest energy absorber and producer during the high-speed running period of a maximal effort sprint.

Bobbert *et al*. (1986) found that plantarflexion occurs mainly due to the recoil of elastic components and transported energy from knee extension during one-legged jumping.

Concentric muscle contractions of the GAS and soleus, therefore, do not play a dominant role in plantarflexion during one-legged jumping running. GCTs are much longer during one-legged jumping compared to sprinting and there is, therefore, much more time for concentric muscle contractions to contribute to energy production. During the high-speed running period of sprinting, when GCTs are very short, it is expected that the contribution to total energy production at the ankle joint originating from concentric muscle contraction of the GAS and soleus would be even less than during one-legged jumping. Therefore, concentric muscle contractions of the GAS and soleus are expected to also not play a dominant role in plantarflexion during the high-speed running period of sprinting.

11.4.2. SWING PHASE OF HIGH-SPEED RUNNING PERIOD

In this section, the swing phase during the high-speed running period will be discussed in detail. Firstly, general aspects of the swing phase during the high-speed running period will be discussed. Secondly, the motion of the swing leg when it is the trailing leg and lastly the motion of the swing leg when it is the leading leg will be discussed in detail. The discussions of the motion of the swing leg when it is the trailing leg and when it is the leading leg will be structured by firstly discussing the motion in the hip joint followed by the motion in the knee joint and lastly the motion in the ankle joint in detail.

During high-speed running, the projection of the body at toe-off is more vertical compared to the acceleration period and FTs are at their longest during high-speed running. Due to the high running speed, the GCT is very short and FT lasts longer than GCT (Moravec *et al.*, 1988; Hobara *et al.*, 2010). The swing phase lasts from toe-off until foot strike of the same leg. There are two floating phases during a single swing phase with a stance phase of the contralateral leg in between the two floating phases (Novacheck, 1998). The first floating phase immediately after toe-off concerns the motion of the relevant leg when it is the trailing leg and the second floating phase when it is the leading leg. The motion of the leg in the two floating phases will now be discussed focussing on the motions in the hip, knee and ankle joints along with the muscle actions involved to produce those motions.

11.4.2.1. Motion of swing leg when it is the trailing leg

Hip joint

Hip flexion occurs after toe-off through the action of the hip flexors. The only difference in hip motion during the swing phase between high-speed running and the acceleration period is that during high-speed running, peak hip flexion is less, due to the body being upright and the resultant effect of having an upright trunk described in the acceleration period section. For more detail on the motion of the hip during this phase, see (11.3.2.1).

Knee joint

After toe-off, knee flexion also occurs. The REC contracts to control the knee flexion and is the only active quadriceps muscle during mid-swing (Novacheck, 1998). Knee and hip flexion should occur simultaneously as soon as possible after toe-off to tuck the heel in under the GLU during the recovery phase. The trailing leg knee should be flexed >90° as soon as possible (Bosch & Klomp, 2005:133). The average maximum knee flexion angle during sprinting has been reported to be 105° and elite athletes may flex the knee up to 130° (Novacheck, 1998). The speed at which the leg swings forward is determined solely by the angular velocity of hip flexion and, therefore, the concentric contraction of the hip flexors play an important role. Simultaneously, flexing the knee and hip joints rapidly decreases the moment of inertia (I) of the leg. The decreased I of the leg increases the effect of the moment generated by the hip flexors and, therefore, can increase angular acceleration (α) around the hip allowing a fast recovery phase (2.4.3). This motion will be referred to as good back side mechanics throughout the rest of the theoretical background. Good back side mechanics will cause the ankle to be brought forward in a more linear way making the circular path the ankle travels behind the body lower and smaller (Figure 11.7 A).

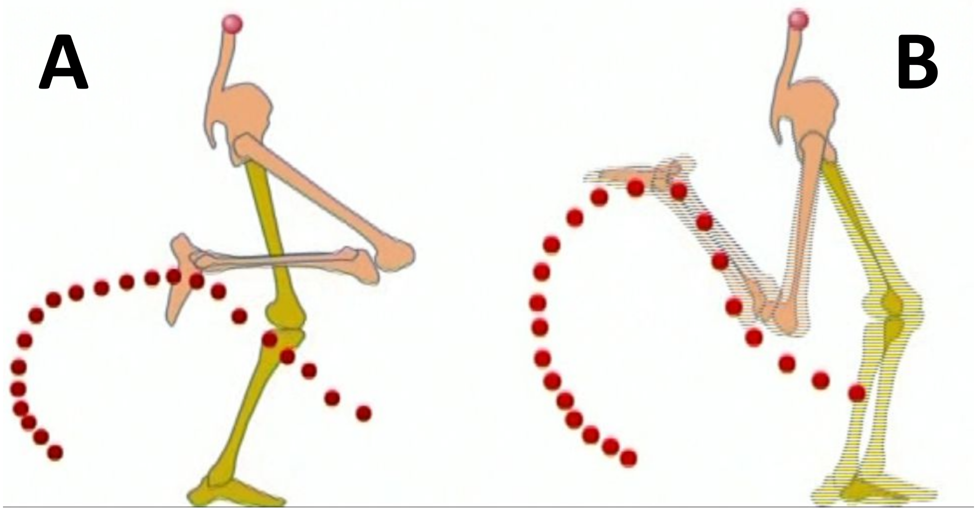

Figure 11.7. The path the ankle takes during good back side mechanics (A) and during poor back side mechanics (B). Adapted from Bosch and Klomp (2006).

Inexperienced sprinters do not flex the hip and knee simultaneously. Their knee flexes first without simultaneous hip flexion and the ankle follows a long and high circular path behind the body before being brought forwards (Figure 11.7 B) (Bosch & Klomp, 2005:132). This causes the leg's radius of gyration (k) to be longer, on average, resulting in an increased moment of inertia (I) and, therefore, a slower angular velocity (α). This motion will be referred to as poor back side mechanics and results in a slow recovery phase as well as a lower SF.

Ankle joint

The ankle is plantarflexed after toe-off and should be dorsiflexed as soon as possible as the leg is swung forwards. Dorsiflexing aids to decrease k and, therefore, increase α when the toes are brought up closer to the hip. Dorsiflexion is done by the tibialis anterior that is seen to be active soon after toe-off and throughout the entire swing phase (Figure 11.1).

11.4.2.2. Motion of swing leg when it is the leading leg

The motion of the swing leg when it is the leading leg may be divided into two parts. During the first part, the knee joint extends and during the second part, the leg is brought down forcefully to the ground during hip extension and is sometimes described as a scissors like motion.

Hip joint

The iliopsoas continues hip flexion until maximum hip flexion is reached. After peak hip flexion, the hip extends to bring the foot to the ground as fast as possible. Hip extensors are dominant at the hip joint during the second half of the swing phase and first half of the stance phase (Novacheck, 1998). The GLU and the HAM are particularly active at the end of swing and work together to extend the hip during the scissors like motion (Novacheck, 1998). A fast scissors motion will make it easier for good foot placement below the body's CoM at foot strike (Bosch & Klomp, 2005:132). In this way, an important part of the drive phase impulse is already generated during the swing phase. The motion can be likened to a swinging hammer. The energy to deliver impulse to a nail is generated during the swing phase and is rapidly released over a short contact time (Bosch & Klomp, 2006). The foot strike following the swing phase is as forceful as possible to rapidly transfer force to the ground and to maximally utilise the elastic components in the lower leg (Bosch & Klomp, 2005:174).

Knee joint

During the first part mentioned above, the knee extends and the HAM contract eccentrically to prevent hyperextension of the knee (Novacheck, 1998). Elastic energy is then stored in the HAM, stimulating it to help the GLU with rapid hip extension during the second part (Bosch & Klomp, 2005:44). During knee extension when the tibia is swung out, the REC is not very active. Before foot strike the vastus group and the REC contract to develop pre-tension in anticipation of impact and the accompanying flexion moment the GRF has around the knee joint (Novacheck, 1998). At high-speed running, impact forces are very high and the quadriceps' role is important to counteract the moments these forces cause.

Ankle joint

During high-speed running a FFS is often used and the ankle is then pre-tensed in a plantar flexed position in preparation for foot strike (Novacheck, 1998; Krell & Stefanyshyn, 2006; Toon *et al.*, 2009; Theophilos *et al.*, 2014; Hébert-Losier *et al.*, 2015). This is in contrast to the dorsiflexed ankle angle at foot strike seen during the acceleration period.

11.4.3. SUMMARY OF HIGH-SPEED RUNNING PERIOD

The strategy to increase running speed from near top speed to top speed sprinting is to further increase SL. During top speed sprinting the aim is simply to maintain and not to further increase sprinting speed, therefore, the vertical component of the GRF is much higher than the horizontal component. Here FTs are at their longest and lasts longer than GCTs. Most people use a FFS in this phase, horizontal speed is high and GCT is, therefore, short. Due to the short GCT there is a larger reliance on the use of elastic components in the lower limbs and the body posture should be upright since there is not enough time to counterbalance a large forward lean. Compared to the initial acceleration period, extensions in the legs are smaller and are accompanied by smaller movements in the arms for counterbalance. Motion of the legs is cyclic and good back side mechanics should be used instead of poor back side mechanics.

APPENDIX TWELVE

ADDITIONAL RESULTS

Table 12.1. Physical characteristics and mean shoe mass for girls and boys according to age group.

GIRLS	Height (cm)		Body mass (kg)		Shoe mass (g)	
	n	mean ±SD	n	mean ±SD	n	mean ±SD
>13	50	147 ±12	51	40.60 ±10.95	33	540 ±98
13-15	32	160 ±7	37	51.10 ±9.55	20	503 ±110
>15	24	164 ±6	28	61.45 ±8.15	12	506 ±82

BOYS	Height (cm)		Body mass (kg)		Shoe mass (g)	
	n	mean ±SD	n	mean ±SD	n	mean ±SD
>13	48	148 ±21	56	46.10 ±11.70	50	569 ±122
13-15	46	166 ±10	50	56.10 ±12.40	32	558 ±92
>15	41	180 ±7	55	77.10 ±12.70	23	630 ±96

Table 12.2. Average running speed over last 10m (m/s) where foot strike pattern was determined for boys and girls according to age group.

		Girls				Boys			
		n	mean	95%CI		n	mean	95%CI	
<13	barefoot	50	5.75	5.55	5.95	56	5.95	5.76	6.14
	shod	42	5.66	5.46	5.86	53	5.80	5.60	5.99
13-15	barefoot	37	6.28	6.05	6.52	50	6.64	6.43	6.84
	shod	21	6.19	5.94	6.43	33	6.50	6.30	6.71
>15	barefoot	28	6.30	6.03	6.57	55	7.44	7.25	7.64
	shod	17	6.28	6.00	6.56	35	7.31	7.11	7.51

Table 12.3. Foot strike pattern distributions for boys and girls according to age group.

Age group		Girls				Boys			
		FFS/MFS		RFS		FFS/MFS		RFS	
		barefoot	shod	barefoot	shod	barefoot	shod	barefoot	shod
<13	Count	16	4	18	23	31	13	8	23
	%	80%	20%	44%	56%	70%	30%	26%	74%
13-15	Count	21	5	14	15	42	17	6	13
	%	81%	19%	48%	52%	71%	29%	32%	68%
>15	Count	21	9	7	8	45	22	9	13
	%	70%	30%	47%	53%	67%	33%	41%	59%

Table 12.4. Sprint times and spatiotemporal variables for girls according to age group.

Girls		<13			13-15			>15		
		n	mean	(95% CI)	n	mean	(95% CI)	n	mean	(95% CI)
10m sprint (s)	barefoot	50	2.31	2.27 -2.35	37	2.16	2.11 -2.21	27	2.16	2.10 -2.22
	shod	42	2.35	2.31 -2.40	21	2.19	2.13 -2.24	16	2.19	2.13 -2.26
20m sprint (s)	barefoot	50	4.07	3.98 -4.15	37	3.77	3.67 -3.87	28	3.73	3.61 -3.84
	shod	42	4.14	4.05 -4.22	21	3.82	3.72 -3.92	17	3.77	3.65 -3.88
Step frequency (Hz)	barefoot	23	3.990	3.880 -4.100	19	3.863	3.742 -3.983	9	3.977	3.802 -4.152
	shod	23	3.728	3.618 -3.837	19	3.684	3.563 -3.804	9	3.868	3.693 -4.043
Stride length (cm)	barefoot	23	274	265 -283	19	299	289 -309	9	300	286 -314
	shod	23	282	274 -291	19	309	299 -318	9	311	297 -325
Flight time (s)	barefoot	23	0.100	0.095 -0.106	19	0.104	0.098 -0.110	9	0.107	0.098 -0.115
	shod	23	0.106	0.101 -0.111	19	0.107	0.101 -0.113	9	0.105	0.096 -0.113
Ground contact time (s)	barefoot	23	0.151	0.144 -0.158	19	0.156	0.149 -0.164	9	0.147	0.136 -0.158
	shod	23	0.163	0.157 -0.170	19	0.166	0.158 -0.173	9	0.154	0.143 -0.165
Swing time (s)	barefoot	23	0.352	0.342 -0.363	19	0.365	0.353 -0.376	9	0.360	0.343 -0.377
	shod	23	0.375	0.365 -0.386	19	0.380	0.369 -0.392	9	0.364	0.347 -0.380

Table 12.5. Sprint times and spatiotemporal variables for boys according to age group.

Boys		<13			13-15			>15		
		n	mean	(95% CI)	n	mean	(95% CI)	n	mean	(95% CI)
10m sprint (s)	barefoot	55	2.23	2.19 -2.27	50	1.98	1.93 -2.02	55	1.87	1.83 -1.91
	shod	52	2.26	2.21 -2.30	33	2.02	1.97 -2.07	35	1.89	1.85 -1.94
20m sprint (s)	barefoot	56	3.91	3.83 -3.99	50	3.50	3.42 -3.59	55	3.23	3.15 -3.31
	shod	53	3.98	3.90 -4.06	33	3.57	3.48 -3.66	35	3.28	3.20 -3.36
Step frequency (Hz)	barefoot	33	4.193	4.103 -4.284	20	4.124	4.006 -4.242	2	4.447	4.147 -4.748
	shod	34	3.953	3.863 -4.043	20	3.922	3.804 -4.040	4	4.153	3.890 -4.415
Stride length (cm)	barefoot	35	267	260 -275	20	283	274 -293	2	315	291 -339
	shod	36	279	272 -287	20	292	283 -301	4	329	308 -350
Flight time (s)	barefoot	37	0.092	0.087 -0.096	20	0.092	0.086 -0.098	2	0.079	0.064 -0.094
	shod	38	0.094	0.090 -0.099	20	0.092	0.086 -0.098	4	0.088	0.075 -0.101
Ground contact time (s)	barefoot	39	0.146	0.140 -0.152	20	0.150	0.143 -0.158	2	0.145	0.126 -0.164
	shod	40	0.159	0.153 -0.165	20	0.164	0.157 -0.171	4	0.158	0.141 -0.174
Swing time (s)	barefoot	41	0.330	0.321 -0.339	20	0.335	0.323 -0.346	2	0.304	0.274 -0.334
	shod	42	0.348	0.339 -0.356	20	0.348	0.337 -0.359	4	0.334	0.308 -0.359