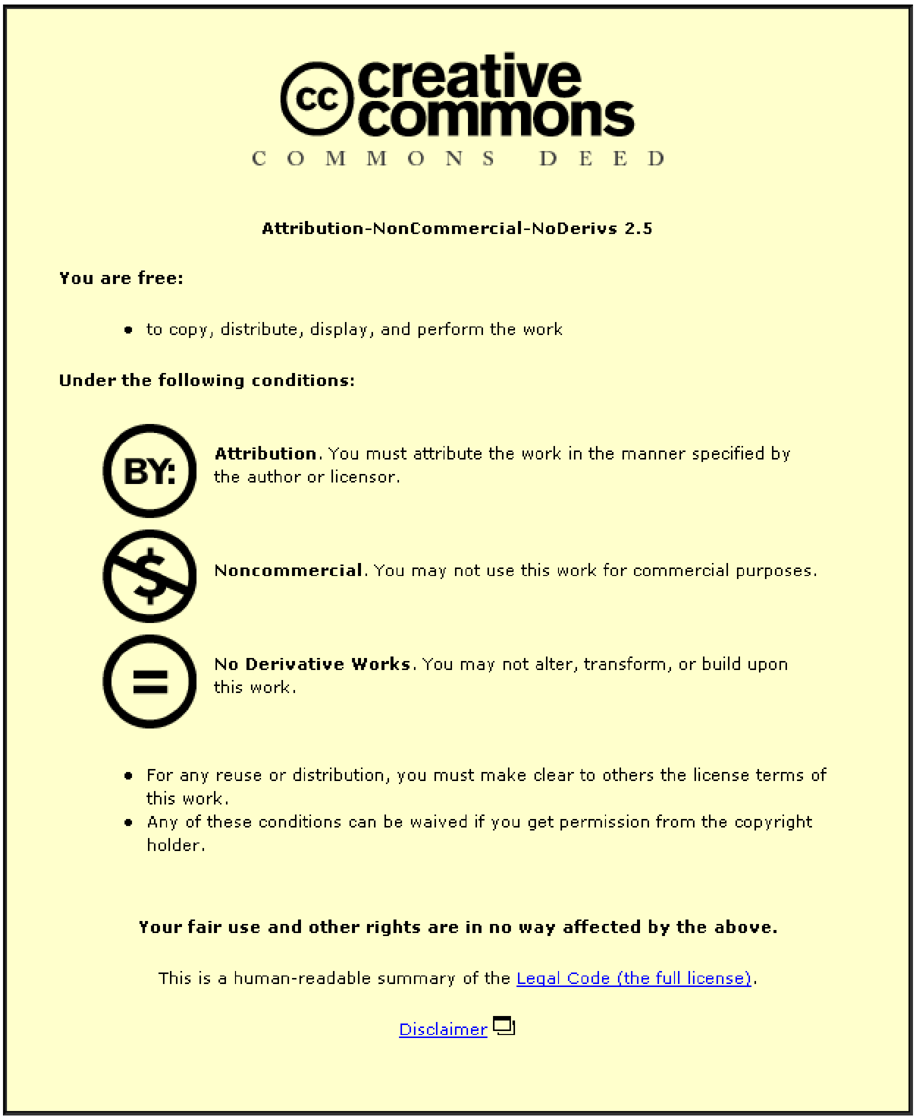

THE DESIGN, CONSTRUCTION AND EVALUATION OF SPRINT FOOTWEAR TO INVESTIGATE INCREASED SPRINT SHOE BENDING STIFFNESS ON SPRINT PERFORMANCE AND DYNAMICS

ABSTRACT

Previous work has shown the potential to improve sprinting performance through adaptations to the bending stiffness of sprint shoes. In addition, it has been suggested that the bending stiffness need customising to the individual to achieve maximal performance. However, ambiguous sprint performance results in recent literature with increasing bending stiffness of sprint shoes, in addition to a lack of detailed biomechanical data collected, has lead to considerable uncertainty of the potential to customize the bending stiffness of sprint shoes to individuals for maximal performance. Thus, the aim of this work is to develop functional sprint footwear in a range of different bending stiffnesses in order to explore the effects of increased sprint shoe bending stiffness on sprinting performance and lower limb dynamics.

Mechanical test procedures were implemented to both validate the mechanical testing methodologies and benchmark the mechanical properties. A novel mechanical test apparatus and methodology were specifically designed to evaluate the traction properties of sprint shoes. A minimum level of traction generated among commercially available shoes was identified as the minimum level of sufficient traction. The methodology developed by Toon (2008) was used to measure bending stiffness. No trends were detected towards the introduction of stiffer commercially available sprint shoes. A novel construction method using laser sintered (LS) nylon-12 was introduced, producing bespoke sprint shoes sole units in a range if bending stiffnesses with sufficient traction for sprinting. A novel process for assembling the LS sole units with standard uppers was presented, producing durable shoes with a high quality finish.

Methodological concerns were addressed in an examination of the effect of commonly used sampling rates (*SR*), filtering frequencies (*fc*), and definition of the MPJ on resulting metatarsophalangeal joint (MPJ) kinematics and kinetics in sprinting. MPJ angular range of motion and angular velocity were significantly reduced with changes in *SR, fc* and MPJ definition, while significant differences in MPJ kinetics with changes of MPJ definition.

The influence of shoe stiffness on sprinting performance and step characteristics was assessed using three sprint shoe conditions, up to 7 times stiffer than average commercially available. Results showed a significant increase in sprint time and a significant decrease in ground contact time in the stiffest shoe condition, with all of the participants producing their best sprints in the least stiff shoe condition, indicating the shoe conditions were too stiff. The differences in the trends observed between the group mean and the individual results indicate that both a single subject and group mean analysis be carried out in future research.

The influence of shoe stiffness on sprinting performance and the kinematics and kinetics of the MPJ and ankle was assessed separately in the acceleration and maximal speed phases using three sprint shoe conditions, up to 3.5 times stiffer than the average commercially available. Results showed no change in sprinting performance. Increasing the bending stiffness resulted in significant decreases in the amplitude of MPJ and ankle kinematics, in addition to temporal changes in the occurrence of peak values. The effects of increasing the bending stiffness of sprint shoes on the kinematics and kinetics of the lower limb were more pronounced in the acceleration phase compared to the maximal speed phase.

ACKNOWLEDGEMENTS

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PUBLICATIONS ARISING FROM THIS WORK

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Conference papers

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Vinet, A. and Caine, M. (2011). Methodological considerations when determining energy contribution of the metatarsophalangeal joint during sprinting. In: Frederick, E. C., *10th Footwear Biomechanics Symposium, Tubingen, Germany*. pp. s162-s163

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INTRODUCTION

The success of a sprint performance is dependent on a variety of factors, both internal and external to the sprinter. The margins by which sprint races are won or lost at the elite level can be minute, while the rewards at stake can be huge for both athlete and the sponsoring company. Endorsement deals for top-level athletes can be significant and the brand recognition achieved by an athlete winning the 100 m sprint at a major athletics championship is huge, especially if an improvement in performance can be attributed to the technology in the footwear or apparel worn. Recent research has highlighted the potential to influence sprinting performance through the bending stiffness of sprint footwear. In addition, it has been suggested that to achieve maximal performance, the mechanical properties of this footwear requires customising to an individual athlete.

Recent work at Loughborough University has focused on the customisation of athletic footwear utilising Additive Manufacturing (AM) technologies (Toon, 2008). Projects involved in this work range from optimising the AM processes themselves, making available the technology necessary for the production of low cost, personalised, one-off components utilised in athletic footwear, to projects utilising the advancements in the AM process to manufacture components of athletic footwear and investigate the relationship of footwear mechanical properties and athletic performance.

With regards to sprint footwear and sprinting performance, earlier work in the Sports Technology research group at Loughborough University has focused on the examination of the relationship between the bending stiffness of sprint shoes and sprint related jump metric performance, utilising AM to create one-off sprint shoe sole units in a range of bending stiffnesses. This work demonstrated the feasibility of utilising AM, specifically Laser Sintering (LS) of Nylon-12, to produce sprint shoe sole units with the desired levels of bending stiffness at suitable levels of thickness to carry out sprint related jump metrics, and sufficient levels of durability to carry out an adequate amount of mechanical and biomechanical testing for research purposes. These results indicate the opportunity to validate the suitability of utilising LS Nylon-12 to construct sprint shoes in a range of bending stiffnesses to be utilised in actual sprinting performances.

With regards to human performance testing, this work demonstrated that changes to the bending stiffness of sprint shoes resulted in changes to lower limb dynamics, and further that the personalisation of the bending stiffness of sprint shoes was required for optimal performance. However, the limitations of using jump metrics as the performance measure as opposed to actual sprinting limit the external validity of the results. Although utilising sprint related jump metrics as compared to actual sprinting generally improves the internal validity of the results, as a greater level of repeatability may be achieved and fatigue is minimised through repeated performances, it is unknown if the results obtained utilising sprint related jump metrics hold true in actual sprinting performances.

Previous research conducted in other groups have highlighted the effects of increasing the bending stiffness of athletic footwear on athletic performance, from Stefanyshyn and Nigg (2000) demonstrating a decrease in MPJ energy generated and an improvement in jump height to Roy and Stefanyshyn (2006) observing a 1% metabolic saving in stiffer footwear conditions. However, while early research attributed this improvement in athletic performance to a decrease in the energy loss at the MPJ with increased bending stiffness, a direct relationship between the two has not been established.

Previous research directly investigating the effect of increasing the bending stiffness of sprint shoes on sprint performance, however, has shown confounding results. The first study (Stefanyshyn and Fusco, 2004) identified an average sprint running improvement 0.69% in sprint shoes modified to be stiffer than a standard commercially available option. In addition, while on average increased bending stiffness improved sprinting performance, the authors found that the stiffness each participant required for their maximal performance was subject specific. The authors argue that since not all the sprinters had their optimal performance in the stiffest shoe condition, the notion of minimized energy loss at the MPJ could not solely be responsible for the observed improvement in sprinting performance. Based on the minimisation of energy loss concept, as shoe stiffness increased performance should continue to increase, which was not the case (Stefanyshyn and Fusco, 2004). The authors theorise that a potential influence of changing the shoe bending stiffness could be a change in the point of application of the GRF, which would result in a change of the lever arm length and joint velocities, influencing as shift in the force-velocity relationship at the ankle plantarflexors. This hypothesis, however, has never been explored in publish literature.

However, in two further studies conducted by different research groups (Smith et al., 2010; Ding et al., 2011), neither found any significant difference in sprint performance when increasing the bending stiffness of sprint shoes above commercially available options. Several differences in the methodologies and the footwear conditions used between these research groups make it difficult to compare the results obtained. In addition, there is a lack of detailed biomechanical data collected between the research groups previously mentioned. Due to these methodological limitations, and the lack of detailed biomechanical data collected, the influence of sprint shoe bending stiffness on the dynamics of the lower extremity during sprint running remains largely unexplained and is subject to considerable speculation.

In addition, without knowledge on changes to lower limb dynamics with changes to bending stiffness of sprint footwear, it is difficult to speculate as to which of the athlete's particular characteristics the bending stiffness of the sprint shoes need to be 'tuned' to maximise sprinting performance. However, even though the literature investigating the effect of increasing the longitudinal bending stiffness directly on sprint performance has been inconclusive, any potential for improvement of elite sprinting performance is worth further investigation. The limitations in the previous investigations in addition to the unexplored hypothesis of the potential influence on the point of application of the GRF from the literature (Stefanyshyn and Fusco, 2004) present a number of potential research opportunities in clarifying the role of increasing the bending stiffness of sprint shoes on lower limb dynamics and sprinting performance.

PRIMARY AIMS AND OBJECTIVES

The focus of this research is the interaction between the mechanical property of the bending stiffness of sprint footwear, sprinting performance and the dynamics of the lower limb in sprinting as previous research has shown the potential to influence performance through changes to the bending stiffness of footwear (Stefanyshyn and Fusco, 2004; Toon, 2008). Functional sprint footwear in a range of bending stiffness is developed, manufactured and mechanically evaluated. The gap in literature with regards to consistent, systematic research in this area will be addressed. An overarching aim is to inform subsequent research methodologies by focusing on improvements to methods and procedures utilised. These aims will be addressed through the following objectives:

- Development and evaluation of a mechanical test procedure for the suitable evaluation of the traction properties of commercially available and future bespoke sprint shoe designs

- Quantification of mechanical properties (traction and bending stiffness) of current commercially available sprint spikes for the purposes of benchmarking and informing future bespoke sprint shoe designs

- Design, development and mechanical testing (traction and bending stiffness) of bespoke sprint wear constructed using AM sprint shoe sole units in a range of longitudinal bending stiffness, with sufficient traction for maximal sprinting

- Implementation of human performance testing to explore the role of data collection and processing methodology on the role of the MPJ in sprinting

- Implementation of human performance testing to explore the feasibility of using AM sole units in maximal effort sprinting and utilising sprinting performance as the measure of performance to assess the effect of increasing the longitudinal bending stiffness of sprint shoes on simple measures of sprinting performance and step characteristics

- Implementation of human performance testing of the effect of the bending stiffness of sprint footwear on the dynamics of the lower limbs in the acceleration and maximal speed phases of sprinting

Details of the associated literature are reported in Chapter 1. The development of methodologies for the evaluation of the mechanical properties of sprint footwear are reported in Chapter 2, with a focus on benchmarking the properties of traction and longitudinal bending stiffness in current commercially available sprint shoes. Chapter 3 focuses on the design and development of bespoke sprint shoes sole units constructed using LS technologies, with the aim of developing a range of sprint shoes sufficient traction in a range of increasing longitudinal bending stiffness to be used in subsequent human performance testing in this work.

When examining the function of the MPJ in sprinting, several different data collection and processing methodologies have been utilised throughout the literature examining the effects of increased bending stiffness on athletic performance. The effect use of commonly used data collection and processing methodologies on the resulting MPJ kinematics and kinetics in sprinting is described in Chapter 4, with the results used to inform ensuing research in this area. Implementation of human performance testing is carried out in Chapter 5, exploring the effect of increasing the bending stiffness of sprint shoes on sprinting performance and step characteristics. The feasibility of using sprint shoes approximately 6 times stiffer than the average commercially available options is also assessed. In addition, due to the observed individual responses of athletes to increased bending stiffness, the use of a group versus a single subject approach is discussed.

When examining the effect of increased bending stiffness in sprinting, little is known on the changes to lower limb dynamics and the potential relationship to changes in sprinting performance. Specifically, at the MPJ and ankle, very little is known on the kinematic changes, while the effect on the kinetics has never been explored in sprinting with increased sprint shoe bending stiffness. Thus, the study described in Chapter 6 explores the implementation of human performance testing of the effect of increased bending stiffness of sprint footwear on both performance and the kinematics and kinetics of the MPJ and ankle in both the acceleration and maximal speed phases of sprinting.

1 LITERATURE REVIEW

1.0 INTRODUCTION

This research aims to advance the understanding of the effect of sprint shoes bending stiffness on the dynamics of the lower limb and sprinting performance. A comprehensive review and evaluation of previous work in this field is presented, focusing specifically on the dynamics of the lower limb and athletic performance with footwear interventions. Fundamental elements of sprinting are presented in section 1.1, while biomechanics of the foot and ankle are presented in section 1.2. Both of these sections are presented as a knowledge platform and reference, required for the interpretation of work carried out in subsequent chapters. Subsequently, a review of current sprint shoe design parameters is presented in section 1.3.

Section 1.4 summarises the literature most relevant to the present study and draws together important observations to shape the current research. A review of the literature regarding changes to the mechanical properties of athletic footwear and athletic performance and lower limb dynamics is presented, with an emphasis on changes to the bending stiffness of sprint shoes and sprinting performance. Particular attention is paid to the mechanical properties of the footwear, the methodologies of assessment, and performance indicators used.

In summary, section 1.5 outlines the scope of the current work by drawing together the gaps in the literature and key observations that will form the basis for this PhD research.

1.1 FUNDAMENTALS OF SPRINTING

The fundamental elements of sprinting biomechanics are documented below, with a focus on defining the primary characteristics of sprinting, including the components of the gait cycle and basic biomechanical characteristics. This information is presented as a knowledge base, examining basic components of sprinting, and reviewing the literature focusing on performance predictors to form a reference for interpretation of the research carried out in further chapters.

1.1.1 THE GAIT CYCLE

The term sprinting is used quite liberally as an athletic term within sport, typically meaning a maximal effort acceleration of the body to achieve maximal speed over a short distance. Rapid movement of the body from one place to another is advantageous in many sporting activities, especially in athletics where sprint running forms the competition itself, not a component of a game. In simple terms, the goal of sprint racing is to cover a predetermined, short distance in the least possible time, with the body and its segments moving as rapidly as possible throughout. The International Association of Athletics Federations (IAAF) defines a sprint race as 400 m or less in distance. The focus of this research is on the 100 m sprint race, the shortest common outdoor race distance, and one of the most popular and prestigious events in the sport of athletics.

Sprinting is an activity that requires a complex sequencing of muscle activation and coordination of the joints in the body. The gait cycle is a basic unit in gait analysis, with the cycle typically defined as beginning when one foot contacts the ground and ending when the same foot contacts the ground once more. The gait cycle can be subdivided into the ground contact and swing phases. Walking and running are typically differentiated when periods of double support (both feet simultaneously in contact with the ground) during the stance phase of the gait cycle change to two periods of double float (neither foot is touching the ground), at the beginning and the end of the swing phase of gait. The distinction between running and sprinting is not as clear as walking and running.

Novacheck (1998) distinguishes between running and sprinting as the point at which initial ground contact occurs on the forefoot as opposed to the hindfoot. However, the change from an initial heel contact to a forefoot contact has been shown to occur at running speeds as low as 5 $m \cdot s^{-1}$ (Nigg et al., 1984) while sprinting speeds have been shown to be as high as between 8 to 10 $m \cdot s^{-1}$ at maximum constant velocity (Dillman, 1975; Mero et al 1992). Another characteristic of sprinting is the relative amount of ground contact to swing phase time. As the speed of running increases, less time is spent in the stance phase, with toe off for elite sprinters occurring as early as 22% of the gait cycle compared with 39% for running (Novacheck, 1998).

In practicality, the difference between running and sprinting is in the goal to be achieved. Running is performed over longer distances at slower pace while sprinting activities are done over a shorter distance and at faster speeds with maximal effort. For the research in subsequent chapters, sprinting is defined as rapid, maximal effort movement over a short distance, with initial ground contact of the foot occurring at the forefoot.

SWING VS GROUND CONTACT PHASE

The motion of the limb in both the swing and the ground contact phases contribute to a sprint. The motion of the lower limb in the swing phase of sprinting is important as it prepares the body for impact upon initial ground contact. It is essential to prepare for the stance phase while still in flight as the peak ground reaction forces take place 10 to 40 ms after initial ground contact in sprinting (Mero & Komi, 1987). This short amount of time may not be sufficient for the body to fully prepare itself to react to this high loading rate and therefore it is important that there be a high level of pre-activation in the leg musculature, ensuring the muscles of the lower limb are stiff prior to and at the moment of impact. In sprinting, a high level muscular activity in the leg has been observed before ground contact (Dietz et al., 1979; Mero and Komi, 1987). Location of initial foot placement upon ground contact is also determined through the dynamics of the swing (Mero et al., 1992). It has been speculated that kinematics of the foot upon touchdown may be influenced by sprint shoe design (Krell and Stefanyshyn, 2006; Toon, 2008). However, it is generally agreed that the critical factor influencing sprinting performance is the action of the leg during the ground contact period (Ae et al, 1987; Bezodis et al., 2008; Fukunaga et al., 1978; Mann and Sprague, 1980; Stefanyshyn and Fusco, 2004).

BRAKING/PROPULSION

The ground contact phase in sprinting can be divided into braking and propulsion phases (Mero et al., 1992). This division can either be done using the movement of the body centre of gravity or the negative and positive horizontal ground reaction forces (GRF) during ground contact (Luhtanen and Komi, 1978). From initial ground contact, the body centre of gravity falls (braking phase) and then rises during the last part of contact (propulsion phase). On the other hand, upon initial ground contact in the anterior-posterior plane, a negative horizontal force is observed (braking phase) followed by a positive horizontal force (propulsion phase). Typically, the direction of the anterior-posterior GRF is used to define these phases.

STRIDE LENGTH AND STRIDE FREQUENCY

Sprinting velocity is a function of stride length and stride frequency. Faster speed can be achieved by increasing either one of both of these variables. Although this concept is straightforward, the relationship between the two variables is generally an inverse relationship at maximal effort. Typically, as one variable increases, the other decreases. Thus, it is important to find an optimal balance between stride length and stride frequency for an individual. The importance of each of these variables has been shown to vary throughout the phases of a sprint. During the acceleration phase, stride length and stride rate both increase and approach values reported for maximal speed. While stride length and stride rate have been shown to increase linearly with speed at a jogging pace (Luhtanen and Komi, 1978), at faster speeds the rate of increase of stride length reduces and begins to level off at speeds in excess of 8 $m \cdot s^{-1}$ (Dillman, 1975). Stride rate also increases at higher speeds, but is often the source of deceleration towards the end of a sprint race, as fatigue sets in and a compensatory reduction in stride frequency occurs (Mehrikadze and Tabatschnik, 1983).

There is, however, no definitive evidence in literature of which factor, stride length or stride frequency, is of more importance to improvements of sprinting performance for an individual. Hunter et al. (2004) found that, at the group level, stride length was significantly related to sprinting velocity while stride frequency was not (at the 16 m mark). At the individual level, however, it was shown that sprinters produced significantly higher stride frequencies in their fastest sprint run compared to their slowest, while stride length did not reveal any significant differences. It was argued by Hunter et al. (2004) that stride frequency might play a more significant role in improving sprinting performance in the short term, but conversely that stride length might be more significant in the long term, but require the development of strength and power. Salo et al. (2011) also found varying characteristics of stride frequency and stride rate reliance between athletes. Salo et al. (2011) suggest that athletes should take their individual reliance into personal training programs, with stride frequency reliant athletes focusing on neural factors for quick turnover and stride length reliant athletes requiring more focus on strength parameters. Although there seem to be clear trends on the changes to stride length and frequency throughout a sprint race, the dependence on stride length and frequency for improvements to sprinting performance appear to vary by individual.

JOINT ENERGY

The forces and energy produced by the sprinter during each ground contact period in sprinting are a fundamental determinant of the sprint performance outcome (Bezodis et al., 2008; Stefanyshyn and Fusco, 2004). The joint energy contribution to sprinting is important since it is this mechanical energy which performs the work of moving the body’s segments (Stefanyshyn and Nigg, 1997). Analysis of athletic activities indicates that there are phases when energy is absorbed and when energy is generated at each joint. Joint power and energy at the ankle, knee and hip during running and sprinting has been investigated in several studies (Buczek and Cavanagh, 1990; Martin et al., 1993; Simpson and Bates, 1990; Stefanyshyn and Nigg, 1997). The ankle, knee and hip have all been shown to both absorb and generate energy during the stance phase of sprinting (Stefanyshyn and Nigg, 1997). The ankle has been shown to be the largest energy absorber (50%) and generator (54%) of the lower limb during the stance phase of sprinting with the knee shown to make the smallest energy contribution, generating only 13% of the total energy of the lower limb (Stefanyshyn and Nigg, 1997).

There is, however, a limited amount of literature on the energy contribution of the metatarsophalangeal joint (MPJ) and conflicting views on the role of the MPJ in sprinting. Typically, the MPJ has been regarded as a large absorber (32%) of energy while generating (3%) very little to none in sprinting (Stefanyshyn and Nigg, 1997). However, the data collection and processing methodologies utilised have come into question (Smith and Lake, 2007). Further investigation is needed to clarify the role of the MPJ in sprinting and will be discussed further in the section 1.4.

1.1.2 PHASES OF SPRINTING

When investigating sprinting performance, it is important to recognize that a typical sprint race has a distinct velocity profile which can be broken down into separate phases. A typical sprint velocity curve for a 100 m distance is presented in Figure 1.1. Sprint performances are typically divided into three phases: acceleration, maximum speed and deceleration phases (Bruggeman and Glad, 1990; Delecluse *et al.,* 1995; Murase *et al.,* 1976; Volkov and Lapin, 1979). The start phase, when the sprinter is in contact with the starting blocks, may also be considered as a separate phase (Mero *et al.,* 1992). Some authors (Bartonietz and Gullich, 1992; Joch, 1988) further argue the subdivision of the acceleration phase into two separate phases: an initial phase dominated by the athletes' strength, and a second phase determined by the ability to develop a high stride frequency (Delecluse *et al.,* 1995).

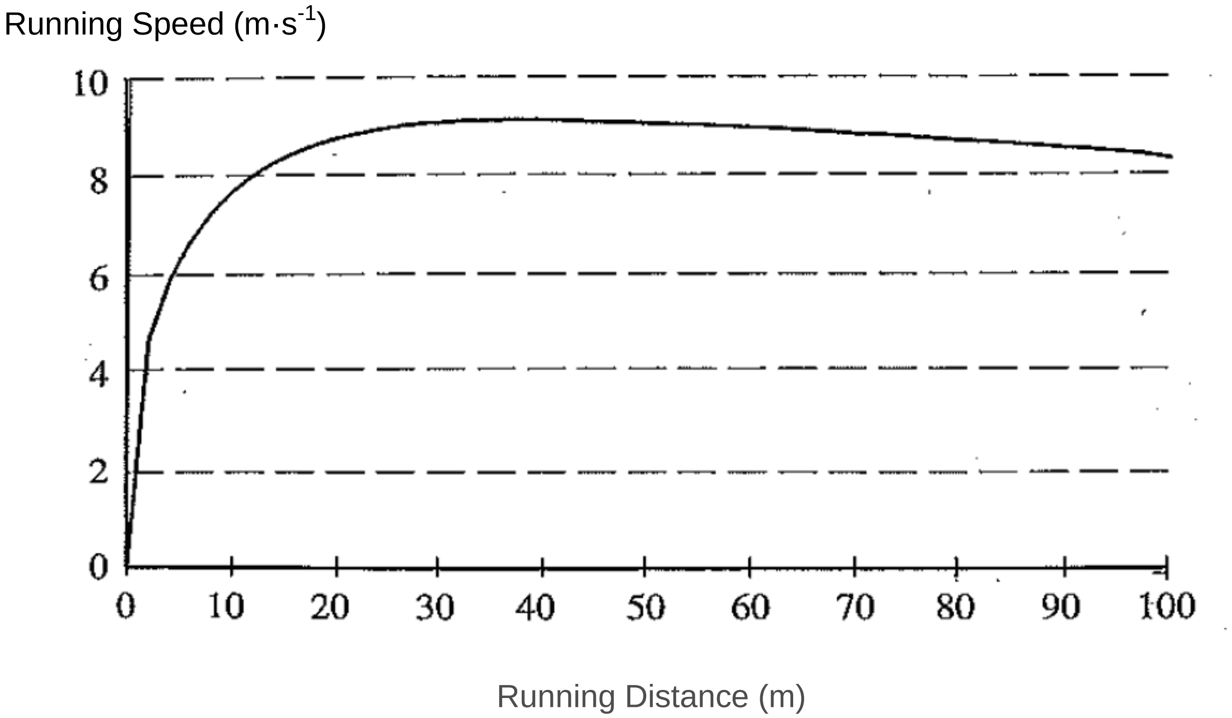


FIGURE 1.1: MEAN SPEED CURVE OVER 100 M SPRINT (DELACLUSE ET AL., 1995)

In a 100 m sprint race, the acceleration phase lasts typically from leaving the blocks to between 30 to 50 m, at which point maximal speed is attained and maintained for approximately 30 to 40 m, followed by a period of deceleration caused by athlete fatigue (Mero *et al.,* 1992). Delecluse *et al.* (1995) divided the 100 m sprint into three specific phases; the generation of high acceleration over the first 10 m, where the steepest increase in velocity is observed (Figure 1.1), the continued acceleration up to reaching maximal sprinting speed (10 – 36 m), and the maintenance of maximal speed over the remaining distance (36 – 100 m). As the velocity profile of a 100 m sprint race is constantly changing and techniques employed by athletes throughout these phases are distinctly different (Mero *et al*., 1992), the number and definition of sprint phases may be somewhat arbitrary. However, it is important to recognise these phases demonstrate prominent differences in technique, and that performance related factors differ from phase to phase, especially when considering footwear design and the specific demands of the individual phases when reporting lower extremity dynamics. To understand how sprinting velocity is successfully attained and maintained throughout a sprint, it is necessary to determine the most important biomechanical parameters in each of the sub phases.

ACCELERATION

Sprinting performance relies on an initial phase of acceleration, through which the sprinter achieves maximal speed from the stationary start position. The execution of the acceleration phase will determine the sprinter's maximal velocity attained and the time to reach this top velocity. Due to the rapidly changing velocity and joint movement patterns in the acceleration phase as compared to the maximal speed phase, it is difficult to generalise biomechanical values obtained throughout this phase.

The forces produced during the acceleration phase can be characterised as being produced for a longer period of time and with larger horizontal propulsive forces compared to the maximal speed phase (Mero *et al*., 1992). A high correlation has been shown between the propulsive force and sprinting velocity during the first ground contact from the blocks, emphasising both the role of the propulsion forces and the importance of strength during this phase (Mero *et al*., 1992). In sprinting, all periods of ground contact have a braking and propulsion phase. The ratio of braking and propulsion, however, are constantly changing throughout the acceleration phase. The braking phase of the first step from the blocks is reported as only 12.9% of the total ground contact time (Mero, 1988) compared to reported values of 43% at maximal speed (Mero and Komi, 1987), thus indicating that the proportion of braking in ground contact period increases throughout the acceleration phase.

MAXIMAL SPEED

The maximal speed phase occurs from the point when the athlete reaches their maximal speed until fatigue occurs with a subsequent deceleration. In this phase the athlete has reached a fully upright body position. The ground contact time is very short, ranging from 0.080 to 0.100 s (Mero *et al*, 1992; Moravec et al., 1988). Mann and Herman (1985) identified several kinematic factors which dictate superior performances, summarising that better performances stemmed from the following: less upper leg extension at take-off; higher upper leg velocity during support; higher lower leg velocity at touchdown. The foot has received a great deal of attention with regards to lower body kinematics. The placement of the foot close beneath the body's centre of gravity upon initial touchdown has been shown to be related to faster sprinting performances (Deshon and Nelson, 1963; Kunz and Kaufmann, 1981; Mann and Herman, 1985). In agreement, Krell and Stefanyshyn (2006) suggest that faster sprinting speeds are achieved with placement of the foot close to the centre of mass. With regards to foot velocity prior to touchdown, Fenn (1930), Hay (1978) and Payne *et al*. (1968) argue that in order to minimize horizontal braking at touchdown, the foot should be moving backward with a horizontal velocity at least equalling that of the forward velocity of the body. Mann and Herman (1985) found that faster sprinters had higher foot velocity at touchdown relative to the body. It has been speculated that kinematics of the foot upon touchdown may be influenced by sprint shoe design (Krell and Stefanyshyn, 2004).

In maximal speed sprinting, the contact time is very short, but the impact forces are very large. Both the horizontal and vertical forces increase from those reported in the acceleration phase (Mero *et al*., 1992). Peak horizontal force values ranging between 445 and 1000 N in braking and 312 and 600 N in propulsion have been reported, with peak vertical forces between 1707 and 3400 N (Mero and Komi, 1987; Bezodis, Kerwin and Salo, 2008). Data on mediolateral forces, however, have only been reported for slow running, with small changes reported with increases in speed, with typical values being less than 0.3 BW (Cavanagh & Lafortune, 1980, Roy, 1982). A typical ground reaction force trace for maximal speed sprinting is presented in Figure 1.2.

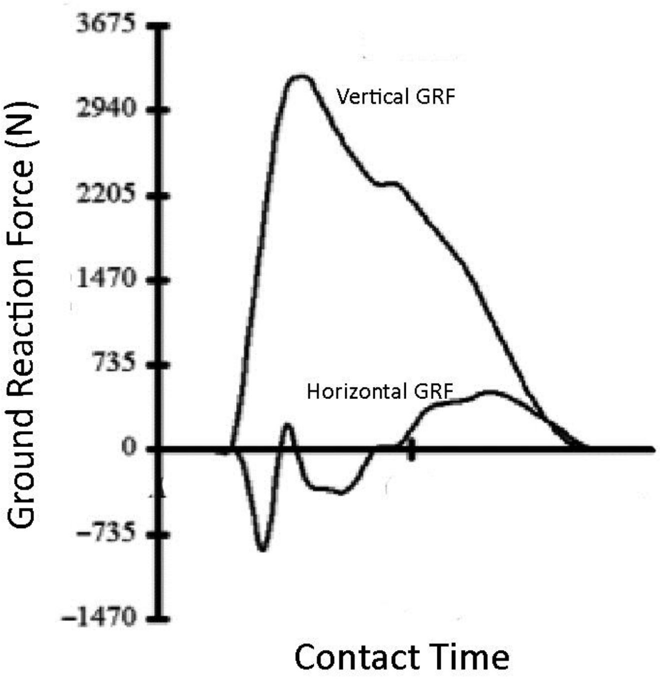


FIGURE 1.2: A TYPICAL MAXIMAL SPEED PHASE GROUND REACTION FORCE TRACE (BEZODIS, KERWIN AND SALO 2008)

A schematic representation of the force vector in the stance phase of maximal speed sprinting is shown in Figure 1.3. The magnitude and directionality of the GRF is important when carrying out mechanical performance testing on sprint footwear, as will be completed in Section 2 of this work.

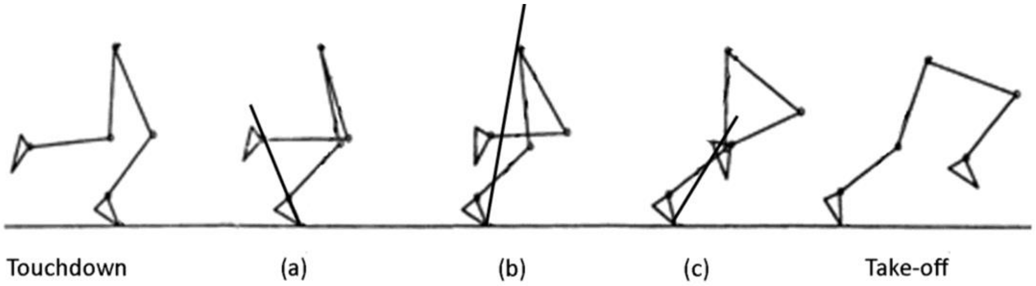


FIGURE 1.3: SCHEMATIC OF A TYPICAL STANCE IN THE MAXIMAL SPEED PHASE AT DIFFERENT TIME SAMPLES. GROUND REACTION FORCE VECTORS AT (A) PEAK BRAKING FORCE (B) PEAK VERTICAL FORCE AND (C) PEAK PROPULSIVE FORCE ARE SHOWN.

IN ORDER TO MAXIMIZE SPRINTING PERFORMANCE, MERO *ET AL*. (1992) RECOMMEND THE RESULTANT GRF SHOULD BE DIRECTED AS VERTICALLY AS POSSIBLE IN THE PHASE IN ORDER TO MINIMIZE THE HORIZONTAL BREAKING FORCE. THERE IS, HOWEVER, SOME DEBATE OVER THE RELATIVE IMPORTANCE OF THE HORIZONTAL AND VERTICAL MAXIMAL SPEED SPRINTING. SEVERAL AUTHORS HAVE SHOWN INCREASES IN BOTH THE VERTICAL AND HORIZONTAL GRF WITH INCREASED VELOCITY (BELLI, 2002; BRUGHELLI, KYROLAINEN, 2001; MUNRO *ET A*L., 1987). WEYAND *ET AL.* (2000) INDICATE THAT FASTER RUNNING SPEEDS MAY BE ACHIEVED THROUGH GREATER VERTICAL GRF. HOWEVER, EXAMINATION OF THE PERCENTAGE INCREASE IN

Figure 1.4 shows that the percentage of horizontal forces seem to increase more with increased running speed. Although there is no consensus among the literature as to the relative importance of the horizontal versus the vertical component, it is clear that the GRF plays an important role in the determination of maximal speed.

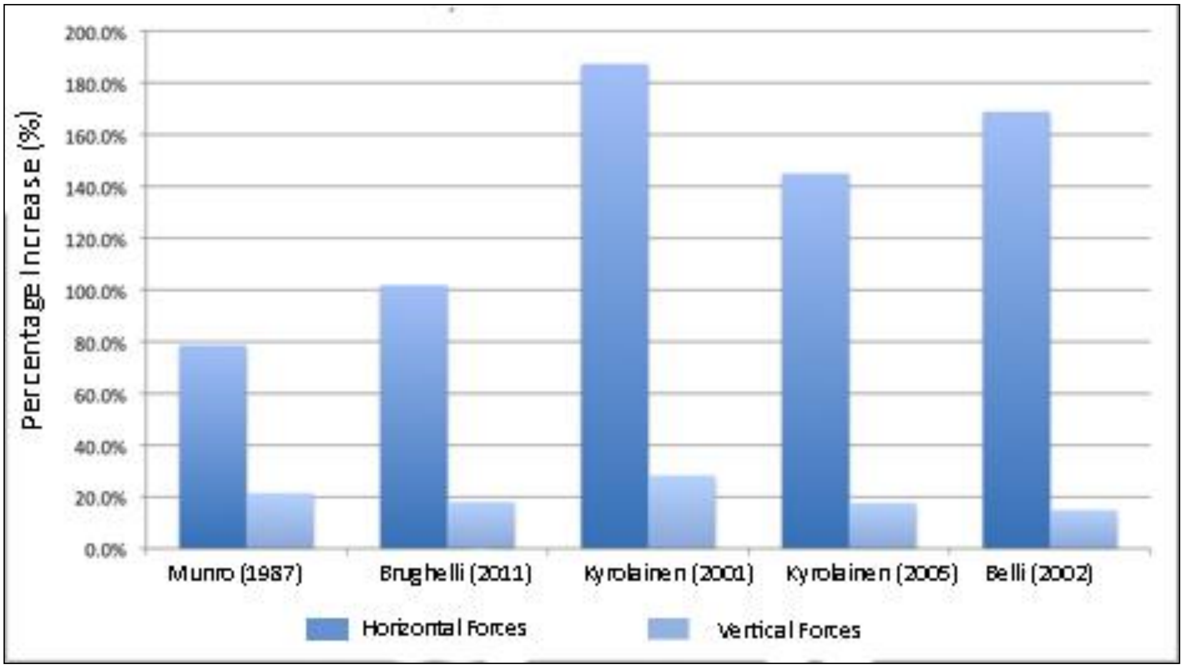


FIGURE 1.4: PERCENTAGE INCREASE IN HORIZONTAL AND VERTICAL GROUND REACTION FORCES WITH INCREASING RUNNING SPEED (ADAPTED RANDELL *ET AL*. 2010)

1.1.3 MUSCULAR CONSIDERATIONS IN SPRINTING

An understanding of function of the muscles of the lower limb is important in understanding and optimising sprinting performance. For many sports, such as sprinting, force and power output of specific muscles is of paramount importance to the performance outcome. Muscles have unique properties that determine the muscular force and power output at a given instant in time. Commonly accepted mechanisms governing the muscular force and power output in sprinting include the force-length, force-velocity and stretch-shortening cycles. Maximising force and power output from the muscles is an important consideration in maximising sprinting performance and an aspect which Stefanyshyn and Fusco (2004) speculate may be enhanced through footwear.

FORCE-LENGTH AND FORCE-VELOCITY CHARACTERISTICS OF MUSCLES

The amount of force generated by a muscle is a function of both its length and velocity (Hill, 1938; Katz, 1939). The force-length and force-velocity relationships document how force output of muscle varies at different lengths and contractile velocities. During a sprint, as the stride length and stride frequencies increase, both the range of motion of the muscles and the velocity at which they contract will vary. As the velocity of the sprint increases, the muscles accelerating the body forward must contract at progressively increasing speed (Cavagna, 1977), affecting the force output. A typical force-length and force-velocity curve for the contractile components of muscle are shown in Figure 1.5.

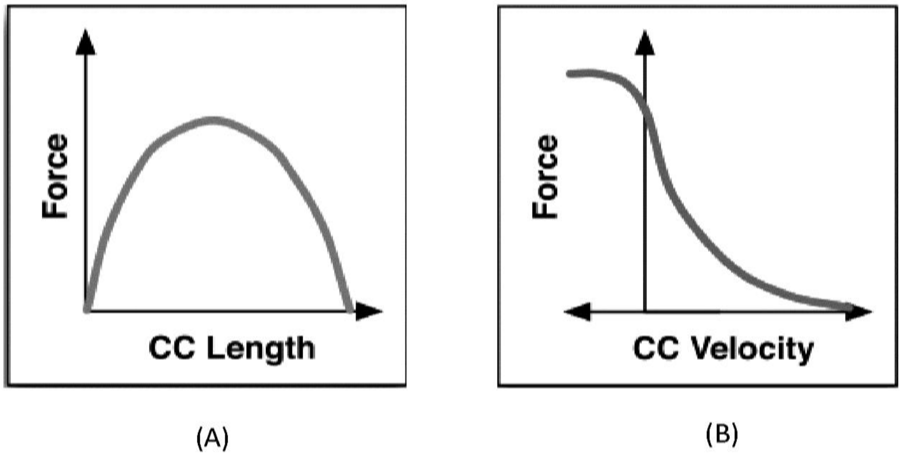


FIGURE 1.5: TYPICAL CURVES FOR THE CONTRACTILE COMPONENT (CC) (A) FOCE-LENGTH AND (B) FORCE-VELOCITY RELATIONSHIP OF SKELETAL MUSCLE (ADAPTED FROM MILLER, UMBERGER AND CALDWELL, 2012)

The force-length and force-velocity relationships also vary during individual ground contacts. Specifically at the ankle plantarflexors, as the foot goes through the range of motion from touchdown to toe off, the length of the plantarflexors are constantly changing and at varying speeds. As this range of motion is different for the different phases of sprinting, the power output of the ankle plantar flexors will also vary substantially. It is speculated that keeping the ankle plantar flexors in their optimum or near optimum position in the individual force-length and force-velocity relationship could be advantageous to maximise power output in sprinting (Miller *et al*. 2011).

STRETCH SHORTENING CYCLE

Another mechanism that affects the power output from muscles in sprinting is the stretch-shortening cycle (SSC). The SSC is characterised by an eccentric muscular contraction followed immediately by a concentric muscular contraction. Forcibly stretching the muscle immediately before a concentric contraction has resulted in increased force production and power output from the muscles when compared to performing a concentric contraction alone (Komi and Bosco, 1978). Certain movements are more suitable than others for utilizing the SSC. During the braking phase of ground contact in sprinting, the plantar flexor muscles are forcibly stretched, storing elastic energy. The subsequent propulsion phase consists of contracting the plantar flexors, using the stored elastic energy to increase the force and power outputs from the ankle plantar flexors (Cavagna, 1977).

The effectiveness of the SSC is governed by the rate and magnitude of the pre-stretch and the time between the completion of the stretch and the initiation of the concentric contraction (Schmidtbleicher, 1992). The motion of the foot will therefore dictate the magnitude of these variables. Maximizing the effectiveness of the SSC through tuning the motion of the foot would be advantageous.

At low sprinting speeds, approximately up to 6 $m \cdot s^{-1}$, the contractile component of the muscle is mainly responsible for the power output, increasing the importance of the force-length and force-velocity relationships in the acceleration phase (Cavagna, 1971). At higher sprinting speeds, the SSC plays a larger role in the power output, increasing its importance in the maximal speed phase (Cavagna, 1971). These muscular characteristics therefore provide different challenges for footwear design in the different phases of sprinting performance.

1.1.4 SUMMARY

Sprinting is defined in this research as a rapid, maximal effort movement over a short distance in a linear direction. The action of the leg during the ground contact period of the gait cycle is regarded as the critical factor influencing sprinting performance. During each ground contact phase there is a period of braking and propulsion. Through the duration of the ground contact phase, the energies produced by the sprinter are a fundamental determinant of sprint performance. The hip, knee and ankle have all been shown to both generate and absorb energy during the stance phase of sprinting, with the ankle as both the largest generator and absorber of energy. The role of the MPJ, however, remains ambiguous and further investigation is needed to clarify its role as, compared to a rigid lever, the intermediate break at the MPJ is important facilitating gait.

Sprinting speed can be broken down into a function of stride length and stride frequency. Speed can be increased with the increase of either of these variables, as long as there is not a greater decrease in the other variable. There is no definitive evidence in the literature to suggest the importance of one variable over the other as the dependence on stride length and frequency for improvements to sprinting performance appear to vary by individual.

When examining sprinting performance, it is important to recognize the different phases and the different demands in each of the phases. Although there is no one clear definition of the length of the different phases, it is important to recognise these phases demonstrate prominent differences in technique, and that performance related factors differ from phase to phase. This is especially pertinent when considering footwear design and the specific demands of the individual phases when reporting lower extremity dynamics.

When considering the function of the muscles of the lower limb in sprinting, optimising force and power output of the muscles is important. The two main mechanisms governing the muscular force and power output at a given instant are the force-length-velocity and stretch-shortening cycles. Maximising both of these muscle mechanisms would be advantageous. However, the different characteristics provide different challenges for footwear design.

1.2 BIOMECHANICS OF THE FOOT AND ANKLE

The foot and ankle are integral components of the lower limb, facilitating the interaction between the leg and the ground in sprinting, translating the energy produced at the joints of the lower limb into forward motion. The foot itself is a complicated and intricate structure, as depicted in Figure 1.6, with unique qualities allowing it to be both flexible and rigid to perform different tasks. These changes in the motion or function of the foot and ankle may have a significant impact on the propulsive and stabilizing functions of the lower limb. As the foot and shoe act as a system, development and evaluation of sprint footwear requires an understanding of the biomechanics of the foot.

The following section details the joints of the foot and ankle. Musculoskeletal properties concerning the foot and ankle are also briefly examined. The role of the MPJ is highlighted as its role in sprinting remains ambiguous and has been the focus of interest recently in considerations of performance enhancement through footwear modifications.

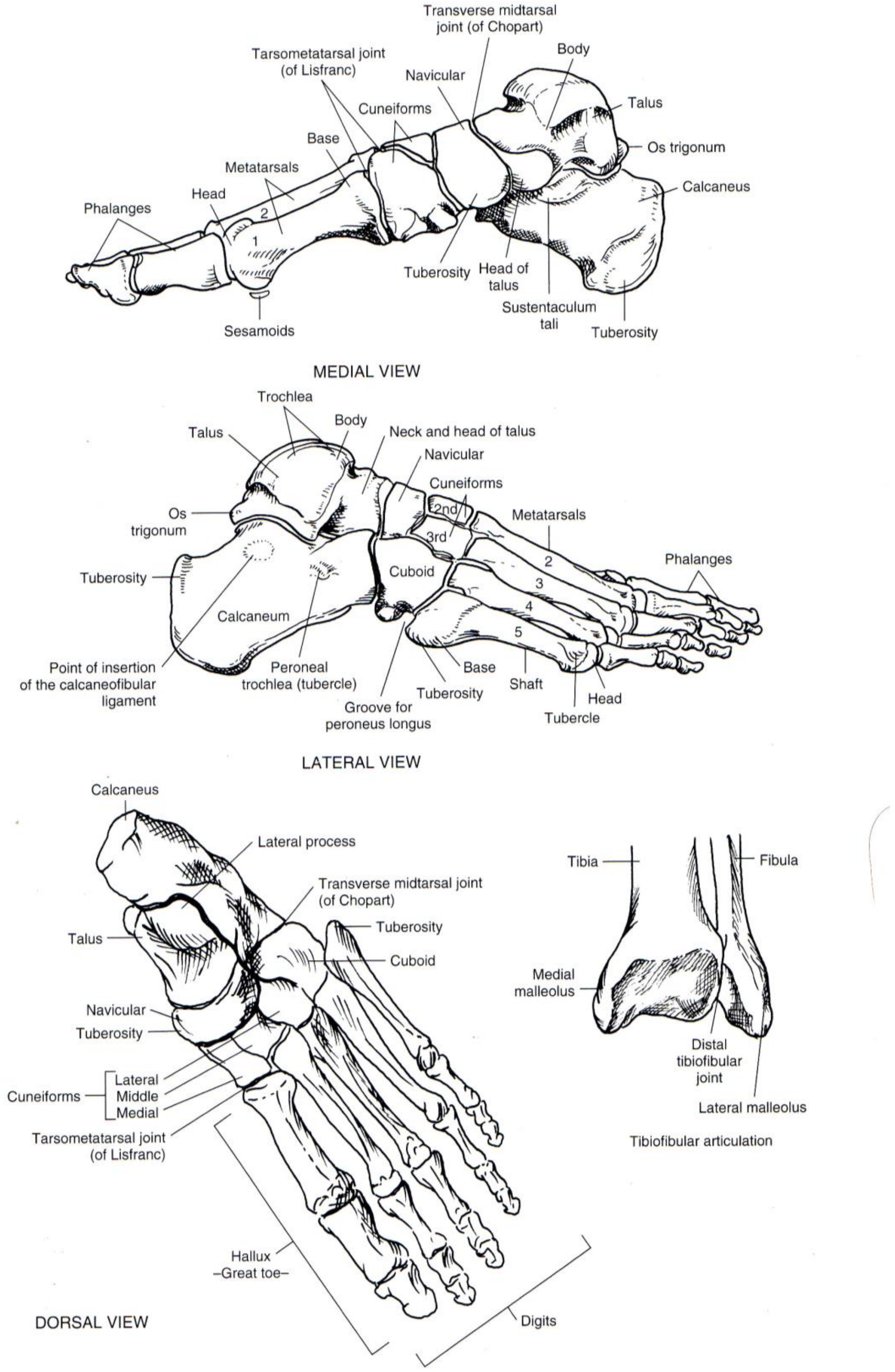


FIGURE 1.6: MEDIAL, LATERAL AND DORSAL VIEWS OF THE FOOT AND ANKLE BONES (SAMMARCO AND HOCKENBURY, 2001)

1.2.1 ANATOMY AND KINEMATICS

Total motions of the foot occur around three axes on three planes: flexion-extension (sagittal plane), abduction-adduction (transverse plane) and inversion-eversion (coronal plane) (Figure 1.7). The foot is comprised of 26 bones, whose motions are closely interconnected. In the following sections, the joints of the foot and ankle complex are documented.

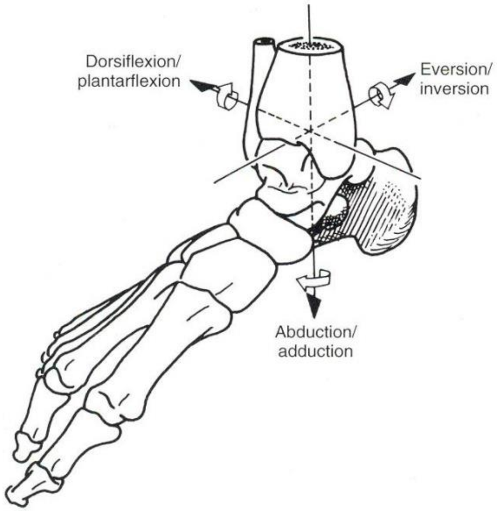


FIGURE 1.7: AXES OF MOTION IN THE FOOT AND ANKLE (SAMMARCO AND HOCKENBURY, 2001)

Pronation and supination are two common terms associated with the movement of the foot. While simple definitions of pronation and supination are used by runners to describe either rolling of the foot towards the medial (pronation) or lateral (supination) border of the foot, pronation and supination are more accurately defined as triplanar movement in the foot. Pronation describes the simultaneous eversion, abduction and dorsiflexion of the foot relative to the lower leg while supination describes simultaneous inversion, adduction and plantarflexion. The different positions of the foot in pronation and supination allow the foot to act in different capacities in gait. With pronation upon ground contact allows the foot to be more flexible and able to adapt to varying surfaces and contribute to shock absorption while supination allows the foot to act as a rigid lever towards the end of stance to aid in propulsion.

ANKLE AND MIDFOOT JOINTS

Movement of the foot relative to the lower leg is a result of motion at the ankle and subtalar joint. The subtalar joint is located at the meeting of the talus and calcaneus. The ankle (or talocrural joint) is located where the foot and leg meet, consisting of a uniaixal hinge joint formed by the tibia and fibula and the talus. Although it has been shown that the ankle axis of rotation does not remain constant with motion of the foot (Sammarco et al., 1973), it is common to approximate the ankle joint as a hinge joint with a transverse axis of rotation, normal to the sagittal plane and passing through the most prominent point of the lateral malleolus (Scott and Winter, 1990).

Moving through the midfoot, the transverse tarsal joint, often referred to as Chopart’s joint, consists of the talonavicular and calcaneocuboid joint. The motion at the transverse tarsal joint is dependent on the subtalar joint position. When the subtalar joint is in pronation, the transverse tarsal joint is unlocked and the foot becomes flexible, allowing the foot to be very mobile in absorbing shock and adapting to uneven surfaces. During supination of the subtalar joint, the transverse tarsal joint is locked, creating rigidity in the foot necessary in the later stages of gait (Sammarco and Hockenbury, 2001).

Anteriorly along the foot lies the tarsometatarsal joint, formed between three cuneiforms, cuboid, and five metatarsals. This joint is also called Lisfranc’s joint. Movements at this joint change the shape of the foot arch. Lisfranc’s joint is intrinsically stable and relatively immobile as a result of its arch like structure and the key like structure of the second tarsometatarsal joint, providing stability to the midfoot. A strong ligament, Lisfranc's ligament, connects the second metatarsal base to the medial cuneiform.

METATARSALS AND TOES

The metatarsophalangeal joint (MPJ) is located between the metatarsals and the phalanges in the forefoot, and comprises of five separate joints at the proximal attachment of each of the phalanges. The MPJ provides an intermediate break in the foot, to aid in the smooth accomplishment of gait (Bojsen-Moller and Lamoreux, 1979). Compared to having a rigid lever from the ankle to the toes, the intermediate break at the MPJ has three distinct advantages for the smooth accomplishment of gait:

1) the resistance arm of the foot about the ankle is reduced by nearly 30% during the antigravitational acceleration, reducing the demands on the triceps surae;

2) the triceps surae are able to provide useful forces over a longer period of time due to the length of the resistance arm of the foot increasing as the horizontal speed of the foot increases and

3) dorsiflexion of the toes stretches the plantar fascia, activating the Windlass mechanism and allowing it therefore to reach a higher tension, forcing the big toe back to a neutral position and enabling a final thrust during toe-off (Bosjen-Møller and Lamoreux, 1979).

Motion analysis in the sagittal plane shows that the centre of motion of the hallux is often located within the centre of the first metatarsal head (Sammarco and Hockenbury, 2001). However, the forward prominence of the second metatarsal bone allows push off in gait to be performed about two alternative axes: a transverse axis through the heads of the first and second metatarsal bones or an oblique axis through the second to fifth metatarsal heads, as shown in Figure 1.8. It is reasoned that the transverse and oblique axes can be used for different mechanical purposes, as the distance from each axis to the ankle joint varies, providing a mechanism for variable gearing during a running step (Carrier et al., 1994). The resistance arm of the foot about the transverse axis is 20% longer in the digitigrade phase (with only the phalanges touching the ground) compared to the oblique axis (Bosjen-Møller, 1978). Additionally, the length of the resistance arm is further increased with the transverse axis as the final advancement of the resistance arm to the tip of the big toe during push off. As push-off in the oblique axis finishes as a roll over the ball of the foot, there is no increase in lever length about the ankle. It is argued that the two axes about the MPJ create a high a high- and low- gear forefoot propulsive mechanism (Volger and Bosjen-Møller, 2000).

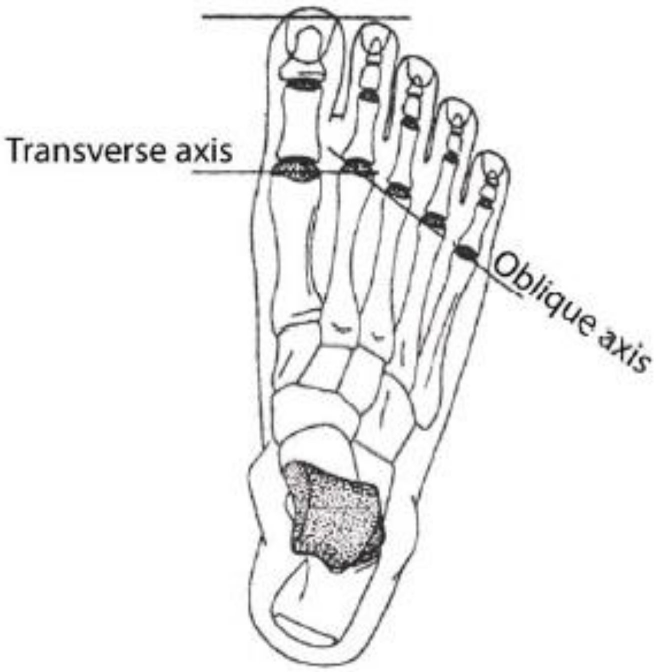


FIGURE 1.8: THE TRANSVERSE AND OBLIQUE AXES OF THE MPJ (VOLGER AND BOJSEN-MOLLER, 2000)

It is speculated that the foot rotates about either the oblique or transverse axis during push off in order to allow the ankle plantarflexors to work in their optimal power-length region. This variable gearing at the MPJ may be useful when considering the ankle extensor muscles in sprinting, enhancing muscle performance by keeping muscles nearer their high-efficiency or high-power portion of the force-extension-velocity curve during push-off in the different phases of a sprint (Carrier et al., 1994). A longer lever arm will increase torque and reduce velocity about the ankle joint. At slower ankle angular velocities, such as in the acceleration phase of sprinting, it is thought this will cause a shift away from the power-velocity optimum, indicating the oblique axis might provide favourable conditions for push off. However, at high ankle angular velocities, such as in the maximal speed phase of sprinting, push off about the transverse axis would likely cause a shift towards the power-velocity optimum. The functionality of the MPJ to select the oblique or transverse axis in sprinting, however, has not been fully examined.

Using high speed video of walking, Bojsen-Moller (1979) observed that during push-off through the oblique axis, the foot is inverted as the contact area was transferred to the lateral part of the forefoot. Push off continued as a roll over the ball of the foot, through the 3rd to 5th MPJs, with the lateral toes lacking the strength to continue the advancement of the axis onto the toes (Bojsen-Moller and Lamoreux, 1979). In contrast, with push-off occurring about the transverse axis, pronation of the forefoot occurred as the contact area was transferred from the heel to the medial part of the forefoot, through the 1st and 2nd MPJs. The contact area further progressed onto the great toe, with stabilisation of the transverse tarsal joint and a more effective tightening of the plantar fascia, thus transforming the foot into a rigid lever for push-off by activating the Windlass mechanism. While it has been suggested that a stiff sprint shoe may compromise the free selection of the oblique axis for push off, compromising the management of force production in the early acceleration phases of a sprint (Toon, 2008), it has yet to be established that the oblique axis is freely selected as an axis for push off in sprinting in a barefoot or unrestricted condition, therefore limiting the inference of this mechanism to sprinting performance and the requirements of footwear for optimal performance. Smith and Lake (2009) have shown that in maximal speed sprinting, although lateral loading was evident at touchdown, during the majority of stance loading was confined to the medial side of the foot and progressed medially and distally for take-off, through the 1st and 2nd metatarsals.

WINDLASS MECHANISM

During push off from the stance phase, toe function consists both of active and passive components. The main active function is driven by the muscles about the foot and ankle (Mann and Hagy, 1979) while the main passive function of the foot is achieved through the ‘Windlass mechanism’ (Hicks, 1954). This passive mechanism is driven through a thick connective tissue called the plantar fascia. The plantar fascia supports the arch on the bottom of the foot and spans the length of the foot from the tuberosity of the calcaneous, inserting into the base of each proximal phalanx through the plantar pad. During terminal stance, the toes dorsiflex passively as the body passes over the foot and the plantar fascia tightens, winding around the heads of the metatarsals like a cable being wound to a windlass. This acts to raise the arch and the distance between the metatarsal heads and the heel is thus shortened, as shown in Figure 1.9. This function imparts rigidity to the entire foot, becoming a rigid lever for propulsion, and facilitating push-off.

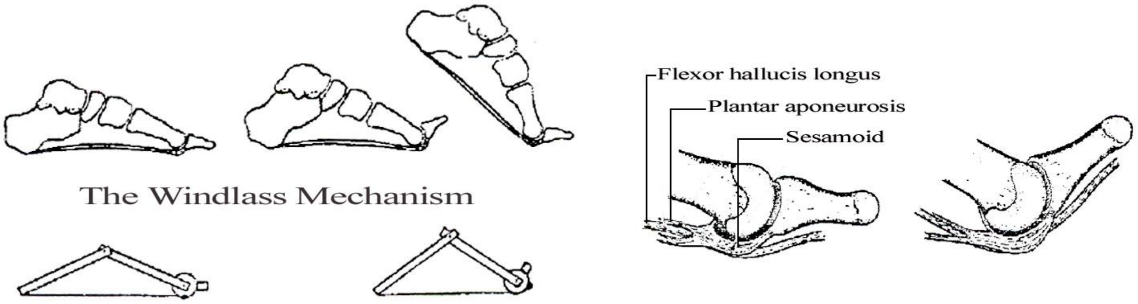


FIGURE 1.9: THE WINDLASS MECHANISM (HICKS 1954)

The effectiveness of the Windlass mechanism depends on the amount of stretch that is placed on the plantar fascia. Although the windlass mechanism occurs at each of the five toes, the first MPJ/hallux is more effective as a windlass than the four lateral toes due to the large radius of its drum. The head of the first metatarsal bone is not only the biggest of the five heads, but its radius is further enlarged by the presence of two sesamoid bones. In addition, pre-tightening of the plantar fascia has been observed when push-off is performed about the transverse axis (through the 1st and 2nd metatarsal heads), allowing tension to build as soon as the heel leaves the ground and the toes become dorsiflexed (Bojsen-Møller, 1979). Alternately, when push-off is performed about the oblique axis, with the COP moving through the 3rd to 5th metatarsal heads, the windlass must first take up slack in the plantar fascia (Bojsen-Møller, 1979).

Footwear may also play a role in the effectiveness of the Windlass mechanism. Early research by Bojsen-Moller and Lamoreux (1979) showed that walking in a stiff shoe limited the natural dorsiflexion of the toes during push off in stance, thus limiting the motion of the toes, controlling the stretch that is able to be put on the plantar fascia. The authors (Bojsen-Moller and Lamoreux, 1979) speculated that stiff shoes prevented the free selection between transverse and oblique MPJ axes. Limiting free selection of the appropriate axis in this way, particularly with typically high bending stiffness sprint shoes, may impede the natural functional response required for efficient propulsion, as further discussed in the following section.

In more recent research, footwear has been shown to both enhance (Payne, Zammitt and Patience, 2005) and minimize (Lin et al., 2013) the effects of the Windlass mechanism. While the Windlass mechanism may lead to a more effective push off from stance if enhanced, the subsequent increase in the force in the plantar fascia may potentially increasing the risk of injury with repeated loading. Although both research groups (Payne, Zammitt and Patience, 2005; Lin et al., 2013) did find that footwear affected the Windlass mechanism, both studies used walking and no measure of performance was collected, limiting the applicability to this work.

1.2.2 MPJ DYNAMICS IN SPRINTING

The first study to investigate the energy contribution of the MPJ in sprinting was Elftman (1940), which was done for a single trial and a single subject. Investigations into running, jumping and sprinting show that the MPJ encounters large forces and rotations during these dynamic movements (Stefanyshyn and Nigg, 1997). In sprinting, upon ground contact the MPJ goes through an initial period of extension. The heel then begins to lift in preparation for toe off, resulting in flexion at the joint. During the final stages of toe off, the toes begin to lift, starting at the MPJs, while the anterior tips remain on the ground, resulting in a final extension of the MPJ, as illustrated in Figure 1.10.

Modelling the MPJ during sprinting has been debated in recent literature. As the MPJ is in fact made up of five separate joints and has two axis of rotation, agreement on one representation of the joint is not clear. While Stefanyshyn and Nigg (1997; 1998; 2000) define the MPJ as an ideal hinge rotating about the location of the head of the fifth MPJ, both Smith and Lake (2007) and Toon (2008) have demonstrated that MPJ representation based on lateral markers underestimated the MPJ kinematics. Smith and Lake (2007) indicated an underestimation in peak MPJ flexion by 29° in a lateral representation compared to the medial aspect of the joint. The medial aspect of the MPJ has further demonstrated a high extension velocity before take-off not observed in the lateral aspect, permitting the possibility of positive MPJ power and energy generation (Smith and Lake, 2007). Toon (2008) alternatively modelled the MPJ as a single ideal hinge joint rotating about a transverse axis by taking a mean of the first and fifth MPJ centres. Typical practice in recent literature (Stefanyshyn and Nigg, 1997; 1998; 2000, Toon, 2008) has also considered the resultant forces and moment at the MPJ to be zero until the ground reaction force acted distal to the joint. A joint representation utilising the fifth MPJ means that the resultant for cross the joint sooner, acting distal to the joint for longer with an increased lever arm length about the MPJ. However, this representation might also underestimate important aspects of the joint kinematics demonstrated by a medial representation. A clarification of the implications of each MPJ definition is necessary to facilitate further research into the role of the MPJ in sprinting and sprint footwear.

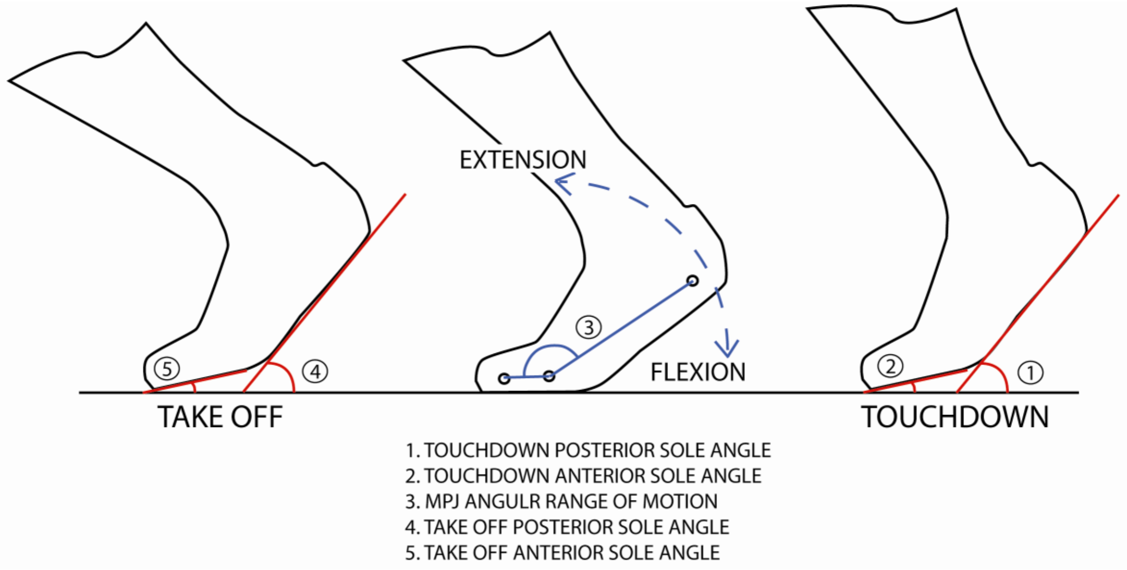


FIGURE 1.10: SCHEMATIC DEFINING MPJ MOVEMENT DURING GROUND CONTACT AND POSTERIOR AND ANTERIOR SOLE ANGLES AT TOUCHDOWN AND TAKEOFF (ADAPTED FROM TOON (2008))

In an attempt to clarify the role of the MPJ kinematics in sprinting, Krell and Stefanyshyn (2006) examined the relationship between extension of the MPJ and sprint time for 100m sprints at the 2000 Summer Olympic Games. It was found that faster male sprinters experience higher maximal rates of MPJ extension while faster female sprinters touchdown with higher posterior sole angles and take off with lower posterior sole angles. The authors suggest that athletes with the greatest rate of MPJ extension would be able to translate the high rates of MPJ rotation into the larger linear velocity of the centre of mass during take-off.

In a series of two papers, Stefanyshyn and Nigg (1997, 1998) investigated the contribution of the lower extremity joints to running, sprinting, running long jumps and running vertical jumps. The MPJ was defined in the sagittal plane as an ideal hinge rotating perpendicular to the fifth metatarsal head, about a transverse axis. The authors (Stefanyshyn and Nigg, 1997; 1998) determined the individual energy contribution of the MPJ was primarily as absorbing substantial amounts of energy and generating very little to none. The mean values of energy absorption were 20.9 ± 6.6 J for running (Stefanyshyn and Nigg, 1997), 47.8J ± 16.6 J (Stefanyshyn and Nigg, 1997) for sprinting, 24.5 ± 9.6 J for running vertical jumps and 43.6 ± 12.4 J for running long jumps (Stefanyshyn and Nigg, 1998). On the other hand, the highest value of mean energy generation for the MPJ has been reported as 8.0 J for sprinting (Stefanyshyn and Nigg, 1997).

The energy absorption at the MPJ observed by Stefanyshyn and Nigg (1997, 1998) is reasoned to be due to the MPJ flexing as the athlete rolls onto the forefoot, while extension of the joint does not occur until after take-off when the return of energy is too late to have an influence on performance. Extension of the MPJ would have to occur during the stance phase in order to generate energy at the joint. In contrast, both Smith and Lake (2007) and Toon (2008) have indicated that there is a phase of MPJ plantarflexion (or extension) prior to take off, therefore introducing possibility of MPJ energy generation not previously observed. Differences in data collection, processing and in representation of the MPJ have been highlighted in recent literature as a possible cause for this discrepancy (Smith and Lake, 2007).

In addition to the differences in MPJ definition, the data collection and processing of the kinematic data utilised by Stefanyshyn and Nigg (1997; 1998; 2000) may also lead to underestimations of the MPJ angular range and angular velocity of the MPJ. Smith and Lake (2007) have shown that a kinematic sampling rate of 1000 Hz and a filtering cut off frequency of 100 Hz resulted in substantial increases in MPJ range of flexion and peak angular velocities when compared to the approach used by Stefanyshyn and Nigg (1997; 1998; 2000) of a 200 Hz sampling rate and a filter cut off frequency of 8 Hz. The influence of each of these factors separately is necessary to determine their individual impact on the resulting kinematics of the MPJ in sprinting. As the potential for MPJ extension and the enhancement of energy generation through sprint shoe design remains unknown, an examination of the joint definition and methodology to examine the motion at the MPJ is required before conclusions can be made about the energy generating capabilities of the MP joint in sprinting.

1.2.3 MUSCULAR CONTROL OF THE FOOT

The strongest flexor of the ankle is the tibialis anterior, and is necessary to allow for foot clearance from the floor during the swing phase. The strongest inverter of the foot and ankle is the posterior tibialis muscle, a dynamic supporter of the medial longitudinal arch and inverts the subtalar joint during stance. The primary everters of the foot and ankle are the peroneals. The peroneus longus acts to depress the metatarsal head while the peroneus brevis acts to stabilise the foot laterally by resisting inversion. The strongest movement at the ankle or foot, however, is plantarflexion.

Plantarflexion is used in forward propulsion of the body, contributing to forces in toe-off, while plantarflexor muscles are also used eccentrically to slow down a rapidly dorsiflexing foot or to assist in the control of the forward movement of the body (Hamill and Knutzen, 2003). The dominant generators of ankle planterflexion are the gastrocnemius and soleus muscles, termed the triceps muscle group. Achilles tendon is the common insertion of the gastrocnemius and soleus muscles onto the posterior superior aspect of the calcaneous of the foot.. It is through the Achilles tendon that the majority of the force developed in the lower limb is transferred through the ankle joint, to the foot and applied to the ground allowing for propulsion of the body.

Lee and Piazza (2009) draw attention to research in comparative functional morphology, suggesting that the skeletal structure of the foot and ankle, in combination with muscle moment arms, are determinative of speed. Lee and Piazza (2009) have found that the Achilles tendon moment arm of sprinters were 25 % smaller on average than in non-sprinters, with sprinters' fascicles 11 % longer. Although a large Achilles tendon moment arm improves the mechanical advantage of the triceps surae, by generating a larger torque about the ankle, it may also reduce the amount of force produced by the triceps surae. A larger moment arm would cause the triceps surae to shorten more for a given rotation, thus possibly attenuating muscle force production during shortening due to the force-velocity properties of the muscle. In addition, sprinters were shown to have longer toes than non-sprinters (Lee and Piazza, 2009). Through computer simulation, it was shown that shorter plantarflexor moment arms and longer toes permit the generation of larger forward impulse. Simulated propulsion was also improved by increasing the length of the toes, and thus the 'gear ratio' of the foot, maintaining plantarflexor fibre length and reducing peak fibre shortening velocity. The longer toes especially prolonged the ground contact time through propulsion, allowing for greater time forward acceleration by propulsive ground reaction force. Although the sprinters' Achilles tendon moment arm and fascicles length are factors that are difficult to influence, artificial lengthening of athletic footwear to mimic a longer toe length is more easily achieved. This has been briefly investigated by Roy and Stefanyshyn (2002), who found that increased shoe length resulted in an increase in jump height and peak force from a standing countermovement jump. Although Roy and Stefanyshyn (2002) show interesting results, this topic will not be addressed in this work but is suggested for further research.

1.2.4 SUMMARY

The foot and ankle facilitate the interaction of the lower limb and the ground throughout stance, translating the energy produced at the joints of the lower limb into forward motion. The foot is able to carry out different functions through its functional anatomy, adapting to different terrain and functional demands with many different mechanisms functioning simultaneously. The effects of sprint footwear on some of the more important mechanisms remain unknown, such as variable gearing at the MPJ and the effectiveness of the Windlass mechanism.

Early research has identified the MPJ as a large absorber of energy while generating little to none in sprinting, reasoned to be due to a lack of MPJ extension while the toe is still in contact with the ground during toe off. However, more recent research has highlighted differences in definition of the MPJ, data collection and processing methodologies that may lead to an underestimation of the kinematics and kinetics of the joint. An examination of the joint definition and methodology to examine the motion at the MPJ is required before conclusions can be made about the energy generating capabilities of the MP joint in sprinting.

The strongest movement at the ankle and foot is plantarflexion, with the triceps surae muscle group as the strongest contributor to the motion. It is through the Achilles tendon that the majority of the force developed in the lower limb is transferred through the ankle joint, to the foot and applied to the ground allowing for propulsion of the body. In terms of functional morphology, a smaller Achilles tendon moment arm, longer fascicles and longer toes are attributes of sprinters compared to non-sprinters. Artificial lengthening of the toes through increases in shoe length is an interesting research area, with regards to changes to the properties of footwear and athletic performance, and it is suggested for further research outside of the scope of this work.

1.3 CURRENT SPRINT SHOE DESIGN PARAMETERS

The majority of literature pertaining to footwear in athletics involves the development of running shoes (Bates et al., 1982; Bates et al., 1983; Boumans and Claeys, 1988; Cavanagh, 1980; Cavanagh, 1989; Clarke et al., 1983; Nigg, 1986; Nigg and Sesseger, 1992; Shorten, 1993). The main areas of focus for running shoe design have been the attenuation of the shock at heel strike, the control of hindfoot motion during loading and forefoot stability in the stance phase (Novacheck, 1998). Winter and Bishop (1992) stated that function of footwear for runners is to absorb shock at heel contact, protect against the rough ground surface and distribute the force at chronic injury sites. There is much less literature pertaining to the design and functionality of sprint shoes.

In the vast majority of sprinting races, sprint shoes are worn as opposed to running shoes. A sprint shoe differs from a running shoe in many ways. The focus in the design of a sprint shoe is on increased performance as opposed to comfort and injury prevention. The purpose of shoes for competition stated by the International Association of Athletics Federations (IAAF) is to give protection and stability to the feet and a firm grip on the ground. A sprint shoe has spikes located on the forefoot for increased traction and the sole is generally thinner than a running shoe, with a minimal heel pad and a more rigid forefoot plate. These functional differences are due to the different kinematics and kinetics of the lower limbs during ground contact compared to running. In sprinting, initial ground contact is made in the forefoot region as opposed to the heel and the centre of pressure remains in a much more anterior position on the foot compared to running (Novacheck, 1998). The attenuation of shock at the initial heel strike is therefore minimal in sprint shoe design. It is for these reasons that kinematic and kinetic results obtained using running shoes may not be applied to sprinting performances where sprint shoes are worn. An exploration of the main areas of focus for sprint shoe design may highlight areas for the enhancement of sprinting performance and are presented below.

1.3.1 MASS

Studies have shown that shoe mass has an effect on both the energy expenditure and work during running. Catlin and Dressendorfer (1979) showed that at marathon running pace, the energy cost of running wearing shoes weighing 0.87 kg was increased by 0.51 $kcal \cdot min^{-1}$ compared to wearing shoes weighing 0.52 kg. However, it was concluded that the effect of the shoe weight had only a small effect when compared to the total body energy expenditure (Catlin and Dressendorfer, 1979). Nigg and Segesser (1992) investigated the additional work associated with additional shoe mass during running and estimated that at a running speed between 5-7 $m \cdot s^{-1}$ an increase in shoe mass of 100 g required an additional 5 J of work per stride. The additional work associated with increased shoe mass can be attributed to the additional work required to lift, accelerate and decelerate the additional mass (Nigg and Segesser, 1992). Further results also indicated that as running speed increases the influence of increased shoe mass also increased (Nigg and Segesser, 1992). Current commercially available running shoes typically weigh between 200 and 400 g while sprint shoes weigh between 98 and 250 g. Since the concept of minimization of shoe mass is generally accepted as a means to reduce energy expenditure and work during running and sprinting, it will not be explored further in this work.

1.3.2 TOE SPRING

Toe spring is defined as the angle of the forepart of the shoe relative to ground level when the shoe is on a level surface. Toe spring is a design feature which accounts for natural foot flex between the rearfoot and forefoot and facilitates the forward rolling action of the foot about the MPJ in shoes with high levels of bending stiffness (Toon, 2008). The toe spring angle in sprint shoes is also designed to improve the efficiency of the movement pattern of the foot while in the ground contact phase. The mean value of toe spring was found to be 26° when benchmarking shoe properties from a range of sprint shoes commercially available (Toon, 2008). It has been suggested that touchdown posterior sole angle (the angle between the ground and rearfoot) may be affected by the design of toe spring in sprint shoes (Krell and Stefanyshyn, 2006). The authors explain that sprint shoes constructed with a stiff, highly contoured midsole may tend to cause the athletes to touchdown with larger posterior sole angles. This functionality may be used to improve sprinting performance as it has been observed that faster sprinters tend to touchdown with greater posterior sole angles (Krell and Stefanyshyn, 2006). The authors (Krell and Stefanyshyn, 2006) reasoned that athletes with higher posterior sole angles would tend to plant the foot close to the vertical line of action from the centre of mass upon initial ground contact, decreasing the horizontal braking force from the ground. Toon (2008) contests that stiff sprint shoes do not necessarily cause an athlete to contact the ground with larger posterior touchdown angles and that the technique used upon touchdown is likely to be dependent upon an individual’s technique rather than the footwear. There is no previous literature pertaining to the influence of the modification of toe spring in sprint shoes on sprinting performance. Although this is an interesting area of further research, it falls outside of the scope of this research.

1.3.3 TRACTION

Traction features are an integral component of sprint shoes in order to facilitate the generation and transmission of large forces without slippage occurring between shoe and track. There is a dearth of information, however, on the traction generating properties of sprint shoes. Modern, commercially available sprint shoes typically provide traction via 5-9 removable spikes (screw-threaded, tapered metal pins) and moulded features incorporated into the sole plate of the shoe, which create a form locking connection with the track. Regulations set by the governing body for athletics (IAAF) permit the use of up to 11 removable spikes. Spike housings consist of separate metal threaded inserts, allowing for different types of spikes to be screwed into place. There have been commercially available sprint shoes with fully incorporated, permanent traction features in the sole unit. However, these types of permanent traction features are rarely commercially available as once the traction features wear out or break, the shoe is no longer functional, as opposed to the removable spikes, which can simply be replaced.

Only two known published research studies have examined the traction interaction between sprint shoes and track surfaces (Laananen and Brooks, 1978; Kilani and Adrian, 1986). Laananen and Brooks (1978) investigated the time variation of the ground reaction force and simultaneous foot orientation between a sprinter and the track during the initial acceleration phase of sprinting to clarify an optimum type and pattern of spikes on sprint shoes. They found that 1) the spike plate of the shoe, where all of the traction features of the sprint shoe are located, was in total contact with the track at the time of maximum horizontal force application and 2) due to rotation of the foot during the period of maximum force application, a comprehensive analysis of the design of racing shoes would likely yield benefits in performance and prevention of injury. Kilani and Adrian (1986) investigated the effect of spike configuration on the ground reaction force generated during sprinting performance. The authors examined differences in the shape and length of the spike, utilising two different shapes (cone and blunt) and two different lengths (3.2 and 6.3 mm), with sprinters performing sprint starts from a crouch position in order to examine the ground reaction forces generated with the different spike configurations. While there were no significant differences found between the spike conditions, provisional conclusions were drawn that all the spikes provided an equal and sufficient grip between the spiked shoe and track surface. No information, however, is given with regards to a minimum level of traction required to prevent slipping. Additionally, as human performance testing was utilised, no mechanical test procedure for quantifying the traction properties of sprint shoes has been established. Although traction is fundamental to sprinting performance, minimum and optimum levels of traction remain unknown.

It is accepted that all modern commercially available sprint shoes provide, as a minimum, sufficient traction to prevent slipping as slipping of sprinters under normal sprinting conditions is unheard of in modern athletics. This may be the reason for the lack of information on the traction generating properties of sprint shoes. However, excessive or redundant traction may also have a detrimental effect on sprinting performance with the potential to increase the energy cost during a foot strike and is an interesting area for further investigation outside of the scope of this research.

1.3.4 STIFFNESS

As the potential to influence sprinting performance through adjustments to the bending stiffness of sprint shoes forms the focus of this research, a number of key studies regarding the influence of footwear mechanical properties on athletic performance are discussed in the following section.

1.4 ATHLETIC FOOTWEAR AND PERFORMANCE

A number of key studies pertaining to the influence of footwear mechanical properties on athletic performance are discussed in the following section. Initial work in the area of increased bending stiffness of athletic footwear on athletic performance is presented, followed by the literature most relevant with regards directly to the influence of the bending stiffness of sprint footwear on sprinting performance. Particular attention is given to the influence of increased bending stiffness on sprinting performance and sprint related jump metrics and identifying changes to the lower limb kinematics and kinetics responsible for any observed changes in performance. The final section, section 1.4.3, examines the personalisation of bending stiffness for optimal sprinting performance. The literature is discussed and critically evaluated in order to identify knowledge gaps in need of further research.

1.4.1 ATHLETIC FOOTWEAR AND LOWER LIMB DYNAMICS

In a series of studies conducted within the same research group (Stefanyshyn and Nigg, 2000; Roy and Stefanyshyn, 2002; Roy and Stefanyshyn, 2006), the influence of increasing the bending stiffness on athletic performance was investigated. As the MPJ had been shown to be a large dissipater of energy during ground contact while generating very little to none in running, sprinting and jumping (Stefanyshyn and Nigg, 1997; Stefanyshyn and Nigg, 1998), it was hypothesised throughout this research that increasing the bending stiffness of running shoes would lead to a decrease in the amount of dorsiflexion at the MPJ prior to toe-off, resulting in a reduction of the energy lost at the MPJ. It was further hypothesised that this decrease in the energy lost at the MPJ would result in an improvement in athletic performance.

The relationship between the bending stiffness of athletic shoes and athletic performance was first investigated by Stefanyshyn and Nigg (2000) who examined the influence of increased bending stiffness of running shoes on lower limb kinematics and kinetics in running and jumping. Participants completed runs at 4.0 $m \cdot s^{-1}$ and a one legged maximal effort vertical jump in three shoe conditions (control, stiff, very stiff). Kinematic data was collected using a passive reflective marker system sampling at 200 Hz and kinetic data collected using a force plate sampling at 1000 Hz. Vertical jump heights were evaluated for a separate group of participants using two shoe conditions (control and stiff), to be used as a measure of performance. The results indicated that while the energy generation and absorption at the ankle, knee and hip remained unchanged in both running and jumping in the running shoes with increased bending stiffness, a reduction in the energy lost at the MPJ was observed in both the stiff and very stiff conditions. This reduction in the energy lost at the MPJ was attributed to an observed decrease in MPJ flexion during the ground contact phase while wearing the stiffer shoe conditions. A significant increase in vertical jump height was also subsequently observed with the second group of participants. It was concluded by the authors that increasing the bending stiffness of the running shoes lead to a reduction in the MPJ dorsiflexion and subsequently energy lost at the joint. This observed decrease in energy lost at the MPJ was in turn considered to be the mechanism responsible for the observed improvement in vertical jump height. However, as information on the MPJ energies were not collected during the completion of the vertical jumps used to evaluate performance, it is difficult to establish a direct link between the observed changes at the MPJ with increased bending stiffness of running shoes and the improved performance in the vertical jump height.

Subsequently, Roy and Stefanyshyn (2002) investigated the effects of increasing the bending stiffness of running shoes and shoe length on jump height.

Participants completed maximal effort counter movement jumps in three running shoe conditions (control, stiff and stiff with anterior extension). Only kinetic data and jump height were measured, using a force platform and a Vertec height measurement system, respectively. Once again, the idea of minimizing the energy lost at the MPJ formed the basis of the hypothesis that increasing the shoe stiffness and length would result in a reduction in the energy dissipated at the MPJ and result in an increase in jump height. Although the results were not significant, an improvement in jump height of 1.1 cm and impulse of 2.65 N·s in the stiff shoe compared to the control shoe were observed.

Further, the effect of increased bending stiffness on running economy has been investigated by Roy and Stefanyshyn (2006). Utilising three shoe conditions (control, stiff and stiffest), oxygen consumption was evaluated followed by a separate collection of kinematic, kinetic and EMG data from participants running at 3.7 $m \cdot s^{-1}$. Approximately a 1% metabolic energy saving was observed in the stiff shoe condition compared to the control. There were, however, no significant differences in energy absorption at the MPJ in the stiff shoe compared to the control. It was hypothesised that improvements in running economy might be achieved through a decrease in the energy absorbed at the MPJ during ground contact with increased shoe bending stiffness. As this trend in the decrease of energy loss at the MPJ with increased bending stiffness was not observed, the underlying mechanism that could be attributed to the improvement in running economy remains ambiguous.

From this set of research papers, it is clear that increasing the bending stiffness of sprint footwear results in a decrease in the amount of dorsiflexion at the MPJ, resulting in a decrease in the energy absorbed at the joint. However, a link between this decrease in MPJ energy loss and an improvement in athletic performance has not been established and the underlying kinematic or kinetic mechanism attributed to improved athletic performance with increased shoe bending stiffness remains ambiguous. Nevertheless, although these studies examined the effect of increased bending stiffness of running shoes as opposed to sprint shoes, and examined running and jumping rather than sprinting, it was highlighted that increased bending stiffness of athletic shoes could lead to changes in athletic performance. This insight provided the motivation for further work into the effect of increased bending stiffness on sprinting performance, and the relevant literature is discussed in the following section.

1.4.2 SPRINT FOOTWEAR AND SPRINT PERFORMANCE

In the first paper to directly examine the effect of increased sprint shoe bending stiffness on sprinting performance, Stefanyshyn and Fusco (2004) measured the sprint times of thirty-four athletes from 20 to 40 m in a maximal effort 40 m sprint. In addition, simple anthropometric measures of height, weight and shoes size were collected to investigate a potential correlation to predict shoe bending stiffness for optimal performance. Four shoe conditions were utilised, consisting of a standard condition (their own sprint shoes) and three manually adapted conditions, where carbon fibre inserts were used to systematically increase the bending stiffness of a sprint shoe. The stiffness of the carbon fibre inserts were determined using a three-point bend test and measured 42, 90, and 120 $N{\cdot}mm^{-1}$. On average, the authors found a significant decrease in sprint times in the first shoe stiffness condition (42 $N{\cdot}mm^{-1}$) compared to the standard condition, with a 0.69% improvement in sprinting performance. In addition, the stiffness each athlete required for their best performance was subject specific, with a significant improvement in sprint performance of 1.2% when comparing the best stiffness condition for each individual to the standard condition.

Although Stefanyshyn and Fusco (2004) did find a significant improvement in sprinting performance, due to a lack of biomechanical data collected in addition to sprint times, it was difficult to speculate on the mechanism responsible for both the observed improvement in sprint performance and which of the athletes' characteristics determines their individual optimal sprint shoe stiffness. In addition, there was no correlation between anthropometric measures of height, weight or shoe size and optimal shoe stiffness. The authors speculated that one potential influence of increasing the bending stiffness of the sprinting shoes was a shift in the point of application of the ground reaction force in the anterior direction. A further speculation was that a change in the position of the ground reaction force could result in changes to the kinematics at the MPJ and ankle, changing the joint angular velocities and thus shifting the position in the force-velocity relationship of the ankle plantarflexors. Further kinematic and kinetic information would be necessary to address these speculations.

Smith et al. (2010) further investigated the effect of increased bending stiffness of sprint shoes on sprinting performance, recording sprint times of twelve sprinters from 30 to 40 m in a maximal effort 40 m sprint. In addition, the effect of bending stiffness of sprint shoes on the kinematics of the MPJ was investigated separately, collecting high speed video data (600 Hz) from four subjects during one stance phase during a separate sprint. Four shoe conditions were utilised, consisting of a standard condition and three manually adapted conditions where carbon fibre inserts were used to systematically increase the bending stiffness of a commercially available sprint shoe. The stiffness of the shoes were determined using a two-point bend test and measured 276 (control), 329, 388, and 518 $N \cdot mm^{-1}$. In contrast to Stefanyshyn and Fusco (2004), no significant difference in sprint performance between the four stiffness conditions were observed. In agreement with Stefanyshyn and Fusco (2004), however, the best stiffness condition was subject specific, with 7 of 12 subjects demonstrating improved sprinting performance in sprint shoes stiffer than the standard condition, with a mean improvement of 0.02 ± 0.01 s, agreeing with the notion of personalisation of the bending stiffness of sprint shoes. With regards to the kinematics, the mean MPJ angular range of motion was observed to be reduced by 5.4° in the stiffest sprint shoe condition, although not significant. While the performance and kinematic differences shown in this study (Smith and Lake, 2010) where small and not significant, Hopkins *et al* (1999) suggested that the smallest worthwhile performance enhancement for an elite sprinter to be approximately 0.36 to 0.63%, thus highlighting the importance of documenting even small changes.

Ding et al. (2011) introduced a more comprehensive research design for the evaluation of the effect of bending stiffness on sprint performance, examining the relationship between the individual athlete's MPJ stiffness, the stiffness of sprint footwear and sprinting performance. Two shoe conditions were utilised, consisting of a stiff and even stiffer shoe condition, adapted with carbon fibre inserts used to systematically increase the bending stiffness of a sprint shoe. There was no mention of the method used to test the bending stiffness of the shoes or a measure of stiffness given. The participants' passive MPJ stiffness was measured during stance using a custom made device, with no more detail on the actual methodology used. Sprint performances were evaluated over 25 m, utilising measures of the sprint velocity. Biomechanical variables were additionally collected from a separate 10 m sprint, which included measures of front and rear foot impulse in the starting blocks, propulsive anterior-posterior impulse and maximum MPJ flexion angle in the first and second step from the blocks. No influence of MPJ stiffness or sprint shoe stiffness on sprinting performance was observed for either the measured change in velocity at any of the 5 m intervals throughout the 25 m sprint or for the biomechanical variables of impulse and maximum MPJ flexion collected. Again, however, in agreement with Stefanyshyn and Fusco (2004), differences in the sprint velocity, impulse and maximum MPJ flexion in the two different sprint shoe conditions were subject specific.

In an attempt to examine the influence of increased bending stiffness on sprinting performance using a more repeatable method and minimize fatigue, Toon (2008) investigated the influence of sprint shoe bending stiffness on jump performance and lower limb dynamics utilising discrete jump metrics representing the acceleration and maximal speed phases of sprinting. Concentric squat jumps were used to represent the acceleration phase while bounce drop jumps represented the maximal speed phase. Seven shoe conditions were utilised, consisting of a barefoot equivalent condition and six stiffness conditions. The sprint shoes were constructed using sole units of increased thickness to increase the bending stiffness and manufactured using laser sintered nylon-12. The thickness of the conditions used in testing were 2, 4, 5, 6, 7 and 8 mm and had corresponding measured stiffnesses of 15, 27.6, 43.2, 58.6, 74.6, and 103.7 N, respectively, The stiffness of the shoes were determined using a two-point bend test.

Increasing the midsole bending stiffness affected the kinematics at the MPJ and ankle during both the squat and bounce drop jumps, with a significant decrease in both the MPJ and ankle angular velocity in both the squat and drop jumps with increased shoe stiffness. However, highlighted in the results were the individual responses to the increase bending stiffness and the differences in response across the different jump metrics, indicating personalising mechanical properties of sprint shoes not only to the requirements of a particular athlete but additionally to the particular phase in a sprint for maximal performance. For the squat jump, ankle moments, joint power and energy increased with bending stiffness and reached an optimal level within the shoe stiffness range for each individual. In the bounce drop jump, MPJ energy generation increased with shoe bending stiffness.

It was further speculated by the author (Toon, 2008) that the different stiffness requirements for the different phases in sprinting may be related to the variable gearing functionality of the foot, as presented by Bojsen-Moller (1978). Toon (2008) suggested that perhaps the inability to select the oblique axis for push –off during the squat jump, due to a stiffness that is too high, may compromise the management of force production at the ankle plantarflexors. The bounce drop jump on the other hand, may have required a higher gear and the stiffer shoes create a rigid system that may be facilitating propulsion. According to this theory, it appears that the bending stiffness requirements for maximal performance in the acceleration and maximal speed phases of sprinting are not only different, but in opposition. Furthermore, individual responses to the different levels of stiffness highlighted the importance of personalising mechanical properties to the requirements of a particular athlete for maximal performance. As sprint related jump metrics and not actual sprinting were used as the measure of performance and the variable gearing at the MPJ not investigated, the applicability of these results and speculated mechanism responsible for changes in performance are limited.

1.4.3 TUNING SPRINT FOOTWEAR

It is evident from the highlighted studies (Ding et al., 2011; Stefanyshyn and Fusco, 2004; Smith et al., 2010; Toon, 2008) that mechanical properties of sprint shoes should be tuned to the requirements of a particular athlete for maximal performance. Further, it has been inferred that the mechanical properties need also be tuned for the specific sprint phase (Toon, 2008). The personal requirements that dictate the optimal bending stiffness in order to achieve maximal performance, however, remain ambiguous and subject to speculation.

As previously discussed, early research of the influence of increased shoe bending stiffness on athletic performance (Stefanyshyn and Nigg, 2000; Roy and Stefanyshyn, 2002; 2006) focused on the role of the MPJ as it has been shown to be a large absorber of energy in running, jumping and sprinting (Stefanyshyn and Nigg, 1997, 1998). Increased running shoe bending stiffness was shown to have resulted in a reduction in the energy lost at the MPJ in sprinting and vertical jumps (Stefanyshyn and Nigg, 2000). This observed reduction of energy loss at the MPJ was attributed to a decrease in the MPJ dorsiflexion with increased shoe bending stiffness (Stefanyshyn and Nigg, 2000). The data collection and processing methodologies used by Stefanyshyn and Nigg (1997, 2000), however, have come into question, with Smith and Lake (2007) indicating that the MPJ definition, data collection and processing methods used may result in an underestimation of the MPJ kinematics and kinetics, confounding the earlier assumptions on the role of the MPJ in sprinting. Further investigation into the effect of data collection and processing methods are needed in order to establish adequate methods for analysis to clarify the role of the MPJ in sprinting.

In addition, Stefanyshyn and Fusco (2004) questioned the hypothesised decrease of energy loss at the MPJ as the possible mechanism for the observed improvement in sprinting performance. It was initially speculated by Stefanyshyn and Fusco (2004) that an improvement in sprinting performance with increased sprint shoe bending stiffness would be the result of a decrease in the energy lost at the MPJ. This hypothesis was based on the findings of Stefanyshyn and Nigg (2000). However, Stefanyshyn and Fusco (2004) showed that on average, sprint performance in sprint shoes of increasing bending stiffness only improved up until a point, at which performance decreased with increased bending stiffness, indicating there is an upper limit to the level of beneficial stiffness. Although earlier work (Stefanyshyn and Nigg, 2000) attributed an increase in jump height in stiffer shoe conditions to a decrease in the energy lost at the MPJ, this relationship cannot be entirely responsible for the improvement in sprinting performance. Otherwise, as shoe stiffness increased, the energy lost at the MPJ would continue to decrease, hence resulting in improved performance in the stiffest shoe condition. In addition, there was no correlation either between anthropometric measures of height, weight or shoe size and optimal shoe stiffness.

The authors (Stefanyshyn and Fusco, 2004) speculate that a potential influence of changing the bending stiffness may move the point of the ground reaction force anteriorly, resulting in an increased lever arm and greater moments about the ankle plantarflexors. A further speculation was that a change in the position of the ground reaction force could result in changes to the kinematics at the MPJ and ankle, changing the joint angular velocities and thus shifting the position in the force-velocity relationship of the ankle plantarflexors. This indicates that tuning to the muskulo-skeletal characteristics of the individual may be necessary in order to personalise the stiffness of the sprint shoes

The results of Toon (2008) support the notion that increasing the bending stiffness of the sprint shoes may influence moments about the ankle plantarflexors. Toon (2008) speculated that increasing the midsole bending stiffness caused compromised MPJ and ankle joint coordination and angular velocity. Consequently it was proposed by Toon (2008) that the threshold stiffness levels of sprint shoes are achieved at the point where the force-velocity relationship at the ankle is compromised to the extent that an unmanageable demand on the plantarflexors occurs for the individual. This is due to the stiffening of the MPJ, not allowing it to function as an intermediate break when the joint is constrained in stiff shoes and therefore the management of force production about the ankle is compromised to the extent that the triceps surae can no longer do the required work to cope with the effective increased moments. However, as sprint related jump metrics and not actual sprinting were used as the measure of performance, the applicability of these results are limited. It is clear that in order to gain a better understanding of the mechanisms to which sprint shoe bending stiffness should be tuned for an individual, a realistic view of changes to lower limb dynamics with increased sprint shoe bending stiffness is required. In addition, the relationship between sprint shoe bending stiffness and sprinting performance need be examined in the different phases of a sprint as Toon (2008) indicated that the different stiffness requirements may vary according to the particular phase.

1.4.4 SUMMARY

In a series of studies conducted within the same research groups, the influence of increasing the bending stiffness of athletic shoes on athletic performance was investigated. While improvements to vertical jump height and running economy were observed with increased bending stiffness, the mechanism responsible for these improvements in performance was not clear. It was observed that increased shoe bending stiffness resulted in a decrease in the MPJ dorsiflexion, leading to a decrease in the energy absorbed at the joint. However, a clear link between a decrease in energy lost at the MPJ and an improvement in athletic performance was not established.

The effect of increasing the bending stiffness of sprint footwear on sprinting performance has been the focus of recent research. With regards to kinematics, increasing the bending stiffness of sprint footwear has been shown to decrease the angular range of motion and the angular velocity of the MPJ. However, the effect of increasing the bending stiffness on sprinting performance remains ambiguous. However, the lack of consistent results across the research presented may be due to the inconsistencies in the testing conditions, such as inconsistent test shoe stiffness conditions and methodologies for assessing sprinting performance, rather than a lack in potential to improve sprinting performance.

However, highlighted in the previous research was that the performance response to increased bending stiffness was individual, indicating the importance of personalising the bending stiffness of sprint shoes for the individual characteristics of sprinters. In addition, tuning the bending stiffness to the particular phase of a sprint has also been emphasized. Which individual characteristics which dictate the optimum level of bending stiffness required for individuals, however, remains ambiguous and subject to speculation. A biomechanical assessment of changes to lower limb dynamics with increased bending stiffness of sprint shoes throughout a sprint while measuring changes in performance is necessary to provide some insight.

1.5 SCOPE OF CURRENT WORK

Prior to the design and construction of bespoke sprint shoes, information pertaining to the mechanical properties of commercially available sprint shoes is necessary in order to inform the subsequent design of bespoke sprint shoes. In addition, to allow for a direct comparison of the measured mechanical properties between commercially available and bespoke sprint shoes, robust, valid and repeatable mechanical testing methodologies are necessary. In particular, benchmarking the traction and bending stiffness properties of sprint shoes is of interest. In order to benchmark the traction properties, a novel mechanical test procedure is developed and evaluated, and traction properties of current commercially available sprint spikes are reported. With regards to measuring the bending stiffness of sprint shoes, a validated mechanical bend test rig was available from previous research at Loughborough University and is used to benchmark commercially available sprint shoes in both extension and flexion. Utilising the same rig and methodology previously developed by Toon (2008) allows for the direct comparison of measures of bending stiffness, permitting the investigation of any changes in trends with regards increased bending stiffness in current commercially available sprint shoes since the initial benchmarking of commercial sprint shoes carried out by Toon (2008).

In order to carry out human performance testing, there is a requirement for sprint shoes in a range of bending stiffness with adequate traction to allow for maximal effort sprinting to be performed. While manually adapting commercially available sprint shoes has been used by a number of research groups, it has been speculated that this method compromises the integrity of the test shoes by introducing unquantifiable interactions. An alternative approach to this previous method of construction of sprint shoes is undertaken using additive manufacturing technologies, namely laser sintering (LS) used to 3D print sprint shoe sole units. This methodology, first applied to the construction of sprint shoe sole units by Toon (2008), has shown favourable mechanical properties with regards to producing acceptable levels of bending stiffness at suitable levels of thickness and a sufficient level of durability in order to carry out human performance testing for research purposes. However, the sole units constructed by Toon (2008) lacked the traction features necessary to be used to conduct maximal effort sprint performances. An iterative process is undertaken to identify a novel design incorporating traction features into a LS sprint shoe sole unit. The mechanical test procedures previously established during benchmarking are applied to the mechanical testing of LS nylon sole units to ensure adequate levels of traction prior to human performance testing. Once adequate traction was achieved, sprint shoe sole units for future testing are engineered with different bending stiffness exceeding that of current commercially available sprint shoes.

An exploration of the effect of commonly used data collection and processing methodologies on the dynamics of the MPJ is undertaken due to ambiguity of the function of joint in sprinting. Previous research has categorised the MPJ as a large absorber of energy with very little to no energy generated during running, jumping and sprinting. However, the previous data collection and processing methodologies used have been questioned and suggested to lead to an underestimation of MPJ dynamics. An analysis of the effect of the definition of the MPJ, data collection rates and filtering frequencies used on MPJ dynamics in sprinting is therefore undertaken to understand the impact of each individual variable on the resulting MPJ kinematics and kinetics. Such a comparison between, the kinematics and kinetics of the MPJ, while systematically exploring assessing individual data collection and processing variables is novel and is implemented to facilitate insights into methodologies for further human performance testing in this research.

An explorative study of the influence of sprint shoe bending stiffness on sprint performance and step characteristics is undertaken. The aim of this investigation is to both evaluate the effect of increased sprint shoe bending stiffness of sprint shoes on measures of sprint time and step characteristics and to assess the reliability of the sprint parameters obtained. A novel approach for evaluating the influence of sprint shoe bending stiffness on sprint performance in both the acceleration and maximal speed phase in a maximal effort sprint is adopted, with measures of sprint time collected throughout a 50 m sprint. Step characteristics of ground contact time, step length and step rate are reported for the maximal speed phase. The reliability of the sprint parameters are evaluated using measures of effect size, standard deviation and coefficient of variation, allowing for the identification of appropriate experimental designs for future studies in this area. In addition, both the variables of sprint performances and reliability are examined both as single subject and group mean to facilitate inspection of trends perhaps masked by a group mean or to highlight trends in the group mean that are not apparent at the single subject level.

A detailed biomechanical evaluation into the influence of sprint shoe bending stiffness on both sprint performance and lower limb dynamics, evaluated simultaneously, during sprinting has not been previously explored in literature. Therefore, a detailed examination of the influence of sprint shoe bending stiffness on sprint performance and the dynamics of the lower limb during both the acceleration and maximal speed phases of a sprint is carried out. In particular, MPJ and ankle joint kinematics, moments, powers and mechanical energy contributions are compared.

2 BENCHMARKING THE MECHANICAL PROPERTIES OF SPRINT SHOES

2.0 INTRODUCTION

This chapter presents the development and evaluation of mechanical testing procedures in order to address three objectives;

- provide an objective means to characterise and compare the mechanical properties of currently available sprint shoes

- provide information on the mechanical properties of sprint shoes to inform the design and development of bespoke sprint shoes in subsequent chapters of this work

Traction and bending stiffness of sprint shoes are the two mechanical properties of interest in this work. Before these mechanical measures can be quantified, however, test methodologies must be shown to be valid, repeatable and reproducible. Although several test methods exist for the evaluation of general athletic footwear, there is a dearth of mechanical testing methodologies used to assess sprint footwear.

With regards to traction, a mechanical testing methodology to measure the traction properties of sprint shoes has never been reported in literature. Therefore, the design and development of a test fixture and methodology for the evaluation of the traction properties of sprint footwear is firstly undertaken and the assessment of the repeatability and reproducibility of the methodology is carried out.

On the other hand, the mechanical evaluation of the bending stiffness of sprint shoes has previously been carried out in literature. Section 2.2 explores the evaluation of a test rig and methodologies to mechanically quantify the longitudinal bending stiffness of sprint shoes. An established apparatus and methodology developed by Toon (2008) is used to benchmark the longitudinal bending properties of commercially available sprint shoes in order to identify any changing trends in commercially available sprint shoes and to inform the design process of subsequent bespoke sprint shoes.

2.1 BENCHMARKING TRACTION PROPERTIES OF SPRINT SHOES

Traction features are an integral component of sprint shoes in order to facilitate the generation and transmission of large forces without slippage occurring between shoe and track. There is a dearth of information, however, on the traction generating properties of sprint shoes. This chapter explores the development and evaluation of a test rig and methodology to mechanically quantify the traction generating properties of sprint shoes. Quantifying the traction generating properties of sprint shoes is important in this work for several reasons: 1) to discern the range of traction among commercially available sprint shoes, 2) to determine a minimum level of traction generated by commercially available sprint shoes to inform the design process for bespoke sprint shoes in subsequent chapters, 3) to provide an objective means for comparison between commercially available and bespoke sprint shoes.

The design and construction of bespoke sprint shoe sole units is carried out in subsequent chapters of this work for use in human performance testing, with the focus on the effect of increasing bending stiffness on lower limb dynamics in sprinting. In order to facilitate human performance testing, functional traction features will be integral to the design of the sprint shoe sole units. A mechanical evaluation of the traction properties of these sprint shoe sole units prior to human performance testing would be useful to give an indication as to whether they will provide a sufficient level of traction in order to prevent slipping for athlete safety.

It is accepted that all modern commercially available sprint shoes provide, as a minimum, sufficient traction to prevent slipping, as slipping of sprinters under normal sprinting conditions is unheard of in modern athletics. In the absence of a known specific threshold of traction needed to prevent slipping, benchmarking the minimum level of traction generated among commercially available sprint shoes would provide a minimum threshold level to which bespoke sprint shoes should be equivalent before use in human testing. This minimum level of traction to prevent slipping could be measured using human performance testing, with the measurement of the ground reaction forces and the removal of traction until slipping occurs. However, only two known published research studies exist examining the traction interaction between sprint shoes and track surfaces (Laananen and Brooks, 1978; Kilani and Adrian, 1986). No information, however, is given with regards to a minimum level of traction required to prevent slipping. Additionally, as human performance testing was utilised, no mechanical test procedure for quantifying the traction properties of sprint shoes has been established. The quantification of the magnitude and range of traction forces generated by commercially available sprint shoes will therefore be investigated.

The difficulties of mechanically representing human movement have long been recognised, such as difficulties representing forces, loading rates, and movement patterns. However, robust and repeatable mechanical tests remain an integral factor in quantifying the characteristics of footwear-surface interactions (Barry, Krummer and Milburn, 2000; Frederick, 1993; Valiant, 1989). While it is easy to develop a mechanical test that is robust and repeatable, the difficulty is achieving this while additionally trying to achieve a level of external validity, replicating as many factors as the footwear would encounter in human performance. Although there is a lack of any published data on the mechanical traction testing specifically pertaining to sprint shoes, many mechanical tests devices have been developed to measure the traction properties of sports shoes that achieve traction through penetration of cleats or studs into the playing surface (Barry *et al.*, 2000; Clarke *et al.*, 2008; McNitt *et al.*, 1997). The common approach in literature for laboratory based mechanical testing of the traction properties of athletic footwear is to construct an apparatus that is able to apply both vertical and horizontal forces typically encountered in the specific sporting activity whilst simulating the general movement of the sports shoe over the specific sporting surface. A device for measuring both linear and translational traction for athletic footwear of various sports, including athletics, is outlined in the ASTM test standard F2333-04: Standard Test Method for Traction Characteristics of the Athletic Shoe-Sports Surface Interface. The application of this test method specifically to the sprint shoe-track surface interaction, however, has never been published and will be investigated in the present chapter.

The following section outlines the design and development of a test fixture and the evaluation of a methodology, with the aspiration for a level of external validity, for the evaluation of the traction properties of sprint footwear. The methodology was principally designed to provide a means to establish the minimum level of traction generated by a sprint shoe, characterised through the traction generating properties between the sprint shoe-track interaction, allowing an objective means for comparison between commercially available and bespoke sprint shoes. The evaluation of commercially available sprint footwear is also carried out, not only to benchmark and discuss the traction generating properties among commercially available sprint shoes, but to also inform the development of future, bespoke sprint shoe sole unit designs. The mechanical performance of a selection of currently available sprint spikes is evaluated and reported and the repeatability, reproducibility, and validity of this methodology is evaluated and discussed.

2.1.1 METHODOLOGY

DESIGN OF TEST FIXTURE

The design of the test fixture and methodology was based on ASTM F 2333-04: Standard Test Method for Traction Characteristics of the Athletic Shoe-Sports Surface Interface. The ASTM F 2333-04 test methodology outlines the specifications for the performance of sports shoe-surface traction measuring devices but does not require a specific device to be used. The test method outlined in the test standard encompasses the measurement of traction characteristics achieved through penetration of cleats or studs into the playing surface. Although the test method identifies methodologies for both linear and rotational traction, this work will focus on linear traction as the motion of the foot in the 100m sprint is primarily linear, there are no directional changes during the sprint and medio-lateral forces are minimal. A schematic diagram of a generic device for measuring linear traction outlined in the test standard is detailed in Figure 2.1. All individual components were designed using SolidWorks 2007, a three-dimensional computer aided design software package, and manufactured in the Loughborough University Sports Technology Institute workshop. The test fixture was designed with the intention of being able to apply a range of vertical and horizontal forces typical of those encountered throughout the acceleration and maximal speed phases in sprinting.

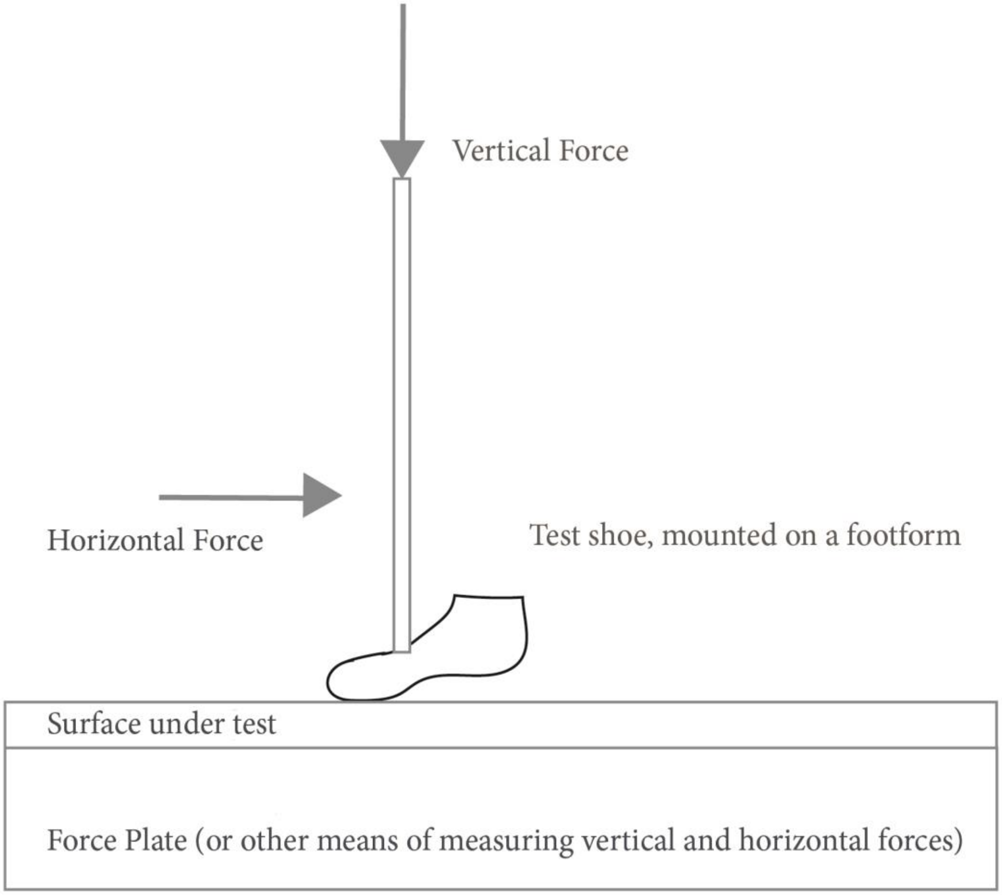


FIGURE 2.1: DIAGRAM OF A DEVICE FOR MEASURING LINEAR TRACTION OUTLINED IN ASTM F233-04

The test fixture, as shown in Figure 2.3, was designed for use on a materials testing machine (Instron 3365 Dual Column Testing machine, 5kN load capacity, 1000 mm/min maximum vertical speed). Horizontal, rectilinear motion between the test shoe and the track surface was produced by pulling the track surface below the test shoe while the test shoe was held stationary, mounted on a rigid last. The horizontal motion of the track surface was produced coupling a low friction sled and Instron testing machine, with the Instron material testing machine moving in a vertical plane. A horizontal force was applied to the track surface, mounted in a specially constructed sled, through a pulley system with a cable linking the front of the sled and Instron machine.

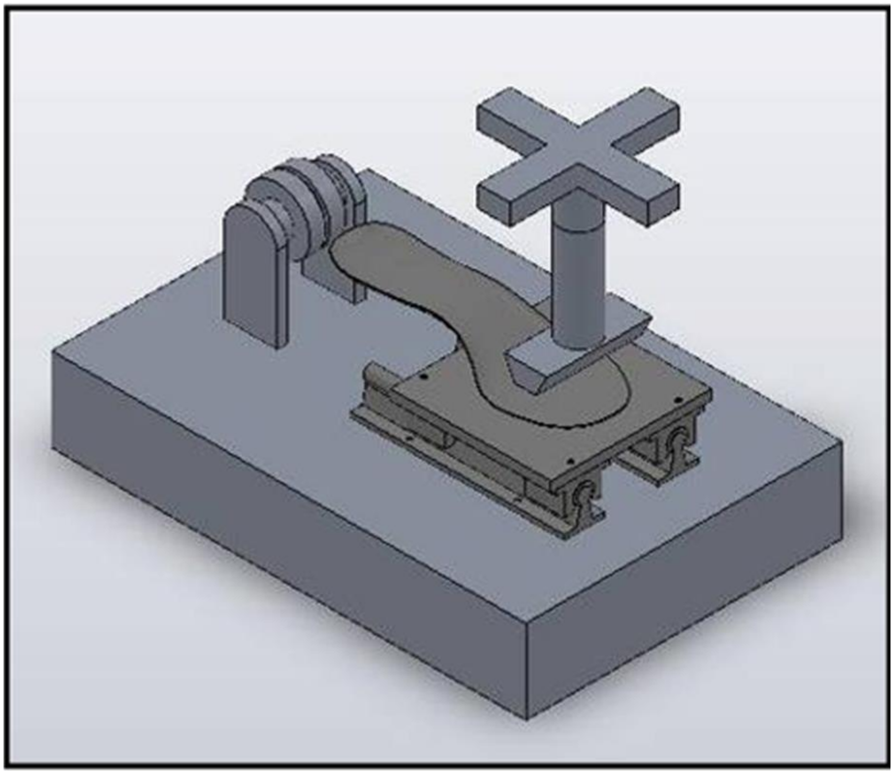


FIGURE 2.2: TEST FIXTURE SCHEMATIC DESIGN

The specially constructed sled (250 x 150 x 15 mm) to contain a sample of a track surface was mounted on a low friction linear guide rail and carriage system. The carriage system consisted of a double rail (DryLin® Double Rail WS-16-60-300, L300 mm) and carriage (DryLin® Carriage W16-60-20, L200mm x W104mm, static load capacity Coy, Coz of 8400 N). The guide rails and carriage were mounted on an aluminium base plate (Grade 6082). The guide rails were coated with liquid polytetrafluoroethylene (PTFE) in order to reduce the amount of friction in the system. The track surface was fastened in the sled using double sided carpet tape.

In order to hold the test shoe stationary, a rigid last was secured to the apparatus, on which the shoes were placed for testing. A specified vertical force was applied to the shoe/track system using a screw thread clamp, compressing the forefoot of the last/test shoe onto the track. The vertical force was measured using an in-shoe pressure measurement system (Tekscan® F-Scan Mobile system), located on the bottom of the last, inside the test shoe.

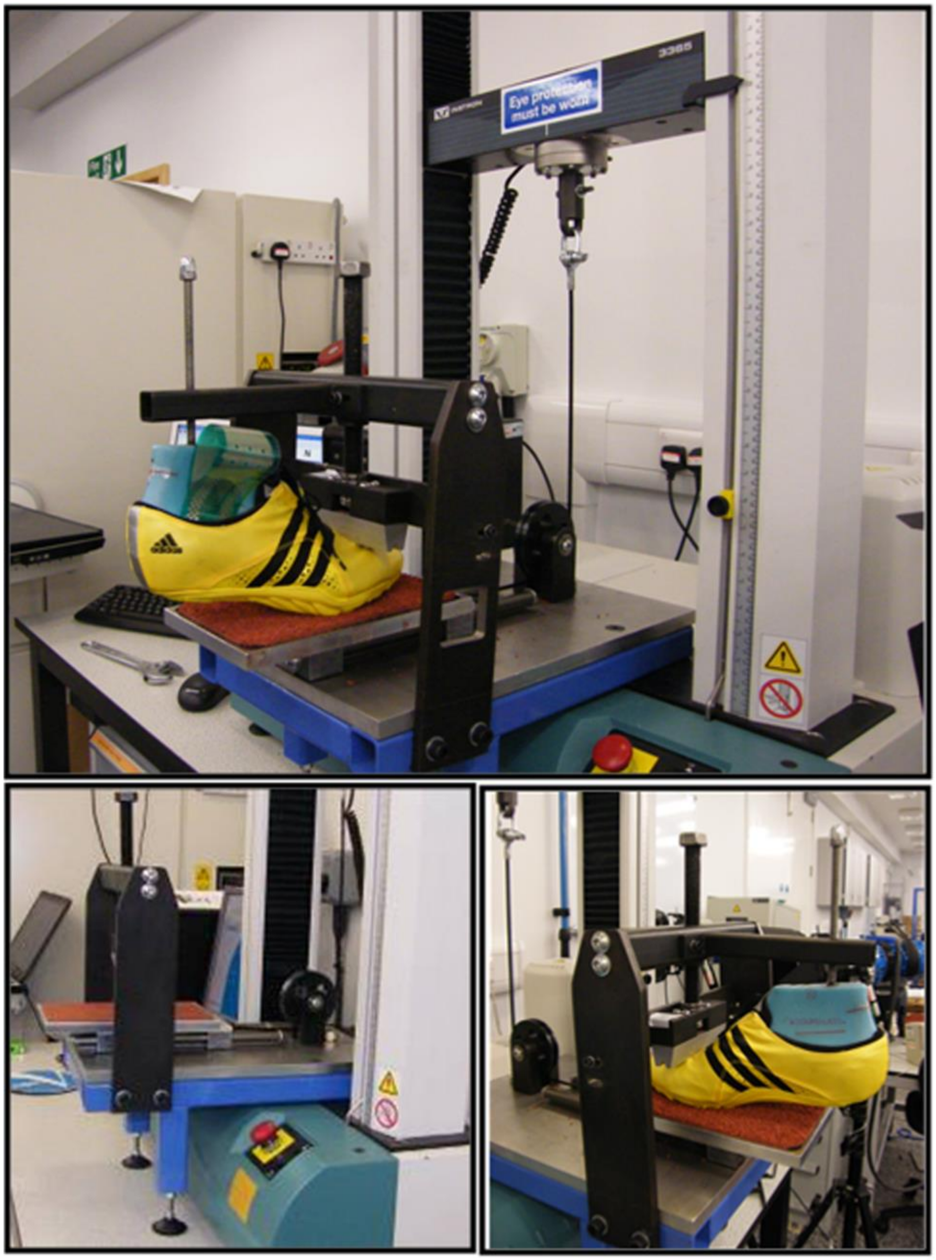


FIGURE 2.3: EXPERIMENTAL SET UP OF THE TRACTION TESTING FIXTURE

MECHANICAL TESTING

Shoe Selection

The shoes used for benchmarking were selected to represent a cross-section of currently available sprint shoes across the leading sports brands marketed towards 100 m sprinters based on literature supplied with the shoe. The sprint shoes tested are detailed in Table 2.1. All of the test shoes had removable spikes, with the number of varying from 6 to 8. For the benchmarking procedure it was desirable to have a consistent shoe size, although restrictions in commercial availability meant there was a degree of variation (Range 27.5 – 28.0 cm).

TABLE 2.1: SPRINT SHOES TESTED

SHOE	**BRAND**	**MODEL**	**UK SIZE (cm)**	**NUMBER OF SPIKES**
A	adidas	Meteor	9 (27.5)	6
B	adidas	Demolisher	9 (27.5)	8
C	Reebok	Anthem Sprint II	9 (28.0)	8
D	Mizuno	Tokyo Sprint	9 (28.0)	6
E	Nike	Zoom Superfly R2	9 (28.0)	8
F	Asics	Hyper Sprint	8.5 (27.5)	7

Test Methodology

Prior to testing, the base plate of the test fixture was secured to the base of the materials testing machine, using a nut and bolt, to prevent any unwanted movement of the apparatus throughout testing. The test shoe was then mounted on the last, with the in-shoe pressure measurement insole (Tekscan® F-Scan Mobile system) located inside the test shoe. The clamp was then brought down onto the forefoot of the last, pressing the forefoot onto the track surface, until the desired vertical load was achieved. All trials were completed with the clamp applying force at approximately ¾ of the shoe length from the heel counter, allowing for the vertical load to be distributed beneath the forefoot of the test shoe.

Testing was conducted at vertical loads of 500, 1000 and 2000 N, respectively, applied to the forefoot. The test shoes were subjected to these loading conditions in order to try to replicate the vertical loading conditions experienced in both the acceleration and maximal speed phases of sprinting, as the values and timing of peak horizontal and vertical forces differ notably between each phase (Bezodis *et al.*, 2008; Mero, 1988). The Tekscan® pressure insoles were initially calibrated using an air bladder before each of the shoes were tested and the forces measured by the Tekscan® pressure insoles were verified after every second trial conducted, applying the designated vertical load to the forefoot region of the insole using a materials testing machine (Instron 5569 Dual Column Testing machine, 50 kN load capacity, 1000 mm/min maximum vertical speed). During the verification, the force measured by Tekscan® had to be within a tolerance of ±50 N of the desired load or the Tekscan® pressure insoles were re-calibrated using the air bladder.

Once the test shoe was in the correct starting position, with the desired vertical load applied, the sled containing the track surface was pulled by the materials testing machine. In order to ensure the cable in the pulley system was taut, the test shoe/track system was pre-loaded horizontally with 50 N and held for 5 s. The track surface was then pulled a distance of 100 mm at a rate of 1000 mm/min, which was the maximum speed of the materials testing machine. In order to establish the minimum level of traction generated by a sprint shoe, the peak static traction force generated by the sprint shoes was assessed since the point at which a sprint shoe slips relative to the track surface is the point at which the traction features have been deemed to have failed in sprinting. The peak static traction force is defined as the horizontal force produced between the sprint shoe and the track surface at the point just prior to slipping of the sprint shoe relative to the track surface. The ASTM F2333-04 standard specifies that the distance of the sliding motion between the shoe and the surface shall be a minimum of 200 mm. However, since the variable of interest in this test was the peak static traction rather than the dynamic traction, the track surface was pulled a distance of only 100 mm, which was thought to be a sufficient distance to reach the point of peak static traction. Horizontal forces were recorded at 100 Hz, the maximum capacity of the materials testing machine.

Four trials at each of the three vertical loading conditions were performed for each of the test shoes. Although ASTM F2333-04 indicates that five trials at each level of vertical loading condition should be conducted, four trials was chosen in order to ensure there were a sufficient number of track surface samples for testing as there was a limited supply of samples of the track surface. The track surface used in this testing was a poured, polyurethane track surface (Polytan PUR poured surface, Polytan Sports Surfaces Ltd, Loughborough, UK), and was replaced when visible wear was apparent. This typically occurred after 3-4 trials at low vertical loads and 2-3 trials at higher vertical loads.

The peak values of static traction force generated are reported. Repeatability of the testing methodology was assessed using a coefficient of variance (CV) [$CV=\sigma/\mu$ where σ=standard deviation and μ=mean]. The reproducibility was assessed by comparing the results of re-testing one of the shoe conditions on a separate day using a CV. The relationship between the peak static traction force generated and the number of pins on the sprint shoe was investigated using Pearson's correlation.

2.1.2 RESULTS

THE RESULTS FOR THE BENCHMARKING OF COMMERCIALLY AVAILABLE SPRINT SHOES PRESENTED AS A MEAN OF THE FOUR TRIALS. THE GRAPHICAL DATA IN FIGURE 2.4,

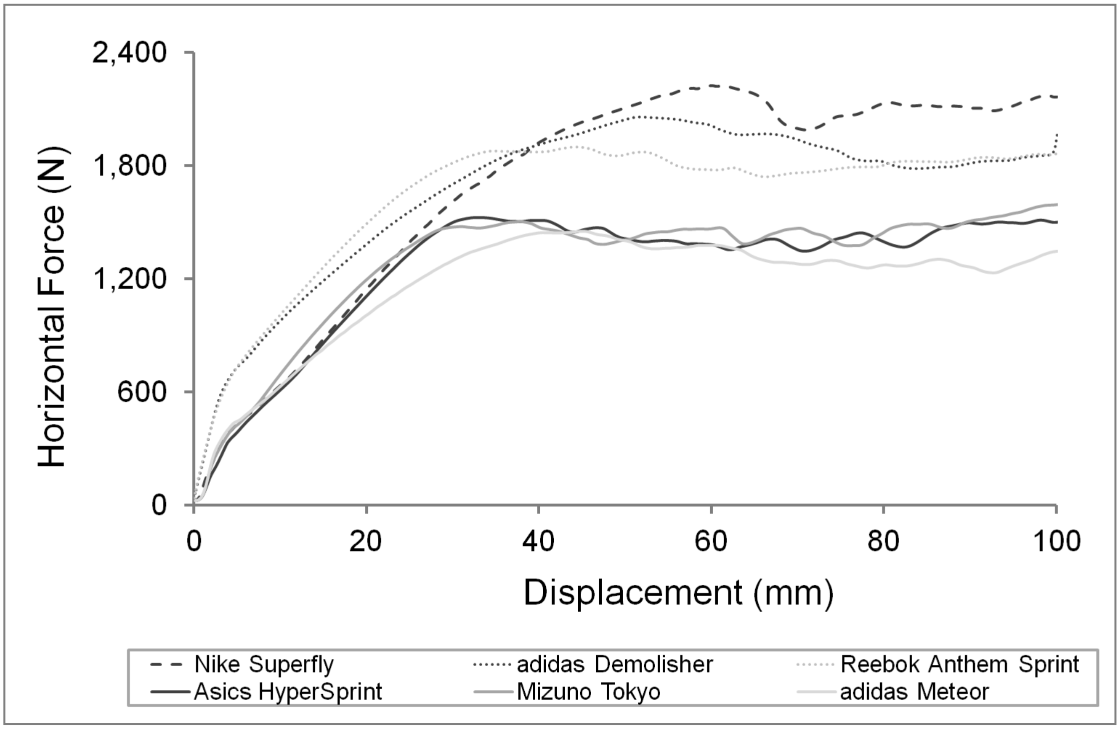


Figure 2.5 and Figure 2.6 show the horizontal traction force generated through the displacement of the 100 mm of track surface beneath the stationary sprint shoe at the prescribed levels of vertical loading. The initial slope in the graphs shows an increasing force with initial horizontal extension until the peak static force is reached. Following this point, the dynamic traction forces were recorded throughout the remainder of the 100 mm displacement.

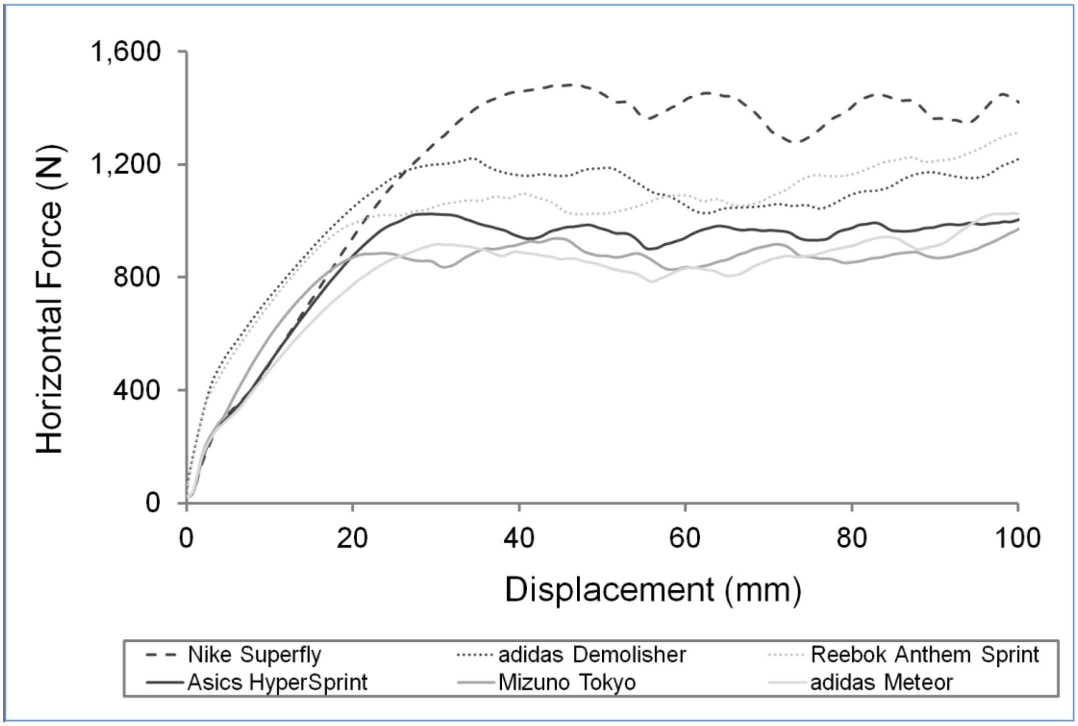


FIGURE 2.4: MEAN HORIZONTAL FORCE VERSUS EXTENSION AT A VERTICAL LOAD OF 500 N.

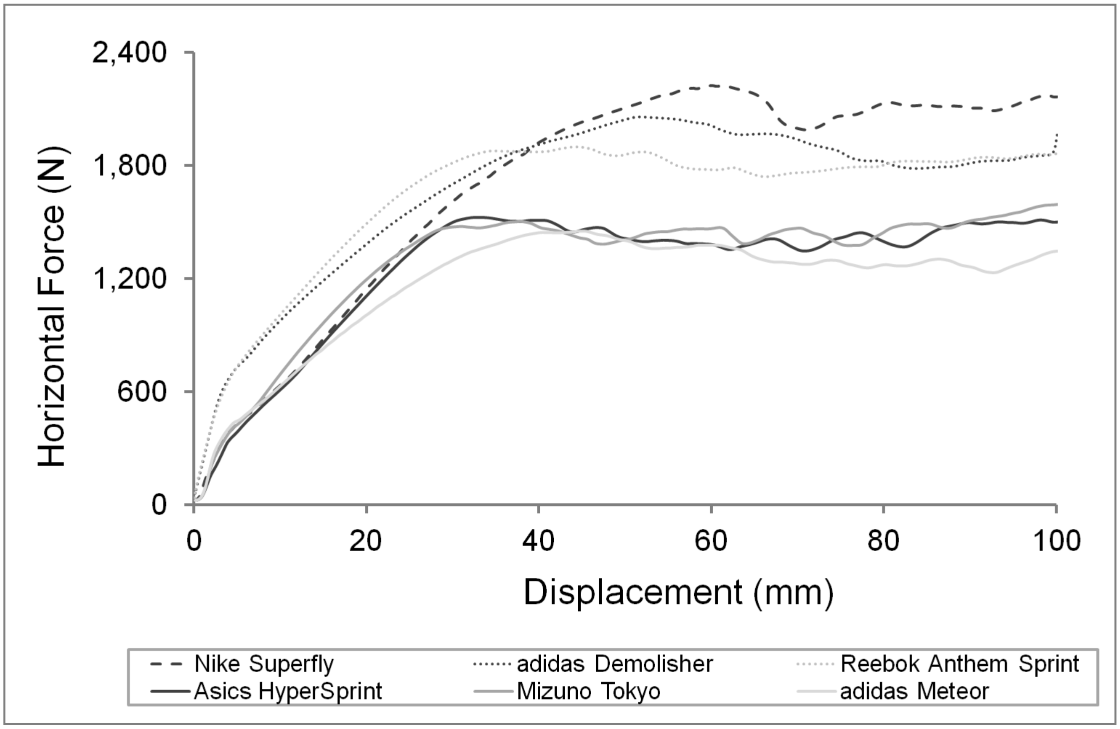


FIGURE 2.5: MEAN HORIZONTAL FORCE VERSUS EXTENSION AT A VERTICAL LOAD OF 1000 N.

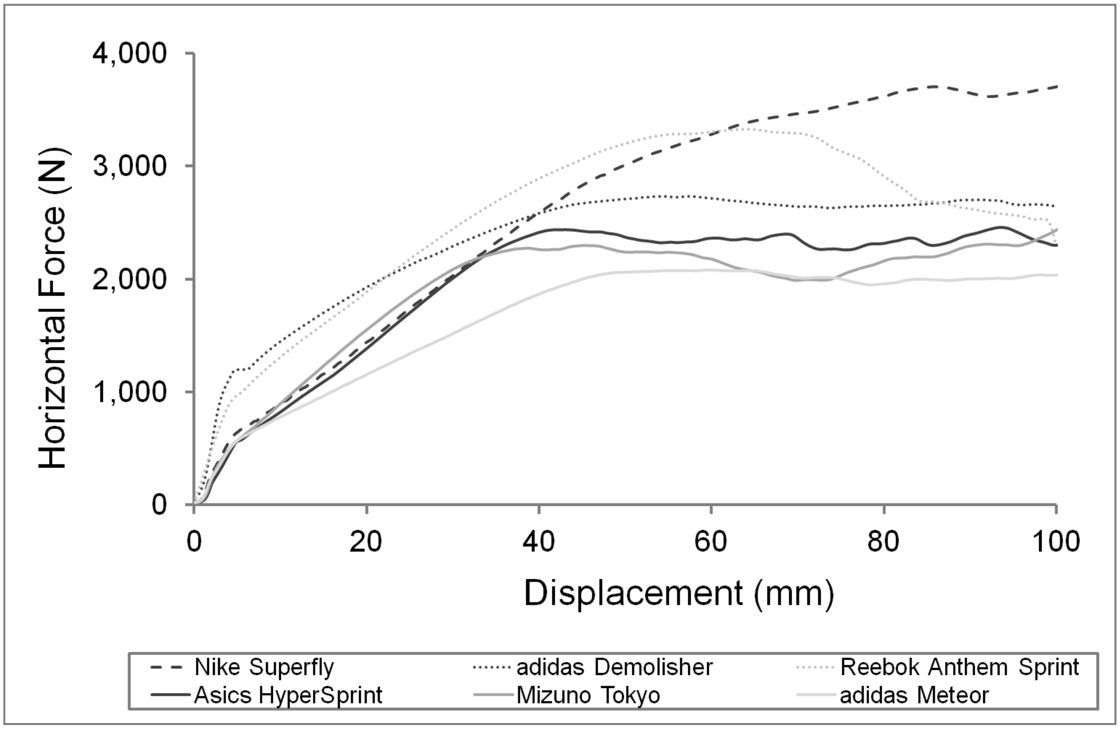


FIGURE 2.6: MEAN HORIZONTAL FORCE VERSUS EXTENSION AT A VERTICAL LOAD OF 2000 N.

The mean peak static traction force generated, the standard deviation and intra-trial CV for each test shoes across all vertical loads are presented in Table 2.2. The Nike Zoom Superfly generated the highest mean peak static traction forces across all levels of normal loads, measuring 1444 ± 57 N, 2223 ± 73 N and 3689 ± 231 N at vertical loads of 500 N, 1000 N and 2000 N, respectively. The Mizuno Tokyo generated the lowest mean peak static traction force at a normal load of 500 N, measuring 906 ± 63 N while the adidas Meteor generated the lowest mean peak static traction forces at normal loads of both 1000 N and 2000 N, measuring 1472 ± 74 N and 2115 ± 150 N, respectively. The range of mean peak static traction force generated between all the shoes tested, across the various levels of vertical loading were 537 N, 752 N and 1574 N at vertical loads of 500 N, 1000 N and 2000 N, respectively, indicating a considerable difference in the traction generating properties of the sprint shoes tested.

Pearson’s r-test provided evidence that a significant relationship existed between the peak static traction force generated and the number of pins on the sprint shoe. A significant relationship was shown to exist for all three levels of vertical loading (500 N: $r = 0.817$, $P<0.05$; 1000 N: $r = 0.909$, $P<0.05$; 2000 N: $r = 0.849$, $P<0.05$).

TABLE 2.2: MEAN OF PEAK TRACTION, STANDARD DEVIATION AND COEFFICIENT OF VARIANCE FOR THE TEST SHOES AT VERTICAL LOADS OF 500 N, 1000 N, AND 2000 N

		Mean of Peak Static Force Generated	Standard Deviation	Coefficient of Variation
500 N		(N)	(N)	(%)
Nike	Zoom Superfly	1444	57	4.0
adidas	Demolisher	1206	96	7.9
Reebok	Anthem Sprint	1090	61	5.6
Asics	HyperSprint	1031	88	8.6
adidas	Meteor	924	88	9.5
Mizuno	Tokyo	906	63	7.0
	Mean	1100		7.1
1000 N				
Nike	Zoom Superfly	2223	73	3.3
adidas	Demolisher	2067	191	9.2
Reebok	Anthem Sprint	1901	173	9.1
Asics	HyperSprint	1546	57	3.7
Mizuno	Tokyo	1478	60	4.1
adidas	Meteor	1472	74	5.0
	Mean	1781		5.7
2000 N				
Nike	Zoom Superfly	3689	231	6.3
Reebok	Anthem Sprint	3309	106	3.2
adidas	Demolisher	2727	67	2.4
Asics	HyperSprint	2569	254	9.9
Mizuno	Tokyo	2304	119	5.1
adidas	Meteor	2115	150	7.1
	Mean	2786		5.7

The mean CV for the peak static traction force generated between the trials across all the test shoes for all the normal load conditions was 6.2%, with none of the shoe conditions having a CV between trials greater than 10% (Table 2.2).

The mean CV of the peak static traction generated for one shoe condition tested on two separate occasions is presented in Table 2.3. The results are calculated from a total of 8 trials, with 4 trials conducted on each day. Across all three levels of vertical loading, the mean CV for the peak static traction force generated is 7.1%, with none of the conditions having a CV among the trials greater than 10%.

TABLE 2.3: MEAN OF PEAK TRACTION, STANDARD DEVIATION AND COEFFICIENT OF VARIANCE FOR ONE TEST SHOE TESTED ON TWO SEPARATE OCCASIONS AT VERTICAL LOADS OF 500 N, 1000 N, AND 2000 N

	Mean of Peak Static Force Generated	Standard Deviation	Coefficient of Variation
Between Days	(N)	(N)	(%)
500 N	889	76	8.5
1000 N	1439	81	5.6
2000 N	2163	154	7.1
		Mean	7.1

2.1.3 DISCUSSION

The previous section outlined the design and development of a test fixture and the evaluation of a test methodology, with aspirations of external validity, principally designed to provide a means to characterise the traction force generating properties between the shoe-track interactions. This investigation benchmarked the traction force generating properties of currently available sprint shoes marketed towards 100 m sprinters across a range of leading manufactures in order to both discuss the range of traction across the sprint shoes and establish the minimum level of traction force generated by a sprint shoe, which is assumed to provide, at a minimum, sufficient traction. This information was obtained in order to inform the design process of subsequent design and mechanical testing of bespoke sprint shoes to be constructed as part of this work.

The benchmarking of the traction properties of current commercially available sprint shoes identified a considerable difference between the mean peak static forces generated among the six sprint shoes evaluated. At a vertical load of 500 N, the highest traction force generated was 60 % larger than that of the lowest traction force generated. In addition, a significant relationship between the number of pins on the sprint shoe and the level of peak static traction force generated was shown, with increased traction force generated with increasing number of pins on the sprint shoe. While the ability of commercially available sprint shoes to create sufficient traction to prevent slipping between the sprint shoe and track surface is not of concern, given this wide range of traction observed, the notion of excess or redundant traction is introduced.

The implications of increased traction on lower limb dynamics and sprinting performance are unknown. Stucke *et al.* (1984) highlights that while higher traction may lead to higher absolute peaks in force development, it might not necessarily constitute a larger impulse or shorter stance time, indicative of changes in performance. Therefore, the increased traction of the shoe-surface interface may not lead to improvements in sprint performance.

The literature shows conflicting views with regards to increased traction and performance. With regards to sports shoes, a large increase in traction properties of running shoes has been shown to result in an increase in ankle and knee moments in a cutting movement while there was no difference in cutting performance observed by the authors in the different footwear conditions (Wannop *et al*., 2010). Showing conflicting results, increasing the available traction on running shoes has shown an improvement in running speed (Worobets *et al*., 2011), indicating that traction is not merely to prevent slipping but can also help maximise performance. The application of the results obtained from running to sprinting, however, are limited, with the effects of increased traction in sprint footwear on lower limb dynamics and performance remaining unknown and are an interesting area for further study as the effects of excessive or redundant traction are unknown in sprinting. Human performance testing is recommended for further insight into the traction generating properties of commercially available sprint shoes in order to understand the effect of traction on sprinting performance and infer conclusions on the actual performance of sprint shoes in sprinting.

In the absence of a known specific threshold of traction needed to prevent slipping, benchmarking the minimum level of traction generated among commercially available sprint shoes has provided a minimum threshold to which bespoke sprint shoes should be equivalent before use in human performance testing. However, although the results obtained in this work will help inform future bespoke sprint shoe construction, the quantification of the actual minimum level of traction necessary to prevent slipping remains unknown. As previously mentioned, slipping between the shoe and track in a commercially available sprint shoe is unheard of in modern athletics under dry weather conditions, indicating there might be a large disparity between the minimum level of traction generated among commercially available sprint shoes and the minimum level of traction necessary to prevent slipping. Quantifying the minimum level of traction necessary to prevent slipping is suggested for further work.

With regards to repeatability and reproducibility of this testing methodology, ASTM F2333-04 state that, based on published data and a preliminary inter-laboratory study, the 95 % repeatability and reproducibility for measurements of linear traction are estimated to be ±0.05 and ±0.10, respectively, with greater variability expected for test of friable surfaces (for example, cleated outsoles on natural turf). As these guidelines are merely estimates, with a mean CV between repeated trials across the test shoes and loading conditions of 6.2 %, and no one shoe condition exceeding 10 %, and a mean CV for the reproducibility of 7.1 % across the three prescribed levels of vertical loading, the current test methodology has demonstrated to be both acceptably repeatable and reproducible and therefore appropriate for further use in subsequent work.

While this testing methodology has provided some initial insight into the traction properties of current commercially available sprint shoes, several limitations exist. Although achieving external validity was only an aspiration of this work, several potential limitations to the external validity of the testing methodology are of concern and are subsequently listed. The first is the unrealistic loading of the shoe-track interface, including the low strain rate on the test shoes and the stationary position of the shoe, which is not representative of a sprinting foot strike. During sprinting, the foot is moving at a much higher rate upon initial touchdown on the track surface than the loading rate utilised in this methodology and the position of the foot is constantly changing, while not all of the pins are in contact with the track surface throughout stance. Additionally, compliance of the test shoe on the last, excessive compliance in the track surface and the small sample size of the track surface, leading to edge effects (ie the track surface moving/stretching more than it would should there be an entire surface) were of concern. The large displacement of the track surface recorded prior to reaching the peak static traction force is thought to be due to movement of both the test shoe and the track surface. As the track surface was pulled beneath the test shoe, stretching of the upper of the test shoe and stretching of the track surface were both observed prior to relative movement between the test shoe and track surface. Although these aspects were not quantified, the intention to benchmark and compare the traction generating properties between commercially available and bespoke sprint shoes is still be achievable as testing conditions have been shown to be sufficient repeatability and reproducibility across all the test shoes. External validity, however, was an aspiration and not a necessity, as the mechanical testing is mainly to be used to make comparisons between sprint shoes and not to infer conclusions on the actual performance of sprint shoes in sprinting. However, although mechanical testing has its advantages, human performance testing is suggested for further work in order to validate the mechanical testing.

2.1.4 CONCLUSION

The design and development of a test fixture and a methodology for the evaluation of the traction properties of sprint footwear has been carried out. Although limitations in the mechanical testing may undermine the external validity of the results obtained, the test rig and methodology were shown to be sufficiently repeatable and reproducible to be used in this and future work, providing an objective means for comparison between commercially available and bespoke sprint shoes. Further human performance testing is suggested for further validation of the mechanical testing.

The benchmarking of commercially available sprint shoes has provided both insight regarding the performance of current commercially available sprint shoes and informed the development of future bespoke sprint shoes. Although not all of the current commercially available sprint shoes marketed towards 100 m sprinters were benchmarked, it is thought that this sampling provides enough variation to give a diverse representation. With regards to current commercially available sprint shoes, a large disparity between the traction generating properties was observed, with a significant relationship between increased traction generated and increased number of pins on the sole unit. As even the lowest traction generating sprint shoes generate sufficient traction to prevent slipping in an actual sprint, the advantage of increased traction is questioned and notion of redundant traction is introduced. Human performance testing is recommended for further insights into the effects of increased traction generation on sprinting performance.

With regards to informing future bespoke sprint shoe designs, a minimum level of traction generated by commercially available sprint shoes was identified in order to provide a minimum level of traction to which bespoke sprint shoes should provide prior to be utilised in future human performance testing. However, as even the lowest performing sprint shoe provides sufficient traction to prevent slipping, quantifying the actual minimum level of traction necessary to prevent slipping is suggested for further work.

2.2 BENCHMARKING LONGITUDINAL BENDING STIFFNESS OF SPRINT SHOES

2.2.1 INTRODUCTION

The potential to improve sprinting performance through modifications to the longitudinal bending stiffness of sprint shoes has been highlighted in recent literature (Stefanyshyn and Nigg, 2000; Stefanyshyn and Fucso, 2004; Toon, 2010). Methodologies quantifying the longitudinal bending stiffness, however, have varied between studies and research groups, making direct comparisons to the functionality of sprint shoes throughout literature difficult. Previous methodologies utilised to quantify the bending stiffness of running shoes typically involved a modified three point bend test on the forefoot of the shoe (Kleindienst *et al*., 2003; Roy and Stefanyshyn, 2006; Stefanyshyn and Fusco, 2004). However, while a three point bend test may be a reliable and repeatable methodology for assessment, it is felt that the three point bend test does not best represent the motion and loading of sprint shoes during sprinting. In order to evaluate the relationship between the mechanical properties of sprint shoes and the dynamics in sprinting, it is important to firstly employ a methodology that accurately and repeatedly measures the appropriate structural parameter of the sprint shoe in a manner that aims to replicate the loading conditions encountered in sprinting.

Another methodology employed to quantify bending stiffness of running and sprint shoes in previous literature is a two point bend test (Oleson et al., 2005; Smith et al., 2010; Toon, 2008). This methodology offers an improved representation of the loading during the ground contact phase of sprinting, with the forefoot remaining in a relatively fixed position on the ground and the rearfoot rotating about the MPJ until the final stages of push-off. An apparatus and methodology specifically to measure the longitudinal bending stiffness of sprint shoes was developed by Toon (2008), based on ASTM F911 ‘Standard Test Method for the Flexibility of Running Shoes’. This test methodology allows the testing of longitudinal bending stiffness of sprint shoes in both flexion and extension, about either the approximated MPJ transverse or oblique axes of flex.

Another significant advantage to using this apparatus and methodology is the ability to make direct comparisons between the measured levels of bending stiffness of sprint shoes arising from this work and results previously obtained by Toon (2008). This is useful both for benchmarking the longitudinal bending stiffness of current commercially available sprint shoes, investigating any changes in trends among commercially available sprint shoes since Toon (2008), and for subsequent use in quantifying the bending stiffness of sprint shoes constructed as part of this research, allowing for direct comparisons of the longitudinal bending stiffness of bespoke sprint shoes. The apparatus used by Toon (2008) was developed for use at Loughborough University and was available for use. The apparatus and methodology will be investigated in the section 2.2.3 to benchmark the longitudinal bending stiffness of current commercially available sprint shoes.

2.2.2 APPARATUS

The apparatus described below, developed by Toon (2008), will be used to measure the longitudinal bending stiffness of sprint shoes throughout the entire thesis, both to benchmark commercially available sprint shoes and measure bespoke sole units and assembled sprint shoes sprint shoes constructed as part of the work in subsequent chapters.

The apparatus was designed based on the ASTM standard test method for flexibility of running shoes (F911-85). The flex fulcrum of the shoe is designated at a location 70% of the shoe length from the rearmost part of the heel counter, while the loading probe contacts the rearfoot of the shoe at a distance of 45% of the shoe length rearward of the flex fulcrum, as outlined in Figure 2.7. The flex fulcrum and point of load application were taken from ASTM F911-85. The apparatus allows for the testing of sprint shoes to be carried out along an axis at either 90° or 70° from the length line of the shoe, approximating the transverse or oblique axes of the MPJ, respectively.

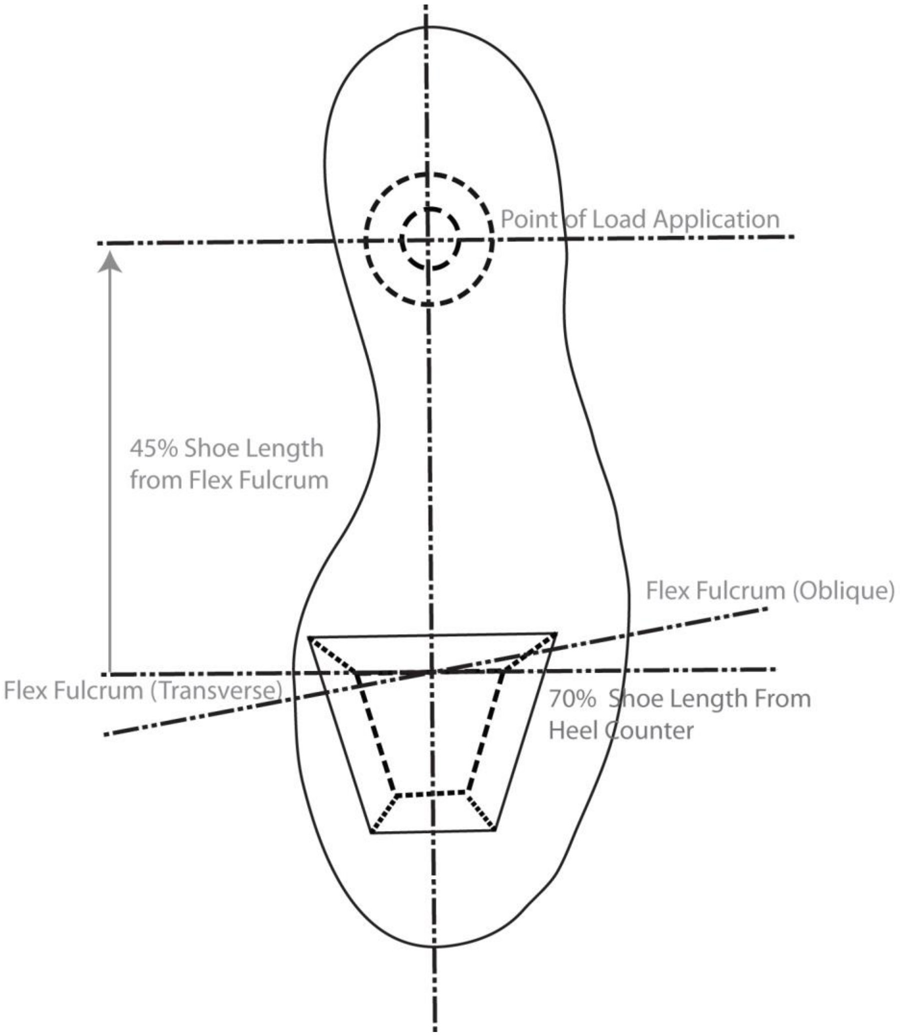


FIGURE 2.7: SCHEMATIC DIAGRAM OF ASTM F 911-85 TEST METHOD FOR FLEXIBILITY OF RUNNING SHOES (ADAPTED FROM TOON (2008))

A forefoot hold-down clamp, shown in Figure 2.8, was designed with dimensions according to the ASTM standard. The clamp is split in order to accommodate the testing of both a sole unit and a fully constructed sprint shoe with an upper. The long edge of the hold-down clamp is designed to line up with the axis of the flex fulcrum.

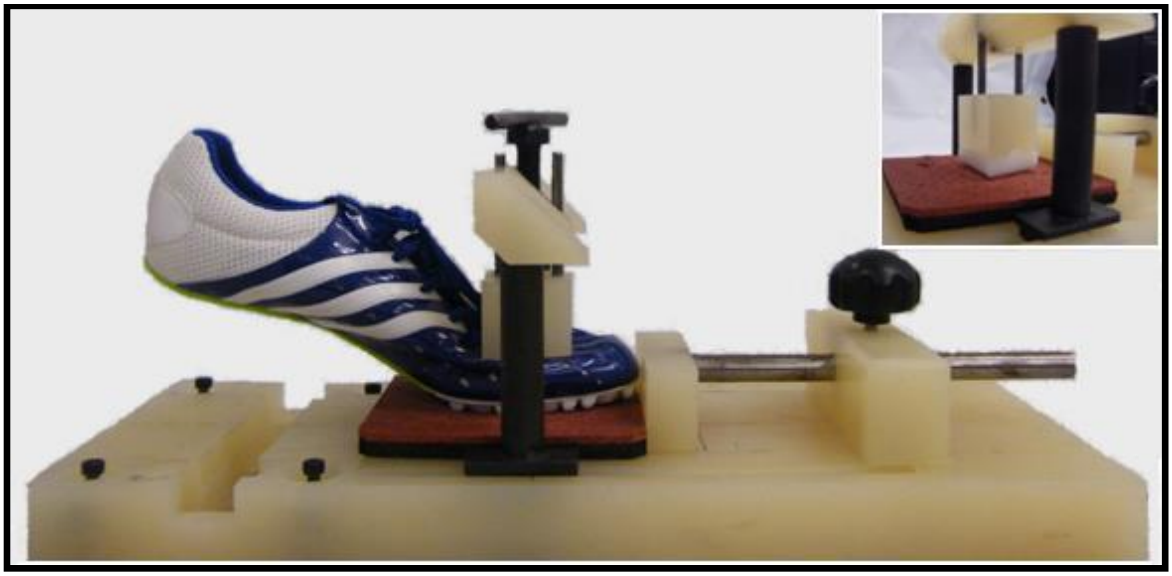
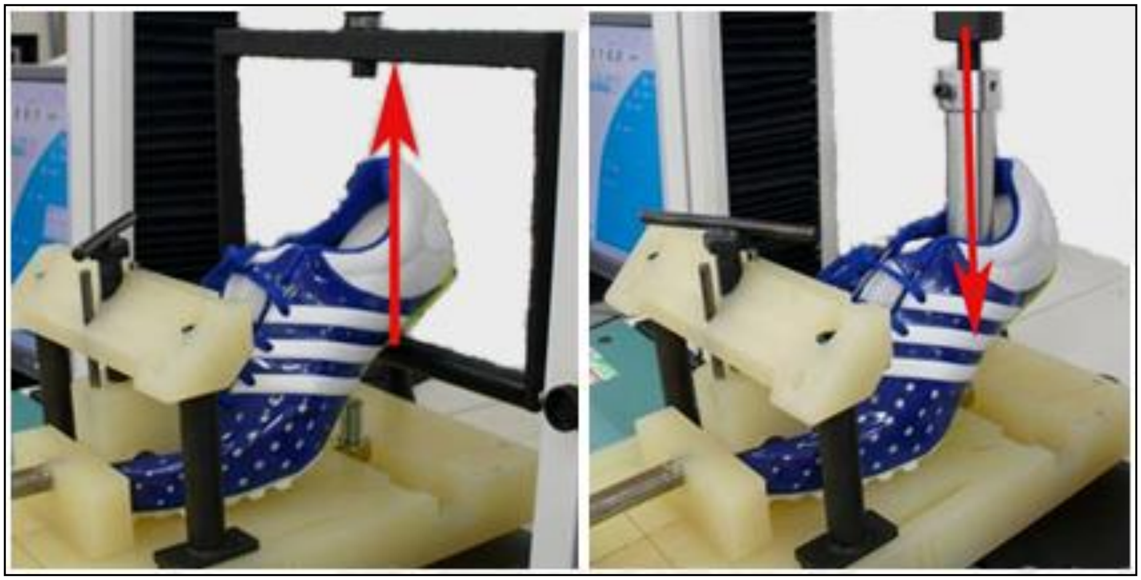


FIGURE 2.8: TEST SPRINT SHOE SECURED IN THE TEST FIXTURE, AND CLOSE UP OF THE SPLIT CLAMP

ASPECTS OF THE ASTM STANDARD WERE MODIFIED TO ACCOUNT FOR THE TESTING OF SPIKES, RATHER THAN STANDARD ATHLETIC RUNNING SHOES. THE MAIN DIFFERENCE REQUIREMENT TO MEASURE FORCE THROUGHOUT A PERIOD OF FLEXION (VERTICALLY AS WELL AS THE STANDARD EXTENSION (VERTICALLY DOWNWARDS). IN ORDER TO TWO END EFFECTORS WERE DESIGNED BY TOON (2008) TO ACCOUNT FOR THE TWO TYPES, AS SHOWN IN

Figure 2.9.



(A) (B)

FIGURE 2.9: SPRINT SHOE BENDING STIFFNESS EXPERIMENTAL SET UP FOR (A) FLEXION AND (B) EXTENSION

2.2.3 METHODOLOGY

The longitudinal bending stiffness of a range of currently available sprint shoes marketed towards 100 m sprinters was measured and benchmarked. The methodology is based on that outlined by Toon (2008). Testing was carried out with the test fixture mounted on an Instron 3365 materials testing machine (Instron 3365 Dual Column Testing machine, SN 3365 J5402). Measurements were taken in both flexion and extension of the shoes. Although the test fixture was designed to measure the bending stiffness at both the transverse and oblique axes, at 90° and 70° to the longitudinal axis of the shoe respectively, as Toon (2008) found no significant differences between measured longitudinal bending stiffness of the two axes, only the transverse axis was used to quantify longitudinal bending stiffness in this research.

The shoe was secured on the test fixture, aligned so that the forefoot hold-down clamp used to secure the position of the shoe created a flex fulcrum at 70% of the shoe length from the rearmost part of the heel counter, as outlined in Figure 2.7. The shoe was also aligned such that the loading probe contacted the rearfoot of the shoe at a distance 45% of the shoe length rearwards of the flex fulcrum. Once the shoe was in position, a compressive load was applied to the forefoot hold-down clamp in order to hold the shoe in place throughout testing. The base plate of the apparatus was securely fastened to the Instron 3365 materials testing machine and the appropriate loading probe was positioned at the start point, just touching the surface of the shoe while the shoe was in its natural resting place. The force and extension on the materials testing machine were then zeroed.

For extension testing, a loading probe applied a downward vertical force to the internal surface of the rearfoot of the sprint shoes, as shown in

Figure 2.9 b. Once the shoe was securely fastened in the test fixture, the shoe was extended from the point of zero displacement (natural position of the rearfoot of the sprint spike when fixed in the apparatus) to a maximum vertical distance of 45 mm at a loading rate of 1000 mm•min^{-1} and vertical force was recorded throughout the entire period of flexion at 100 Hz. A rest period between cycles of approximately 30 s was used and the test was repeated five times. The reported data was a mean of the last three cycles.

For flexion testing, the stirrup loading cradle applied an upward, vertical force to the underside of the sprint shoes, as shown in

Figure 2.9 a. From the point of zero flexion (natural position of the rearfoot of the sprint shoe when fixed in the test fixture), the shoe was flexed to a maximum vertical distance of 60mm at a loading rate of 1000 mm•min^{-1} and the vertical force was recorded throughout the entire period of flexion at 100 Hz. A rest period between cycles of approximately 30 s was used and the test was repeated five times. The reported data was a mean of the last three cycles.

2.2.4 RESULTS

The results of the extension bending test data are listed in Table 2.4. The mean maximum and mean force recorded over 45 mm of vertical displacement are reported. The adidas Demolisher showed the highest bending forces in extension averaged between trials with a maximum force of 106.4 ± 0.8 N and a mean force of 46.8 ± 0.3 N. The mean of the maximum and mean flexion force across the test shoes were 62.5 N and 29.0 N, respectively.

TABLE 2.4: EXTENSION BENDING TEST RESULTS FOR CURRENT COMMERCIALLY AVAILABLE SPRINT SPIKES

Extension					
Brand	Model	Max Force (N)	S.D.	Mean Force (N)	S.D.
adidas	Demolisher	106.4	0.8	46.8	0.3
Nike	Zoom Superfly	77.3	0.7	34.3	0.6
Nike	Monster Fly	70.9	1.0	30.1	0.5
Mizuno	Tokyo	71.5	1.1	35.4	0.9
Asics	Hyper Sprint	40.0	0.2	20.6	0.2
Asics	Japan Lite-Ning	35.7	0.2	17.1	0.2
Reebok	Anthem Sprint	35.6	0.3	18.6	0.2
adidas	Meteor	33.8	0.1	19.9	0.2

	MEAN	62.5	0.6	29.0	0.4

GRAPHICAL PLOTS OF THE EXTENSION BENDING FORCE FOR THE STIFFEST, MID-RANGE, LEAST STIFF SHOE ARE SHOWN IN

Figure 2.10. Data presented are a mean of 3 cycles.

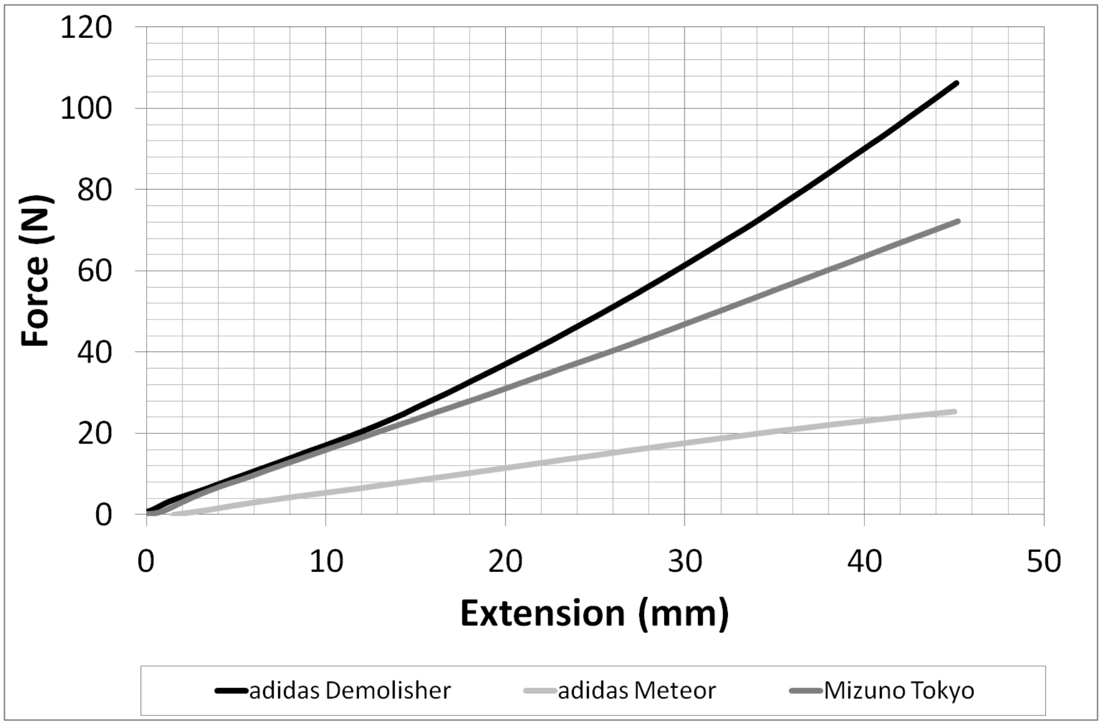


FIGURE 2.10: FORCE (N) VS. EXTENSION (MM) FOR THE ADIDAS DEMOLISHER, ADIDAS METEOR AND MIZUNO TOKYO COMMERCIALLY AVAILABLE SPRINT SHOES

The results of the flexion bending test data are listed in Table 2.5. The mean maximum and mean force recorded over 60 mm of vertical displacement are reported. The adidas Demolisher showed the highest flexion bending force with a mean maximum force of 31.0 ± 0.2 N and a mean mean force of 21.8 ± 0.2 N. The mean of maximum and mean extension force across the test shoes were 17.9 N and 13.2 N, respectively.

TABLE 2.5: FLEXION BENDING TEST RESULTS FOR CURRENTLY AVAILABLE SPRINT SPIKES

Flexion					
Brand	Model	Max Force (N)	S.D.	Mean Force (N)	S.D.
adidas	Demolisher	31.0	0.2	21.8	0.2
Nike	Zoom Superfly	22.9	0.2	17.0	0.3
Nike	Monster Fly	22.7	0.1	15.6	0.2
Mizuno	Tokyo	21.3	0.2	15.9	0.2
Reebok	Anthem Sprint	12.6	0.1	10.0	0.1
Asics	Hyper Sprint	12.5	0.0	10.3	0.2

Asics	Japan Lite-Ning	10.8	0.1	7.8	0.1
adidas	Meteor	9.4	0.3	7.2	0.1
	MEAN	17.9	0.2	13.2	0.2

GRAPHICAL PLOTS OF THE EXTENSION BENDING FORCE FOR THE STIFFEST, MID-RANGE, LEAST STIFF SHOE ARE SHOWN IN

Figure 2.11. Data presented are a mean of 3 cycles.

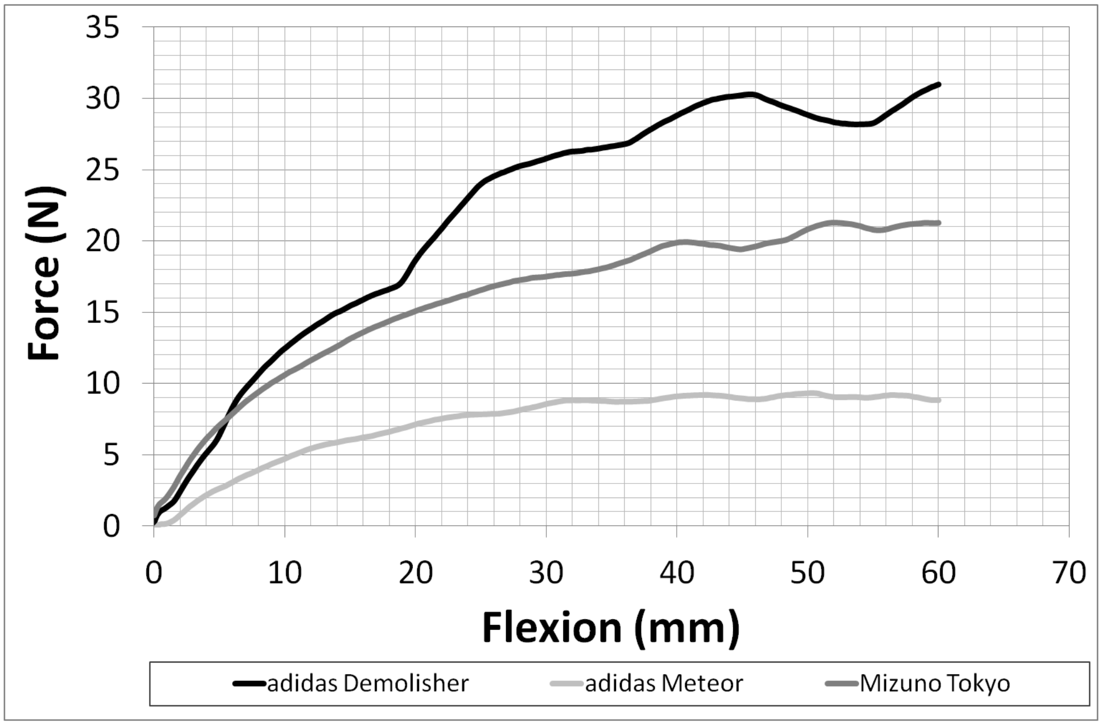


FIGURE 2.11: FORCE (N) VS. FLEXION (MM) FOR THE ADIDAS DEMOLISHER, ADIDAS METEOR AND MIZUNO TOKYO COMMERCIALLY AVAILABLE SPRINT SHOES

The percentage difference between mean force in extension and flexion for each shoe is listed in Table 2.6, in descending order. The mean percentage difference between mean extension and flexion force was 92.9 ± 45.8%.

TABLE 2.6: PERCENTAGE DIFFERENCE BETWEEN FLEXION AND EXTENSION MEAN FORCE

Shoe		% Diff. Between Mean Force in Flex. and Ext.
Adidas	Meteor	175.3
Mizuno	Tokyo	122.2
Adidas	Demolisher	114.3
Asics	Japan Lite-Ning	99.8
Asics	Hyper Sprint	99.8
Nike	Monster Fly	92.5
Reebok	Anthem Sprint	86.1
Nike	Zoom Superfly	50.3
MEAN		105.0

S.D.	35.6

2.2.5 DISCUSSION

This current investigation benchmarked the longitudinal bending stiffness of current commercially available sprint shoes marketed towards 100 m sprinters. The methodology and apparatus developed by Toon (2008) were utilised. The advantage of making direct comparisons in the measured longitudinal bending stiffness of sprint shoes quantified in this work to those obtained by Toon (2008) was the principal motivation for utilising this methodology. It is also for this reason that this methodology will be used in subsequent chapters of this work to measure the longitudinal bending stiffness of bespoke sole units and sprint shoes.

The results from the current benchmarking did not show any obvious changes in trends with regards to increased bending stiffness in either flexion of extension in current commercially available sprint shoes from those previously tested by Toon (2008). Despite the recent indication that increased bending stiffness over commercially available sprint shoes may improve sprinting performance (Stefanyshyn and Nigg, 2000; Stefanyshyn and Krell, 2004), the longitudinal bending stiffness force values in flexion were similar to those generated by Toon (2008). In extension, however, Toon (2008) obtained slightly higher levels of longitudinal bending stiffness than found in this work, with Toon (2008) reporting the highest maximum and mean force values of 155.0±1.3 N and 52.5±1.4 N and a range of 42.3 N across all the test shoes. It is thought this is due to the use of an inconsistent vertical range of bending rather than the indication of a trend towards less stiff sprint shoes in extension. The test shoes utilised in Toon (2008) were extended from the point of zero displacement until contacting the horizontal base surface of the test fixture, while the actual range of extension for each sprint shoe was not reported. It is thought that Toon (2008) may have had a larger range of extension, resulting in a larger maximum and mean value of longitudinal bending stiffness.

It is hypothesised that the reluctance to increase the longitudinal bending stiffness of sprint shoes at the commercial level is due the lack of information on the effects of increased bending stiffness on the biomechanics of sprinting. Firstly, there is no general consensus in the literature on the effects of increased sprint shoe bending stiffness on sprinting performance. In addition, where improvements in sprinting performance with increased bending stiffness have been shown (Stefanyshyn and Fusco, 2004), optimal levels of bending stiffness have been shown to vary between individual sprinters, making it difficult to extend these results to sprint shoe design for the mass commercial market, highlighting the necessity for personalised sprint shoes. As commercially available sprint shoes are currently made for the mass market, i.e. not personalised, the mechanical properties of commercially available sprint shoes must be determined based on obtaining the best sprinting performance over a wide range of sprinting styles and ability. In addition, as lack of information on the exact mechanisms responsible for this previously observed improvement in sprinting performance is apparent (Stefanyshyn and Nigg, 2000; Stefanyshyn and Fusco, 2004), it is difficult to speculate on the potential for increased risk of injury to athletes in the long term.

It is apparent from the results that, in agreement with Toon (2008), there is a large disparity between the levels of longitudinal bending stiffness between the most and least stiff shoe, in both flexion and extension. Additionally, in agreement with Toon (2008), all of the test shoes had a higher measured force in extension compared to flexion. While the percentage difference between mean flexion and extension force found in this work was substantially lower than that found by Toon (2008) i.e.105.0 ± 35.6 % vs 200.7 ± 100.3 %, it is again reasoned to be due to an inconsistent, larger range of flexion used by Toon (2008), resulting in higher force values in extension, rather than an indication of any trends in current, commercially available sprint shoes.

Considering the motion of the foot during ground contact in sprinting, it terms of functionality it seems to fit that the stiffness in extension be greater than flexion. Toon (2008) hypothesised that the higher levels of bending stiffness are required to compensate for the higher forces and velocities during the braking phase of ground contact, potentially aiding the muscles of the lower extremity in resisting impact with the ground as peak ground reaction forces take place 10 to 40 ms after initial ground contact (Mero et al., 1992), which may not give the stretch reflex mechanism ample time to become fully active. Alternately it is hypothesised that excessive bending stiffness in flexion would restrict the motion of the foot excessively upon initial ground contact, potentially restricting the stretch reflex mechanism in the lower limb. There is no research to indicate, however, the consequences of having a sprint shoe that has either insufficient or excessive bending stiffness in extension.

The implications of bending stiffness in flexion at the MPJ have been more widely explored. It is widely established that increasing the longitudinal bending stiffness of athletic footwear reduces the range of movement of the MPJ throughout the ground contact phase of sprinting (Stefanyshyn and Nigg, 2000; Smith et al., 2010, Toon, 2008). With regards to the optimal level of longitudinal bending stiffness for athletic performance, Bojsen-Møller and Lamoreux (1979) found that a stiff shoe had a detrimental effect on the function of the foot in walking, compromising the role of the plantar aponeurosis and minimizing the Windlass mechanism. Improvements in sprinting and jumping performances, however, have been found with increases in the longitudinal bending stiffness of athletic footwear (Stefanyshyn and Nigg, 2000; Stefanyshyn and Fusco, 2004; Toon, 2008). It has been argued that the decrease in MPJ motion during ground contact with increased longitudinal bending stiffness, and an associated minimization of energy lost at the joint is responsible for the improvements to athletic performance (Stefanyshyn and Nigg, 2000). It appears that the longitudinal bending stiffness of sprint shoes can affect sprinting performance. Additionally, just as there may be the opportunity to enhance sprinting performance, there is also the risk of having not only a detrimental effect on sprinting performance but also an increased risk of injury with inappropriate levels of longitudinal bending stiffness. The design of sprint shoe sole units in subsequent chapters should therefore be considered carefully as a potential opportunity to enhance performance through the bending properties of the shoes.

LIMITATIONS

Although the apparatus and methodology for measuring the longitudinal bending stiffness of sprint shoes developed by Toon (2008) has shown to be repeatable and consistent, some concerns over the external validity have been called attention to. One such concern is the variation in the point of application of force along the length of the shoe throughout the vertical loading, causing changes to the length of the lever arm about the point of flex throughout flexion and extension. As a result, the measured force does not give a precise indication of how the force profile changes with angular rotation due to the continuing changes in the length of the lever arm. However, as this change in lever arm is consistent between the different shoes, reporting the raw force values, consistent with Toon (2008) allows for a like comparison to be made between shoe conditions.

Another limitation to the methodology was the potential inconsistency in the longitudinal alignment of the loading probe in the shoes as differences in shape of the sprint shoes meant that slight adjustments needed to be made to ensure the end effector used to load the shoe entered the shoe without interfering with the upper. The effect slight adjustments in positioning affect the forces measured is unknown. Although external validity is of concern, this methodology, which allows direct comparisons to previous work of Toon (2008), has previously been shown to be repeatable and consistent, deeming it suitable for further use in this work to compare the functionality of commercial and bespoke sprint shoes.

2.2.6 CONCLUSION

The methodology presented by Toon (2008) for measuring the longitudinal bending stiffness of sprint shoes has been shown to be repeatable. Although there are concerns relating to external validity, as it is felt that the two point bend test is better representative of the motion and loading of sprint shoes during sprinting, it will be used in further work. In addition, it allows the direct comparison of the functionality of sprint shoes between this work and that of Toon (2008).

Although recent work has indicated that increasing the longitudinal bending stiffness of sprint shoes above what is available commercially may improve sprinting performance, there are no trends detected towards the introduction of stiffer commercially available sprint shoes. This may be due to a lack of information on the changes to the dynamics of the lower limb with increases in longitudinal bending stiffness and the potential for increased risk of injury.

In terms of functionality, sprint shoes were shown to have higher bending stiffness values in extension than in flexion. The higher stiffness values in extension are thought to be necessary to help prevent contact of the heel with the ground in the braking phase of ground contact, with the higher forces and velocities experiences compared to the propulsion phase.

3 DESIGN AND CONSTRUCTION OF SPRINT SHOES

3.0 INTRODUCTION

The enhancement of athletic performance through modifications of the bending stiffness of athletic footwear has recently been the focus of several investigations (Roy and Stefanyshyn, 2006; Stefanyshyn and Nigg, 2000; Stefanyshyn and Fusco, 2004; Toon, 2008). In order to continue biomechanical research of the effects of increasing the bending stiffness of sprint shoes on sprinting performance, the construction of a set of sprint shoes in a range of bending stiffnesses is required, with suitable functionality to allow for maximal effort sprinting to be performed. Previous literature has detailed the design and construction of a range of sprint shoe sole units with increasing longitudinal bending stiffness using laser sintered (LS) nylon-12 (Toon, 2008). The current chapter focuses on traction and details the design, construction and evaluation of sprint shoes for subsequent human performance testing.

Sprint shoe sole units for commercial use are typically manufactured using injection moulding. This process imposes design constraints upon outsole geometry due to the necessity for hardened steel tooling and more importantly, with respect to generating personalised footwear, it is very costly for low volume manufacture. The common approach employed in recent literature for producing a range of footwear with varying levels of bending stiffness is to manually adapt commercially available running or sprint shoes, inserting carbon fibre plates to achieve the varying levels of longitudinal bending stiffness (Stefanyshyn and Nigg, 2000; Stefanyshyn and Fusco, 2004; Stefanyshyn and Roy, 2006; Smith et al., 2010; Deng et al. 2011). Although this approach has produced a range of functional footwear with increasing bending stiffness, it does not provide a long-term manufacturing solution for the commercial market to produce personalised sprint shoes.

Recent work at Loughborough University has focused on the customisation of athletic footwear utilising Additive Manufacturing (AM) technologies. AM provides an alternative solution for creating one-off sprint shoes in a range of bending stiffnesses, offering several advantages over both commercial methods and the common approach employed in recent literature. This tool-less process permits production of complex 3D forms and enables cost effective, low-volume manufacture, making it well suited to the manufacture of products where customisation is desired. This enables the production of sprint shoe sole units, to be assembled with sprint shoe uppers to construct complete sprint shoes. In addition, this approach reduces the errors commonly associated with manually adapted conditions such as inconsistencies in the footwear adapted, variability in the placement of the inserts and unquantifiable interactions between the carbon fibre plates. The current research focuses on the use of AM technology, specifically LS, to produce sprint shoe sole units to be assembled with standard sprint shoe uppers to create full sprint shoes.

The use of LS nylon-12 has previously been successfully applied to the construction of personalised football boots and sprint shoes at Loughborough University. With respect to sprint shoes, LS nylon-12 has been shown to produce sole units with desirable mechanical properties, such as appropriate levels of bending stiffness at suitable material thicknesses, the ability to withstand the forces typically encountered while sprinting without failure, and an acceptable level of durability for human performance testing (Toon, 2008). This methodology was adopted by Toon (2008), facilitating the production of complete sprint shoes, each assembled with sole units in a range of different bending stiffness, achieved through incremental changes to thickness. These sole units, however, were used on athletes performing sprint related jump metrics and therefore eliminated the need for any traction features. In order to facilitate the use of these sole units intended for sprinting, traction features must be incorporated into the design.

The following chapter explores the feasibility of using LS nylon-12 to construct a sprint shoe sole unit which incorporates integrated (i.e. non-removable) traction features. An iterative process of concept design of the sprint shoe sole unit is undertaken followed by an experimental, mechanical validation of the functionality of the traction properties of the LS concept sole units constructed. The methodology used for the assembly of sprint shoes sole units and uppers is subsequently described. The work undertaken in this chapter was supported by New Balance Athletic Shoe Ltd., who supplied sprint shoe uppers and allowed shoe assembly at their UK based manufacturing facilities in Flimby, Cumbria.

3.1 CURRENT IN COMPETITION RULES AND REGULATIONS FOR FOOTWEAR IN ATHLETICS

Prior to the design and construction of sprint shoes it is important to examine the present competition regulations. Presented are the International Association of Athletics Federations (IAAF) competition rules for 2010-2011 concerning footwear under rule 143: Clothing, Shoes and Athlete Bibs.

SHOES

Athletes may compete barefoot or with footwear on one or both feet. The purpose of shoes for competition is to give protection and stability to the feet and a firm grip on the ground. Such shoes, however, must not be constructed so as to give an athlete any unfair additional assistance, including by the incorporation of any technology which will give the wearer any unfair advantage. A shoe strap over the instep is permitted. All types of competition shoes must be approved by IAAF.

NUMBER OF SPIKES

The sole and heel of the shoes shall be so constructed as to provide for the use of up to 11 spikes. Any number of spikes up to 11 may be used but the number of spike positions shall not exceed 11.

DIMENSIONS OF SPIKES

When a competition is conducted on a synthetic surface, that part of each spike which projects from the sole or the heel shall not exceed 9mm except in the High Jump and Javelin Throw, where it shall not exceed 12mm. The spike must be so constructed that it will, at least for the half of its length closest to the tip, fit through a square sided 4mm gauge.

THE SOLE AND THE HEEL

The sole and/or heel may have grooves, ridges, indentations or protuberances, provided these features are constructed of the same or similar material to the basic sole itself. In the High Jump and Long Jump, the sole shall have a maximum thickness of 13mm and the heel in High Jump shall have a maximum thickness of 19mm. In all other events the sole and/or heel may be of any thickness.

Note: The thickness of the sole and heel shall be measured as the distance between the inside top side and the outside under side including the above-mentioned features and including any kind or form of loose inner sole.

INSERTS AND ADDITIONS TO THE SHOE

Athletes may not use any appliance, either inside or outside the shoe, which will have the effect of increasing the thickness of the sole above the permitted maximum, or which can give the wearer any advantage which he would not obtain from the type of shoe described in the previous paragraphs.

3.2 SPRINT SHOE TERMINOLOGY

FIGURE 3.1: SPRINT SPIKE SCHEMATIC (NEW BALANCE SDS 1005) (TOON, 2008)

3.3 SPRINT SHOE SOLE UNIT DESIGN AND EVALUATION

The following section primarily details the iterative design process for sprint shoe sole units with traction features. The main aim of the work in the following section is the development of a functional sprint shoe which would provide sufficient traction in order to allow an athlete to sprint maximally. The intention is not to optimise the amount of traction provided but alternately to provide sufficient traction to keep the athlete from slipping. As there is no established value for minimum traction requirements in sprinting, and as it is commonly accepted that all current commercially available sprint shoes create ample traction with typical track surfaces under normal loading conditions to avoid slipping, the three lowest ranking commercially available sprint shoes from section 2.1 were selected to be used as a comparison level of traction, while the lowest performing sprint shoe was held as the benchmark to which the LS sprint shoes should be equivalent. A secondary aim is that the sprint shoes must be sufficiently robust to allow for an adequate number of maximal effort sprints to be completed in order to carry out subsequent human performance testing. The evaluation of the robustness was based on visual inspection, with minimal wear of the traction features considered acceptable while breakage was considered a failure.

Each sole unit concept presented was designed, constructed using LS and subsequently assembled with an upper to form a complete sprint shoe. The process for assembling the sole units with the New Balance sprint shoe uppers is presented subsequently in section 3.4. Once the sprint shoe was assembled with an upper, the experimental, mechanical validation, outlined in Chapter 2.1, of the functionality of the traction properties of the LS concept sole units was then carried out. The robustness of the traction features was also evaluated using visual inspection. If the sprint shoe sole units constructed did not meet the criteria of generating equivalent peak static traction forces to the lowest performing commercially available sprint shoe and/or show failure of the traction features, the process was iterated until a suitable solution was established.

Modern sprint shoes typically provide traction via 5-9 removable spikes (screw-threaded, tapered metal pins) and moulded features incorporated into the sole plate of the shoe. Regulations set by the governing body for athletics (IAAF) permit the use of up to 11 removable spikes. There have been commercially available sprint shoes with fully incorporated permanent traction features in the sole unit. However, these types of permanent traction features are rarely commercially available as once the traction features wear out or break, the shoe is no longer functional, as opposed to the removable spikes which can simply be replaced. Spike housings consist of a hole with separate metal threaded inserts, allowing for different types of spikes to be screwed into place. Incorporating the threading, allowing for metal pins to be screwed into place, was one option allowing for integrating traction features into the design of LS sprint shoe sole units. However, successfully incorporating the necessary threading to hold spikes using LS sole units was shown to be uncertain (Toon 2009, unpublished work), with a number of designed spike housings failing to hold the spikes in place.

However, sprint shoe sole units may have unlimited ridges and protuberances, provided these features are constructed of the same or similar material to the sole unit. As LS permits the production of complex 3D geometries in a single process, the production of a sprint sole which incorporates traction features in one unit allows for almost limitless design freedom. As these sprint shoes were to be used a limited number of times in human performance testing, therefore eliminating the need for the long term durability required for commercially available options, the aspiration was to create a sole unit which fully incorporated traction features, eliminating added complexity of incorporating spike housing. The ability to incorporate traction features into a sole unit utilising LS would allow for personalisation of traction feature design and placement in further iterations beyond the scope of the work in this thesis.

The sprint shoe sole units were designed to fit a New Balance sprint shoe upper. An existing 3D model of a sprint shoe sole unit, without any traction features, used by Toon (2008), was provided and was used as the foundation of the sole unit used in this work, shown in Figure 3.2. The uppers used in this work were of similar style to those utilised by Toon (2008), therefore it was reasoned that the upper surface of the sole unit would give a good fit. When considering assembly of sole units and uppers, consistency between the curvature of two mating surfaces of the sole unit and the upper is important to ensure a good bond strength and structural integrity.

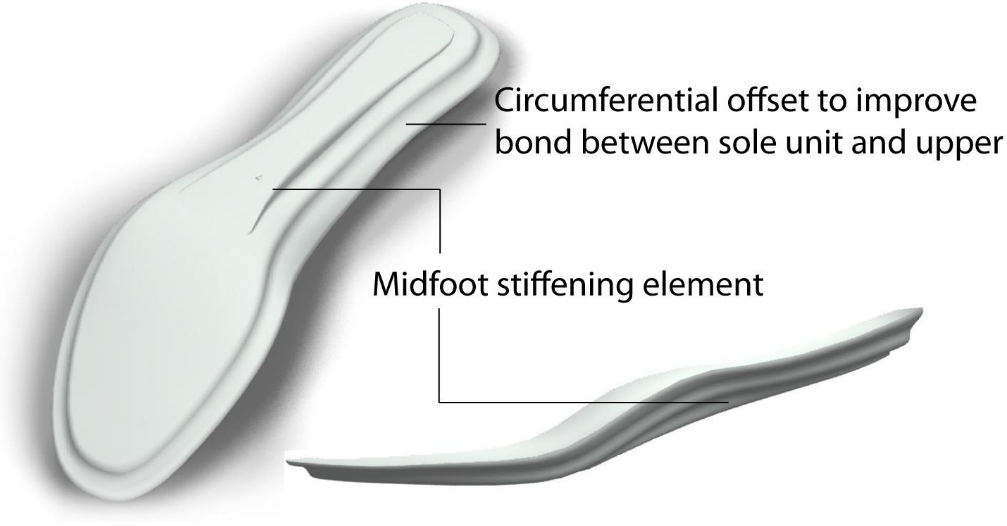


FIGURE 3.2: 3D MODEL SPRINT SHOE SOLE UNIT FOR NEW BALANCE SDS 1005 UPPER (TOON, 2008)

With respect to the bending stiffness of the sole units in this chapter, the desired level was set to be representative of the average, current commercially available sprint shoes. This level of bending stiffness was selected in order to allow for direct comparisons between the traction generating properties of the LS commercially available sprint shoes and eliminate other variables as a contributing factor to any performance differences when measuring the traction generating properties of the sprint shoes. Based on Toon (2008), the thickness of the LS sole units was set to 3mm.

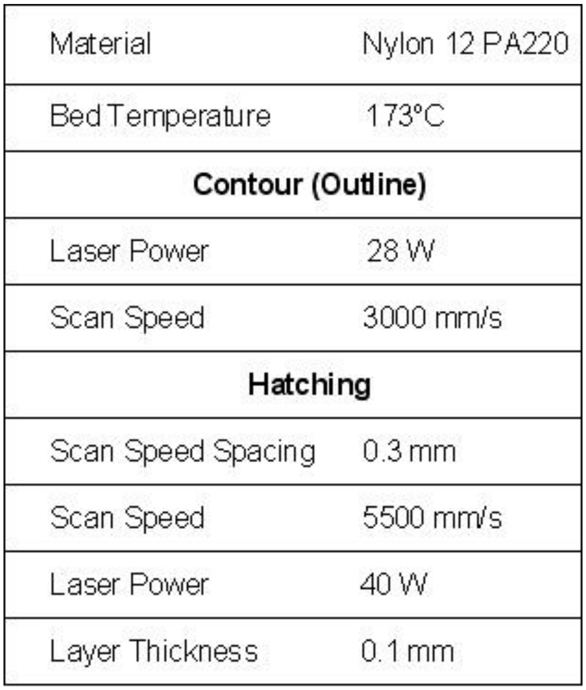
LASER SINTERING (LS)

LS was utilised throughout this work to produce the bespoke sprint shoe sole units. LS is an additive manufacturing process enabling the generation of complex three-dimensional parts by solidifying successive layers of powder material (Kruth, 1991). Solidification is achieved by sintering selected areas of the successive powder layers using thermal energy supplied through a CO_2 laser beam. Once a layer of powder is scanned, a new layer (typically 0.1-0.3 mm thickness) of material is deposited and the process repeated until the entire part is completed.

Unlike other additive manufacturing processes, LS can be used to process almost any material, given it is available in powder form and that the powder particles sinter when heat is applied. Polymer powders are the most widely used materials in LS (Kruth *et al.* 2003). Amorphous polymers produce parts with good dimensional accuracy but poor mechanical properties and are therefore only useful for applications that do not require part strength (Jacobs, 1996). Conversely, semi-crystalline polymers, such as nylon, can be sintered to produce parts with good mechanical properties, approximating those of injection moulded parts, making the parts produced suited for high strength, functional components (Kruth *et al.* 2003).

The sole units were manufactured on an EOS® P390 (Electro Optical Systems, Munich) machine. Further details of the LS build parameters are presented in Table 3.1.

TABLE 3.1: BUILD PARAMETERS FOR EOS P390 LASER SINTERING MACHINE



Material	Nylon 12 PA220
Bed Temperature	173°C
Contour (Outline)	
Laser Power	28 W
Scan Speed	3000 mm/s
Hatching	
Scan Speed Spacing	0.3 mm
Scan Speed	5500 mm/s
Laser Power	40 W
Layer Thickness	0.1 mm

3.3.1 DESIGN ITERATION 1

The first design iteration consisted of three discrete design concepts, which were conceived and modelled in a 3D computer-aided design program (Dassault Systèmes SolidWorks Corp. Waltham, MA). These design concepts were intended as first iteration proof of principle prototypes due to the dearth of literature pertaining to the traction properties of different shapes and sizes of traction features.

This initial design approach in this section was to construct sole units with traction features and investigate their performance, subsequently acquiring information in order to design a more scientifically informed traction design. Traction features were designed based on the popular shapes of spikes and fixed traction features of commercially available sprint shoes. In order to minimise the force encountered by each individual traction feature while sprinting, numerous traction features were added to the sole unit in order to maximise the distribution of the large shear forces. Furthermore, in order to minimise the bending moment on the traction features, the height of the features was decreased from the length of typical sprint spike. It is also noted that there is a lack of peripheral traction features along the perimeter of the sole unit incorporated into the design as the inclusion of these would interfere with the subsequent assembly of the LS sole units with standard sprint shoe uppers. A clearance of approximately 3 mm from the edge of the sole unit was advised to ensure good bonding with the sole unit and upper.

From the design specifications, three alternative sole unit designs with traction features were chosen to be constructed using LS technologies. The three designs are presented below.

CONCEPT 1

The design of the traction features are designed based on the needle and pin spike shape. The pins have a base diameter of 5 mm and a height of 4 mm. There are a total of 80 traction features on one sole unit. The design is shown in Figure 3.3

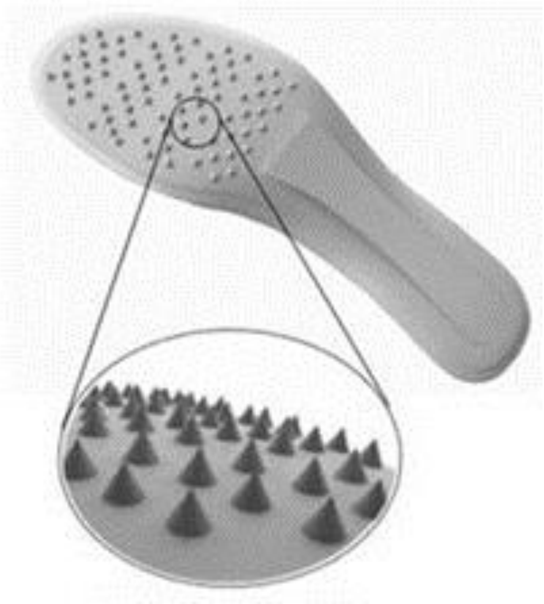


FIGURE 3.3: CONCEPT 1

CONCEPT 2

The design of the traction features are based on the “Christmas tree” shaped spike. The traction features have a base diameter of 6 mm and a height of 4 mm. These traction features include a radius at the base, which has been shown, through finite element modelling, to reduce the maximum stress on the features (Burton, 2007). There are a total of 30 traction features on the sole unit. The design is shown in Figure 3.4

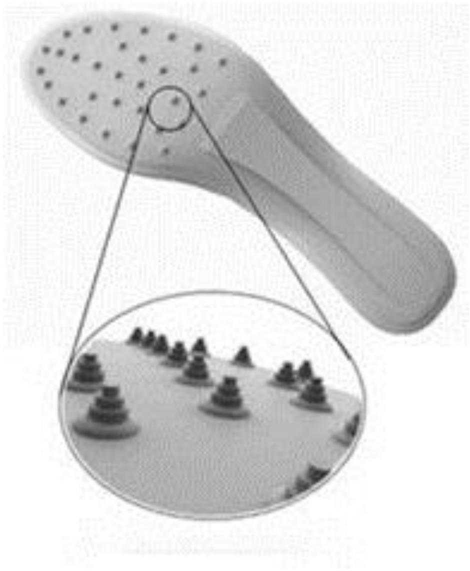


FIGURE 3.4: CONCEPT 2

CONCEPT 3

The design of the traction features is based on the secondary fixed traction features found on currently available sprint shoe sole units. The traction features have a base measuring 4 mm in thickness, a height of 3 mm and vary in length across the sole unit. There are a total of 60 traction features on one sole unit. The design is shown in Figure 3.5.

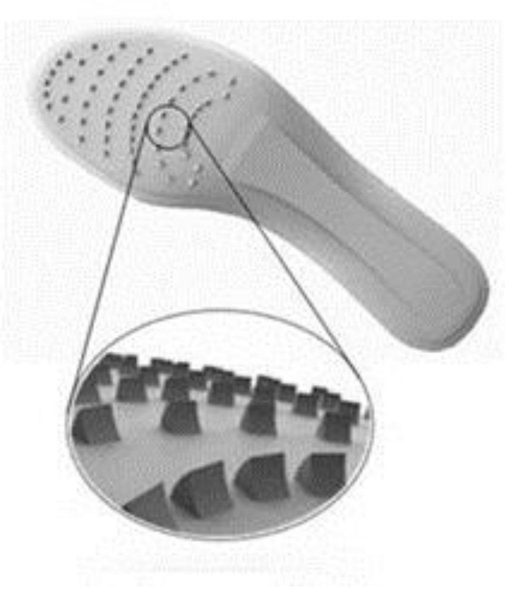


FIGURE 3.5: CONCEPT 3

TRACTION TESTING

THE METHODOLOGY FOR THE TESTING OF THE TRACTION PROPERTIES OF THE LS SPRINT IS THE SAME AS OUTLINED IN CHAPTER 2, SECTION 2.1.1. THE THREE LOWEST RANKING COMMERCIALLY AVAILABLE SPRINT SHOES FROM CHAPTER 2, SECTION 2.1 WERE SELECTED TO BE USED AS A BENCHMARKED LEVEL OF TRACTION TO WHICH TO COMPARE THE LS SPRINT SHOES, WHILE THE LOWEST PERFORMING COMMERCIALLY AVAILABLE SPRINT SHOE WAS HELD AS THE BENCHMARK TO WHICH THE LS SPRINT SHOES SHOULD BE EQUIVALENT. THE THREE COMMERCIALLY AVAILABLE TEST SHOES CHOSEN WERE THE ADIDAS METEOR (SHOE 1), THE MIZUNO TOKYO (SHOE 2) AND THE ASICS HYPERSPRINT (SHOE 3) AND ARE PRESENTED IN

Figure 3.6

FIGURE 3.6: COMMERCIALLY AVAILABLE SPRINT SHOES (A) SHOE 1 (B) SHOE 2 (C) SHOE 3

Testing of the LS sprint shoes was conducted at vertical loads of 500, 1000 and 2000 N. The vertical load applied to the forefoot of the shoe was measured by the in-shoe pressure measurement insole (Tekscan® F-Scan Mobile system). Once the shoe was in position and the desired vertical loading applied, the mounted track surface was pulled by the Instron machine for a distance of 100 mm at a rate of 1000 mm·min^{-1}. The horizontal force achieved by the sprint shoe-track surface interaction and the extension of the Instron were recorded at 100 Hz. Four trials at each of the three vertical loading conditions were performed. The track surface was replaced when visible wear was apparent, which typically occurred after 3-4 trials at low loads and 2-3 trials at higher loads. A coefficient of variance (CV) [CV=σ/μ where σ=standard deviation and μ=mean] was used to assess the repeatability of the testing methodology by retesting one of the shoe conditions.

3.3.2 RESULTS

The results for both the LS and commercially available sprint shoes are presented as a mean of the four trials. The graphical data in Figure 3.7, Figure 3.8, Figure 3.9 show the horizontal force recorded through a displacement of 100 mm at the prescribed levels of normal loading.

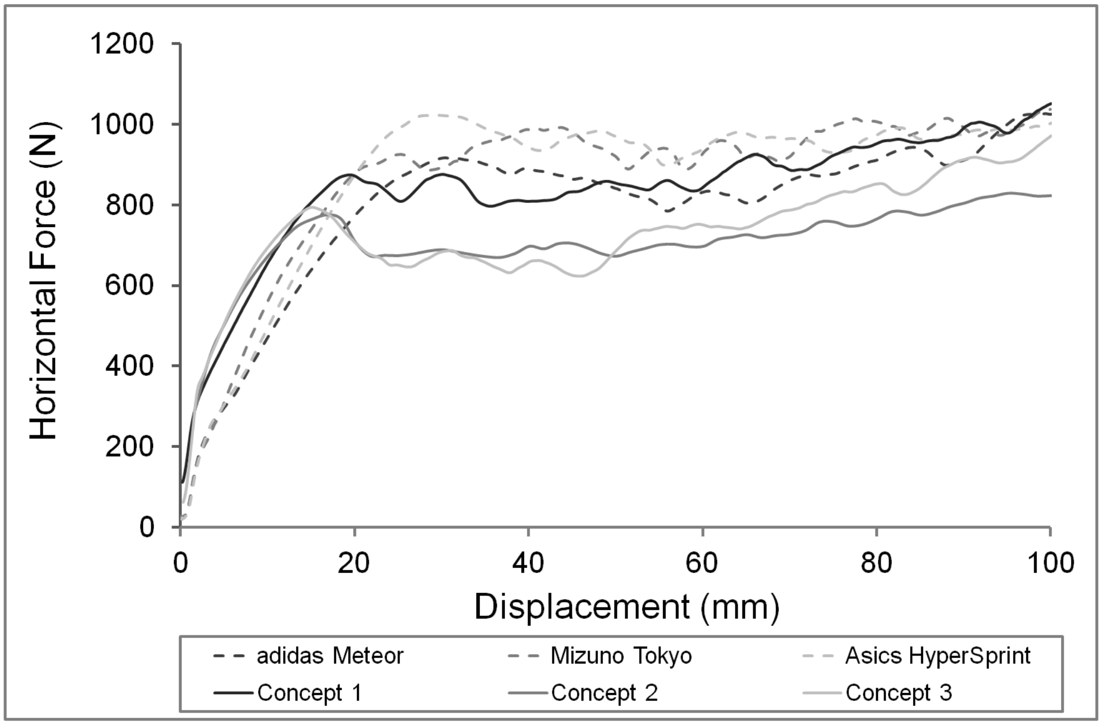


FIGURE 3.7: MEAN HORIZONTAL FORCE VERSUS EXTENSION AT A NORMAL LOAD OF 500 N

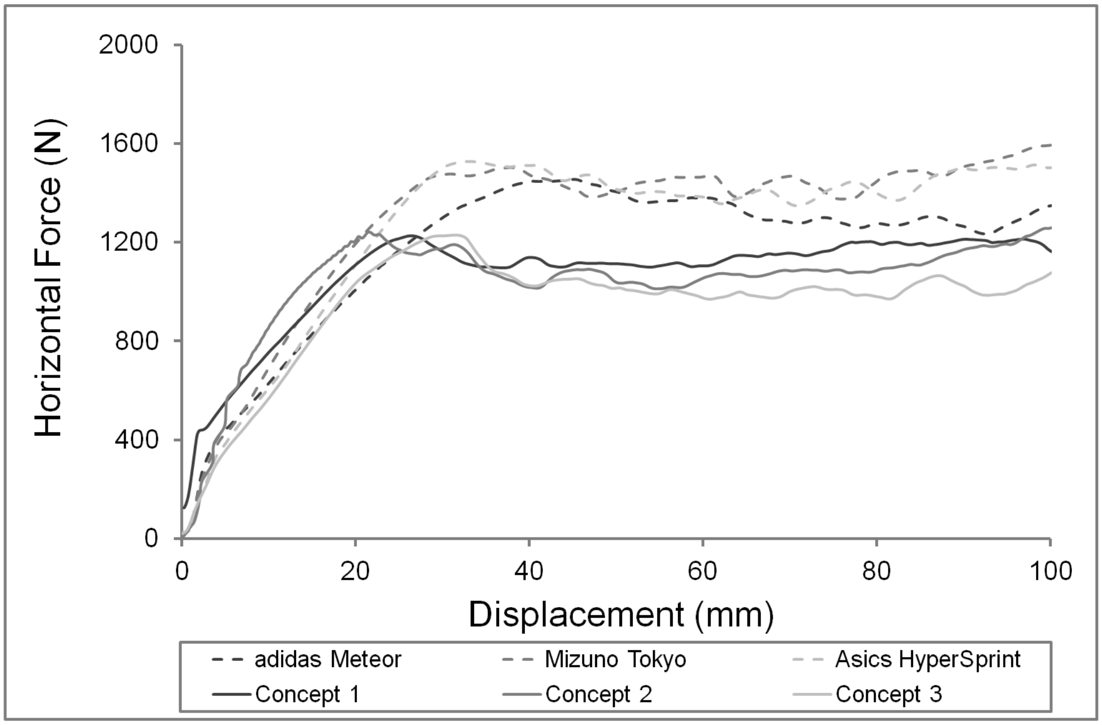


FIGURE 3.8: MEAN HORIZONTAL FORCE VERSUS EXTENSION AT A NORMAL LOAD OF 1000 N

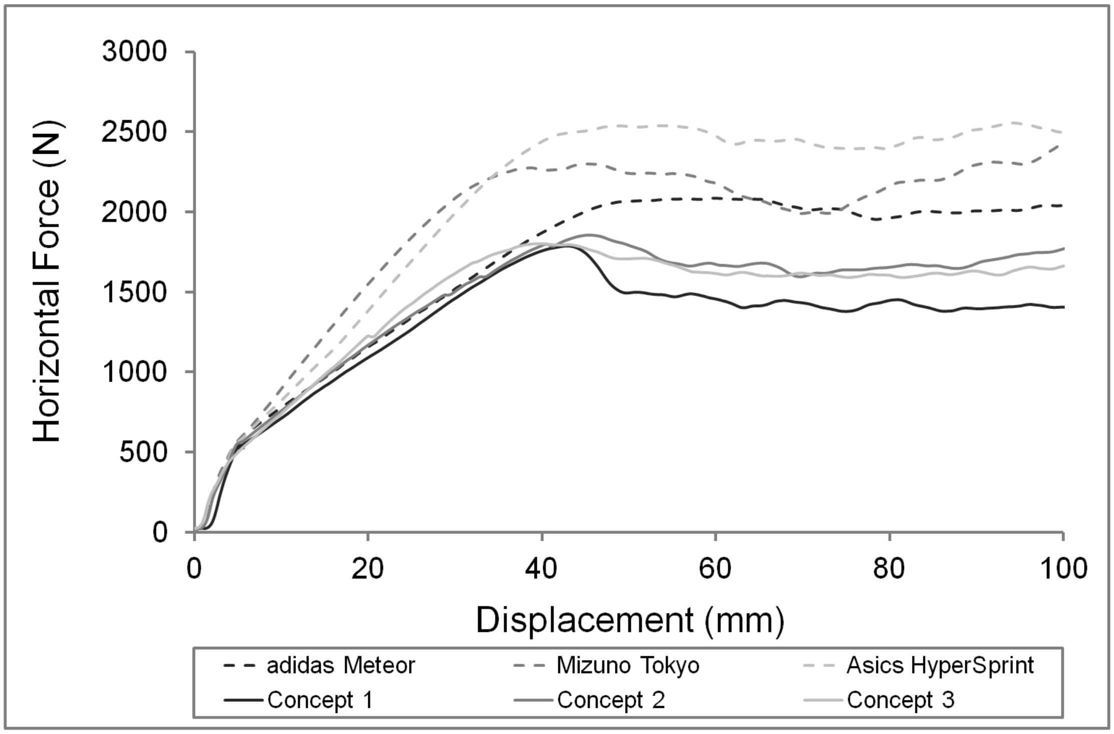


FIGURE 3.9: MEAN HORIZONTAL FORCE VERSUS EXTENSION AT A NORMAL LOAD OF

2000 N

The mean peak static traction, the standard deviation and intra-trial CV for each test shoes across all vertical loads are presented in Table 3.2. The mean CV of peak static traction force between the trials across all the test shoes for all the normal load conditions was 5.8 %, with none of the shoe conditions having a CV between trials greater than 10.0 %.

TABLE 3.2: MEAN OF PEAK TRACTION, STANDARD DEVIATION AND COEFFICIENT OF VARIANCE FOR THE TEST SHOES AT VERTICAL LOADS OF 500 N, 1000 N, AND 2000 N

Shoes	**Mean of Peak Static Traction**	**Standard Deviation**	**Coefficient of Variation**
500 N	(N)	(N)	(%)
Concept 1	890	78	8.7
Concept 2	777	30	3.8
Concept 3	810	19	2.4
Shoe 1	924	88	9.5
Shoe 2	906	63	7.0
Shoe 3	1031	88	8.6
1000 N			
Concept 1	1242	41	3.3
Concept 2	1243	13	1.0
Concept 3	1230	101	8.2
Shoe 1	1472	74	5.0
Shoe 2	1478	60	4.1
Shoe 3	1546	57	3.7
2000 N			
Concept 1	1791	82	4.6
Concept 2	1854	148	8.0
Concept 3	1722	84	4.9
Shoe 1	2115	150	7.1
Shoe 2	2304	119	5.1
Shoe 3	2569	254	9.9

The results demonstrate that throughout the various levels of vertical loading, the LS concept shoes generated lower mean peak static forces than the commercially available sprint shoes (Table 3.2). Comparing the top performing LS shoes against the lowest performing across the various levels of vertical loading, the LS Concept 1 was within 1.8 % of the peak traction forces generated by the Shoe 2 at 500 N. However, at normal loads of 1000 and 2000 N, Concept 2 was within 15.5 % and 12.3 % of the peak traction forces generated by the commercially available Shoe 1.

At higher levels of normal load, heavy wear or failure of the traction features was of main concern as slipping of an athlete is less likely to occur at a lower traction ratio, with increased vertical load increases for a given horizontal load. After completion of the testing at all of the vertical loads, all three concept shoe designs showed signs of wear on the traction features following mechanical testing. Concept shoes 1 and 3 demonstrated minimal wear, in the order of approximately 1mm, and no failure or breakage of any of the traction features. The Concept 2 shoe, however, exhibited failure of the traction features early in testing, showing clear shearing of the tips of the traction features.

DISCUSSION

Three proof of principle concept sprint shoe sole units incorporating traction features were designed, constructed using LS nylon-12, and mechanically tested.

The key concern in the construction of LS concept shoes was minimizing the likelihood of slipping occurring relative to the track surface in subsequent human performance testing. Although Concept 1 generated a mean peak static traction force within 1.8% of Shoe 2 at 500 N, the differences in mean peak static traction of 15.5% and 12.3% between Concept 2 and Shoe 1 at the higher loads was a concern. Although it might be somewhat arbitrary to simply compare the highest performing concept shoe to the lowest performing commercially available option across the various levels of loading rather than comparing the same shoe conditions throughout, at this stage it gives an indication of the relative performance to carry forward into further design iterations.

In terms of wear, all three LS concept shoes showed signs of wear after the mechanical testing. However, while Concept 1 and 3 showed minimal wear, in the order of 1 mm of wear at the tips of the traction features, Concept 3 demonstrated shearing at the tips of the spikes. Hence, geometry of the traction features is an important factor in considering functional traction features able to withstand typical loading conditions encountered in sprinting without failing.

The current investigation has demonstrated the potential to create a fully functional sprint shoe sole unit using LS technologies. This is the first published work to show the feasibility of using LS sole units with integrated traction features, with the initial results indicating that LS sprint shoe sole units incorporating traction features have the potential to generate peak static traction forces nearing the level generated by commercially available sprint shoes. However, as none of the LS concept shoes generated an equivalent level of traction to commercially available options, there is still some uncertainty of how the shoes would perform in human performance testing. In addition, as the geometry was shown to affect the wear and failure of the spikes, a more comprehensive, systematic examination of the size, shape and placement of spikes is recommended.

3.3.3 DESIGN ITERATION 2

In a parallel undergraduate project carried out in conjunction with this project, a systematic examination of the effect of the sprint spike parameters on the level of traction generated and wear was conducted. The four spike parameters examined included: height of spike, size of the end point, number of spikes and shape of spike. Utilising an iterative methodology, one spike parameter was changed at a time.

The same test rig developed in Chapter 2, section 2.1.1 of this work was utilised. However, there were some modifications to the methodology used. Firstly, only the forefoot portion of the sole unit was constructed and tested, shown in Figure 3.10, as opposed to assembling an entire shoe. Secondly, the track surface used was changed. A ‘prefabricated’ track surface (Regupol Kombi 1100 BSW, Germany) similar to those utilised by elite sprinters was used as opposed to a ‘poured’ surface (Polytan PUR poured surface, Polytan Sports Surfaces Ltd, Loughborough, Uk) previously used. This type of surface was used in order to gain some insight into the behaviour of the traction features on the surface type more commonly encountered in competition. The prefabricated track surface had a very different texture which made it very difficult for the sample sprint shoes to be pulled for 100 mm, and therefore the test methodology and assessment of the traction features was altered.

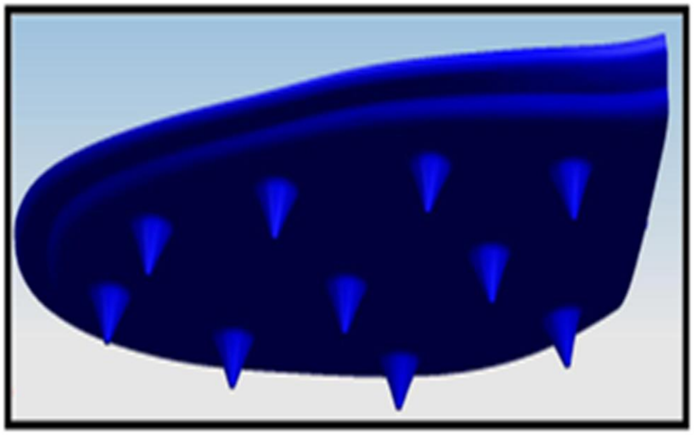


FIGURE 3.10: TYPICAL SAMPLE PORTION OF SOLE UNIT CONSTRUCTED FOR TESTING

The testing of the LS samples was conducted at a vertical load of 500 N only. The 1000 and 2000 N conditions were removed in order to reduce the amount of trials conducted as there was a limited amount of track surface available. As the main concern for slipping is when the vertical force applied is low, with high accompanying horizontal forces, the 500 N vertical load condition was chosen. The vertical load was measured with the pressure insole (Tekscan® F-Scan Mobile system) located underneath the track surface. The LS samples were then subjected to a maximum horizontal force. The Instron machine moved at a speed of 1000 mm·min-1. The end of test was set to be either the sample having been dragged 100 mm or a horizontal force of 3000 N generated. The LS sample was deemed to generate sufficient traction if a horizontal force of 3000 N was generated without the sample slipping relative to the track surface. If there was movement between the LS sample and the track, the design was considered a failure. In addition, if there was obvious failure of the traction features, the design was also considered a failure.

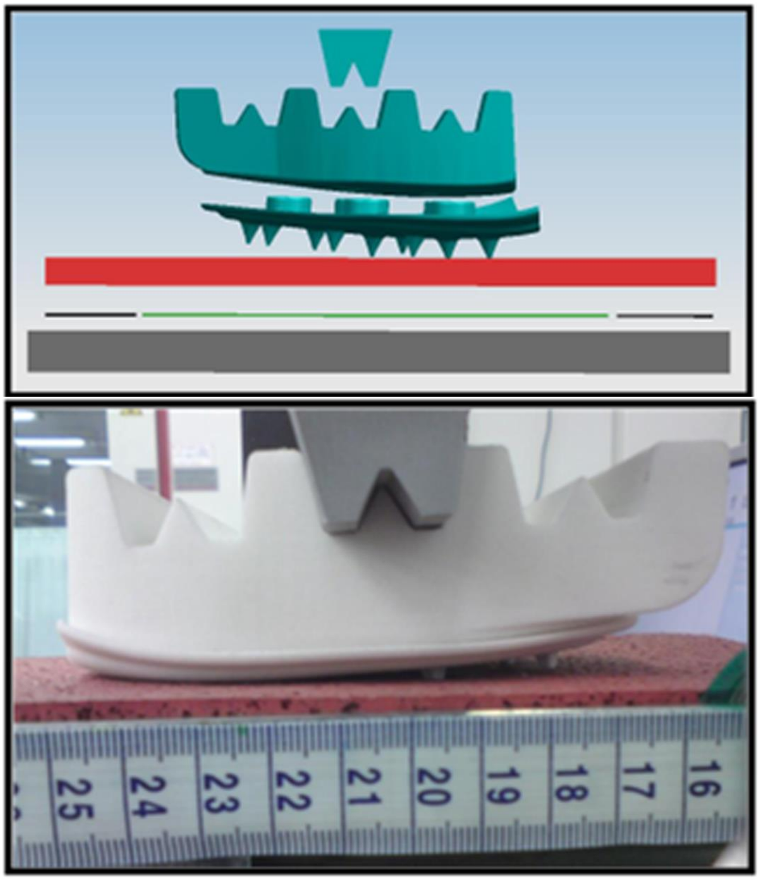


FIGURE 3.11: SCHEMATIC AND PICTURE OF THE MODIFIED TESTING SET-UP

Insights gained from the test results were used to generate design recommendations, detailing the suggested size of the spikes, the size of the end point of the spikes, the number of spikes and the shape of the spikes. With regards to spike size, both 4 mm and 8 mm spikes (with aspect ratio of the same length and height) were deemed suitable. However, it was recommended that if 8 mm high spikes were used, there should be a minimum of 10, whereas at least 15 should be used with 4mm high spikes. An endpoint of 2 mm was recommended with 8 mm spikes. It was suggested that this endpoint could be smaller on spikes that are themselves smaller, but further research would need to be conducted to show this. With regards to spike shape, there were various suitable shapes that could suffice. However, sharp points need to be avoided and a flat end of at least 1mm is recommended for 4 mm high features and 2 mm for 8 mm features. These recommendations were carried forward into a subsequent design, presented in the following section.

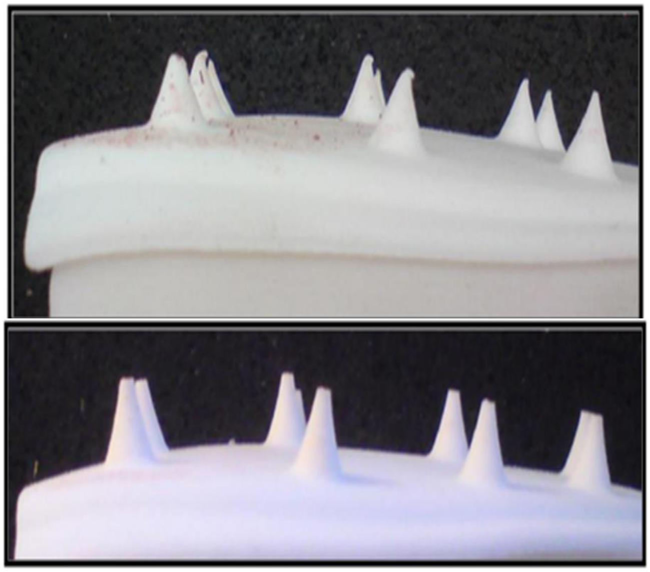


FIGURE 3.12: EXAMPLE OF A (TOP) FAILED AND (TOP) SUCCESSFUL SPIKE SAMPLE AFTER THE MECHANICAL TESTING

3.3.4 DESIGN ITERATION 3

The third design iteration followed the recommendations made by Morris (2010) highlighted in the previous section. In order to be able to compare this design to the previously benchmarked commercially available and LS sprint shoes in section 3.3.1, a full sole unit was constructed using LS and assembled with an upper to create a sprint shoe in order to carry out the same testing procedure.

CONCEPT 4

The design of the traction features are designed based on the needle and pin spike shape. The pins have a base diameter of 8 mm and a height of 7 mm, with an endpoint of 2 mm. There are a total of 12 traction features on one sole unit. The design is shown in

Figure 3.13.

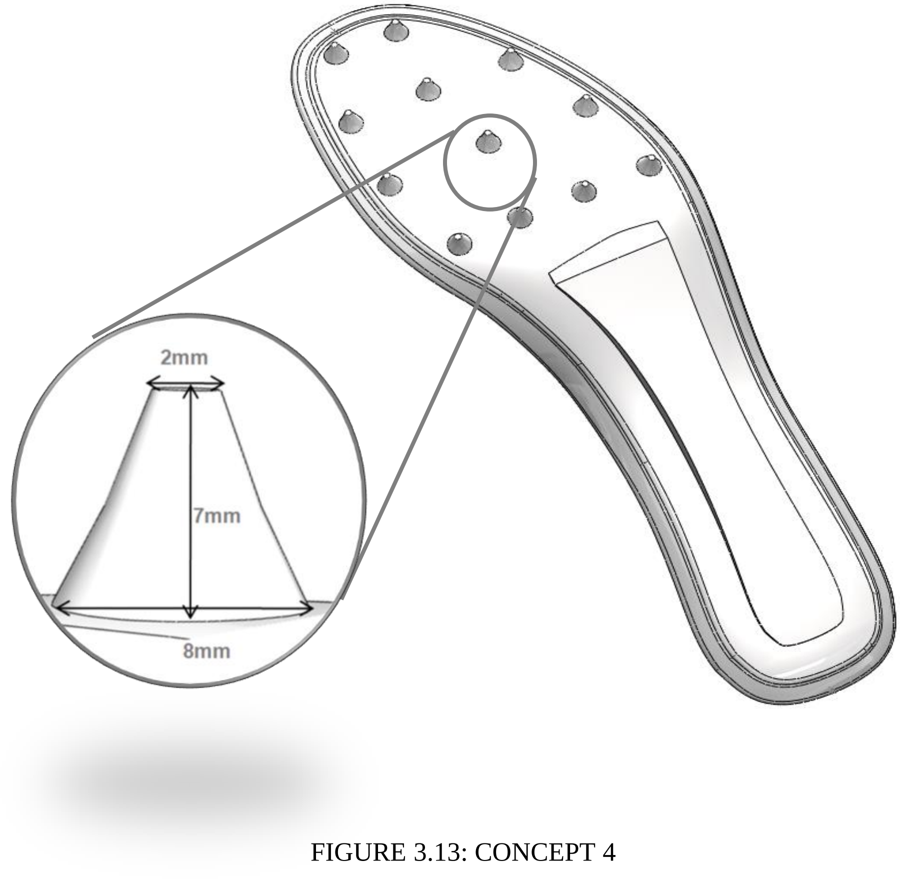


FIGURE 3.13: CONCEPT 4

TRACTION TESTING

The methodology for the testing of the traction properties of the LS sprint shoes is the same as outlined in Chapter 2, section 2.1.1.

3.3.5 RESULTS

The results for the LS Concept 1 through 4 and commercially available sprint shoes 1 through 3 are presented as a mean of the four trials. The graphical data in Figure 3.14, Figure 3.15, and Figure 3.16 show the horizontal force recorded through a displacement of 100 mm at the prescribed levels of normal loading.

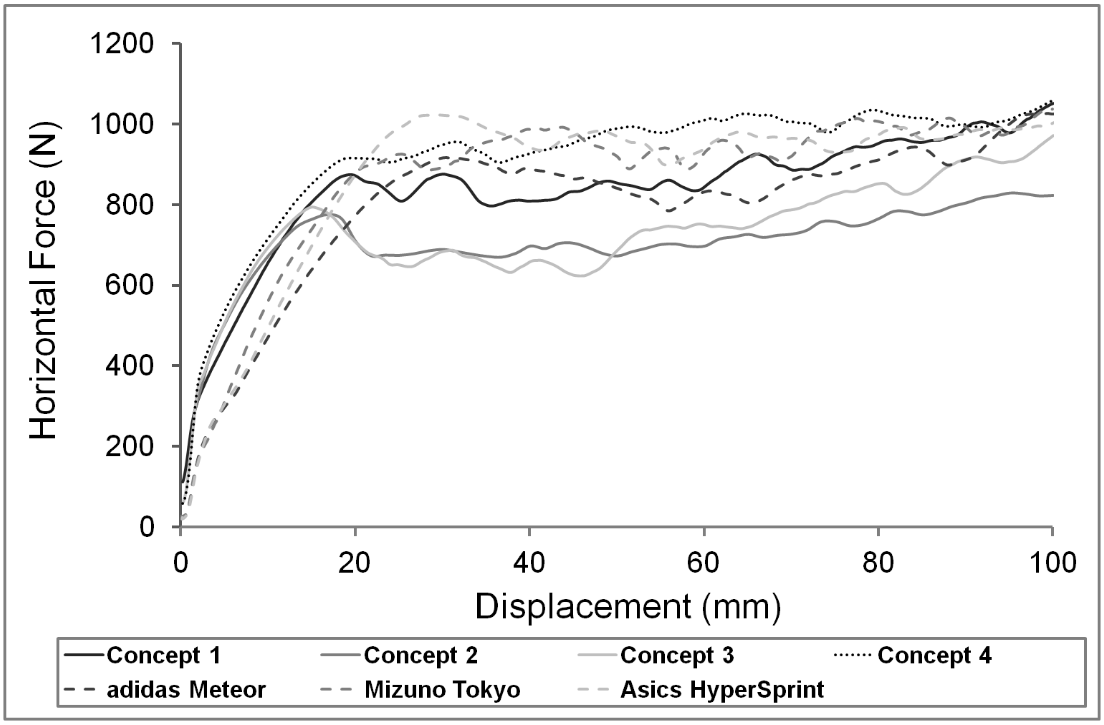


FIGURE 3.14: MEAN HORIZONTAL FORCE VERSUS EXTENSION AT A NORMAL LOAD OF 500 N

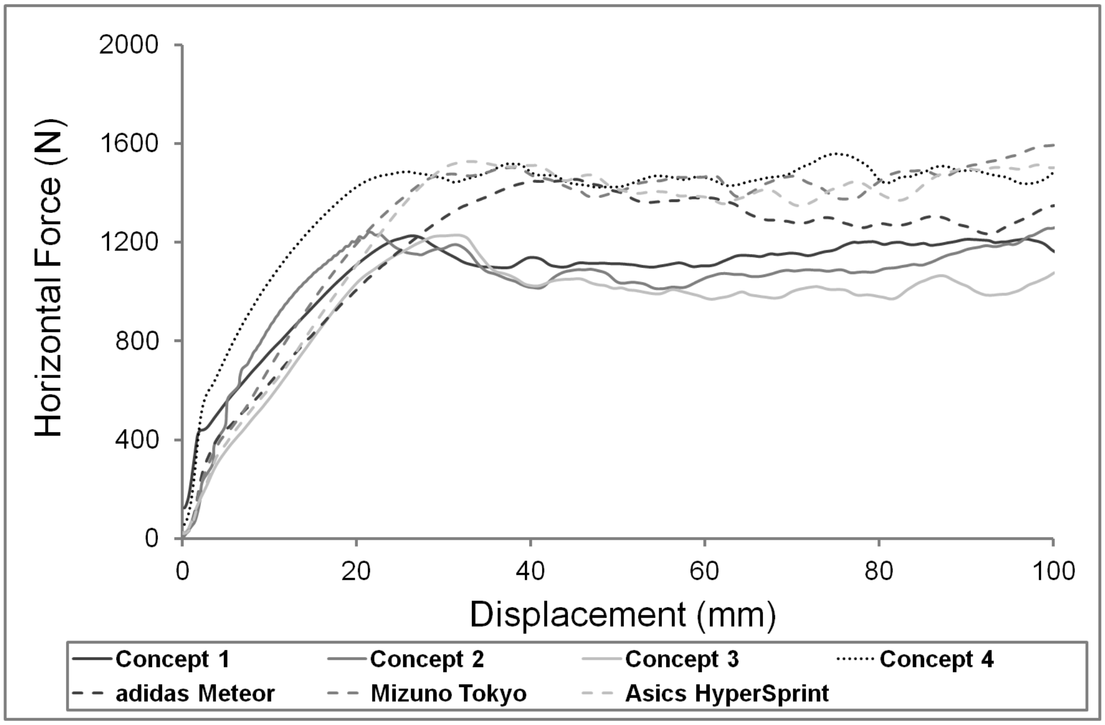


FIGURE 3.15: MEAN HORIZONTAL FORCE VERSUS EXTENSION AT A NORMAL LOAD OF 1000N

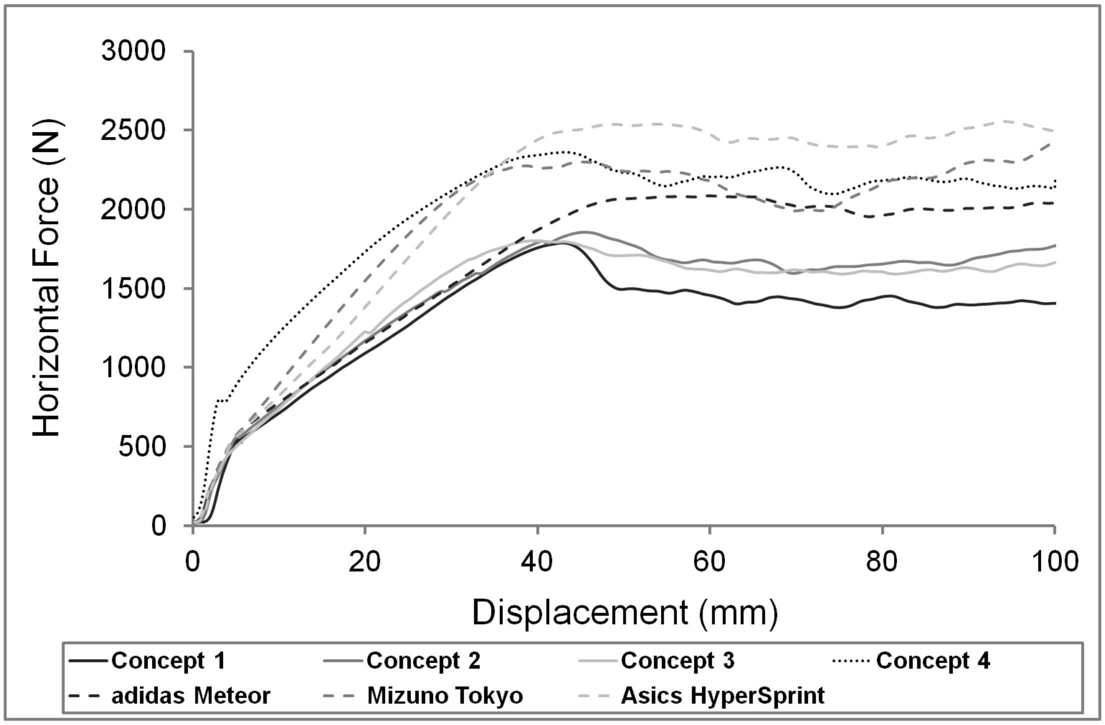


FIGURE 3.16: MEAN HORIZONTAL FORCE VERSUS EXTENSION AT A NORMAL LOAD OF 2000 N

The mean peak static traction, the standard deviation and intra-trial CV for each test shoes across all vertical loads are presented in Table 3.3. With regards to Concept 4, the average CV was 3.7 % with none of the conditions having a CV between trials greater than 10.0 %.

TABLE 3.3: MEAN OF PEAK TRACTION, STANDARD DEVIATION AND COEFFICIENT OF VARIANCE FOR THE TEST SHOES AT VERTICAL LOADS OF 500 N, 1000 N, AND 2000 N

Shoes	**Mean of Peak Static Traction**	**Standard Deviation**	**Coefficient of Variation**
500 N	(N)	(N)	(%)
Concept 1	890	78	8.7
Concept 2	777	30	3.8
Concept 3	810	19	2.4
Concept 4	935	27	2.9
Shoe 1	924	88	9.5
Shoe 2	906	63	7.0
Shoe 3	1031	88	8.6
1000 N			
Concept 1	1242	41	3.3
Concept 2	1243	13	1.0
Concept 3	1230	101	8.2
Concept 4	1475	67	4.5
Shoe 1	1472	74	5.0
Shoe 2	1478	60	4.1
Shoe 3	1546	57	3.7
2000 N			
Concept 1	1791	82	4.6
Concept 2	1854	148	8.0
Concept 3	1722	84	4.9
Concept 4	2382	85	3.6
Shoe 1	2115	150	7.1
Shoe 2	2304	119	5.1
Shoe 3	2569	254	9.9

The results demonstrate that throughout the various levels of vertical loading, the Concept 4 shoe generated higher mean peak static forces than the Concepts 1 through 3. Comparing the Concept 4 shoe against the commercially available sprint shoes, Concept 4 generated a higher mean peak static force than Shoe 1 across all the levels of vertical loading, and Shoe 2 at loads of 500 and 2000 N. After completion of the testing at all of the vertical loads, Concept 4 demonstrated minimal wear, in the order of approximately 1 mm of wear at the tips of the traction features, and no failure or breakage of any of the traction features.

DISCUSSION

A novel LS sprint shoe sole unit concept incorporating traction features was designed, constructed, and mechanically tested. As in the previous section in this chapter, the key concern in the construction of LS concept shoes was minimizing the likelihood of slipping occurring relative to the track surface in subsequent human performance testing. The Concept 4 sprint shoe was shown to generate a higher mean peak static traction force than the commercially available Shoe 1 across all levels of vertical loading. In terms of wear, Concept 4 showed minimal wear and no breakage of the traction features. This sprint shoe sole unit was therefore deemed appropriate for use in further human performance testing.

3.4 CONSTRUCTION

The construction process was carried out in collaboration with New Balance Athletic Shoes Limited at their UK based footwear manufacturing facilities in Flimby, Cumbria. The construction process utilized to assemble the LS sole units and New Balance standard uppers is detailed. Although the general process has been established by Toon (2008), the details of this specific shoe build are presented here as a record of this particular build and starting point for further construction of sprint shoes.

PRE-TREATMENT

Prior to the assembly of the LS sole units and the New Balance uppers, a pre-treatment was performed to each of the mating surfaces of the sole units and uppers in order to achieve the maximum bond when the adhesive is applied. The superior surface of the sole units were liberally coated with Satreat 300 primer, an ethyl acetate based primer, and left to dry for approximately 30 minutes. The preparatory coating of primer is required to improve surface adhesion strength. It is particularly necessary in this case as the nylon sole units are relatively porous and, despite post-process cleaning, have loose powder on the surface.

The inferior surface of the upper was lightly abraded around the perimeter of using a manually driven rotating abrasive cloth. This was done in order to improve the bond between the upper and the sole unit as abraded surfaces have a better affinity for the adhesive. The surface preparation for both the sole unit and upper are detailed in Figure 3.17. Prior to bonding, the inferior surface of the uppers were cleaned using Evo-Stick Cleaner in order to ensure environmental contamination did not interfere with the subsequent bonding process.

FIGURE 3.17: PRE-TREATMENTS OF (A) THE SLS SOLE UNIT WITH SATREAT 300 AND (B) ROUGHING OF THE INFERIOR SURFACE OF THE UPPER.

BONDING

Once the pre-treatment of the surfaces was completed, two layers of Evo-Stick 3140, a cement adhesive, were applied to the superior surface of the sole units and the inferior surface of the lasted upper. The second layer of adhesive was applied after the first layer had dried for 15-20 minutes. In order to heat activate the adhesive, a flash heater was used. One sole unit and corresponding lasted upper were placed in a flash oven, as shown in Figure 3.18, for one cycle. The heater was set such that the temperature of the sole unit reached approximately 110°C while the temperature of the upper reached between 80 and 85°C for one cycle. At this temperature the adhesive is activated and the sole unit is flexible enough to conform under pressure.

FIGURE 3.18: FLASH HEATER USED FOR THE ACTIVATION OF THE ADHESIVE

In order to bond the components, immediately after the sole unit and the upper were removed from the flash heater, they were manually aligned and placed in a Setrum shoe press under approximately 6 bar of pressure for 30 seconds. In order to protect the air bladder in the shoe press, a section of foam was placed on the traction features on the sole units. One concern during the assembly process was that the traction features on the sole unit may distort due to the heat activation and the pressure in the shoe press. However, visual inspection after the assembly process indicated this was not the case. The assembly process is illustrated in Figure 3.19. After this process, the sole unit and upper were securely bonded and the assembly process was complete.

FIGURE 3.19: THE ASSEMBLY PROCESS

Some imperfections in the bond between the sole unit and the upper along the outer perimeter were observed. Particular areas of concern were in the forefoot, at the toe box, in medial aspect of the midfoot and at the rear heel counter of the shoe. An example of this is shown in Figure 3.20. It was suggested that these inconsistencies in the boding at the edges of the sole unit were most likely due to two reasons; the size of the sole unit was estimated to be approximately 1 mm too large along the perimeter and the toe spring of the sole unit was not steep enough to match that of the upper. However, neither of these changes was able to be made whilst at the New Balance factory. In order to attempt to correct this imperfection in the mating of the existing sole units and the uppers, a second assembly process, described as a hot melt, was attempted with the remaining sole units, and described below. It was felt that the different bonding adhesive and higher activation temperatures used in the hot melt process might mould the sole units better to match the shape of the upper and achieve a better bond between the mating surfaces.

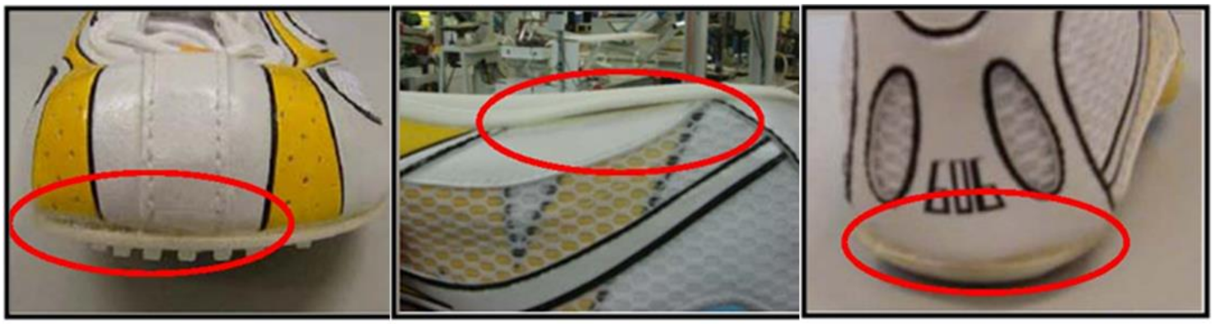


FIGURE 3.20: EXAMPLES OF INCONSISTENT BONDING BETWEEN THE SOLE UNIT AND THE UPPER IN (A) THE TOE BOX, (B) THE MEDIAL ASPECT OF THE MIDFOOT AND (C) THE HEEL COUNTER

HOT MELT PROCESS

Prior to the bonding of the sole unit to the upper, the same pre-treatment procedure as outlined above was performed to the superior surface of the sole units and the inferior surface of the uppers. The difference in the assembly process using the hot melt to the procedure outlined above lies in the bonding process.

Once the pre-treatment of the surfaces was completed, a layer of Purmelt®, a polyurethane based hot melt adhesive, was applied to the superior surface of the sole units and the inferior surface of the lasted upper. In order to heat activate the adhesive, a flash heater was again used. However, in an attempt to improve the bond between the sole unit and the upper, the temperature of the sole unit attained in the flash oven was systematically increased to observe the effects of increasing the activation temperature on the quality of bonding. The suggestion was that increasing the temperature may increase the flexibility of the sole unit around the perimeter, achieving better bond. On the other hand, the concern with increasing the temperature was that it may result in burning of the sole units. The sole units were subsequently subjected to one, two and three cycles in the flash heater, resulting in sole unit temperatures of 140ºF, 170 ºF, and 200 ºF, respectively. None of the sole units subjected to three flash cycles showed any signs of burning having occurred.

As before, immediately after the sole unit and the upper were removed from the flash heater, they were manually aligned and placed in a Setrum shoe press. The pressure applied was increased to 8 bar of pressure for 90 seconds as opposed approximately 6 bar of pressure for 30 seconds applied in the previous method. Again, a concern was that the traction features on the sole unit may distort due to the higher temperature of the heat activation and the pressure in the shoe press. However, again, visual inspection after the assembly process indicated this was not the case. The use of the hot melt process did result in a better bond between the LS sole units and the New Balance upper, and the process described here was used in subsequent sole unit and upper assembly processes. A sample of an assembled sprint shoe, using the sole unit Concept 1, is shown in Figure 3.21.

FIGURE 3.21: ASSEMBLED SPRINT SHOES

3.5 SUMMARY

The current investigation has explored a novel method for constructing sprint shoe sole units. The novel method of using LS nylon-12 to construct a sprint shoe sole unit which incorporates integrated (i.e. non-removable) traction features has been shown to be successful. A systematic, iterative design and evaluation process was undertaken. From this iterative process, the potential to create a fully functional sprint shoe sole unit using LS technologies has been demonstrated. These sprint shoes will facilitate further biomechanical evaluation of the effects of increasing the bending stiffness of sprint shoes on sprinting performance in subsequent work. A novel process for assembling the LS sole units with standard uppers has also been presented. The process developed resulted in a superior bond between the sole unit and upper to previous methods used, producing durable shoes with a high quality finish.

4 METHODOLOGICAL CONSIDERATIONS FOR DETERMINING THE METATARSOPHALANGEAL JOINT FUNCTION DURING SPRINTING

4.1 INTRODUCTION

The role of the MPJ during sprinting and the implications for sprint footwear design and sprinting performance have been the focus of recent investigations (Stefanyshyn and Nigg, 1997; 1998; 2000; Krell and Stefanyshyn, 2006; Toon et al., 2008; Smith et al., 2010; Ding et al., 2011). However, the data collection and processing methodologies used to examine the kinematics of the MPJ in sprinting have recently come into question, limiting the interpretation of the previous results obtained. Recent studies have characterised the MPJ primarily as an energy absorber, generating very little to no energy at the joint during running, jumping and sprinting (Stefanyshyn and Nigg, 1997; 1998; 2000). This lack of energy generation has been attributed to a lack of observed MPJ extension at take-off, associated with energy generation at the joint during ground contact (Stefanyshyn and Nigg, 1997). Further, an observed decrease in MPJ energy absorption with increased sprint shoe bending stiffness has been observed, along with an improvement in athletic performance attributed to this decrease in MPJ energy absorption (Stefanyshyn and Nigg, 2000). However, the commonly used sampling rates (*SR*), filtering frequencies (*fc*), and definition of the MPJ have been shown to lead to underestimations of the kinematics at the joint (Smith and Lake, 2007).

SAMPLING RATES (SR) AND FILTER CUT-OFF FREQUENCY (FC)

Smith and Lake (2007) have indicated that commonly used *SR* and filtering procedures, as those used by Stefanyshyn and Nigg (1997; 1998; 2000) may lead to an underestimation of MPJ segmental derivatives used for kinetic calculations. The authors (Smith and Lake, 2007) found that using a *SR* of 200 Hz and a *fc* of 8 Hz, as used by Stefanyshyn and Nigg (1997; 1998; 2000), resulted in an underestimation of the angular range and peak angular velocity of the MPJ by 12.9° and 8.9 rad/s, respectively, when compared to using a sampling rate of 1000 Hz and a *fc* of 100 Hz. However, the effect of *SR* and *fc* on the MPJ angular range and angular velocity were examined simultaneously and therefore the impact of each of these variables independently on the MPJ segmental derivatives obtained remains unknown. In addition, there are no known explorations of the impact of commonly used data collection and processing methods on MPJ energy contribution in sprinting.

DEFINITION OF THE MPJ

Differences in representation of the MPJ have also been highlighted in recent literature (Smith and Lake, 2007). While Stefanyshyn and Nigg (1997; 1998; 2000) defined the MPJ as an ideal hinge rotating about the location of the head of the fifth MPJ, Smith and Lake (2007) have demonstrated that MPJ representation based on lateral markers underestimated peak MPJ flexion by 29° compared to the medial aspect of the joint. The medial aspect of the MPJ further demonstrated a high extension velocity before take-off, permitting the possibility of positive MPJ power and energy generation (Smith and Lake, 2007). The MPJ is in fact made up of five separate joints, with the ability to rotate about an oblique or transverse axis (Bojsen-Moller, 1978). Typical practice in recent literature (Stefanyshyn and Nigg, 1997; 1998; 2000) has also considered the resultant forces and moment at the MPJ to be zero until the ground reaction force acted distal to the joint. As the 5th MPJ lies proximal to the 1st MPJ, a lateral representation would result in a difference in timings of the forces and moments acting on the joint. Joint representation of the MPJ therefore must be carefully considered as a misrepresentation may miss important aspects of MPJ joint function. As the MPJ has been arguably the most significant joint in the foot with respect to sprint shoe design in recent footwear literature, as most likely to be affected by changes in sprint shoe bending stiffness, methodological considerations pertaining to data collection and processing methodologies with regards to the function of the MPJ in sprinting merit further investigation.

The aim of this work was to investigate the effect of commonly used data collection and processing methodologies on the MPJ kinematics and kinetics during the stance phase in sprinting to facilitate objective insights into methodologies to be taken forward into subsequent stages of human performance testing. By applying varying sampling rates, filtering frequencies and MPJ definition to data collected during the early acceleration phase of a maximal effort sprint, differences in MPJ kinematics and kinetics obtained using the different methodologies could be compared and discussed, with both the combined impact and the individual impact of the variables examined and discussed.

It was hypothesised that the combined impact of commonly used kinematic *SR*, *fc*, and MPJ definition used by Stefanyshyn and Nigg (1997; 1998; 2000) would lead to an underestimation of the MPJ angular kinematics and kinetics. However, the contribution of each of these individual variables is unknown and will be examined and discussed. With regards to kinematics, it was hypothesised that the definition of the MPJ will have the largest effect on resulting MPJ variables. With regards to MPJ kinetics, it was hypothesised that commonly used kinematic *SR*, *fc*, and MPJ definition would lead to an underestimation of MPJ energy generation and absorption. Further, it was hypothesised that the changes in MPJ definition would have the largest effect on the resulting MPJ kinetics.

4.2 METHODS

PARTICIPANTS

Following the attainment of informed, written consent and approval from Loughborough University Ethical Advisory Committee, two female subjects (Subject 1: age 27 years, mass: 54.5 kg height 1.61 m. Subject 2: age 19 years, mass: 54.0 kg height 1.60 m.) completed the study. Participants were nationally competitive sprint hurdlers with a minimum of 5 years experience and 100 m personal bests of <12.50 s.

PROTOCOL

The participants completed two separate testing sessions, one in a barefoot condition and one in a shod condition. Both a barefoot and shod condition were utilised as sprint spikes have been shown to have a significant influence on the kinematics of the foot during the ground contact phase when compared to the barefoot equivalent condition, with the magnitude of the effect of sprint spikes increased in the acceleration phase compared to maximal speed (Toon et al., 2009). The barefoot condition was therefore used to represent a condition corresponding to no bending stiffness, removing any restrictions to the motion of the MPJ. However, as the kinematics of barefoot and shod running is known to differ, the shod condition was necessary to demonstrate typical sprinting circumstances. The shod condition involved the subjects wearing a Nike Zoom Super Shift sprint spike.

During each of the two testing sessions, the subject completed four 10 m sprints from competition blocks, in either the barefoot and shod conditions. The testing sessions were completed 48 hours apart to ensure full recovery between sessions. Kinematic and kinetic data were collected during the second stance phase from the blocks. A trial was considered successful if the athlete did not deviate from their normal gait pattern and the entire stance phase was captured in the field of view. In total, eight stance phases were collected and analysed for each athlete, four barefoot and four shod.

Prior to testing, the participants performed their customary warm up protocol. During the warm up, two runs from blocks were performed in order to ensure that a full foot strike on the force platform occurred. All data were collected in the laboratory at Loughborough University Sports Technology Institute on a synthetic Rugepol Kombi 1100 athletic surface (Berleburger Schaumstoffwerk GmbH, Germany, W1.25m x L10.0m), as shown in Figure 4.1.

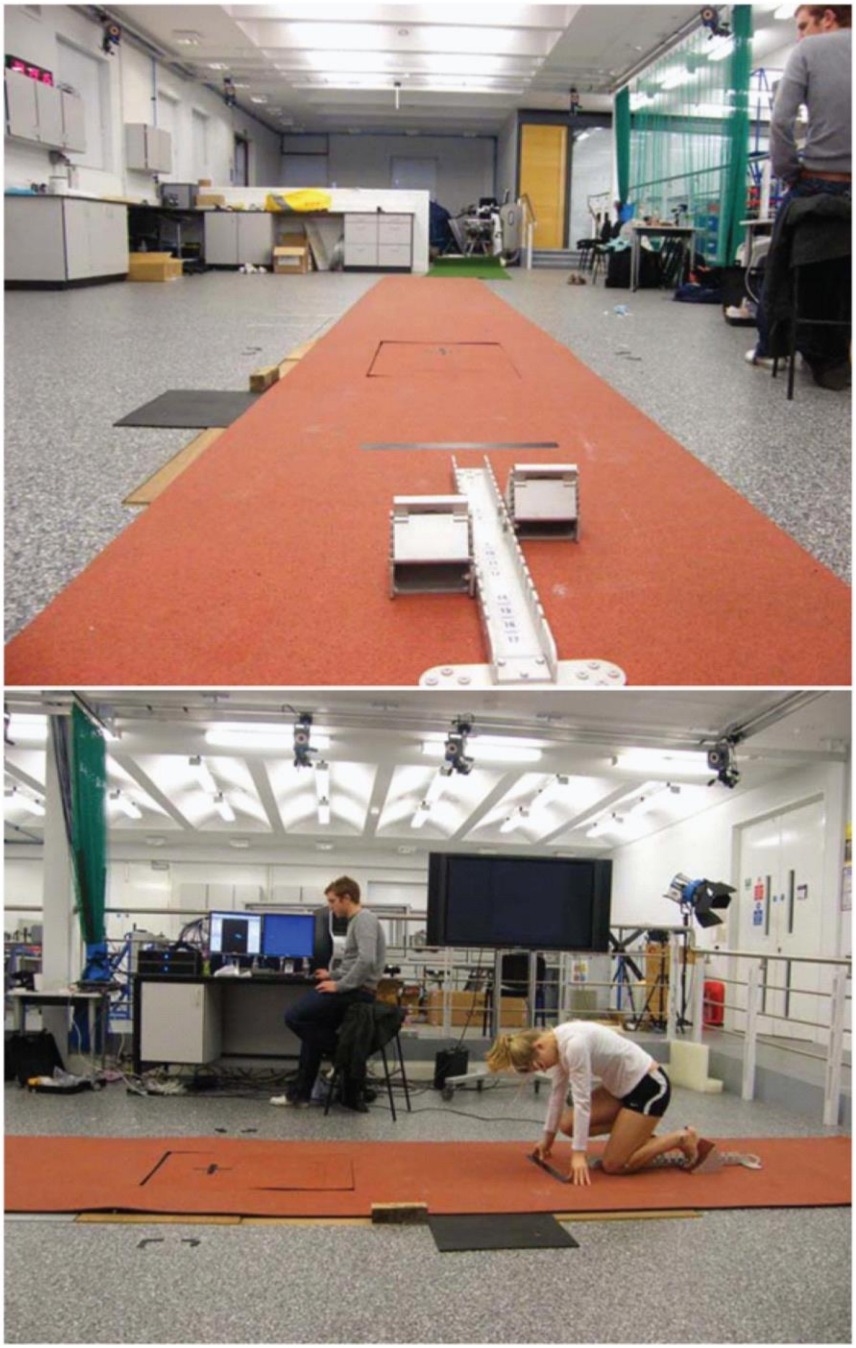


FIGURE 4.1: IN LAB TESTING SET UP

KINEMATIC AND KINETIC DATA CAPTURE

Kinematic data was collected using a 12 camera, passive marker motion capture system (Vicon Motion Systems Ltd., Oxford, UK) sampling at 500 Hz. Markers (14 mm diameter) were placed on the heel, the medial aspect of the ankle, the lateral aspect of the ankle, the lateral aspect of the 5th MPJ, the medial aspect of the 1st MPJ, the superior surface of the foot between the 2nd and 3rd MPJ and on the superior surface of the distal phalanx of the hallux, as shown in Figure 4.2 . The reflective markers were adhered to the skin using double-sided tape. For the shod condition, the sprint shoes were modified such that all the markers, except the heel marker, could be directly placed onto the foot. Kinetic data were sampled synchronously with the motion data using a force platform (Kistler 9278BA, Winterthur, Switzerland, W600mm x L900mm SN 1609256) sampling at 1000 Hz.

FIGURE 4.2: MARKER PLACEMENT

ANALYSIS

Although kinematic data was collected in 3D, a 2D analysis was performed in order to allow for direct comparison between previous research (Stefanyshyn and Nigg,, 1997; 1998; 2000; Toon, 2008). For this investigation, the MPJ was defined as the angle between the forefoot and rearfoot segments. The forefoot segment was defined from the toe to the MPJ marker, while the rearfoot segment defined between the MPJ and the heel marker. Angular motion of the MPJ was categorised into extension and flexion, with extension defined as an increase in the MPJ angle and flexion as a decrease in MPJ angle. An illustration of the definitions of the foot is presented in Figure 4.3. MPJ angular motion was reported as a range in the different periods through ground contact. The initial extension phase, Extension 1, is the first period of angular motion occurring immediately after ground contact until maximum extension. The next phase is the flexion occurring from maximum extension of the MPJ through to maximum flexion. The final phase is extension during the push off, Extension 2, occurring from maximum flexion through toe-off until the foot leaves the ground.

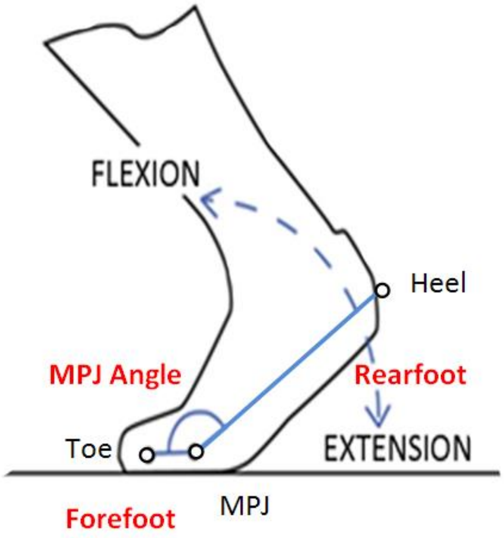


FIGURE 4.3: DEFINITIONS OF THE FOREFOOT, REARFOOT AND MPJ ANGLES OF THE FOOT

To investigate the different data collection and processing methods, the raw kinematic data were subject to several processing techniques, which are outlined in the following sections. Once the appropriate treatment of the kinematic and kinetic data was completed, the data was utilised within the same inverse dynamics analysis to calculate the resultant MPJ dynamics. It was assumed that the resultant joint moment at the MPJ was zero until the point of application of the ground reaction force acted distal to the joint (Stefanyshyn and Nigg, 1997;

1998; 2000). The convention was chosen such that MPJ plantarflexor moments were positive (Winter, 1983). Joint power was calculated using the following equation:

$$P_{j=}\ M_j\,\omega_j$$

where

P_j = the power of the joint

M_j = the resultant moment of the joint

ω_j = the angular velocity of the joint.

Positive power occurs when the angular velocity of the joint is in the same direction as the resultant joint moment. Energy was calculated by trapezoidal integration of the joint power curve (Adams, 1990). Anthropometric data were obtained using the model of Yeadon (1990). modified to account for a fore- and a rearfoot separately. The foot segment, normally modelled as a single segment from the ankle to the distal hallux in the Yeadon (1990) model, was modified to account for a rearfoot segment from the ankle to the MPJ and a forefoot segment from the MPJ to the distal hallux.

DATA COLLECTION AND PROCESSING METHODS

For this investigation, the raw kinematic data were subjected to various processing techniques, outlined below, in order to evaluate the effect of data collection and processing methodologies on the resulting MPJ kinematics and kinetics during a stance phase in sprinting. Commonly used methods (f_c 8 Hz, SR 200 Hz, 5th MPJ) were evaluated, firstly collectively then individually, by utilising different f_c, SR and MPJ definition (described below), comparing the MPJ anglular range, angular velocity and energies obtained.

FILTERING

It is important to account for the presence of noise in the signal acquired during data collection as this noise can greatly affect the results of an inverse dynamics approach. However, too much filtering of the data may miss important aspects of the true signal. Although much of the noise can be minimized through careful experimental procedures, the signal will inevitably be contaminated with some systematic and random errors. When using a low-pass digital filter, selecting an optimal level of filtering ($f_{c\text{-}opt}$) that appropriately removes the noise without affecting the true movement data is important and has been the subject of debate in recent literature (Smith and Lake, 2007).

Before the investigation of the effect of filtering frequency on the dynamics of the MPJ in this work, an optimal f_c ($f_{c\text{-}opt}$) was investigated using a residual analysis as presented by Winter (1990) (and detailed below in Figure 4.4) and visual inspection of the effect of different filtering cut-off frequencies on angle, angular velocity and power at the MPJ. Although the residual analysis provides a means of selecting suitable cut-off frequencies, visual comparisons of the kinematics and kinetics of the MPJ obtained using both unfiltered data and data filtered with different cut-off frequencies were created in order to gain increased insight into the effect of selecting different filtering frequencies in order to justify the selection of $f_{\text{c-opt}}$. This $f_{c\text{-}opt}$ will then be used in subsequent work in this chapter to be compared with the commonly used f_c of 8 Hz. Commonly used in biomechanics, a fourth order low-pass Butterworth filter will be used for filtering the kinematic data in this work.

RESIDUAL ANALYSIS

The residual of a human movement signal is equal to the difference between the filtered data and the unfiltered data. Utilising the method of Winter (1990), the desired cut-off frequency was determined graphically as shown in Figure 4.4.

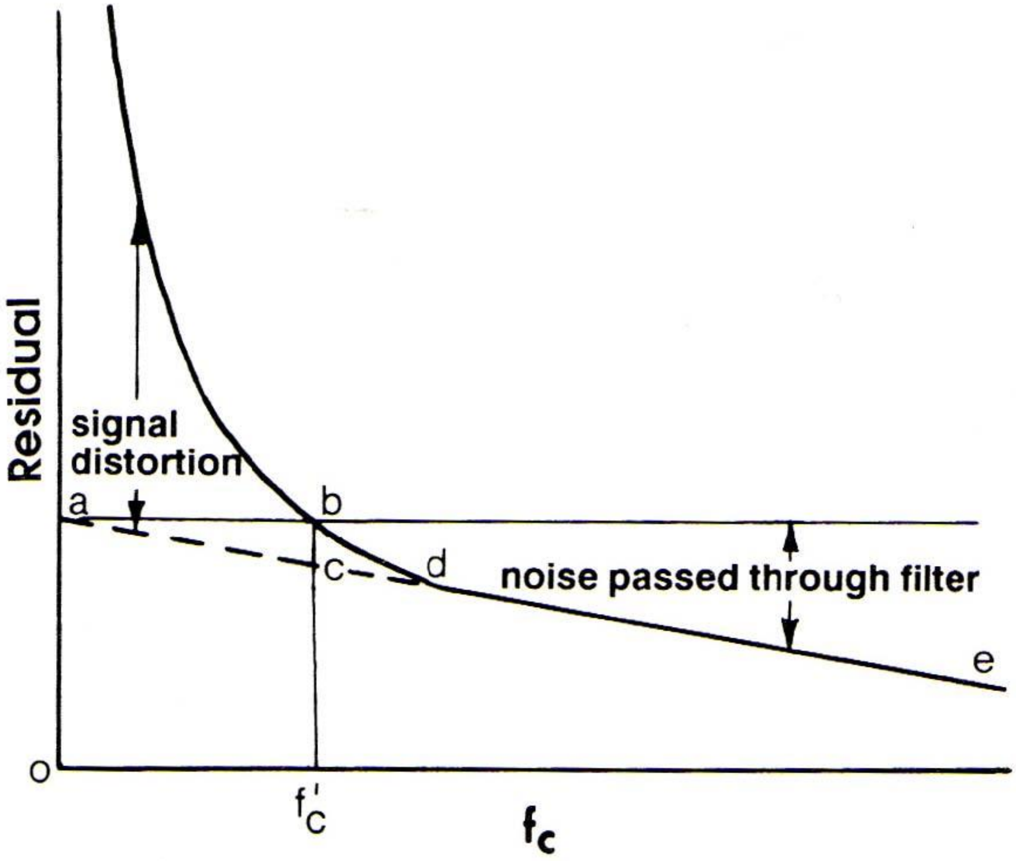


FIGURE 4.4: PLOT OF RESIDUAL BETWEEN FILTERED AND UNFILTERED SIGNAL AS A FUNCTION OF THE FILTER CUT-OFF FREQUENCY (WINTER, 1990)

The residual at any cut-off frequency was calculated using the following equation (Winter, 1990) for a signal of N sample points in time:

$$R(f_c) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X_i - \hat{X}_i\right)^2}$$

where:

$\mathbf{X_i} = \textbf{Raw unfiltered data at the } \boldsymbol{i}\textbf{th sample}$

$\boldsymbol{\hat{X}_i} = \textbf{Filtered data at the } \boldsymbol{i}\textbf{th sample}.$

The line *d* to *e* in Figure 4.4*,* which runs tangential to the asymptote of the residual data, represents the estimated residual noise level. The residual value of data containing a true signal and noise will be seen to rise above the dashed line as the cut-off frequency is reduced and fall between points *d* and *e* as cut-off frequency is increased. Point *a* is equal to the root mean square of the noise and a horizontal line projected from this point to intercept the residual line at *b* objectively generates a cut-off frequency that has equal proportions of both noise and signal distortion. The magnitude of which is quantified by the line *b* to *c*. The residual and subsequent $f_{\text{c-opt}}$ of the seven positional markers utilised in this study were calculated. The raw data was smoothed with a fourth order, low-pass, Butterworth filter. Residual values were calculated for a range of cut-off frequencies between 1 and 100 Hz.

A visual comparison of the MPJ angle, angular velocity and power using both unfiltered data and data filtered with different cut-off frequencies was then completed, further justifying the selection of an $f_{\text{c-opt}}$ to be used in this work.

SAMPLING RATES (SR)

To facilitate the examination of different *SR* on the dynamics of the MPJ, the raw kinematic data was re-sampled at 200 Hz using a linear interpolation in Matlab R2007b (MathWorks, Massachusetts, USA). This processed kinematic data, and kinetic data sampled to 200 Hz, were utilised in the inverse dynamics analysis and the resultant MPJ dynamics obtained and compared.

MODELLING OF THE MPJ

Throughout the inverse dynamics analyses, the MPJ was modelled using two methods: as a single ideal hinge joint, rotating about a transverse axis through the 1st MPJ and the 5th MPJ centres, respectively. The resultant MPJ dynamics were obtained and compared.

CONDITION COMPARISONS

The first comparison examined the combined effect of commonly used (Stefanyshyn and Nigg, 1997, 1998, 2000) data collection and processing methods (Condition 1: f_c 8 Hz, SR 200 Hz, 5th MPJ) against what has been suggested (Smith and Lake, 2007) as more appropriate methods (Condition 2: $f_{c\text{-}opt}$, SR 500 Hz, 1st MPJ). The resulting MPJ angular range, angular velocity and energy were evaluated, highlighting the differences in the MPJ variables obtained.

In order to gain a better understanding of the impact of the individual data collection and processing methods used, an iterative process was utilised in which one data collection and processing method was changed in order to assess the effect on the resulting MPJ angular range, angular velocity and energy. Condition 1 ($f_{c\text{-opt}}$, SR 500 Hz, 1st MPJ) was utilised as the standard condition. Condition 2 highlighted changes to f_c (Condition 2: f_c 8 Hz, SR 500 Hz, 1st MPJ), Condition 3 highlighted changes to SR (Condition 3: $f_{c\text{-opt}}$, SR 200 Hz, 1st MPJ), and Condition 4 highlighted changes to the definition of the MPJ (Condition 4: $f_{c\text{-opt}}$, SR 500 Hz, 5th MPJ). The resulting MPJ angular range, angular velocity and energy were evaluated, highlighting the differences in the MPJ variables obtained.

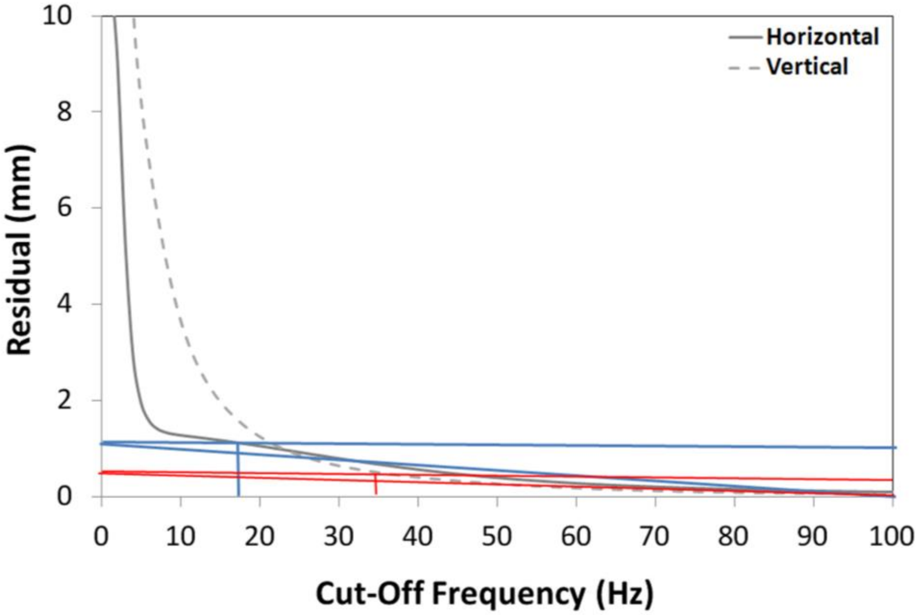
STATISTICAL ANALYSIS

Mean and standard deviations were calculated for all variables across both subjects. A repeated measures ANOVA was used to compare the change in dependent variable (MPJ angular kinematics, joint energy) between the different f_c and *SR* methods. When a significant ($P<0.05$) main effect was observed, Bonferroni *post hoc* tests were calculated to investigate the pairwise differences. A paired *t*-test was used to compare changes in the dependent variables with changes to the MPJ definition ($P<0.05$). All statistical analyses were performed using SPSS for Windows (Version 19.0, SPSSInc., USA)

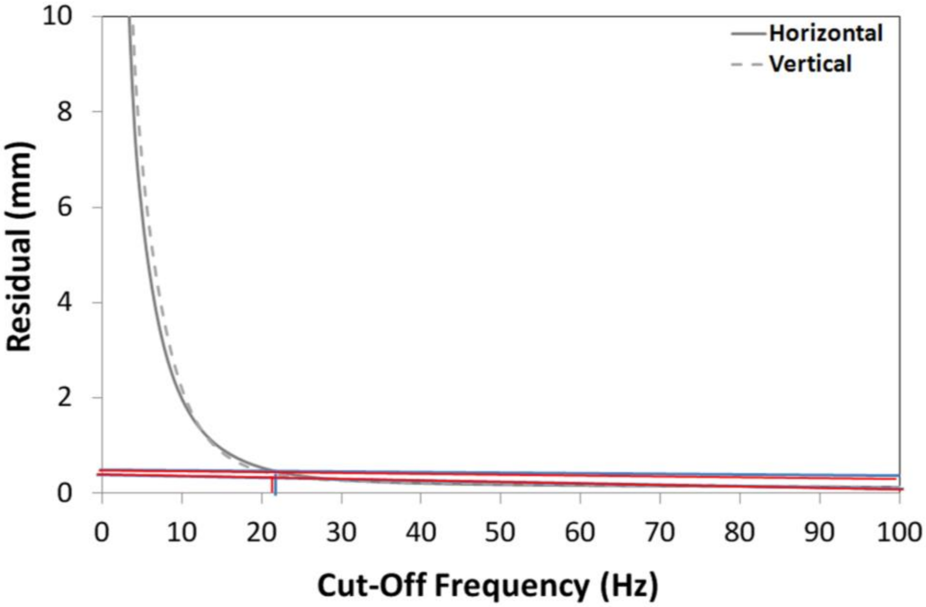
4.3 RESULTS

4.3.1 RESIDUAL ANALYSIS

A sample residual plot for the 5th MPJ is presented in, illustrating the estimated cut-off frequency for motion in the X and Z planes, where X is the anterior-posterior direction and Z the vertical direction, based on an equal balance between signal distortion and the amount of noise which is let through.



(a)



(b)

FIGURE 4.5: RESIDUAL ANALYSIS OF THE 5^{TH} MPJ FOR (A) SUBJECT 1 (B) SUBJECT 2

The f_c selection for each individual marker averaged between both subjects in the barefoot and shod conditions, completed using an objective residual analysis, are listed in Table 4.1.

TABLE 4.1: CUT-OFF FREQUENCIES AVERAGED ACROSS BOTH SUBJECTS

	Cut Off Frequency (Hz)		
Marker Position	Horizontal	Vertical	Mean
Toe	27	26	27
1st MPJ	29	31	30
2/3 MPJ	34	30	32
5th MPJ	20	28	24
Lateral Ankle	18	18	18
Medial Ankle	20	17	19
Average			25

Figure 4.6 compares effect of filtering with an f_c of 8, 16, 24, 32, 48, 64, 80, and 96 Hz on the MPJ angle and angular velocity for ground contact in the acceleration phase of sprinting for each of the subjects.

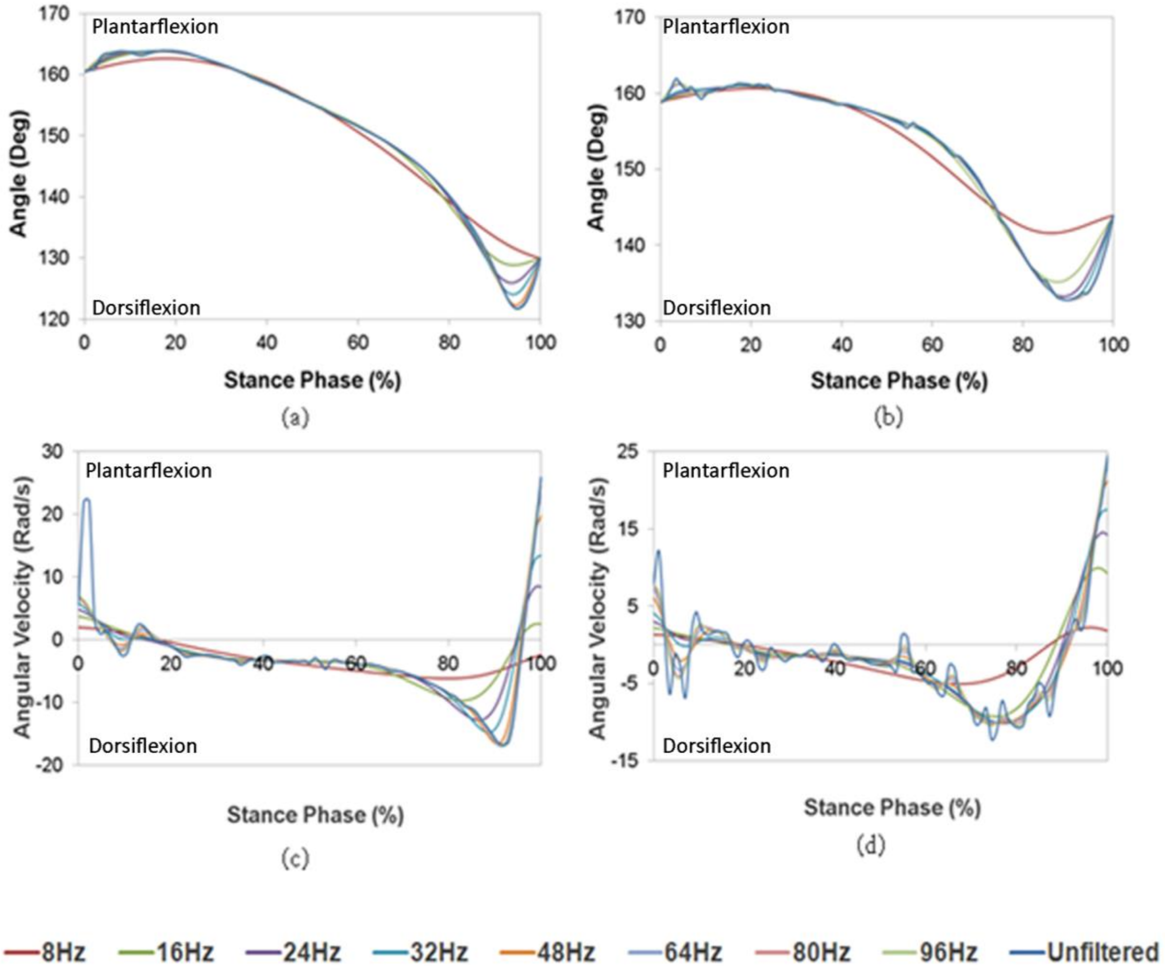


FIGURE 4.6 MPJ ANGLE (AVERAGE 1^{ST} &5TH) FOR (A) SUBJECT 1 (B) SUBJECT 2 AND MPJ ANGULAR VELOCITY FOR (C) SUBJECT 1 (D) SUBJECT 2

The minimum MPJ angle attained was greatly reduced with low cut-off frequencies, for Subject 1 below 48 Hz and for Subject 2 below 24 Hz, when compared to the unfiltered signal. This smoothing of the MPJ angle near take-off reduced the amount of extension at the joint, necessary for joint energy generation. The MPJ angle for data filtered with higher cut-off frequencies produced a much closer approximation of the raw data.

For Subject 1, the MPJ angular velocity appears attenuated with an f_c below 48 Hz. This attenuation is particularly evident at the minimum MPJ angular velocity in dorsiflexion at approximately 90 % of the stance phase. A greatly reduced peak angular velocity at take-off when compared to the unfiltered signal is also evident with an f_c below 48 Hz.

For Subject 2, at the beginning of ground contact, the MPJ angular velocity again appears attenuated, with a filter cut-off frequency below 24 Hz. As the unfiltered data peaks at approximately 13 $rad \cdot s^{-1}$ in plantarflexion, then quickly changes direction to approximately 6 $rad \cdot s^{-1}$ in dorsiflexion early in the stance phase, both of these peaks appear reduced at all levels of f_c compared to the raw condition. As the angular velocity is computed as a derivative of the displacement data, the level of noise is accentuated and it is increasingly difficult to distinguish what the true signal should resemble. Nearing the end of the stance phase, the minimum MPJ angular velocity in dorsiflexion at approximately 75% of the stance phase is similar for cut-off frequencies above 16 Hz. The peak MPJ angular velocity is, however, lower upon take-off when compared to the raw data at cut-off frequencies below 48 Hz.

After reviewing the results of the residual analysis and visual inspection of the effect of filtering on the resulting MPJ dynamics, and averaging the best an optimal f_c of 30 Hz was chosen to be carried forward and utilised in subsequent analyses.

4.3.2 MPJ DYNAMICS

COMPARISON OF COMBINED EFFECT OF ALL DATA COLLECTION AND PROCESSING METHODS

The mean values for MPJ angular range in flexion and extension, maximum and minimum angular velocity, and energy generated and absorbed are presented in Table 4.2, comparing the results obtained utilising the data from Condition 1 (f_c 8 Hz, *SR* 200 Hz, 5th MPJ) versus Condition 2 (f_c 30 Hz, *SR* 500 Hz, 1st MPJ). Both the barefoot and shod conditions are presented.

TABLE 4.2: MEAN MPJ ANGULAR RANGE, ANGULAR VELOCITY AND ENERGY

		Barefoot				**Shod**			
		Condition 1		Condition2		Condition 1		Condition2	
			(SD)		(SD)		(SD)		(SD)
Angle (Deg)	Extension1	1.5	2.7	8.1 *	5.7	0.3	0.6	6.1 *	3.0
	Flexion	34.7	4.8	47.3 *	3.1	29.6	3.9	34.7 *	4.1
	Extension2	2.2	3.6	24.8 *	5.8	0.8	1.7	22.4 *	4.8
Angular Velocity (rad/s)	Min	-6.7	1.1	-21.8 *	3.3	-5.8	0.8	-14.0 *	2.2
	Max	1.7	4.1	44.0 *	7.7	0.6	1.9	40.2 *	7.2
Energy (J)	Generated	0.3	0.6	0.5	0.4	0.2	0.3	0.5	0.4
	Absorbed	-25.2	3.7	-0.5 *	0.6	-12.7	5.9	-0.1 *	0.2

* significantly different from Condition1

There were significant differences between Condition 1 and Condition 2 for each of the variables examined in Table 4.2, apart from in the energy generated at the MPJ, in both the barefoot and shod conditions. As these significant differences in the calculated kinematics and kinetics of the MPJ between Conditions 1 and 2 were so prominent, a detailed examination of the individual effect of the filter cut-off frequency, sampling rate and definition of the MPJ on the MPJ angular range of motion, angular velocity and energy was undertaken.

COMPARISON OF INDIVIDUAL EFFECT OF DATA COLLECTION AND PROCESSING METHODS

MPJ ANGULAR RANGE

The mean MPJ angular range of motion with data subjected to different data collection and processing methods is presented in Table 4.3, for both the barefoot and shod conditions. The data is presented in the individual phases of Extension 1, Flexion, and Extension2 throughout the stance period.

TABLE 4.3: MEAN MPJ ANGULAR RANGE IN BAREFOOT AND SHOD CONDITIONS WITH CHANGES TO F_C, *SR*, AND MPJ DEFINITION (SHADING DENOTES PROCESSING CHANGES FROM CONDITION 1)

MPJ Angular Range								
	Sample Rate (SR)	**Filtering Frequency (*f*c)**	**MPJ**		**Barefoot**		**Shod**	
					Deg	(SD)	Deg	(SD)
Condition 1	500 Hz	30 Hz	1st	Extension1	8.2	5.8	4.9	3.0
				Flexion	-46.0	2.4	-34.6	4.4
				Extension2	23.4	6.7	22.5	4.6
Condition 2	500 Hz	8 Hz	1st	Extension1	6.7	4.7	4.8	3.7
				Flexion	-27.8 *	2.6	-21.4 *	4.7
				Extension2	7.0 *	5.5	9.3 *	5.9
Condition 3	200 Hz	30 Hz	1st	Extension1	8.2	5.8	4.9	3.0
				Flexion	-45.9	2.5	-33.9	5.0
				Extension2	20.3	7.2	16.0	6.4
Condition 4	500 Hz	30 Hz	5th	Extension1	2.3	3.0	0.4	3.0
				Flexion	-38.9 *	2.1	-33.6	4.4
				Extension2	7.2 *	8.7	6.0 *	4.6

* significantly different from *Condition 1*

There was no difference in the MPJ angular range in the Extension 1 phase between any of the processing conditions. There were, however, significant differences in the Flexion and Extension2 phases with changes to the filtering frequency and the MPJ definition. The MPJ angular range of motion for the four conditions is presented in Figure 4.7 for both the barefoot and shod conditions.

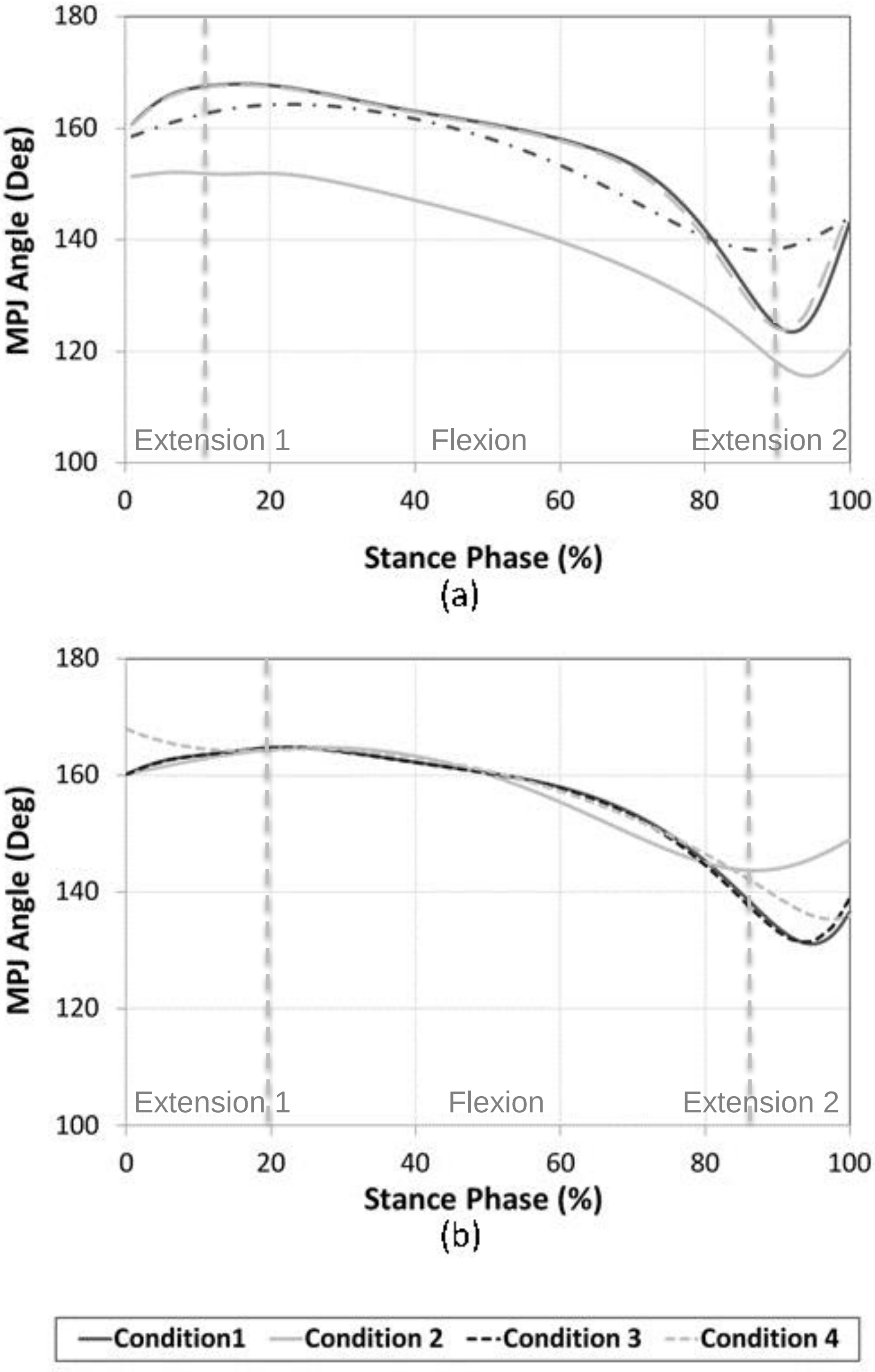


FIGURE 4.7: MEAN MPJ ANGULAR RANGE OF MOTION FOR (A) BAREFOOT AND (B) SHOD CONDITIONS

Utilising an f_c of 8 Hz in Condition 2 compared to an f_c of 30 Hz resulted in the largest decrease in the MPJ angular range in the Flexion and Extension2 phases, for both the barefoot and shod conditions. The plots presented in Figure 4.7 highlight this reduction in MPJ angular range from approximately 80% of the stance phase through to toe off, with evident smoothing of the last stages of flexion, into the Extension2 phase.

Compared to Condition 1, utilising a *SR* of 200 Hz in Condition 3 had no significant effect on any phase of the MPJ angular range. The plots presented in Figure 4.7 display the similarity of the MPJ angle throughout the stance phase comparing a *SR* of 200 and 500 Hz, respectively.

A lateral representation in Condition 4 resulted in significant decreases in MPJ Flexion and Extension 2 ranges of motion compared to the medial representation in Condition1. Examining the plots in Figure 4.7, it is additionally illustrated that for the barefoot condition, the MPJ angle is smaller with a lateral representation throughout the entire stance phase, in addition to visible smoothing late in Flexion and into Extension2 into toe off. Although the visible smoothing late in Flexion and into Extension2 into toe off is also evident in the shod condition in Condition 4 compared to Condition 1, generally the MPJ angle is consistent between the first and fourth condition throughout stance.

MPJ ANGULAR VELOCITY

The mean MPJ angular velocity with the kinematic data subjected to different data collection and processing methods is presented in Table 4.4, for both the barefoot and shod conditions. The data is presented as the minimum and maximum values throughout the stance period.

TABLE 4.4: MEAN MPJ ANGULAR VELOCITY IN BAREFOOT AND SHOD CONDITIONS WITH CHANGES TO F_C, *SR*, AND MPJ DEFINITION (SHADING DENOTES PROCESSING CHANGES FROM CONDITION 1)

MPJ Angular Velocity								
	Sample Rate (SR)	**Filtering Frequency (*f*c)**	**MPJ**		**Barefoot**		**Shod**	
					rad·s^{-1}	(SD)	rad·s^{-1}	(SD)
Condition 1	500 Hz	30 Hz	1st	Min	-20.1	2.3	-13.5	2.3
				Max	37.0	9.5	34.3	5.2
Condition 2	500 Hz	8 Hz	1st	Min	-6.8 *	0.8	-6.2 *	1.3
				Max	10.4 *	4.0	8.1 *	3.8
Condition 3	200 Hz	30 Hz	1st	Min	-19.5	2.3	-13.0	2.1
				Max	30.3 *	9.1	26.3	6.0
Condition 4	500 Hz	30 Hz	5th	Min	-10.8 *	1.6	-9.6 *	3.6
				Max	13.6 *	14.0	11.1 *	8.8

* significantly different from *Condition 1*

There was a significant difference in the minimum angular velocity between Condition 1 and Conditions 2 and 4 in both the barefoot and shod conditions. There was also a significant difference in the maximum angular velocity between Condition 1 and Conditions 2, 3 and 4 in the barefoot conditions and Conditions 2 and 4 in the shod condition. The MPJ angular velocity for the four conditions is presented in Figure 4.8 for both the barefoot and shod conditions.

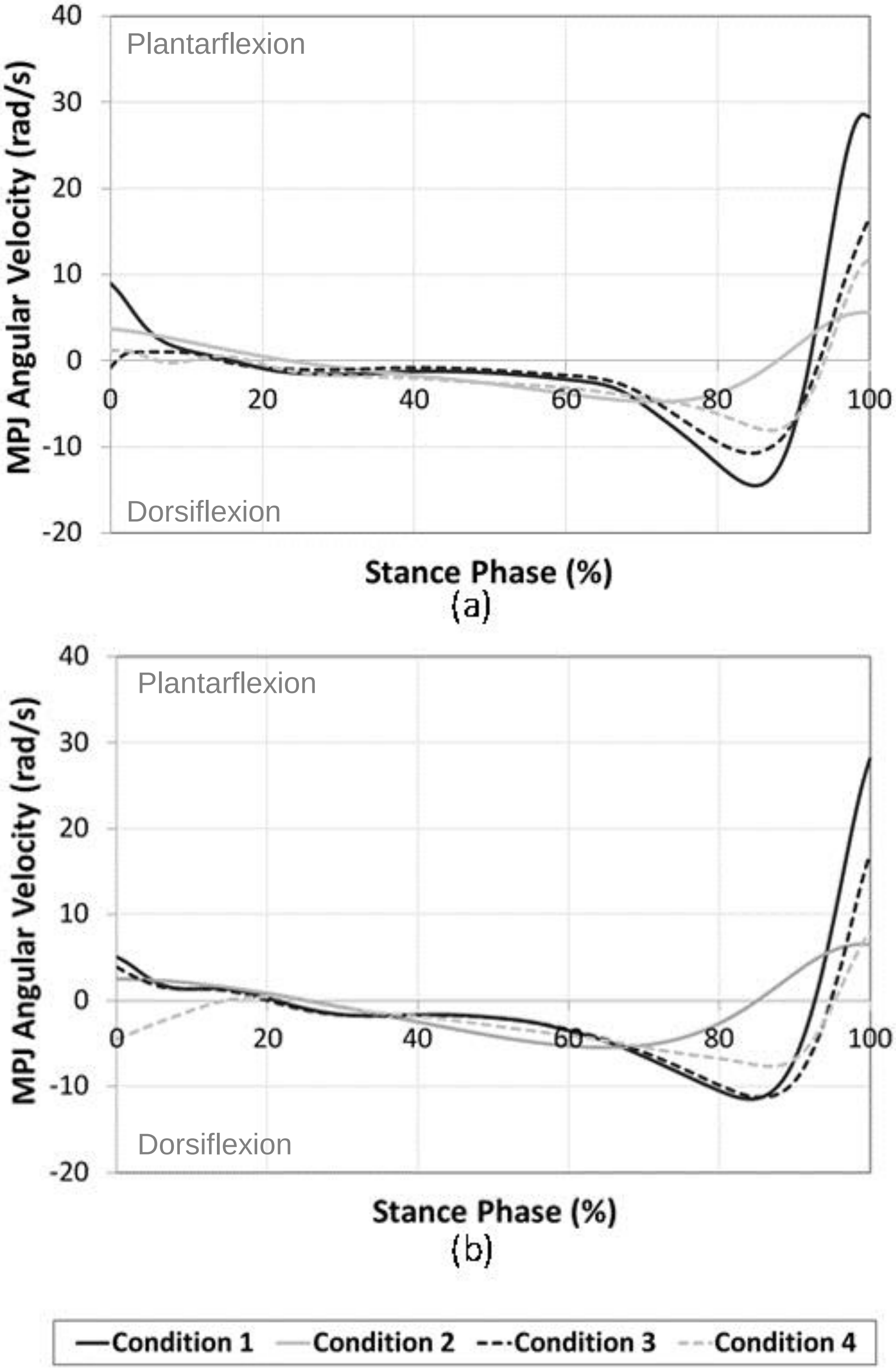


FIGURE 4.8: MEAN MPJ ANGULAR VELOCITY FOR (A) BAREFOOT AND (B) SHOD CONDITIONS

Utilising an f_c of 8 Hz in Condition 2 compared to an f_c of 30 Hz resulted the largest decrease in both the maximum and minimum values of MPJ angular velocity achieved, for both the barefoot and shod conditions. The plots presented in Figure 4.8 highlight this reduction in MPJ peak angular velocities, from approximately 70% of the stance phase through to toe off, with evident smoothing of the last stages of dorsiflexion into the plantarflexion phase.

Compared to Condition 1, utilising a *SR* of 200 Hz in Condition 3 lead to a significant decrease only in the maximum MPJ angular velocity between Conditions 1 and 3 in the barefoot condition. The plots presented in Figure 4.8 show that the MPJ angular velocity for Condition 3 follows the curve of Condition 1 more closely than the other two conditions throughout stance, with less severe smoothing of the peak dorsiflexion and planterflexion values nearing toe-off.

A lateral representation in Condition 4 resulted in significant decreases in MPJ maximum and minimum values of angular velocity compared to the medial representation in Condition1. The plots presented in Figure 4.8 highlight this reduction in MPJ peak angular velocities from approximately 70% of the stance phase through to toe off, with evident smoothing of the last stages of dorsiflexion into the plantarflexion phase.

MPJ ENERGY

The mean MPJ energy with the kinematic data subjected to different data collection and processing methods is presented in Table 4.5, for both the barefoot and shod conditions. The data is presented as the energy generated and absorbed throughout the stance period.

TABLE 4.5: MEAN MPJ ENERGY IN BAREFOOT AND SHOD CONDITIONS WITH CHANGES TO F_C, *SR*, AND MPJ DEFINITION (SHADING DENOTES PROCESSING CHANGES FROM CONDITION 1)

MPJ Energy								
	Sample Rate (SR)	**Filtering Frequency (*fc*)**	**MPJ**		**Barefoot**		**Shod**	
					rad·s^{-1}	(SD)	rad·s^{-1}	(SD)
Condition 1	500 Hz	30 Hz	1st	Generated	0.5	0.4	0.4	0.3
				Absorbed	-0.6	0.6	0.0	0.0
Condition 2	500 Hz	8 Hz	1st	Generated	0.2	0.2	0.3	0.3
				Absorbed	-0.4	0.5	-0.1	0.3
Condition 3	200 Hz	30 Hz	1st	Generated	0.1	0.1	0.1	0.1
				Absorbed	-0.4	0.6	0.0	0.0
Condition 4	500 Hz	30 Hz	5th	Generated	0.9	1.0	0.8	1.3
				Absorbed	-26.6 *	3.8	-18.2 *	3.0

* significantly different from *Condition 1*

The only difference in the MPJ energy from Condition 1 was a significant increase in the MPJ energy absorbed in Condition 4, for both the barefoot and shod conditions. The MPJ power for the four conditions is presented in Figure 4.9 for both the barefoot and shod conditions.

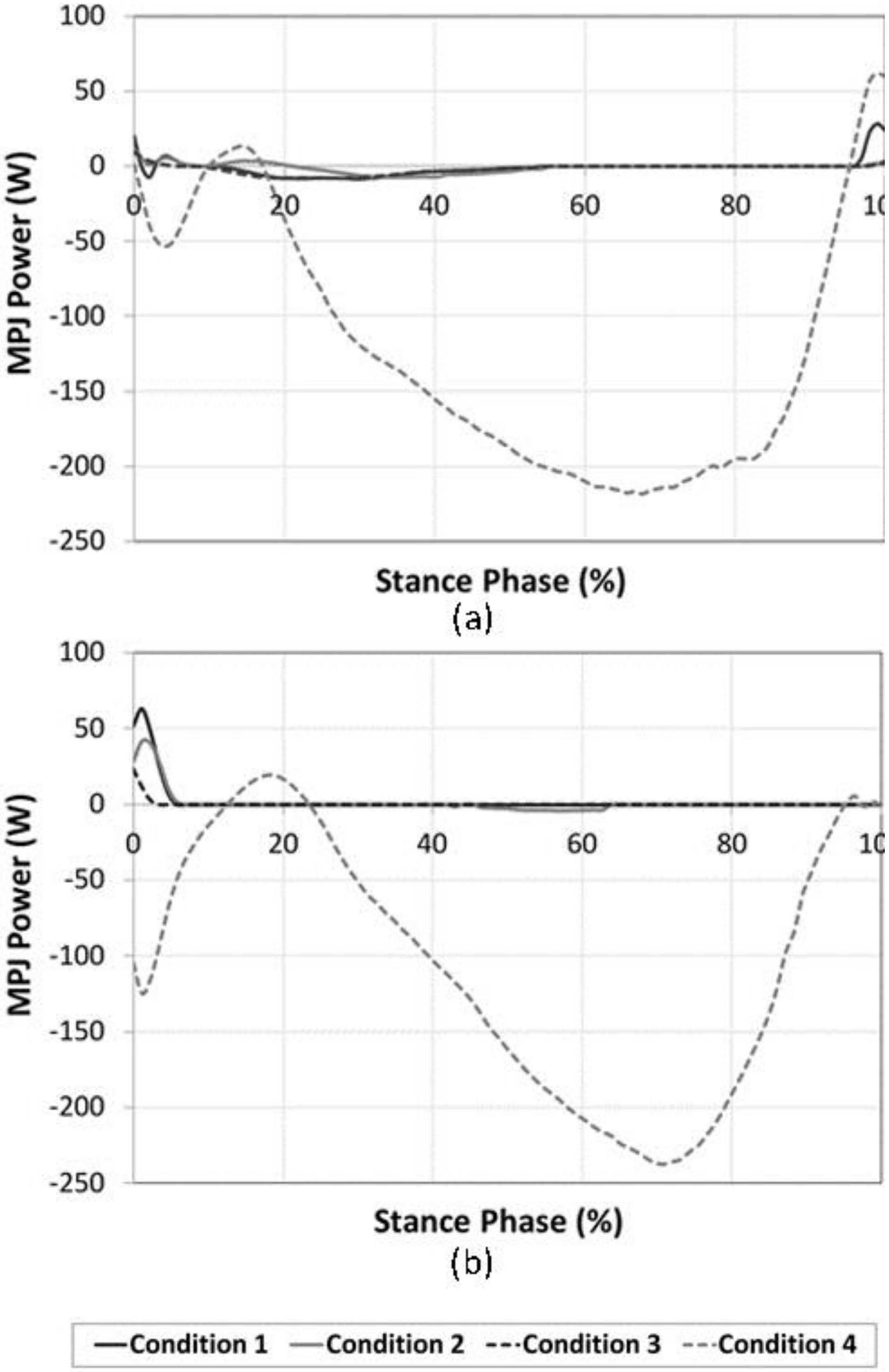


FIGURE 4.9: MEAN MPJ POWER FOR (A) BAREFOOT AND (B) SHOD CONDITIONS

The plots in Figure 4.9 highlight the reduction in MPJ power with a medial representation of the joint, in Conditions 1 through 3, compared to the lateral representation, shown in Condition 4, throughout the stance phase.

4.4 DISCUSSION

The current study found the MPJ angular range of motion to be consistent with previous literature when using similar data collection and processing methods. Bezodis *et al*. (2012) also reported the MPJ dynamics from the second step from the blocks in a maximal effort sprint and found the MPJ mean ranges of motion in excess of 30° (*fc* 24 Hz, SR 200 Hz, 5th MPJ), similar to the value 38.9 ± 2.1° and 33.6 ± 4.4º reported in this work for Condition 4 (*fc* 30 Hz SR 500 Hz, 5th MPJ) in the barefoot and shod conditions, respectively. Bezodis *et al*. (2012) also reported a mean MPJ energy of -31.3 J (*fc* 24 Hz, SR 200 Hz, 5th MPJ), consistent with the -26.6 J and -18.2 J reported in Condition 4 (*fc* 30 Hz SR 500 Hz, 5th MPJ) for the barefoot and shod conditions, respectively.

The purpose of this work was to investigate the effect of commonly used data collection and processing methodologies on the resulting MPJ kinematics and kinetics during a stance phase in sprinting. It was hypothesised that the combined impact of commonly used kinematic sampling rates, filtering procedures, and MPJ definition used by Stefanyshyn and Nigg (1997; 1998; 2000) would to lead to an underestimation of the MPJ angular kinematics and kinetics. With regards to the individual variables, it was hypothesised that changes to the definition of the MPJ would lead to the largest changes in the resulting kinematics and kinetics at the joint.

When comparing the combined effect of utilising commonly used data collection and filtering rates in Condition 1 (*fc* 8 Hz, SR 200 Hz and 5th MPJ), the results showed that compared to Condition 2 (*fc* 30 Hz, SR 500 Hz and 1st MPJ) there were significant differences between all the kinematic and kinetic variables examined at the MPJ, apart from the energy generated at the joint. With regards to MPJ angular range and angular velocity, the hypothesis was supported in that the use of Condition 1 (i.e. the commonly used data collection and processing methods) lead to a significant underestimation of the MPJ angular range of motion, throughout all three phases of flexion-extension, and angular velocity.

With regards to the energy generation and absorption at the MPJ, it was hypothesised that commonly used data collection and processing methodologies used in Condition 1 (f_c 8 Hz, SR 200 Hz, 5th MPJ) would lead to an underestimation of the MPJ energy values obtained compared to Condition 2 (f_c 30 Hz, *SR* 500 Hz, 1st MPJ). However, contrary to the hypothesis, Condition 1 resulted in significantly higher values for the MPJ energy absorption while the energy generated remained unchanged between Condition 1 and 2. Further examination of the effect of the individual data collection and processing methodologies highlighted the individual effect of each variable on the particular MPJ dynamics and are further discussed below.

The MPJ angular range of motion was shown to be affected most with changes to *fc* and MPJ definition, while there were no significant difference in the MPJ angular range of motion with changes to the sampling rate between Condition 1 (SR 500 Hz) and Condition 3 (200 Hz). A decrease in the f_c to 8 Hz in Condition 2 lead to a significant underestimation of the MPJ angular range in Flexion and Extension2, demonstrated in Figure 4.7 as obvious smoothing in the MPJ angular range nearing toe off compared to Condition 1. Further, the use of the 5th MPJ (Condition 4) as opposed to the 1st (Condition 1) lead to a significant underestimation of the MPJ angular range of motion in Flexion and Extension2, in agreement with Smith and Lake (2007), again demonstrated in Figure 4.7 as obvious smoothing in the MPJ angular range nearing toe off compared to Condition 1.

A lack of MPJ plantarflexion at toe off in running has been highlighted by Stefanyshyn and Nigg (1997, 1998), indicating that the MPJ dorsiflexes as the athlete rolls onto the forefoot in preparation for toe off, and remains in this dorsiflexed position during toe-off, with little to no plantarflexion at the joint. This lack of MPJ plantarflexion at toe off, however, may be a result of the combined effect of using an *fc* of 8 Hz and 5th MPJ, underestimating the MPJ angular range, missing important aspect of MPJ plantarflexion at toe off, which would be required for energy production at the joint.

The MPJ angular velocity was shown to be significantly influenced by changes to the *fc* and MPJ definition. As with the MPJ angular range of motion, changes to the *SR* resulted in minimal changes to the MPJ angular velocity. Although the change in SR in Condition 3 resulted in a significant reduction in the maximum value of angular velocity in the barefoot condition compared to Condition 1, the magnitude of this reduction was quite small compared to those observed with changes to the *fc* (Condition 2) and MPJ definition (Condition 4). However, compared to Condition 1 (fc 30 Hz, 1st MPJ), both changes to the *fc* in Condition 2 (fc 8 Hz) and MPJ definition in Condition 4 (5th MPJ) resulted in significant underestimations of both the minimum and maximum MPJ angular velocities. As shown in Figure 4.8, the majority of the disparity between the conditions occurs in late stance, with reduced peak rates of dorsiflexion and subsequent plantarflexion prior to toe off in Conditions 2 and 4 compared to Condition1. This smoothing of the peak dorsiflexion and plantarflexion velocities in late stance may result in misleading results with regards to performance. Krell and

Stefanyshyn (2006) determined that male athletes with higher rates of MPJ extension tended to be faster sprinters. The findings of this study indicate that inappropriate *fc* or MPJ definition may miss important aspects of MPJ angular velocity, particularly peak dorsiflexion and/or plantarflexion prior to toe off, resulting in misleading conclusions.

In agreement with the hypothesis that changes in the definition of the MPJ would have the largest effect on the resulting MPJ kinetics, there were no differences in the MPJ energy generated or absorbed at the joint with changes in *fc* or SR compared to Condition 1, while there was a significant difference in the resulting MPJ energy in Condition 4, with a lateral representation of the joint. Compared to Condition 1, Condition 4 resulted in a significant increase in the MPJ energy absorbed at the joint, while there was no change in the energy generated. The change in the MPJ energy absorption with changes in the MPJ definition can either be due to the changes in the kinematics of a medial versus a lateral representation or changes in the lever arm about the MPJ.

With regards to the changes in kinematics, it has been shown in this and previous work (Smith and Lake, 2007) that a medial representation of the MPJ resulted in larger angular range of motion and larger values of angular velocity. However, this increase in MPJ kinematic values with a medial representation, as shown in Condition 1, should lead to an increase in resulting energy values at the MPJ. Since there was actually less absorbed in Condition 1 compared to Condition4, it must be considered that the changes in the lever arm were the overriding factor affecting the resulting MPJ energy values.

When utilising a lateral versus a medial representation of the MPJ, resulting MPJ energy values will be affected by two factors: the first being the assumption made that the resultant joint moment at the MPJ is zero until the point of application of the GRF acts distal to the joint and the second being the change in lever arm of the GRF about the joint.

As the 5th MPJ is proximal to the 1st MPJ, the ground reaction force will pass the 5th MPJ earliest, remaining distal to the 5th MPJ for a longer time than at the 1st MPJ, resulting in a longer time period for which the MPJ moment to act on the joint. In addition, throughout the period where the GRF is distal to the MPJ, the lever arm about the 5th MPJ will be larger than that about the 1st MPJ, contributing to a larger moment about the joint. Therefore, it is clear that the choice of MPJ definition is one that must be made with careful consideration.

4.5 CONCLUSION

Data collection and processing methodologies have been shown to have a significant influence on the resulting MPJ dynamics in sprinting. In this research, the combined effect of commonly used *fc* (8 Hz), SR (200 Hz) and MPJ definition (5th MPJ) lead to a significant decrease in the MPJ angular range of motion through all the phases of MPJ motion, and a significant decrease in MPJ angular velocity in both plantar and dorsi-flexion, in agreement with the hypothesis. However, contrary to the hypothesis tested, the combined effect of commonly used *fc* (8 Hz), SR (200 Hz) and MPJ definition (5th MPJ) led to a significant increase in the energy absorbed at the MPJ while the energy generated remained unchanged. This, however, is thought to be due to the proximal position of the 5th MPJ and to the assumption made that the resultant joint moment at the MPJ was zero until the point of application of the ground reaction force acted distal to the joint, consistent with Stefanyshyn and Nigg (1997, 1998, 2000) rather than the effect of changes to the MPJ angular range and angular velocity.

The iterative analysis highlighted the individual impact of the f_c, *SR* and MPJ definition on the calculated MPJ angular range, angular velocity and energies at the joint. The MPJ angular range of motion was shown to be underestimated by both commonly used f_c and MPJ definition while there were no significant differences with changes to the *SR*. However, the MPJ angular velocity was shown to be underestimated by all three commonly used data processing variables used. With regards to the MPJ energies, the importance of MPJ definition was highlighted. The definition of the MPJ had the greatest effect on the joint energy, with significantly increased energy absorbed at the joint using a medial representation of the MPJ compared to a lateral marker.

Although it is not appropriate to draw general conclusions on the function of the MPJ during sprinting using such a small sample, when examining the role of the MPJ during sprinting, these methodological differences highlighted in this research should be considered carefully. As there have been varying data collection and processing methods utilised when examining the functionality of the MPJ in the literature relating to sprinting and footwear design, the choice of suitable f_c , SR and MPJ definition should be given special consideration. With regards to the definition of the MPJ, as it actually comprises of five joints and moves in three-dimensions, further work in 3D motion to obtain a better understanding of accurately representing MPJ function is recommended for future work. However, in the subsequent chapters of this research, in order to collect data with athletes sprinting more than 10 m, kinematic data collection is restricted to 2D motion capture. The definition of the MPJ in future human performance research in this work must therefore remain in the sagittal plane.

Based on the results of this research, future human performance testing examining the function of the MPJ in sprinting will carefully consider the choice of *fc*, SR and MPJ definition with caution. Specifically, in subsequent chapters of this research, in choosing an f_c, a residual analysis will be used in order to choose an appropriate level of filtering. In addition, a *SR* of 500 Hz or above will be used. With regards to the MPJ, as a lateral representation of the joint was shown to underestimate the joint kinematics, a medial representation of the joint will be used for the kinematic variables. However, as a medial representation has been shown to underestimate the joint kinetics due to the assumption that the resultant joint moment at the MPJ is zero until the GRF acts distal to the joint, similar to Toon (2008) and Stefanyshyn and Nigg (1997), the average of the 1st and 5th MPJ will be used in calculating the position at with the resultant joint moment crosses the joint

5 THE INFLUENCE OF LONGITUDINAL BENDING STIFFNESS ON SPRINTING PERFORMANCE

5.1 INTRODUCTION

While Stefanyshyn and Fusco (2004) have shown an improvement in sprint performance of 0.7%, on average, when increasing the bending stiffness of sprint shoes over commercially available ones, conversely neither Smith et al. (2010) nor Ding et al. (2011) found, on average, any difference in sprinting performance with increased sprint shoe bending stiffness. However, the differences in methodologies used may have led to the confounding results rather than a lack in potential for improved sprinting performance. With the benefits to an elite sprinter of even a very small improvement in performance being so great, the further investigation of the potential improvement in sprinting performance with increased bending stiffness of sprint shoes is justified. However, methodological and statistical limitations with previous studies need to be considered and where possible addressed.

One difference in the methodologies of the previous research is the collection of performance measures throughout different phases of a sprint. While Ding et al. (2011) examined sprint performance from 0 to 25 m, Stefanyshyn and Fusco (2004) measured performance from 20 – 40 m and Smith et al. (2010) from 30 – 40 m. However, throughout a sprint race, the different phases of acceleration and maximal speed sprinting require differences in technique. Additionally, it has been inferred that sprint shoe bending stiffness requirements may vary according to the phase of the race (Toon, 2008). During maximal sprinting, Toon (2008) showed that the MPJ angular range and velocity were significantly reduced in sprint spikes compared to barefoot conditions and the magnitude of the controlling effect was larger in early acceleration compared to the maximal speed phase. In addition, in the investigation of the influence of sprint shoe bending stiffness on the performance of jump metrics correlated to the acceleration and maximal speed phases, Toon (2008) found that found the relationship between maximal jump performance and shoe stiffness was specific to the jump metrics used. Best jump performance was achieved in intermediate stiffness shoes for the squat jumps and high stiffness for bounce drop jumps, with the squat jump performance correlated to the start and early acceleration phases and the drop jump performance related to the maximal speed phase. The effect of increased sprint shoe bending stiffness on sprinting performance in the different phases of a sprint has never been reported in literature. It is therefore important to examine changes in sprint performance with changes to sprint shoe bending stiffness in the different phases of a sprint.

When quantifying changes in sprinting performance, the most obvious measure to use is time. However, as very little is known about the mechanism by which sprint time may improve with changes to sprint shoe bending stiffness, the examination of changes in step characteristics are also important. An athlete's sprint velocity is a function of step length and step frequency, indicating that faster speeds can be achieved when either one or both of the variables are increased as long as the other variable does not undergo a proportionately similar or larger decrease. Step length, step frequency and ground contact time are examples of kinematic factors considered important to sprint performance (Hunter *et al*. 2004; Mero, Luthanen and Komi, 1983; Mero *et al*, 1983).

Despite the confounding results on sprinting performance, a consistent insight across the previously mentioned research groups (Stefanyshyn and Fusco, 2004; Smith et al., 2010; Ding et al., 2011) was that the stiffness required for each athlete for their best performance was participant specific. This highlights the importance of the personalisation aspect when selecting an optimal level of bending stiffness required for each athlete. This in turn draws attention to the methods of analysis. Observed individual behaviour has been shown to be masked by a descriptive group approach (Bates *et al*, 1983) and it is suggested by Bates (1996) that the use of a single subject analysis to be more appropriate when practitioners are concerned with the response of an individual to an intervention rather than the average behaviour of the group. This individual variation in results observed by Stefanyshyn and Fusco (2004), Smith et al. (2010) and Ding et al. (2011) has led to the suggestion of an alternative approach of a combination of group and single participant analysis, allowing for both the observation of group trends and participant specific requirements.

When considering improvements to sprinting performance, Hopkins et al. (1999) suggested that the smallest worthwhile performance enhancement for an elite sprinter is approximately 0.36 to 0.63%. When examining such small variations utilising a small sample size or single participant design, a high level of reliability in the performance measures is necessary. With a high level of reliability small changes in an athlete’s performance can confidently be detected and smaller sample sizes may also be used (Hopkins, 2000). Despite every effort to ensure optimal reliability of a measurement, the levels of reliability in the data may be too low to confidently detect such small changes in sprinting performance and step characteristics with changes in footwear conditions utilising common measurement techniques. While Stefanyshyn and Fusco (2004) reported a performance improvement of 0.02 s over 20 m between the athletes standard condition and the optimal stiffness condition, Smith et al. (2010) reported a typical variation of 0.02 s over 10 m between two trials in the same condition, therefore indicating that any potential performance differences may have been masked by trial to trial variability. Although improvements in reliability can be achieved by increasing the number of trials collected, often when working with elite athletes the amount of trials collected is limited, often by the amount of trials they are willing to complete in one test session. In addition, ensuring that all trials are completed at maximal effort means limiting the trials per test session to what would typically be completed in training. The examination of the reliability of the measures of biomechanical variables in sprinting in a common testing scenario would allow for the identification of appropriate experimental designs for future studies in this area.

The present study seeks to investigate the effect of increasing the bending stiffness of sprint shoes on performance and step characteristics in sprinting within the separate phases of acceleration to maximal speed. Moreover, this work aims to explore both group and individual analysis, highlighting possible group trends and participant specific requirements, exploring the reliability of the measures of sprint performance and step characteristics, allowing for the identification of appropriate experimental designs for future studies in this area.

It was hypothesised that:

- At the group level: the level of bending stiffness associated with the best mean sprinting performance will be lesser in the acceleration phase as opposed the maximal speed phase;
- The stiffness required for each athlete to achieve their best performance will be participant specific;

- Further, should a significant difference in performance be observed, it is hypothesised that an accompanying difference in step characteristics will also be observed.

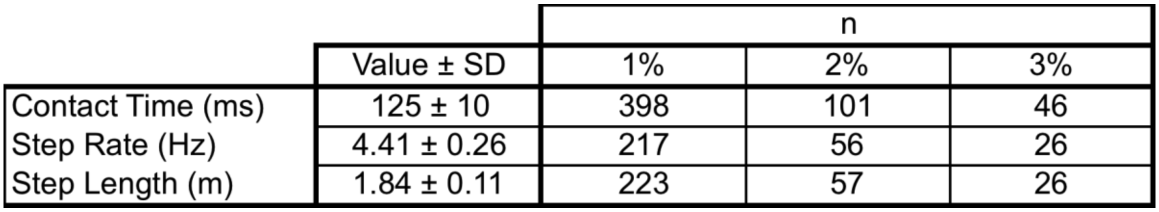
5.2 METHODS

5.2.1 PARTICIPANTS

Three male participants were recruited to participate in the study, designated P1, P2, and P3. Participants were nationally competitive athletes with 100 m personal bests of 10.78 ± 0.35 s with a sprint shoe size of UK8, UK9, or UK10. Experimental methodologies were approved by the Loughborough University ethical advisory committee and informed written consent was obtained prior to testing in accordance with Loughborough University ethical advisory regulations.

A power analysis was conducted a priori to enable a target number of subjects to be identified in order to achieve a power level of 0.8, with a significance level of 0.1. Information on step characteristics in sprinting were utilised from previous literature (Hunter *et al.*, 2004). Since the influence of increased bending stiffness of sprint shoes on step characteristics in sprinting has never been examined, the effect of this intervention is currently unknown. However, as Hopkins *et al.* (1999) suggest that the smallest performance enhancement worthwhile for an elite sprinter is 0.9%, the influence of using a change in step characteristics of 1, 2 and 3% on the necessary sample size were compared in Table 5.1.

TABLE 5.1: VARIATION IN SAMPLE SIZE (N) TO ACHIEVE A POWER OF 0.8 WITH A SIGNIFICANCE OF 0.1 FOR AN EFFECT SIZE OF 1, 2 AND 3%



		n		
	Value ± SD	1%	2%	3%
Contact Time (ms)	125 ± 10	398	101	46
Step Rate (Hz)	4.41 ± 0.26	217	56	26
Step Length (m)	1.84 ± 0.11	223	57	26

The sample sizes necessary to achieve a power level of 0.8 are clearly greater than the three participants identified to participate in this study. However, conducting this research even with such a small sample size will still allow future researchers to gain a better understanding of the potential effect size that increasing the level of bending stiffness of sprint shoes may have on sprinting performance and step characteristics going forward. This will allow for much more educated assessment of the potential effect size and sample sizes necessary to achieve suitable levels of power in future research.

5.2.2 FOOTWEAR

Three different stiffness sprint shoe conditions were evaluated in this work. Each of the footwear conditions had the same traction features as presented in Chapter 3. The three footwear conditions consisted of sprint shoes constructed with different levels of longitudinal bending stiffness: a low (Shoe A), medium (Shoe B) and high (Shoe C) stiffness condition. The bending stiffness of the sprint shoes was modified by increasing the thickness of the sole unit. The low stiffness condition, Shoe A, was chosen to have a bending stiffness to approximately represent the average bending stiffness of current commercially available sprint shoes, acting as the standard condition, and had a sole unit thickness of 2 mm. The high stiffness condition was chosen as the stiffest condition evaluated by Toon (2008), with a sole unit thickness of 8 mm. It was decided that this shoe condition was to be the stiffest considered safe for human performance testing in this work. It was thought that any stiffer might introduce the possibility of injury due to a too severe level of stiffness. This high level of stiffness was chosen in order to examine the feasibility of utilising such a stiff shoe in sprinting and provide a large contrast between the shoe conditions. The middle stiffness shoe was chosen as having a bending stiffness midway between the low and high stiffness conditions, and had a sole unit thickness of 6 mm. The sprint shoes were constructed in sizes UK8, UK9, and UK10 for a total of nine test sprint shoes. A measure of stiffness in both flexion and extension of the all the sprint shoes was obtained using the methodology outlined in Chapter 2, section 2.2. The mechanical properties of the test footwear are documented in Figure 5.1,

Figure 5.2 and Table 5.2. The weight of the shoes were all standardised using strips of lead attached to the outside heel counter and in the tongue, below the shoe laces. The shoes weighed 241 g.

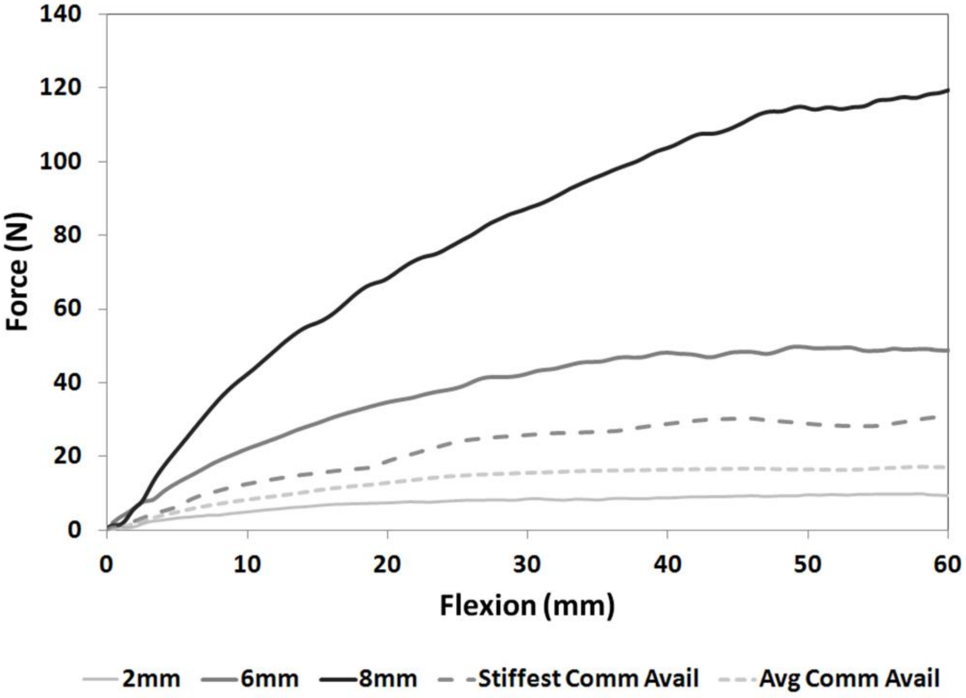


FIGURE 5.1: FORCE VS. FLEXION FOR THE TEST SHOE CONDITIONS AND COMMERCIALLY AVAILABLE OPTIONS (UK9)

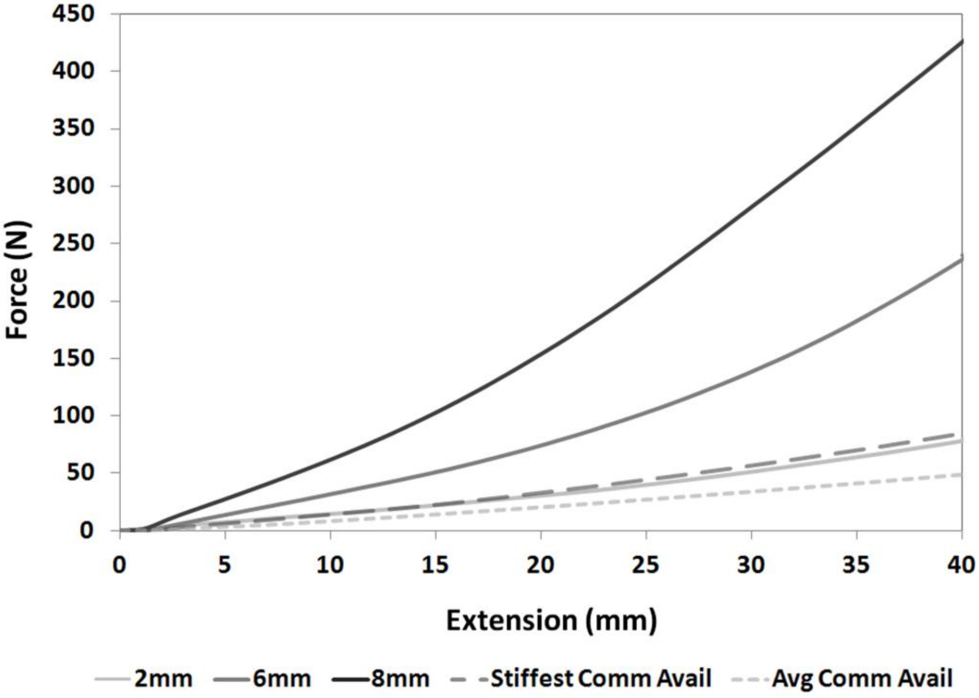


FIGURE 5.2: FORCE VS EXTENSION FOR TEST SHOE CONDITIONS AND COMMERCIALLY AVAILABLE OPTIONS (UK9)

TABLE 5.2: BENDING STIFFNESS RESULTS IN FLEXION AND EXTENSION FOR SHOE CONDITIONS A, B AND C AND THE STIFFEST AND AVERAGE COMMERCIALLY AVAILABLE SPRINT SHOES

	Flexion				Extension			
Shoe	**Mean**	**(SD)**	**Max**	**(SD)**	**Mean**	**(SD)**	**Max**	**(SD)**
UK 9								
A	7.5	0.0	9.9	0.1	34.4	0.1	78.9	0.2
B	37.6	0.2	49.8	0.1	90.9	0.6	240.0	0.2
C	79.9	0.6	119.4	0.5	177.2	0.2	428.0	0.0
UK 10								
A	9.8	0.1	12.5	0.2	42.7	0.2	107.7	0.2
B	37.2	0.2	58.4	0.5	99.8	0.7	254.0	0.2
C	72.9	0.9	105.2	0.9	148.3	1.6	371.4	2.2
UK 11								
A	9.6	0.1	12.3	0.1	37.8	0.1	89.9	0.2
B	46.7	0.5	68.2	0.2	98.1	1.1	277.1	0.9
C	76.9	0.0	108.0	0.6	132.3	1.6	367.8	2.1
Commercially Available								
Stiffest Comm Avail	21.8	0.2	31.0	0.2	42.8	0.7	100.7	1.1
Avg Comm Avail	13.2	0.2	17.9	0.2	24.7	0.6	54.5	0.5

PROTOCOL

Each participant completed three testing sessions. Participants performed their own warm up prior to testing. In the course of one testing session, the participants completed three 50 m sprints. The first testing session (S1) was used to assess the repeatability of the collected data. For this session, the participants completed all three sprint runs in Shoe A. For the remaining two sessions (S2 and S3, respectively), participants completed the three sprint runs in each of the different test shoe conditions. The order in which the shoe conditions were tested was varied in each testing session and the order randomised between the participants. Sufficient rest of a minimum of 5 minutes was given to the athletes between trials. During the warm up, athletes put on the testing shoes for a short, sub maximal sprint for familiarisation and to ensure they were comfortable in the test shoes. Participants started the 50 m sprints from a crouched, ‘rolling’ start position. As the starting performance was not being assessed in this testing, the crouched start position was utilised as an alternative to the more common start from blocks used when racing. The reason for this was to minimise the risk of injury to the athletes as it was thought that starting from blocks might become too difficult as the stiffness of the test shoes increased. Data were collected at an indoor track and field facility when athletes were performing maximum velocity training.

Sprint times were collected using a single beam SmartSpeed wireless timing gate system (Fusion Sport, Australia). The SmartSpeed system has microprocessor capabilities, allowing the timing system to detect and measure the longest break in the beam, ensuring the time recordings are from the torso and not a leading arm or leg breaking the beam. Timing gates were positioned at 15 m intervals at 5, 20, 35 and 50 m. The resolution of the timing system was 0.001 s and a reported typical error of 0.03 s over a distance of 10 to 20 m and a coefficient of variation of 1.7% and 1.0% at a spacing of 10 and 20 m, respectively (D’Auria et al. 1996). The sprint times collected were examined across the entire 45 m interval and at each of the separate 15 m intervals. The first interval (5 to 20 m) was defined as an acceleration phase, the second interval (20 to 35 m) was defined as a mid-acceleration phase, while the last interval (35 to 50 m) was defined as a maximal speed phase.

For each trial, kinematic data in the sagittal plane were collected in the maximal speed phase using a high speed video (HSV) camera (Photron Fastcam – Ultima APX 120K) at a sampling rate of 1000 Hz. Although ideally kinematic data would have been collected in each of the phases in addition to the maximal speed phase, the required set up for this in the available athletics centre were not permitted. The HSV was placed perpendicular to the direction of the sprint, 23 m from the centre of the running lane. A field of view of 4.0 m was used in order to ensure the capture of at least one full step, collecting kinematic data from 40 to 44 m into the sprint run. A step is defined here as from one foot contact to the next contact of the contralateral foot, while a stride refers to two consecutive steps. The resolution of the images was 1024 x 1024 pixels. A 1.0 x 1.0 m calibration frame containing 20 reference points was used for the calibration of the HSV. The frame was positioned in three locations across the 4.0 m field of view, in the centre of the running lane in the sagittal plane. The horizontal and vertical scaling factors were calculated separately and averaged across the three positions to obtain the respective horizontal and vertical scaling factors. A total of 1600 W of floodlighting was used for each HSV capture volume to provide a sufficiently bright image on the camera images.

DATA ANALYSIS

The HSV data collected was used to measure step frequency, step length, and ground contact time. Step length was calculated as the displacement of the distal end of the support foot in the first field after touchdown in two consecutive foot contacts (Bezodis, Salo, and Kerwin, 2007). Ground contact time was obtained using visual assessment of the HSV. Ground contact time was calculated as the time spent on the ground and was averaged between the consecutive, contralateral contact phases. Step frequency was calculated as the number of steps per second, taken as the inverse of the time to complete one step. HSV files were manually digitised (Vicon Motus v9, Vicon Motion Systems, Oxford UK). Data consistency was assessed through the re-digitising of four HSV files on separate days and comparing the resulting step characteristics data with the corresponding original digitised data sets. Root mean square values of ground contact time, stride rate and stride length were calculated for the repeated digitisation.

A repeated measures ANOVA was used to compare the dependent variables (SPSS 19 for Windows, SPSS Inc., USA) for the sprint time and kinematic data averaged across the participants. In statistical studies, the observed sample is assumed to be drawn randomly from the population of interest, with inferences from the smaller group to be applied to the larger population. Although parametric methods make an assumption of a normal distribution of the sample population, which indicates that parametric methods may not be appropriate for use with small sample sizes and single subject studies, Caster et al. (1994), outlines that most statistical tests are robust to deviations from normality, and that the use of a non-normal data set should not limit the use of traditional parametric statistics on small or single subject studies. Additionally, it has been argued that acceptable to use traditional methods to investigate whether a relationship exists in a single subject or small sample and then to subsequently use logical grounds to generalise the results for the remainder of the population (Dixon, 1996; Edington, 1967).

An alternative to the parametric method is the use of non-parametric methods of statistical analysis, which does not make assumptions about the distribution of the sampled population. A disadvantage though, is that they often produce a rank order, rather than numerical results, and have relatively low statistical power. However, as the concern in this work is with the personalisation of footwear for individuals and small groups of subjects, not the general population, the suitability of traditional ANOVA procedures in the analysis of the results from a small sample size is acceptable.

A level of significance of $P < 0.10$ was chosen as the consequences of a Type I error are minor compared to the benefit of a possible positive effect at this point in the research. This level of significant is less stringent than the level typically used in biomechanics research of $P < 0.05$, leading to the increased probability of a Type I error occurring. As the probability of a Type I error is increased, the probability of a Type II error is reduced. In agreement with Franks and Huck (1986), at this stage of exploratory research in the field, Type II errors should be minimised as the failure to reject a null hypothesis when in fact there is a relationship would be detrimental to the continued research in this area. When a significant ($P < 0.10$) effect was observed, Least Significant Differences (LSD) *post hoc* tests were calculated to investigate the pairwise differences. Although the LSD test is quite liberal, and has a high risk of Type I errors, as previously discussed at this point in the exploratory research the occurrence of a Type II error is of greater concern.

A power analysis was conducted post hoc to enable a target number of subjects to be identified for further research in this area. A target power level of 0.8, with a significance level of 0.1, were utilised as the parameters.

Three measures of within-participant variation for the each of the participants were assessed: the largest change in the measured value between trials (maximum effect size), standard deviation (SD) and coefficient of variation (CV) [$CV=(\sigma/\mu)*100$ where σ=standard deviation and μ=mean]. Although the three variables are inter-related, they each give a different perspective for comparison, with the maximum effect size and standard deviation specific comparisons only able to be made within the variable of interest, while the CV allows for the comparison of different variables regardless of the measurement units. The reliability of the data collected was assessed using comparisons between the data collected in S1, where all the trials were completed in the same shoe condition, and S2 and S3, where all the trials were completed different shoe conditions, to see if the variability in the biomechanical data was in fact greater in the different shoe conditions. If the measures of reliability are lower (i.e. a higher level of repeatability) in S1 than S2/S3, it is then considered to be acceptably reliable.

5.3 RESULTS

5.3.1 REPEATABILITY OF DIGITISATION

The mean and RMS differences in ground contact time, stride rate and stride length over three repeated digitisations conducted on separate days are presented in Table 5.3.

TABLE 5.3: MEAN AND RMS DIFFERENCES BETWEEN FOUR REPEATED DIGITISATIONS FOR STRIDE CHARACTERISTICS

		Mean	RMS
Contact Time	(s)	0.0987	0.0003
Stride Rate	(Hz)	4.49	0.02
Stride Length	(m)	2.19	0.01

5.3.2 GROUP MEAN

SPRINT TIMES

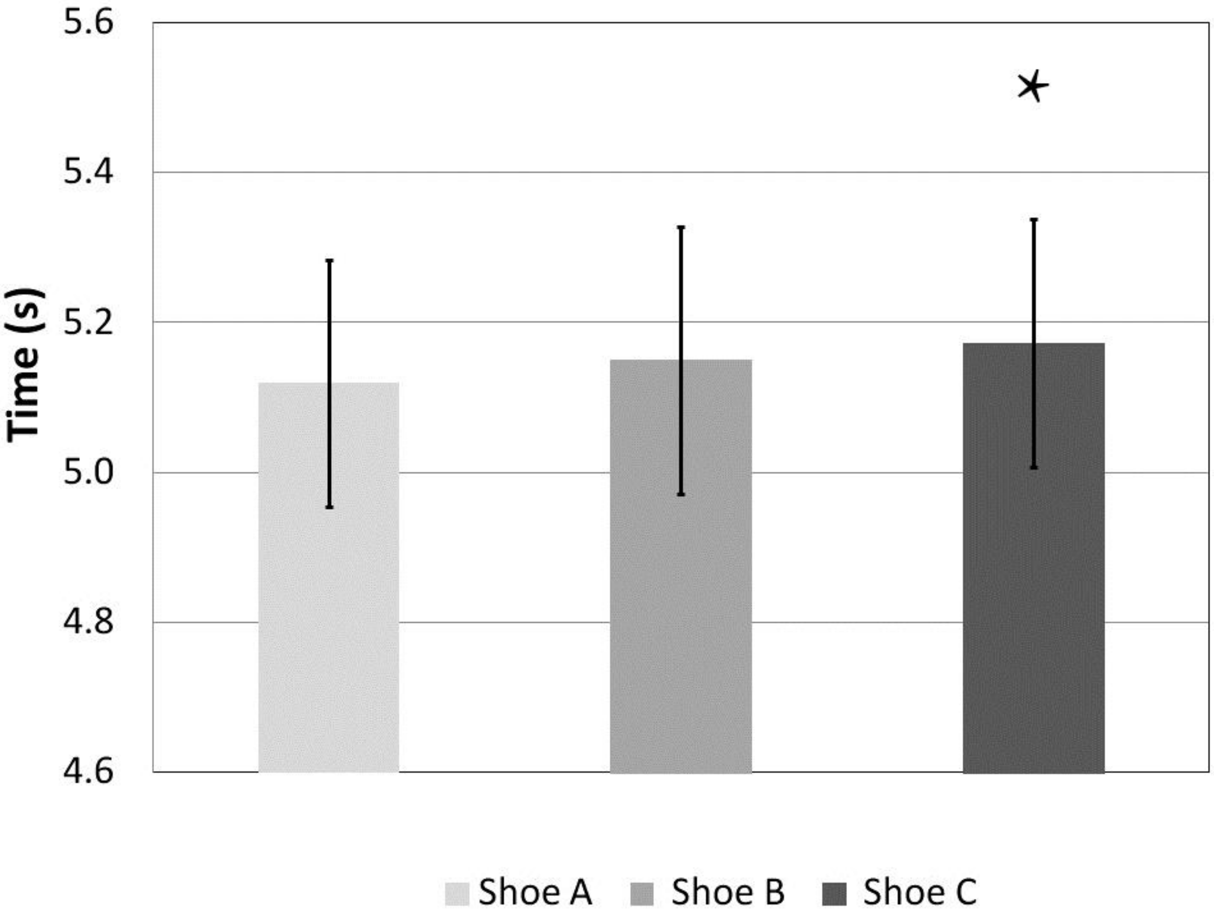


Figure 5.3 shows the group mean sprint time and standard deviation for trials completed in the three shoe conditions between 5 and 50 m, for all the participants. The plot shows that on average, sprint time increased with increased bending stiffness, with a 0.6% increase in sprint time in Shoe B compared to Shoe A and a significant (P = 0.05) increase of 1.1% in sprint time in Shoe C compared to Shoe A.

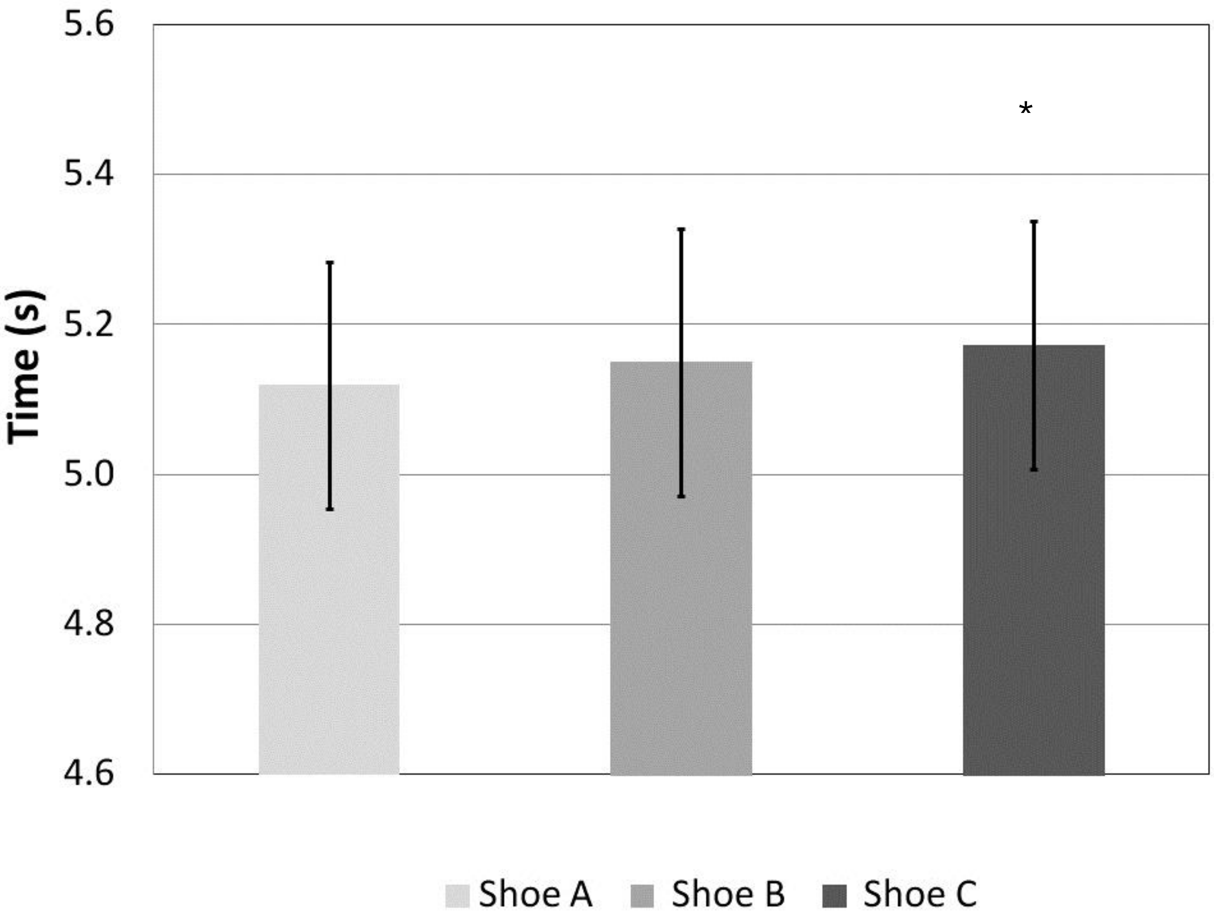


FIGURE 5.3: MEAN SPRINT TIME BETWEEN 5 TO 50 M FOR ALL PARTICIPANTS IN S2 AND S3 (* INDICATES SIGNIFICANT DIFFERENCE FROM SHOE A (P < 0.1))

Figure 5.4 shows the mean sprint time and standard deviation for S2 and S3 in the three shoe conditions for each of the 15 m intervals between 5 and 50 m, across all participants. Between 5 and 20 m, there were no differences between the footwear conditions. Between 20 and 35 m, compared to Shoe A, sprint time increased significantly (P = 0.04) in Shoe B by 1.5% and significantly (P = 0.07) in Shoe C by 1.6%. Between 35 and 50 m, compared to Shoe A, sprint time increased significantly (P = 0.03) in Shoe B by 0.6% and significantly (P = 0.1) in Shoe C by 1.4%.

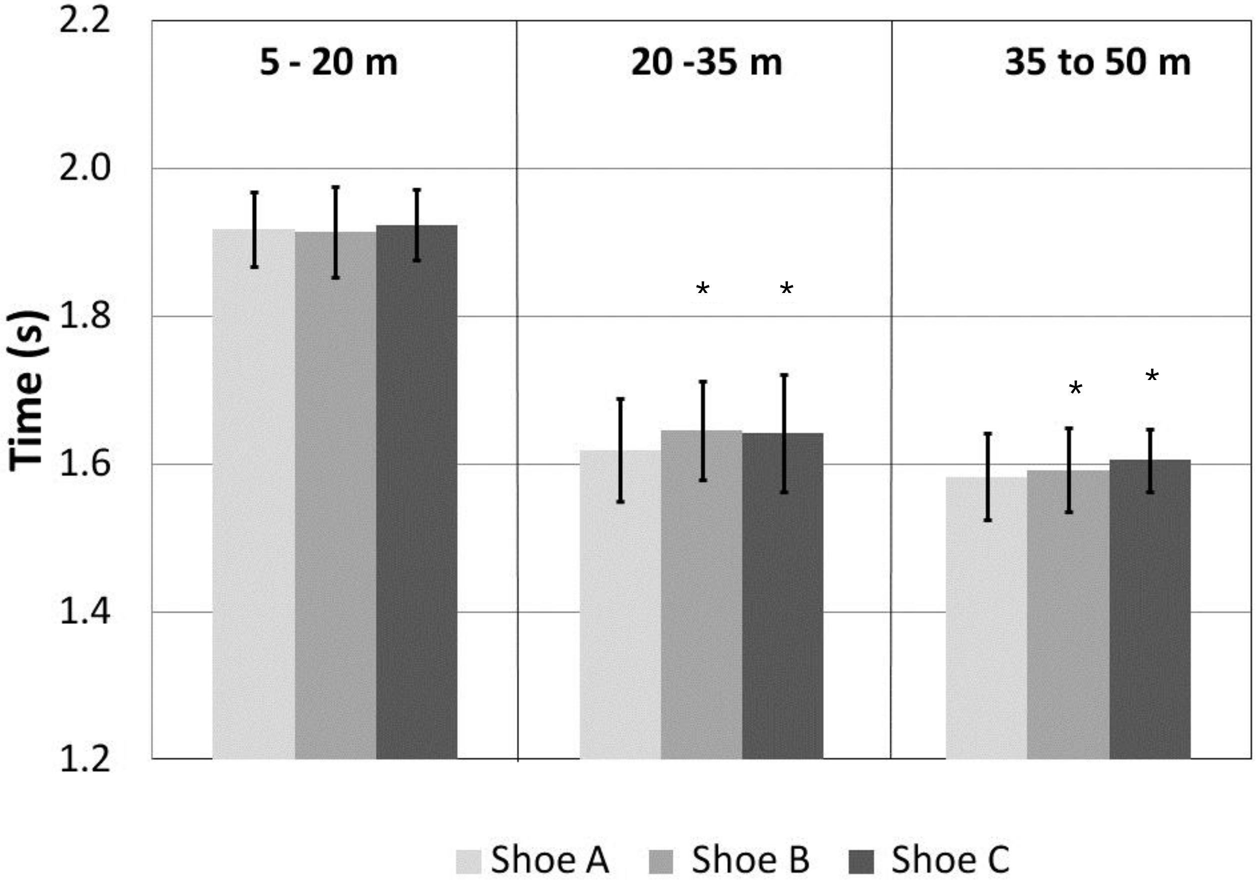


FIGURE 5.4: MEAN SPRINT TIME FOR THE 15 M INTERVALS FOR ALL PARTICIPANTS IN S2 AND S3 (* INDICATES SIGNIFICANT DIFFERENCE FROM SHOE A (P < 0.1))

STRIDE CHARACTERISTICS

Figure 5.5 shows the mean ground contact time and standard deviation for the three shoe conditions for all of the participants in S2 and S3. The plot shows that on average, ground contact time was reduced in both Shoe B and C compared to Shoe A, with a significant (P = 0.03) decrease of 2.1 % in Shoe B and a significant (P = 0.03) decrease of 3.4 % in Shoe C.

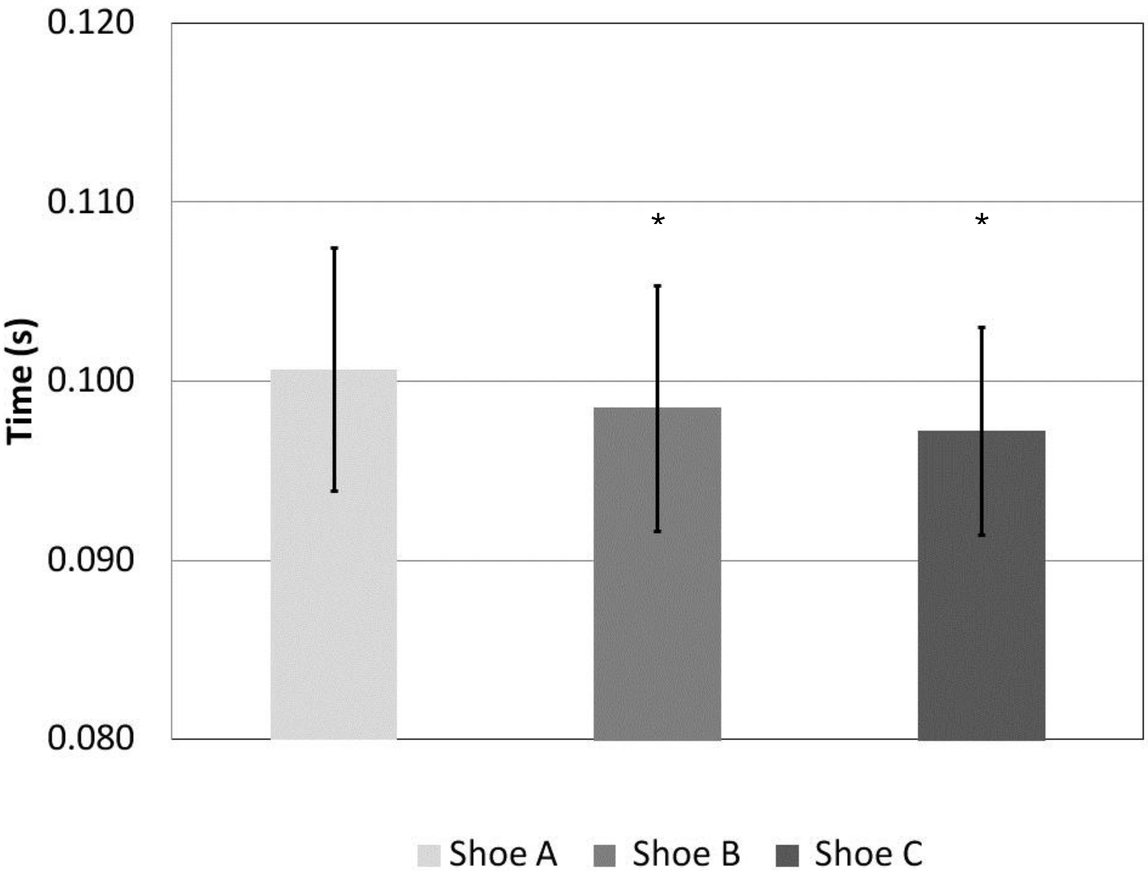


FIGURE 5.5: MEAN GROUND CONTACT TIME AND STANDARD DEVIATION FOR ALL PARTICIPANTS IN S2 AND S3 (* INDICATES SIGNIFICANT DIFFERENCE FROM SHOE A (P < 0.1))

Figure 5.6 shows the mean stride rate and standard deviation for the three shoe conditions for all of the participants in S2 and S3. The plot shows that there were no significant differences in the stride rate between the three shoe conditions.

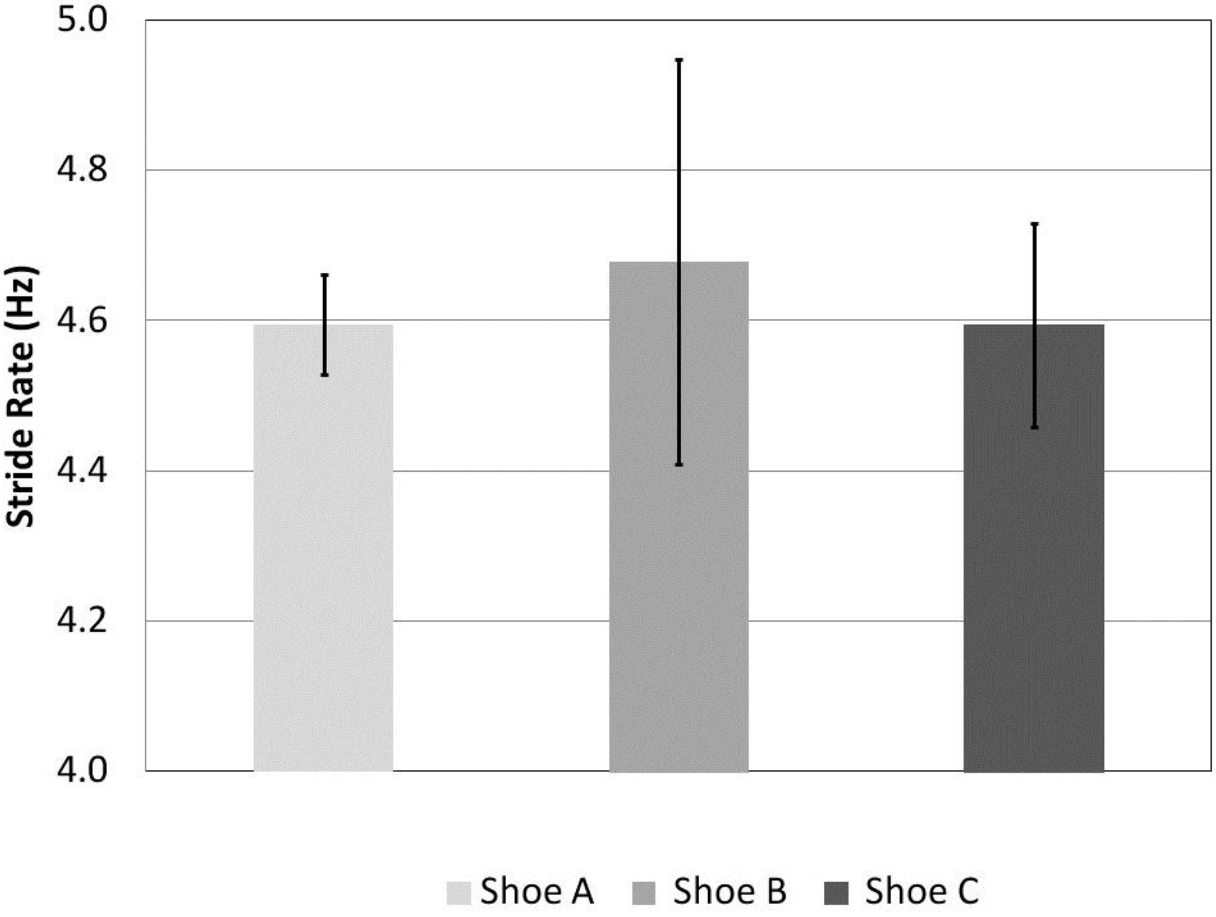


FIGURE 5.6: MEAN STRIDE RATE AND STANDARD DEVIATION FOR ALL PARTICIPANTS IN S2 AND S3

Figure 5.7 shows the mean stride length and standard deviation for the three shoe conditions for all of the participants in S2 and S3. The plot shows that there were no significant differences in the stride length between the three shoe conditions.

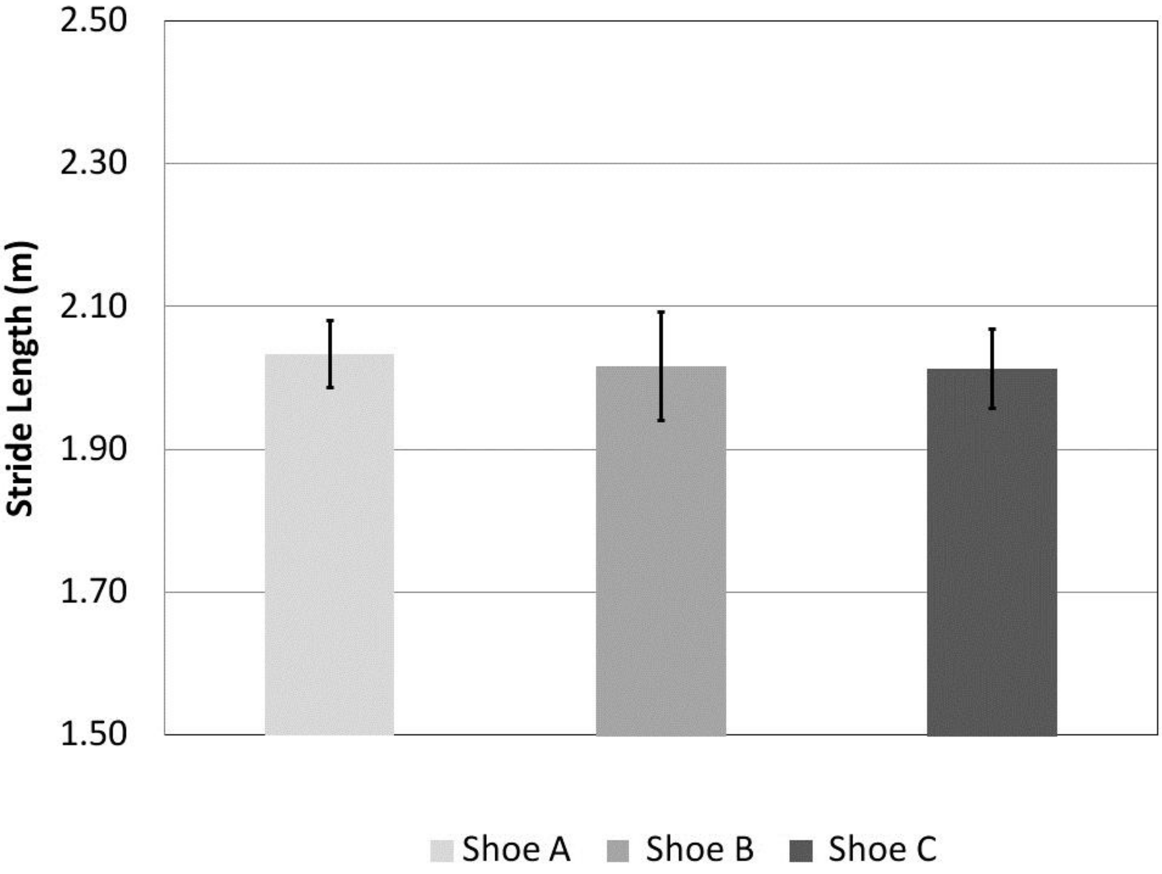


FIGURE 5.7: MEAN STRIDE LENGTH AND STANDARD DEVIATION FOR ALL PARTICIPANTS IN S2 AND S3

The calculated power levels and the associated number of subjects (n) necessary to achieve a power level of 0.8 with the effect size from the current research, with a significance level of 0.1, are presented in Table 5.4.

TABLE 5.4: THE POWER ACHIEVED AND THE TARGET SAMPLE SIZES (N) NECESSARY TO ACHIEVE A POWER OF 0.8 GIVEN THE EFFECT SIZE

	Power		**n**	
Variable	S1-S2	S1-S3	S1-S2	S1-S3
Step Characteristics				
Stance Time (ms)	0.13	0.17	64	23
Step Rate (Hz)	0.16	0.10	27	2560
Step Length (m)	0.12	0.12	85	65
Sprint Times				
5 to 20 m	0.10	0.10	1111	615
20 to 35m	0.14	0.13	43	61
35 to 50m	0.11	0.12	261	94
5 to 50 m	0.11	0.10	189	359

INDIVIDUAL RESULTS

Figure 5.8 shows the mean and individual sprint times between 5 and 50 m for S2 and S3 for each of the participants completed in the three shoe conditions. The plot shows that for the mean of the two sessions, S2 and S3, the best shoe condition for P1 and P3 was Shoe A, while P2 performed best in Shoe B. However, P1 was the only one of the three participants to maintain the same pattern of performance ranking in the different shoe conditions between both sessions.

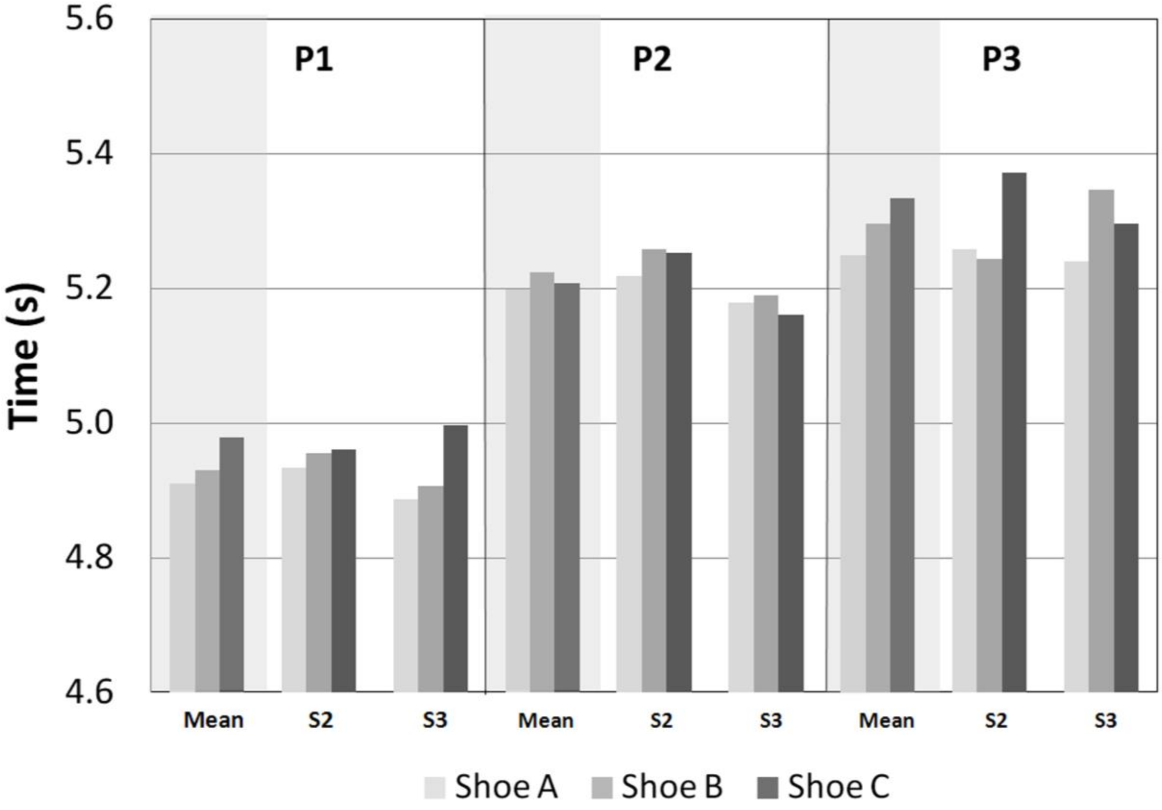


FIGURE 5.8: INDIVIDUAL SPRINT TIME BETWEEN 5 TO 50 M FOR EACH PARTICIPANT IN S2 AND S3

Figure 5.9 through Figure 5.11 show the mean and individual sprint times for the 15 m intervals between 5 and 50 m for sessions S2 and S3, individually for each participant. The mean sprint times for both S2 and S3 show that the best shoe conditions varied between the participants in the acceleration phase, while throughout the mid-acceleration and maximal speed phases, all of the participants performed best in the Shoe A condition. However, examination of the individual trials show very little repeatability in the performance ranking in the different shoe conditions through the majority of the sprint intervals across S2 and S3. Apart from for P1 and P2 between 35 to 50 m, there was no repetition of the same pattern of performance ranking in the different shoe conditions between both S2 and S3.

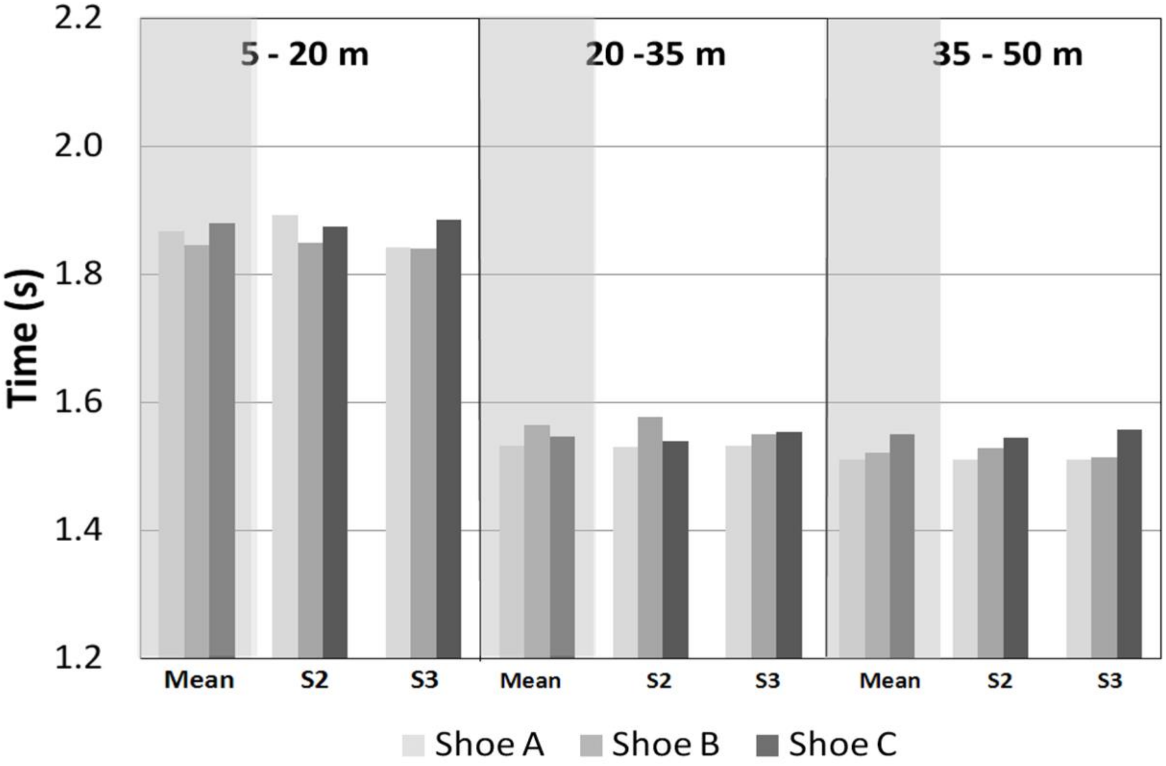


FIGURE 5.9: INDIVIDUAL SPRINT TIMES FOR P1 AT 15 M INTERVALS BETWEEN 5 TO 50 M IN S2 AND S3

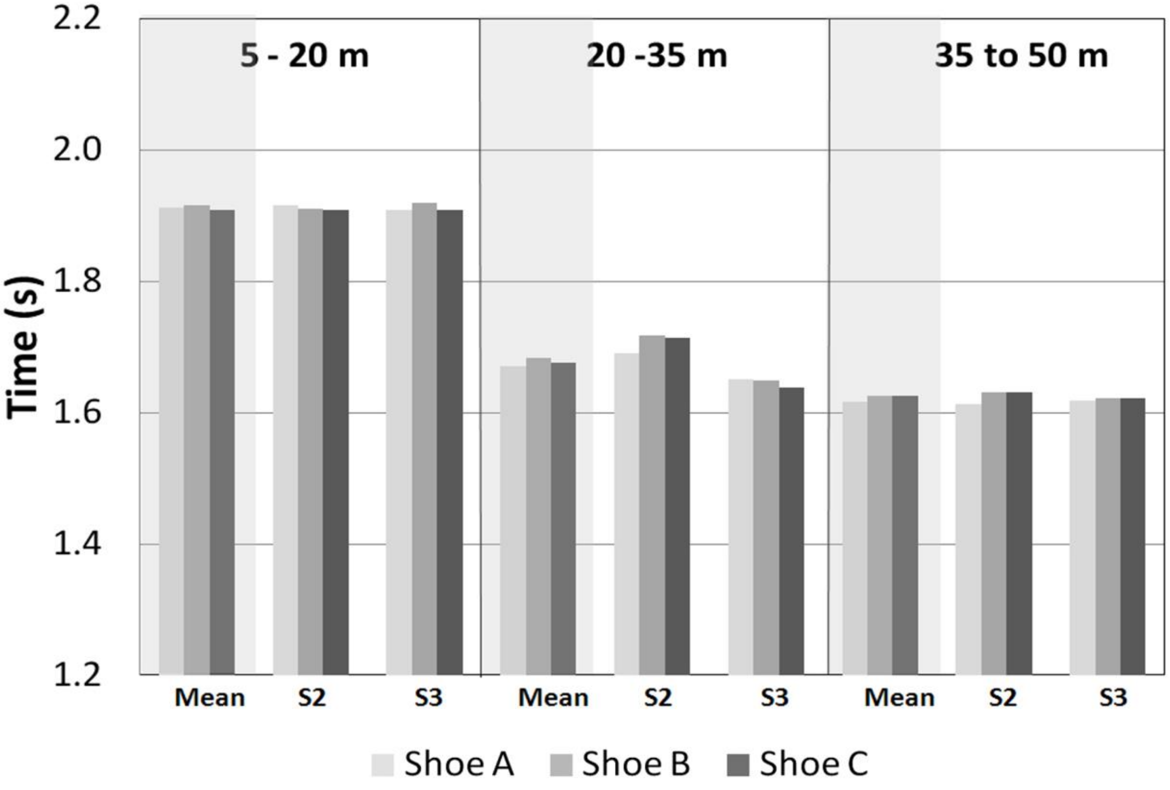


FIGURE 5.10: INDIVIDUAL SPRINT TIMES FOR P2 AT 15 M INTERVALS BETWEEN 5 TO 50 M IN S2 AND S3

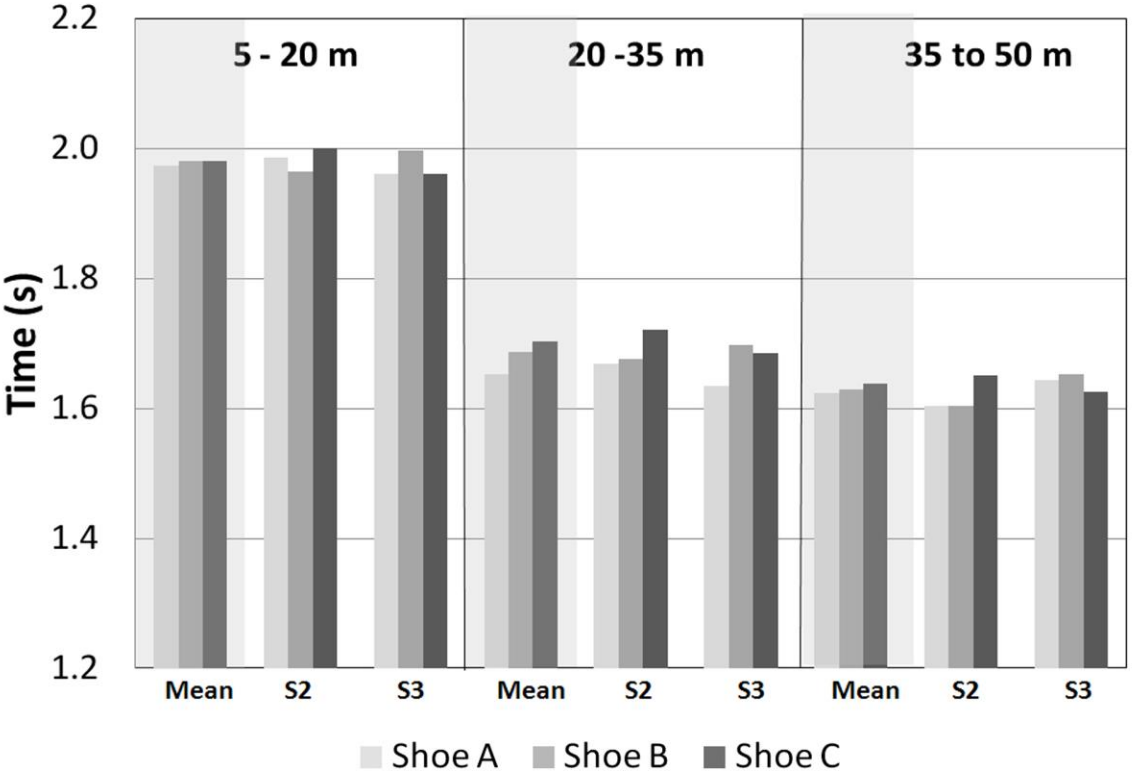


FIGURE 5.11: INDIVIDUAL SPRINT TIMES FOR P3 AT 15 M INTERVALS BETWEEN 5 TO 50 M IN S2 AND S3

When examining the ground contact times for each trial individually in S2 and S3, as shown in

Figure 5.12, the participants displayed a rather consistent pattern of decreasing ground contact time with increases to the stiffness of the sprint shoe. For all of the participants across all of the trials, Shoe A resulted in longer ground contact times compared to Shoe B and C.

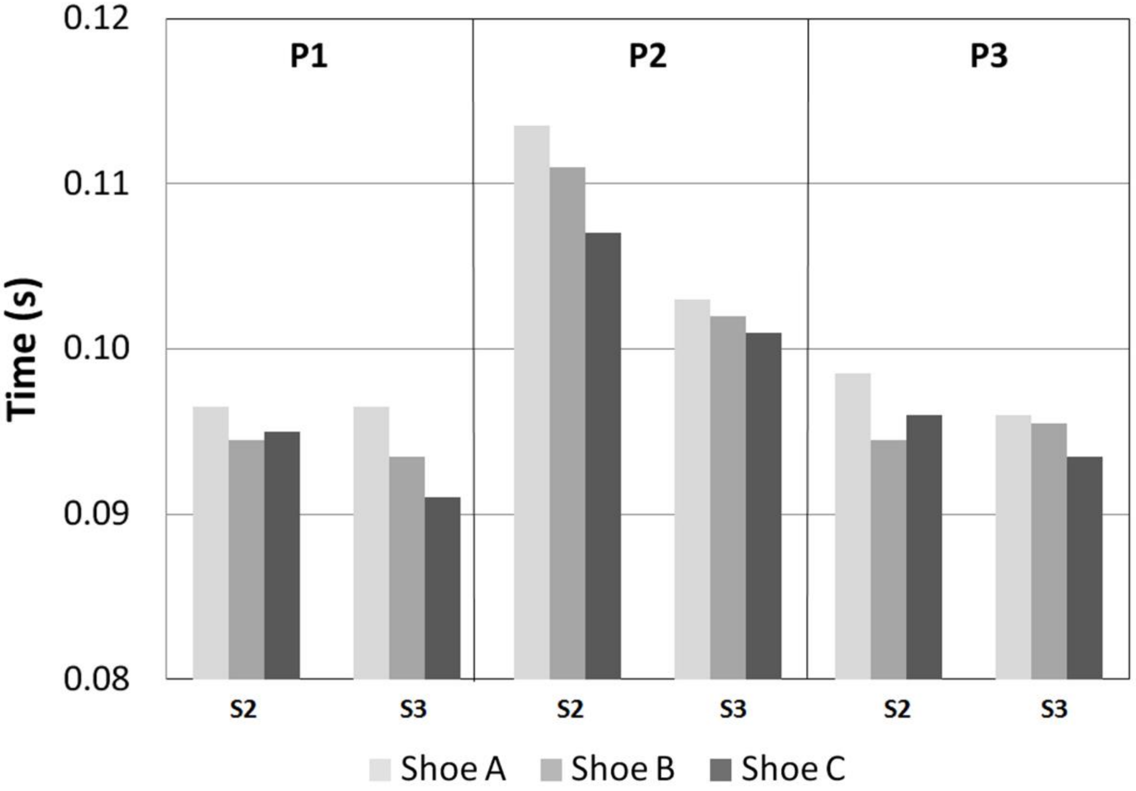


FIGURE 5.12: INDIVIDUAL GROUND CONTACT TIMES (AVERAGED INITIAL AND FINAL GROUND CONTACT) FOR BOTH S2 AND S3

When examining the stride rates for each trial individually, as shown in Figure 5.13, the plots show that none of the participants produced the same pattern of performance ranking in the different shoe conditions between S2 and S3.

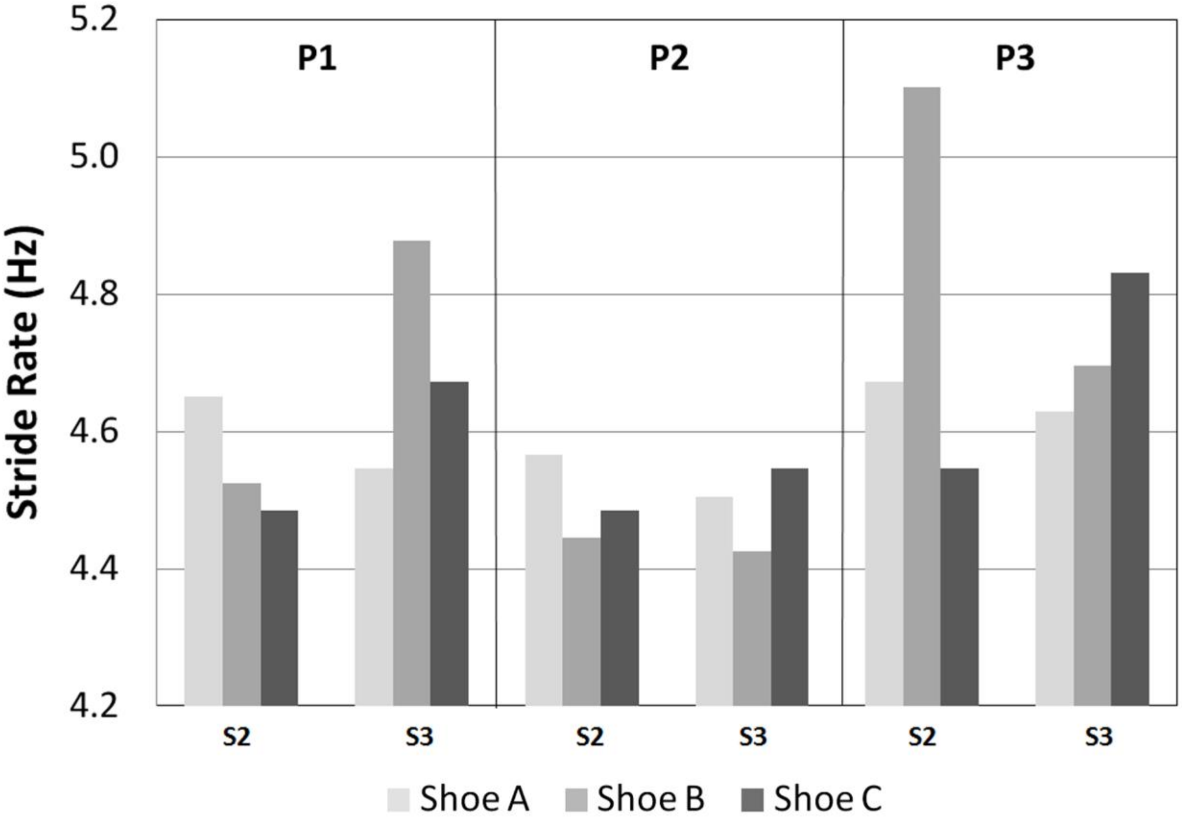


FIGURE 5.13: INDIVIDUAL STRIDE RATE FOR BOTH TRIALS FOR EACH PARTICIPANT IN S2 AND S3

When examining the stride lengths for each trial individually, as shown in Figure 5.14, the plot shows that none of the participants produced the same pattern of performance ranking in the different shoe conditions between S2 and S3.

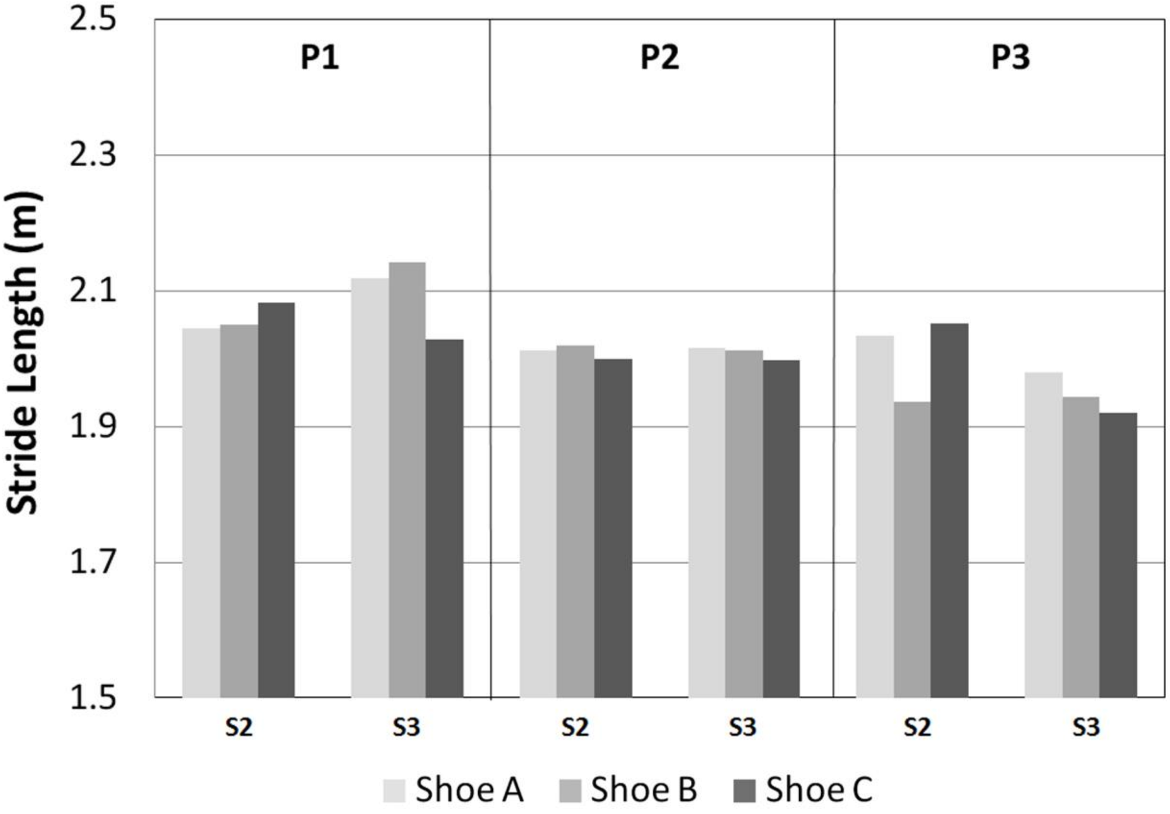


FIGURE 5.14: INDIVIDUAL STRIDE LENGTH AND STANDARD DEVIATION IN S2 AND S3

RELIABILITY

The maximum effect size, SD and CV for the sprint times in each of the three sessions, for each participant individually and the group mean are shown in

Table 5.5.

The group mean measures of reliability show that S2 and S3 had larger maximum effect sizes, SD and CV in the sprint times over all the measured sprint intervals, except for S3 in the acceleration phase (5 - 20 m). However, the results for the individual participants show that the measures of reliability were quite varied. While throughout the majority of the sprint times measured, S1 showed a greater reliability than in S2 and S3, for both P1 and P2 there were some larger variability in S1 than in S2 and S3 throughout the different sprint intervals. P3 was the only participant to have a smaller maximum effect size, SD and CV in S1 than S2 and S3 in all sprint intervals.

TABLE 5.5: MEASURES OF EFFECT SIZE, SDAND CV FOR THE SPRINT TIMES FOR EACH PARTICIPANT AND THE GROUP MEAN FOR THE 15 M AND 45 M INTERVALS († INDICATES A SMALLER VARIATION IN THE VARIABLE COMPARED TO S1)

	Max Effect Size			Standard Deviation			Coefficient of Variation		
	(s)			(s)			(%)		
Sprint Interval	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
5 - 20 m									
P1	0.020	0.044	0.044	0.010	0.022	0.025	0.5	1.2	1.3
P2	0.039	0.006 †	0.011 †	0.020	0.003 †	0.006 †	1.0	0.2 †	0.3 †
P3	0.019	0.036	0.035	0.010	0.018	0.020	0.5	0.9	1.0
Mean	0.021	0.023	0.015 †	0.012	0.013	0.008 †	0.6	0.7	0.4 †
20 - 35 m									
P1	0.037	0.047	0.021 †	0.020	0.025	0.011 †	1.3	1.6	0.7 †
P2	0.016	0.064	0.065	0.009	0.032	0.037	0.5	1.9	2.2
P3	0.013	0.052	0.063	0.007	0.028	0.033	0.4	1.7	2.0
Mean	0.009	0.027	0.044	0.005	0.014	0.022	0.3	0.8	1.4
35 - 50 m									
P1	0.014	0.035	0.047	0.008	0.018	0.026	0.5	1.1	1.7
P2	0.015	0.017	0.003 †	0.008	0.010	0.002 †	0.5	0.6	0.1 †
P3	0.003	0.047	0.028	0.002	0.027	0.014	0.1	1.7	0.9
Mean	0.005	0.017	0.005	0.010	0.033	0.011	0.3	1.1	0.3
5 - 50 m									
P1	0.035	0.026 †	0.110	0.018	0.014 †	0.059	0.4	0.3 †	1.2
P2	0.019	0.039	0.030	0.010	0.021	0.015	0.2	0.4	0.3
P3	0.030	0.127	0.108	0.015	0.070	0.054	0.3	1.3	1.0
Mean	0.008	0.030	0.028	0.015	0.058	0.050	0.2	0.6	0.5

The maximum effect size, SD, and CV for the step characteristics for each participant individually and the group mean are shown in Table 5.6. The group mean results show that the maximum effect size, SD and CV for stride length were smaller for S1, in the same shoe condition, than in S2 and S3, in different shoe conditions. Contact time and stride rate however, did show greater variability in S1 than in S2 and S3. The individual results in Table 5.6 show that the measures of reliability between participants and the step variables varied, with all the participants showing more variability in S1 than in either S2 or S3 for contact time and stride length. Stride rate was the only variable in which all the participants had smaller effect size, SD and CV in S1 than in S2 and S3.

The results of the individual participants show that there was little consistency in the reliability measures of the step characteristics, with varied results throughout the step variables and the sessions.

TABLE 5.6 MEASURES OF EFFECT SIZE, SD AND CV FOR THE STEP CHARACTERISTICS FOR EACH PARTICIPANT AND THE GROUP MEAN († INDICATES A SMALLER VARIATION IN THE VARIABLE COMPARED TO S1)

	Max Effect Size			Standard Deviation			Coefficient of Variation		
	(s)			(s)			(%)		
Step Variable	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
Contact Time									
P1	0.007	0.002 †	0.006 †	0.004	0.001 †	0.003 †	3.6	1.1 †	2.9 †
P2	0.003	0.007	0.002 †	0.002	0.003	0.001 †	1.4	3.0	1.0 †
P3	0.007	0.004 †	0.003 †	0.003	0.002 †	0.001 †	3.4	2.1 †	1.4 †
Mean	0.004	0.004	0.003 †	0.002	0.002	0.002	2.3	1.8 †	1.7 †
Stride Rate									
P1	0.162	0.167	0.333	0.081	0.087	0.168	1.8	1.9	3.6
P2	0.172	0.122 †	0.121 †	0.087	0.062 †	0.061 †	1.9	1.4 †	1.4 †
P3	0.108	0.557	0.201	0.054	0.292	0.103	1.2	6.1	2.2
Mean	0.066	0.095	0.067	0.126	0.186	0.123 †	1.4	2.1	1.4
Stride Length									
P1	0.095	0.037 †	0.112	0.048	0.020 †	0.059	2.2	1.0 †	2.8
P2	0.054	0.020 †	0.018 †	0.027	0.010 †	0.009 †	1.3	0.5 †	0.5 †
P3	0.051	0.115	0.059	0.026	0.062	0.030	1.3	3.1	1.5
Mean	0.019	0.022	0.030	0.037	0.042	0.055	0.9	1.1	1.5

5.4 DISCUSSION

The focus of the first part of this study was on the effect of increasing the bending stiffness of sprint shoes on performance and step characteristics in sprinting for the group mean. The results from previous literature have shown confounding results with regards to increased bending stiffness and sprint performance. Additionally, with minimal biomechanical data pertaining to increasing the bending stiffness and sprinting, there is no information on how the step characteristics in sprinting are influenced by increased bending stiffness. The sprint times were evaluated for a 45 m sprint, at 15 m intervals within the sprint. The intervals were denoted as acceleration (5 – 20 m), mid-acceleration (20 – 35 m) and maximal speed (35 – 50 m) phases while step characteristics were evaluated in the maximal speed phase. Further, the results were presented as both a group mean, consistent with the previous literature in the field, and on an individual basis. As the best level of bending stiffness for sprinters has been shown to vary between individuals, the concern was that presenting the results as a group mean may obscure individual behaviour, with the general results unlikely to reflect the response of the individual.

GROUP MEAN

When examining the group mean performances, in opposition to the hypothesis, it has been shown in this work that increasing the bending stiffness of sprint shoes resulted in increased mean sprint performance (slower times) across all of the participants. Over the 45 m sprint, between 5 and 50 m, the best sprint performance occurred in Shoe A while the worst sprint performance was in Shoe C, with a significant increase in mean sprint time of 1.1 %. With regards to the best shoe condition through the different phases of the sprint, again, the hypothesis that a lower level of bending stiffness in the acceleration phase was required compared to the mid-acceleration and maximal speed phases, was not supported. In the acceleration phase, between 5 and 20 m, there were no significant differences in mean sprint performance between the shoe conditions.

In both the mid-acceleration and maximal speed phases, the best mean sprint performance occurred in Shoe A, with a significant increase in mean sprint time in both of the stiffer shoe conditions Shoe B and Shoe C.

Although the group mean results indicate that increased sprint shoe bending stiffness produced a slower sprint time rather than the hypothesised improvement in sprint performance (faster times), this may be due to the high levels of bending stiffness used. Although improvements to sprint performance and jump height have been shown with increased shoe bending stiffness (Stefanyshyn and Nigg, 2000; Stefanyshyn and Fusco, 2004, Toon, 2008), these improvement in athletic performance however, were found only to improve as stiffness increased to a moderate value, after which performance decreased with further increases in bending stiffness. The intent in this work was to examine changes in sprinting performance over the largest range of bending stiffness considered appropriate for participants to be used in human performance testing. This was done in order to possibly elicit a larger difference in sprint performance than might be observed with smaller incremental increases in bending stiffness as the smallest change in bending stiffness necessary to elicit a kinematic difference is unknown. As only three shoe conditions were used, there was quite a large difference in the levels of stiffness between sprint shoe conditions. Due to concerns of fatigue, it was no possible to increase the number of footwear conditions used. With such a large disparity in stiffness between the footwear conditions, a more suitable level of stiffness for these participants may have been overlooked as it might fall between the shoe stiffness conditions utilised.

Obtaining an indication of the change in stiffness necessary to elicit a performance response would be useful for further work. It is difficult to determine this information from previous literature due to both inconsistent levels of bending stiffness used in testing and inconsistent reporting of the pertinent data. Smith et al. (2010) reported utilising four stiffness conditions with the stiffest condition being two times a commercially available sprint shoe. While the stiffest condition in this work was reported approximately 6 times the average commercially available, due to the different methods used to benchmark the bending stiffness and the large range of stiffness of commercially available shoes make it difficult to accurately compare the bending stiffness of the test shoes used in both studies. Adding to the uncertainty, Stefanyshyn and Fusco (2004) did not measure the standard commercially available shoe condition used in their research, and examined four shoe stiffness conditions. Stefanyshyn and Fusco (2004) did estimate the stiffest shoe condition used in their work to be 5 – 25 times stiffer than a standard commercially available sprint shoe. However, this estimate seems quite broad and therefore not very helpful in comparisons to this work. Ding et al (2011) did not report bending stiffness values at all. While more consistent levels of sprint shoe stiffness conditions may be necessary in order to obtain more consistent results across research groups, in addition it may be important to look at smaller incremental changes in bending stiffness so as to not miss important aspects of performance in future work.

With regards to step characteristics, ground contact time was the only variable to show a significant change with increased sprint shoe bending stiffness, whereas there was no significant difference in either step rate or step length. Ground contact time was shown to decrease significantly in Shoe B by 2.2 % and Shoe C by 3.4 % compared to Shoe A. As there has been no previous research of the effects of increasing the bending stiffness of sprint shoes directly on step characteristics, although the low participant count limits the application of these results across a broader population, this information provides motivation for further investigation.

There are two ways in which an athlete could decrease ground contact time: increase the velocity at which the foot is moving through the range of motion or decrease the range of motion. While there is no evidence to support an increase in angular velocity at either the MPJ or ankle with increased bending stiffness in sprinting, conversely, increasing the bending stiffness of athletic shoes has been shown to decrease the angular range of motion at the MPJ throughout stance (Stefanyshyn and Nigg, 2000; Toon, 2008; Smith et al., 2010). A decrease in the angular range of motion at the ankle may also be responsible for the observed decrease in contact time. A decrease in the angular range of motion at the MPJ or ankle would have an effect on two main mechanisms: the force-length relationship at the plantar flexors and the Windlass mechanism about the MPJ.

A reduction in the angular range of the ankle would change the force-length relationship of the ankle plantar flexors, moving the athlete either further away or closer to where the athlete has their peak power production. With regards to a reduction in the angular range of motion at the MPJ, the Windlass mechanism in the foot would be compromised, reducing the amount of tension attained at the ball of the foot. However, the higher stiffness of the shoes may compensate for this loss of tension at the toes, replacing the leverage lost in the foot structure itself. With regards to energy generation, Stefanyshyn and Nigg (2000) argue that a reduction in MPJ angular range in dorsiflexion decreases the amount of energy lost at the joint. However, this reduction in MPJ angular range in dorsiflexion may also reduce the potential for MPJ energy generation. Although it is clear that increasing the bending stiffness of sprint shoes alters the kinematics of the foot during ground contact, thus varying ground contact times, how these changes influence sprinting performance is not clear and suggested for further investigation.

While the group mean analysis did show significant differences in sprinting performance and step characteristics with increased bending stiffness, the power levels achieved were very low. This was due to the small effect sizes and small sample. However, in order to achieve a power level of 0.8, with a significance of 0.1, the target number of subjects necessary is high. The population of elite sprinters is scarce in relation to the general population who consider themselves athletes, with a limited season when they are actually fit and able to sprint maximally, making it difficult to recruit high numbers of subjects. This indicates that a group mean approach may not be appropriate for further research in this area. This points to the consideration of the alternate methodology of using a single subject methodology as a default in further research in this area.

INDIVIDUAL RESULTS

With regards to individual participants, it was hypothesised that the best stiffness conditions for each participant would be subject specific. This, however, was not reflected in the results obtained. When examining the mean results for the individual participants from S2 and S3, the best sprint performances over the entire 45 m interval were in Shoe A for each of the participants. Examination of the different sprint intervals also showed that while in the acceleration phase (5 – 20 m) the best shoe condition varied between participants, in both the mid-acceleration (20 – 35 m) and maximal speed (35 – 50 m) phases, each of the participants completed their best sprint in Shoe A when taking the mean of S2 and S3. Again, this may be due to the fact that the difference in stiffness between the shoe conditions was too large, missing a more suitable stiffness.

However, of note as well is the variability in sprint times across the two sessions, S2 and S3. There was almost no consistency in the ranking of the shoe conditions between sessions among the participants across the majority of the sprint intervals examined, with the ranking order of the best stiffness conditions changing between the two sessions. This variability among the sessions was also visible in the step characteristics. The ground contact time was the most stable of the variables, while there was no consistency in the measures of stride rate and stride length between the sessions S2 and S3.

RELIABILITY

Improvements in sprinting performance with increased sprint shoe bending stiffness have been reported (Stefanyshyn and Fusco, 2004). However, little regard has been paid to the reporting of reliability of the system and the measures. While differences in opinion exist for the best way to document reliability, there is no one method for defining a critical acceptable level of reliability and it can often be reliant on the application of the data collected. In order to be able to detect small changes in an athlete’s performance, it is important to establish that the observed variables are adequately reliable in order to be able to detect such small changes. In this work, the minimum acceptable level of reliability was established comparing variables obtained from S1, where all the trials were completed in the same shoe condition, to S2/S3, where all the trials were completed different shoe conditions.

The reliability of the sprint metrics collected were assessed using comparisons between the data collected in S1, where all of the trials were completed in the same shoe condition, and S2 and S3, where all the trials were completed in different shoe conditions. The objective was to assess whether the repeatability of the sprint metrics collected in S1 were smaller within the same shoe condition than the effect size observed in the sprint metrics between the different shoe conditions used in S2 and S3. If the measured repeatability between the same shoe condition (C1) used in S1 were lower than the effect size observed between the different shoe conditions (C1, C2, C3) used in S2 and S3, then the data was considered acceptably reliable.

Of all the phases, the sprint times in the acceleration phase (5 – 20 m) showed the lowest levels of reliability for the group mean. The group mean results over the mid-acceleration (20 – 35 m), the maximal speed (35 – 50 m), and the entire sprint (5 – 50 m), however, show adequate levels of reliability with the group mean results showing increased maximum effect size, SD and CV when comparing between shoe condition S1 and S2/S3 than in the repeated trials completed all in S1.

LIMITATIONS

The difference in the measured bending stiffness of the sprint shoe conditions between sizes used was a limitation to this study. A consistent level of bending stiffness in the different shoe conditions between the different sizes was preferred. However, the discrepancies between the sizes was deemed to be minimal, especially as the differences between the shoe conditions A, B, and C were much larger than the differences between the same shoe condition in the different sizes.

The small sample size and limited number of trials completed restrict the wider application of these results to the effect of increased bending stiffness of sprint shoes to the general population of elite sprinters. An increase in the number of subjects and the number of trials per individual subject would improve the validity of the statistical analysis and further substantiate some of the key findings at the group level. However, as the population of elite sprinters is small and as it is difficult to complete multiple maximal effort sprints without a detrimental effect on sprinting performance due to fatigue in one session, when working with elite sprinters, achieving an adequate number of subjects and completed trials will always a concern.

The lack of information on the step characteristics in the acceleration phase of the sprints is also a limiting factor to this work. However, as previously mentioned, practical limitations prevented this from happening.

5.5 CONCLUSION

Across the group mean, increasing the bending stiffness of sprint shoes resulted in significant changes to both sprinting performance and step characteristics. Sprint time was significantly increased by 1.1 % in the stiffest shoe condition over 45 m. This increase in sprint time with increased bending stiffness may be due to the high levels of bending stiffness utilised. With such a large disparity in stiffness between the footwear conditions, a more suitable level of stiffness for these participants may have been overlooked as it might fall between the shoe stiffness conditions utilised. Obtaining an indication of the change in stiffness necessary to elicit a performance response would be useful for further work in deciding the sufficient number of footwear conditions and difference in stiffness between conditions and is suggested for future research.

With regards to the different phases of the sprint, there were no changes to sprinting performance in the acceleration phase (5 – 20 m), while sprinters were significantly slower in both the mid- and stiff- shoe conditions in the mid-acceleration (20 – 35 m) and maximal speed (35 – 50 m) phases. While increased bending stiffness had varying effects on sprint performance in the different phases, in opposition to the hypothesis, the level of stiffness for optimal performance in all of the phases was the least stiff condition. In addition, in agreement with the hypothesis, an accompanying change in step characteristics was observed, with increasing the bending stiffness of sprint shoes resulting in a significant decrease in ground contact time across the group mean. However, no significant differences in stride rate of stride length were identified.

With regards to individual participants, it was hypothesised that the best stiffness conditions for each participant would be subject specific. This, however, was not reflected in the results obtained. Again, it is suggested that the large difference in stiffness between the conditions may have limited the results as a more suitable level of stiffness for these participants may have been overlooked as it might fall between the shoe stiffness conditions utilised.

Examination of the individual results indicated that there was little consistency or reliability between the trials completed by the subjects. The low reliability and consistency shown in sprint performance and the step characteristics across the individual participants and trials calls into question the application of a group mean analysis for this type of research as the inconsistency of an individual sprinter is missed when you simply look at the group mean. In addition, although significant differences in sprint performance and step characteristics were detected, the low power levels achieved and the high target number of subjects necessary to achieve a suitable level of power given the effect size points amy preclude this type of analysis and by default point to the use of a single subject analysis. Both an examination of the group mean and individual responses to increased bending stiffness in sprinting is suggested in further work.

6 LONGITUDINAL BENDING STIFFNESS OF SPRINT SHOES AND THE DYNAMICS OF THE LOWER LIMB IN SPRINTING

6.1 INTRODUCTION

The effect of increasing the bending stiffness of sprint shoes on sprinting performance is ambiguous. Increasing the bending stiffness of sprint footwear has been shown to significantly affect sprinting performance across a group mean in previous research (Stefanyshyn and Fusco, 2004, Ch 5). However, while Stefanyshyn and Nigg (2004) have shown an improvement in sprinting performance with increased bending stiffness, this result has not been replicated in similar research. In Chapter 5 of this research, a significant increase in sprint time with increased bending stiffness was demonstrated for the group mean, while Smith et al. (2010) and Ding et al. (2011) failed to demonstrate any significant difference in sprinting performance with increased bending stiffness. Although the effect of increased bending stiffness on sprint performance is inconsistent in the aforementioned research (Stefanyshyn and Fusco, 2004; Chapter 5, Smith et al., 2010; Ding et al., 2011), rather than providing adequate rationale to dismiss the notion that changes to the bending stiffness of sprint shoes may lead to improvements in sprinting performance, the confounding results may be due to other factors.

One such factor may be the inconsistent levels of bending stiffness in the test shoe conditions across the aforementioned literature. In addition, different methodologies used to measure and report values of bending stiffness for the sprint shoe conditions also makes it difficult to infer relative levels of stiffness across the literature. Further, while Stefanyshyn and Fusco (2004) did show an improvement in sprinting performance with increased bending stiffness, this relationship was shown only to hold until an optimum stiffness was achieved, after which average performance was shown to decrease. If the difference between the shoe conditions had been larger, this peak in performance may have been missed. It is thought that in Chapter 5, the stiffest sprint shoe may have been too stiff, with the disparity in stiffness between the conditions too large. The footwear conditions used in the previous chapter were considered to be very stiff, even among the shoe conditions used in previous literature. However, comparisons are unable to be made between the footwear conditions in the previous literature due to the inconsistent measures of bending stiffness. A more suitable level of bending stiffness may therefore lie between the footwear conditions used in Chapter 5 and therefore utilizing sprint test shoes with a smaller discrepancy in bending stiffness between conditions has been adopted in the present chapter.

An additional confounding factor may be the large variation in individual responses of the participants. Both Stefanyshyn and Fusco (2004) and Smith et al. (2010) have shown that the shoe condition in which the sprinters had their best sprint run were participant specific. While utilising a group mean increases the power of the analysis in detecting a significant difference in performance, with such a variation in performance response across participants, utilising a group mean analysis may obscure any changes in sprinting performance on an individual level and make it difficult to decipher meaningful data for individual participants. However, the examination of the group mean could still be useful in identifying general response patterns among the participants, valuable in generalising results to the remainder of the population, while a single subject approach is required if variations in movement between subjects are the result of individual subjects using different strategies to perform the same task (Bates, 1996). It is suggested that in order to observe both individual and generalised group responses, the combination of a group and single subject design may be appropriate. This approach would aid in identifying when a significant difference in an individual performance is the result of their own sprinting strategy or identify differences in the data that are trends general to all the participants, by observing the individual trends among the participants.

A key factor, however, to the confounding sprint performance results may be the utilisation of sprint time as the performance indicator. While a change in the time to complete a sprint is the most obvious measure of performance, commercially available timing systems used in research have low reliability and high typical error. One such example is a single beam timing gate system (Brower timing gates), used by Stefanyshyn and Fusco (2004). Although a resolution of 0.01 s is reported, typical errors in time measurements between sprints of over 5% have been reported (D'Auria et al., 2006). Small changes in sprint performance, in the order of 0.4 – 0.7 of the within athlete variation (Hopkins et al., 1999) or 0.36 – 0.63 % of sprint time (Stefanyshyn and Fusco, 2004), have been identified as being important to an elite sprinter's chance of winning or losing a particular race. While it might be easier to elicit these small changes in sprinting performance with footwear interventions, it is difficult to accurately and repeatedly measure these small changes. Although a single beam timing system with microprocessor capabilities offers an improvement in reliability over both single and multiple beam systems, reducing the typical error and coefficient of variation by approximately half (D'Auria et al, 2006), it still may not be sensitive enough to reliably detect such small changes in performance. A measure of sprint time, however, may still a valuable tool in order to identify significantly large changes in performance. An example of when this might be useful is in quickly identifying unsuccessful footwear interventions that cause a large decrease in sprinting performance. While it is difficult to measure changes in sprint time, examination of the kinematics and kinetics with increased bending stiffness might provide better indicators to changes in sprinting performance for further research in this area.

The effect of increased bending stiffness on the kinematics of the lower limb remain ambiguous while the effect of increased bending stiffness of sprint shoes on the kinetics of the lower limb, ultimately responsible for changes in sprinting performance, have never been examined. It is clear that increasing the bending stiffness of sprint shoes leads to a decrease in the angular range of motion and angular velocity at the MPJ (Toon, 2009; Stefanyshyn and Nigg, 2000; Smith et al., 2010). However, it is unclear in which particular phases during ground contact the kinematics of the MPJ are reduced. Furthermore, while the early research into bending stiffness and athletic performance reasoned that a measured decrease in the energy lost at the MPJ, a result of the decrease in the angular range of the joint, resulted in an increase in jump height (Stefanyshyn and Nigg, 2000), there are still many unknowns regarding if and how these changes at the MPJ influence sprinting performance. A reduction in the energy lost at the MPJ has never been examined directly while measuring sprinting performance. Although a reduction in energy lost at the MPJ may contribute to an increase in athletic performance, it is reasoned that it is not the largest contributing factor to improved sprinting performance with increased bending stiffness of sprint shoes.

While Stefanyshyn and Nigg (2000) did observe an increase in jump performance with increased bending stiffness of running shoes, which was attributed to a reduction in energy absorbed at the MPJ, they did note that the highest jump performance among the participants did not always correspond to the largest reduction in energy lost at the MPJ. It is further argued that as the stiffness of footwear increased, thus reducing the range of motion and theoretically the energy lost at the MPJ, sprint performance would continue to improve. This has been shown not to be the case, with Stefanyshyn and Fusco (2004) demonstrating that sprint performance only improved as stiffness increased to a moderate value, after which average performance decreased, indicating that the minimisation of energy lost at the MPJ could not be the only mechanism responsible for observed improvements in performance. It was hypothesised by Stefanyshyn and Fusco (2004) that perhaps changing the shoe bending stiffness results in a change in the point of application of the ground reaction force, a variable which has never been reported with regards to changes to bending stiffness in sprinting. The indication therefore is that changes in the kinetics of the lower limb with changes to the bending stiffness of sprint shoes may be more influential to sprint performance than simply decreasing the energy lost at the MPJ. A more complete examination of the effects of increased sprint shoe bending stiffness on the kinematics and kinetics of the MPJ would be useful in highlighting changes potentially affecting sprint performance.

In recent research of increased bending stiffness in athletic shoes, while the MPJ has been the focus, the ankle has been shown to be a large generator and absorber of energy in sprinting (Stefanyshyn and Nigg, 2000) and therefore indicative of the greater potential to affect changes for performance enhancement compared to the MPJ. In the study by Stefanyshyn and Fusco (2004), in which differences in sprinting performance were observed with increased bending stiffness, the authors hypothesised that a potential influence of changing the shoe condition may result in a change in the point of application of the ground reaction force. A potential change in the point of application of the ground reaction force would affect the dynamics of the ankle. In support of this hypothesis, indicating the potential to influence the kinematics and kinetics of the ankle through increase bending stiffness, Toon (2008) observed changes to both the ankle angular velocity and moment with increase bending stiffness in sprint related jump metrics. The ankle angular velocity was shown to decrease with increasing bending stiffness, suggesting either a decrease in the angular range of motion at the ankle or a decreased ground contact time. The moments at the ankle, however, were shown to increase with increased bending stiffness (Toon, 2008). This response, however, was shown to vary, with some participants reaching their highest ankle moment in a moderate stiffness shoe while others reached their maximum ankle moment in the highest stiffness condition. Examination of changes of the kinematics and kinetics of the ankle could be important for determining changes to lower limb dynamics affecting sprinting performance. Clarifying changes at both the MPJ and ankle with increased bending stiffness may elucidate the influence of stiffness on performance and additionally begin to elucidate factors which dictate personalised optimal stiffness required for maximal performance.

The purpose of this investigation was to establish the effects of increased longitudinal bending stiffness of sprint footwear on sprint performance and the kinematics and kinetics of the MPJ and ankle in the acceleration and maximal speed phases of sprinting. It was hypothesised that increasing longitudinal bending stiffness of the sole units of sprint footwear would:

- reduce MPJ and ankle joint angles and angular velocity;
- increase MPJ and ankle joint moments;
- decreased peak negative MPJ power with no change in peak positive power;
- increased peak negative and positive power at the ankle
- decrease MPJ energy absorption with no change to energy generation;
- increase ankle energy absorption and generation.

It is further hypothesised that:

- the effect of increased bending stiffness on the kinematics and kinetics of the participants will be more pronounced in the acceleration phase compared to the maximal speed phase;

- the moments and energy at the MPJ and ankle joint my increase up to a threshold magnitude, dictated by the capabilities of each individual participant to generate force.

A subsequent aim of this study was to examine the response patterns among both the individual participants and the group mean. Patterns that are apparent in the majority of participants indicate a response pattern that is generalisable to the broader population of sprinters as opposed to subject specific responses, dictated by the individual participants force generating capabilities and physiological characteristics (force-length-velocity curves). If all the participants were to show the same trend in the individual data, the argument of a true relationship in the group mean data is stronger, even when a significant difference may not be shown. It is hypothesised that the trends in the kinematic variables with increased bending stiffness of sprint shoes will be generalisable throughout the participant response whereas the kinetic variables will be more diverse and specific to the individual.

6.2 METHODS

6.3 PARTICIPANTS

Four male participants were recruited to participate in the study. Participants were nationally competitive athletes with 100 m personal bests of under 11.30 seconds (10.99 ± 0.25 s) with a sprint shoe size of UK8, UK9, or UK10. Informed written consent was obtained prior to testing in accordance with Loughborough University ethical advisory regulations.

FOOTWEAR

Three different footwear conditions were evaluated in this work. Each of the footwear conditions had the same traction features as presented in Chapter 3, section 2.2.3. The three footwear conditions consisted of sprint shoes constructed with different levels of longitudinal bending stiffness: a low (Shoe A), medium (Show B) and high (Shoe C) stiffness condition. The bending stiffness of the sprint shoes was modified by increasing the thickness of the sole unit. The low stiffness condition, Shoe A, was chosen to have a bending stiffness to represent the average bending stiffness of current commercially available sprint shoes, acting as the standard condition, and had a sole unit thickness of 2 mm. The stiffest shoe condition (Shoe C) was chosen to be the middle stiffness shoe used in Chapter 5, with a sole unit thickness of 6 mm. In the previous chapter, participants indicated that the 8 mm sole unit felt too stiff and found it uncomfortable to sprint. The medium stiffness shoe condition (Shoe B) used in this chapter was chosen as having a bending stiffness midway between the low and high stiffness conditions, and had a sole unit thickness of 4 mm. The sprint shoes were constructed in sizes UK8, UK9, and UK10 for a total of nine test sprint shoes. A measure of stiffness in both flexion and extension of the all the sprint shoes was obtained using the methodology outlined in Chapter 2, section 2.2.3. The mechanical properties of the test footwear are documented in

Figure 6.1, Figure 6.2 and Table 6.1. The weight of the shoes were all standardised using strips of lead attached to the outside heel counter and in the tongue, below the shoe laces.

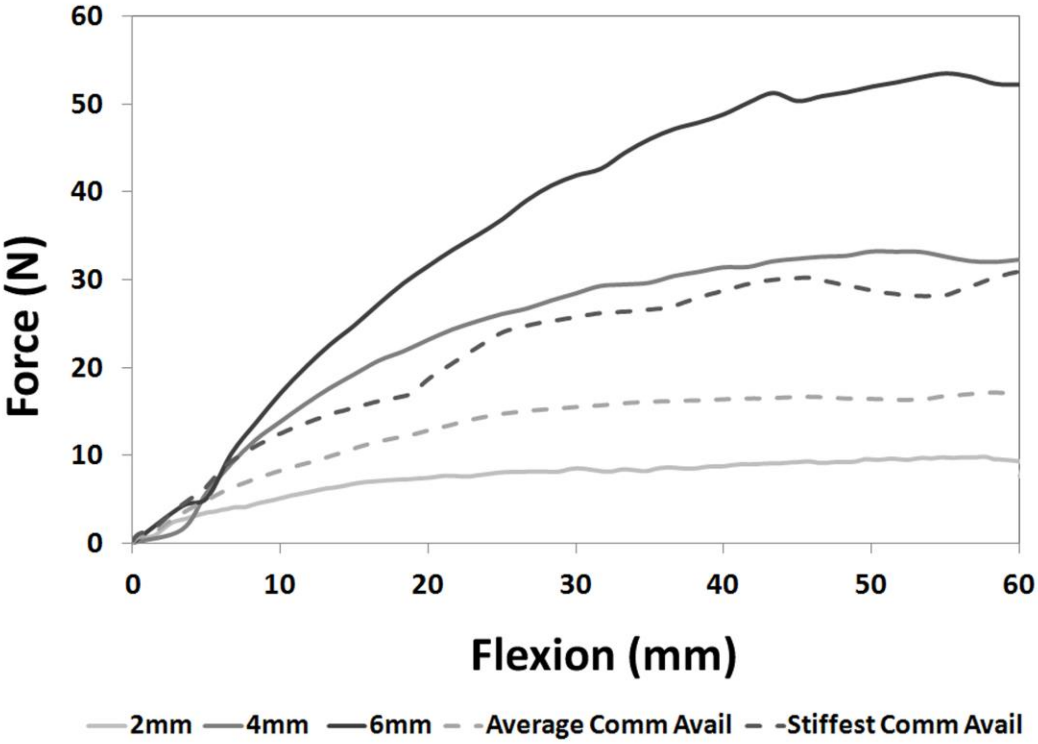


FIGURE 6.1: FORCE VS. FLEXION FOR THE TEST SHOE CONDITIONS AND COMMERCIALLY AVAILABLE OPTIONS (UK9)

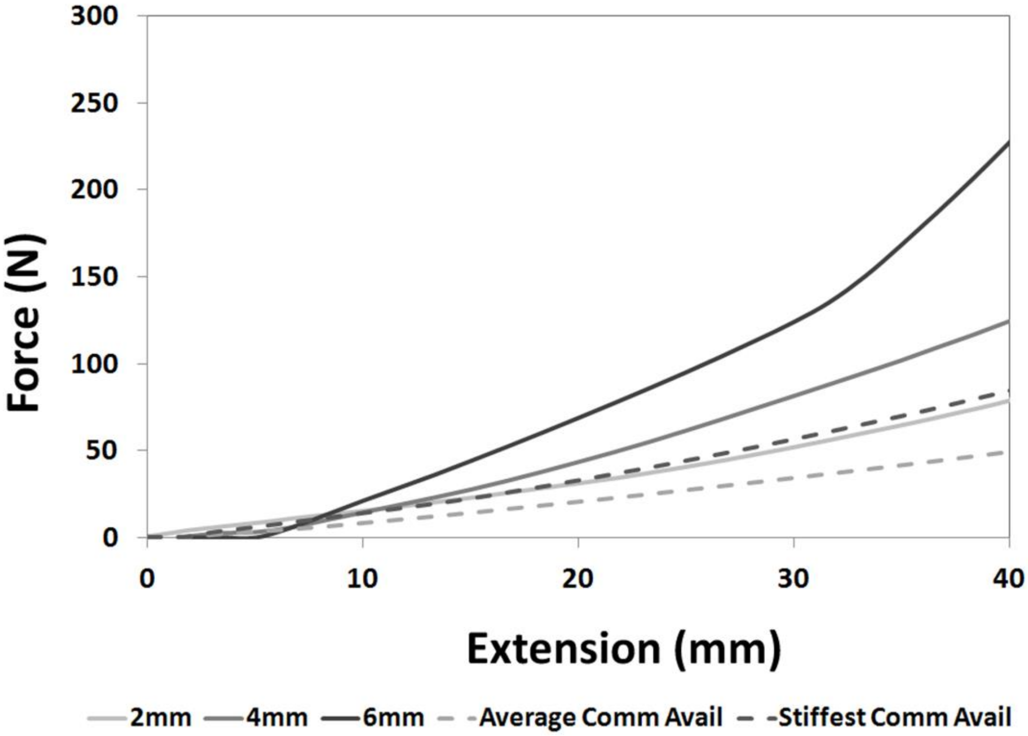


FIGURE 6.2: FORCE VS EXTENSION FOR TEST SHOE CONDITIONS AND COMMERCIALLY AVAILABLE OPTIONS (UK9)

TABLE 6.1: BENDING STIFFNESS RESULTS IN FLEXION AND EXTENSION FOR THE SPRINT FOOTWEAR CONDITIONS IN ACROSS THE VARIOUS SIZES AND THE AVERAGE AND STIFFEST COMMERCIALLY AVAILABLE SPRINT SHOE

	Flexion				Extension			
Shoe	Mean		Max		Mean		Max	
UK 9	(N)	(SD)	(N)	(SD)	(N)	(SD)	(N)	(SD)
A	7.5	0.0	9.9	0.1	35.5	0.1	80.3	0.2
B	15.6	0.1	21.0	0.5	68.0	0.9	152.2	0.8
C	37.8	0.4	53.5	0.7	83.1	1.1	210.7	1.0
UK 10								
A	11.2	0.1	13.7	0.2	41.9	0.1	89.5	0.0
B	25.2	0.2	33.3	0.4	77.2	0.7	161.2	0.8
C	44.7	0.4	60.3	0.2	118.0	1.2	299.1	0.6
UK 11								
A	9.6	0.1	12.3	0.1	37.8	0.1	89.9	0.2
B	21.1	0.2	29.1	0.3	75.1	0.4	174.2	0.5
C	46.7	0.5	68.2	0.2	108.9	1.1	277.1	0.9
Commercially Available								
Stiffest Comm Avail	21.8	0.2	31.0	0.2	42.8	0.7	100.7	1.1
Avg Comm Avail	13.2	0.2	17.9	0.2	24.7	0.6	54.5	0.5

PROTOCOL

Each participant completed two testing sessions. The testing sessions were carried out at an indoor athletics facility, late into the outdoor competition season when the participants were regularly performing maximal velocity training. Participants performed their own warm up prior to testing. In the course of one testing session, the participants completed nine sprint runs, with three runs per shoe condition. One testing session focused on the acceleration phase while the other testing session focused on the maximal speed phase of a sprint. For the acceleration phase, the participants completed 30 m maximal effort sprints, starting in competition blocks. For the maximal speed phase, the participants completed 50 m sprints from a crouched start position, as described in Chapter 5. The participants changed shoe conditions between each sprint, with the order in which the shoe conditions were tested randomised between the participants. A rest period of a minimum of 5 minutes was given to the athletes between trials, with a maximum of 10 minutes allowed. During the warm up, participants put on the testing shoes for one short, sub maximal sprint for familiarisation and ensure they were comfortable in the test shoes. During each of the sprints, sprint time, high speed video (HSV) and force data were recorded, as outlined below.

Sprint times were collected using a single beam SmartSpeed wireless timing gate system (Fusion Sport, Australia). The SmartSpeed system has microprocessor capabilities, allowing the timing system to detect and measure the longest break in the beam, ensuring the time recordings are from the torso and not a leading arm or leg breaking the beam. Timing gates were positioned at 10 m intervals. For the acceleration phase testing session, timing gates were placed at 10, 20 and 30 m marks. For the maximal speed phase testing session timing gates were placed at 10, 20, 30, 40 and 50 m marks. The resolution of the timing system was 0.001 s and a reported typical error of 0.03 s over measurements between 10 to 20 m and a coefficient of variation of 1.7% at a spacing of 10 m and 1% at a spacing of 20 m (D’Auria et al. 1996).

For each trial, force and video data were collected simultaneously, as triggered by a synch pulse. Force data were collected at 1000 Hz using two force plates in sequence (Kistler 9281CA, 400 x 600 mm). If the participant landed on both the force plates, the centre of pressure (COP) was calculated by combining the values calculated from each plate using the equations supplied by the force plate manufacturer (Kistler). The mean error in COP location utilising this method has been presented as 0.0027 m, which resulted in joint power error errors of 0.27% at the ankle (Exell *et al*., 2011). Video data in the sagittal plane were collected using two HSV cameras (Photron Fastcam – Ultima APX 120K) at a sampling rate of 1000 Hz, placed perpendicular to the direction of the sprint, one on the medial and one on the lateral side one, respectively. A field of view of 1.4 m was used, containing the length of the two force plates and the lower extremity from the knee and below. The resolution of the images was 1024 x 1024 pixels. A 0.6 x 0.6 m calibration frame containing 16 reference points was used for the calibration of the HSV. The distance between the points on the reference frame were measured to the nearest 0.5 mm using a meter stick, with measurements made on three separate occasions and mean values used. The exact positions of the points were measured relative to the edge of the force plates. The calibration frame was constructed with slats to fit onto the sides of the force plate, ensuring that the central marker of the calibration frame rested directly above the centre of the force plate. The frame was positioned in two locations across the 1.4 m field of view, in the centre of the running lane in the sagittal plane, on each of the force plates. The horizontal and vertical scaling factors were calculated separately and averaged across the two horizontal positions to obtain the respective horizontal and vertical scaling factors. A total of 1600 W of floodlighting was used for each HSV capture volume to provide a sufficiently bright image on the camera images.

For the acceleration phase testing session, the force plate data was collected at 5 m into the sprint (where the 5 m mark was located at the centre of the two force plates). This position was chosen in order to examine the early acceleration phase rather than the mid- or late- acceleration phases in order to provide a larger contrast to the maximal speed phase. For the maximal speed phase testing session, the force plate data was collected at 45 m into the sprint (where the 45 m mark was located at the centre of the two force plates). Although it has been shown that sprinters reach their maximal speeds between 50 and 60 m (Mehrikadze and Tabaschnik, 1983), space limitations prevented data collection any further into a sprint run. These distances varied slightly for each participant as the starting positions were varied slightly in order to ensure a complete foot strike occurred on the force plates.

A kinematic model of the lower extremity was developed to include three separate segments representative of the shank, rearfoot and forefoot. Markers were placed on (1) the medial aspect of the distal phalanx of the hallux, (2) the medial aspect of the 1st metatarsal, (3) the lateral aspect of the 5th metatarsal, (4) lateral aspects of the malleolus, (5) and the lateral condyle of the femur. These markers served to divide the lower limb into forefoot, rearfoot and shank segments. The MPJ was modelled as a single ideal hinge joint rotating about a transverse axis about the head of the 1st MPJ. Joint centres were identified through palpation and manual manipulation of the joint at the start of each test session. A fine felt pen was used to draw markers of approximately 5 mm in diameter on the participants. In order to define the joints on the foot, three holes were cut out of the uppers of the sprint shoes approximating the location of the first and fifth MPJ's and the distal phalanx of the hallux, allowing for markers to be positioned directly onto the skin. The body landmarks were digitised for each field of the ground contact phase using Vicon Motus v9 (Vicon Motion Systems Ltd., Oxford, UK).

MPJ and ankle angles and angular velocities were calculated following digitising. Both the MPJ and ankle angular motion is reported as a range of motion in the different periods through ground contact. As presented in Chapter 4, the initial extension phase, Extension 1, is the first period of angular motion occurring immediately after ground contact until maximum extension. The next phase is the flexion occurring from maximum extension of the MPJ through to maximum flexion. The final phase is extension during the push off, Extension 2, occurring from maximum flexion through toe-off until the foot leaves the ground. The ankle range of motion is broken in to the range of motion in Dorsiflexion, occurring from initial touchdown until peak flexion occurs, and Plantarflexion, the range of motion from peak flexion through to toe off.

An inverse dynamics approach (Bresler and Frankel, 1950) was used to calculate resultant joint kinematics and kinetics in the sagittal plane for the MPJ and ankle after smoothing the kinematic data. The kinematic data was filtered at 24 Hz, chosen as the mean optimal cut-off frequency for the data collected as calculated utilising a residual analysis (Winter, 1990). The inertial parameters of each segment were determined by modelling the participant's segments as a series of geometric solids using a modified version of Yeadon (1990) with separate fore- and rear-foot segments. Joint angles were defined according to Winter (1983) and moments were defined such that those causing joint extension were positive. The analysis assumed that the resultant forces and moments at the MPJ were zero until the ground reaction force acted distal to the joint (Stefanyshyn and Nigg, 1997). For this aspect, the position of the MPJ was modelled as the average of the 1st and 5th MPJ. Positive power occurred when the angular velocity of the joint is in the same direction as the resultant joint moment. Energy was calculated by trapezoidal integration of the joint power curve (Adams, 1990), with energy absorption occurring when the resultant joint moment is the opposite direction to the joint angular velocity and energy generation occurring when the resultant joint moment is the same direction as the angular velocity. MPJ and ankle moments, powers and energy were calculated and presented.

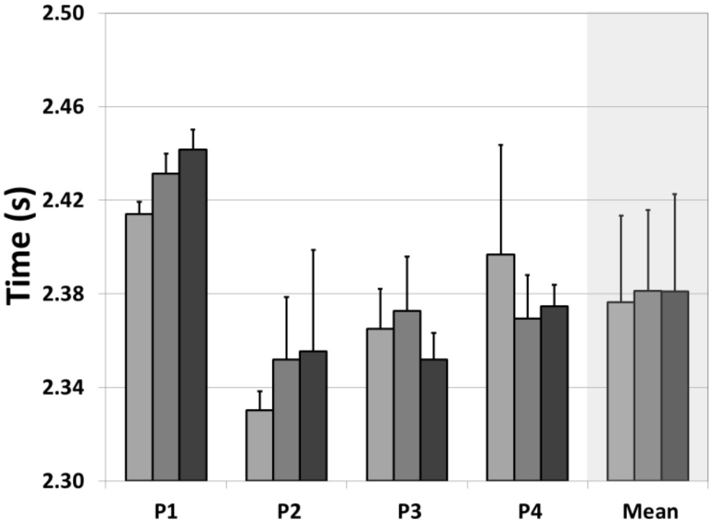
The effect of sprint shoe stiffness on lower limb dynamics and sprint performance variables were assessed with a one-way repeated measures analysis of variance (ANOVA) (SPSS 19 for Windows, SPSS Inc., USA) for both the individual participant and data averaged across the participants. A level of significance was set at $P < 0.10$. Although this level of significance is less stringent than typically used, the consequences of a Type I error are minor compared to the benefit of a possible positive effect. When a significant ($P < 0.10$) effect was observed, Least Significant Differences (LSD) *post hoc* tests were calculated to investigate the pairwise differences. Although the LSD test is quite liberal, and has a high risk of Type I errors, as previously discussed at this point a Type II error is of greater concern.

A power analysis was conducted post hoc on select kinematic, kinetic, and sprint time variables in order to enable a target number of subjects to be identified for further research in this area. A target power level of 0.8, with a significance level of 0.1, were utilised as the parameters.

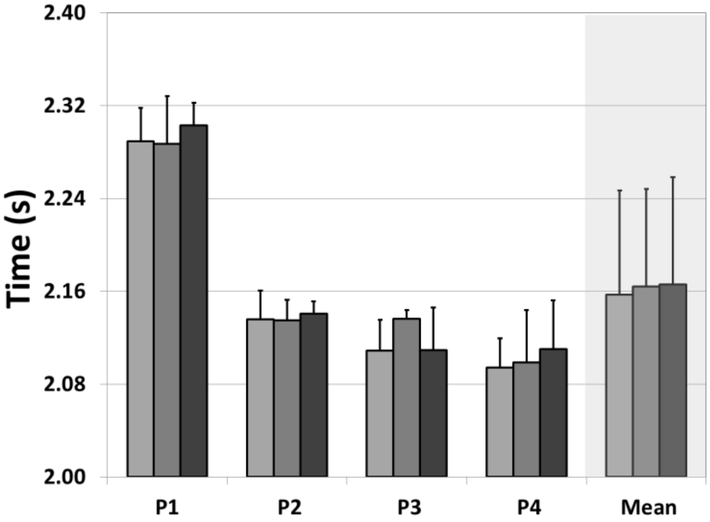
6.4 RESULTS

6.4.1 SPRINT PERFORMANCE

The mean sprint times between 10 and 30 m in the acceleration phase and 30 and 50 m in the maximal speed phase for the participants and the group mean in the different footwear conditions are presented in Figure 6.3. There were no significant differences in sprint times in either Shoe B or Shoe C compared to Shoe A in either the individual participants or the group mean.



(A)



(B)

FIGURE 6.3: MEAN SPRINT TIMES FROM (A) 10 – 30 M AND (B) 30 – 50 M FOR THE INDIVIDUAL PARTICIPANTS AND THE GROUP MEAN IN FOOTWEAR CONDITIONS SHOE A, B AND C

Kinematics

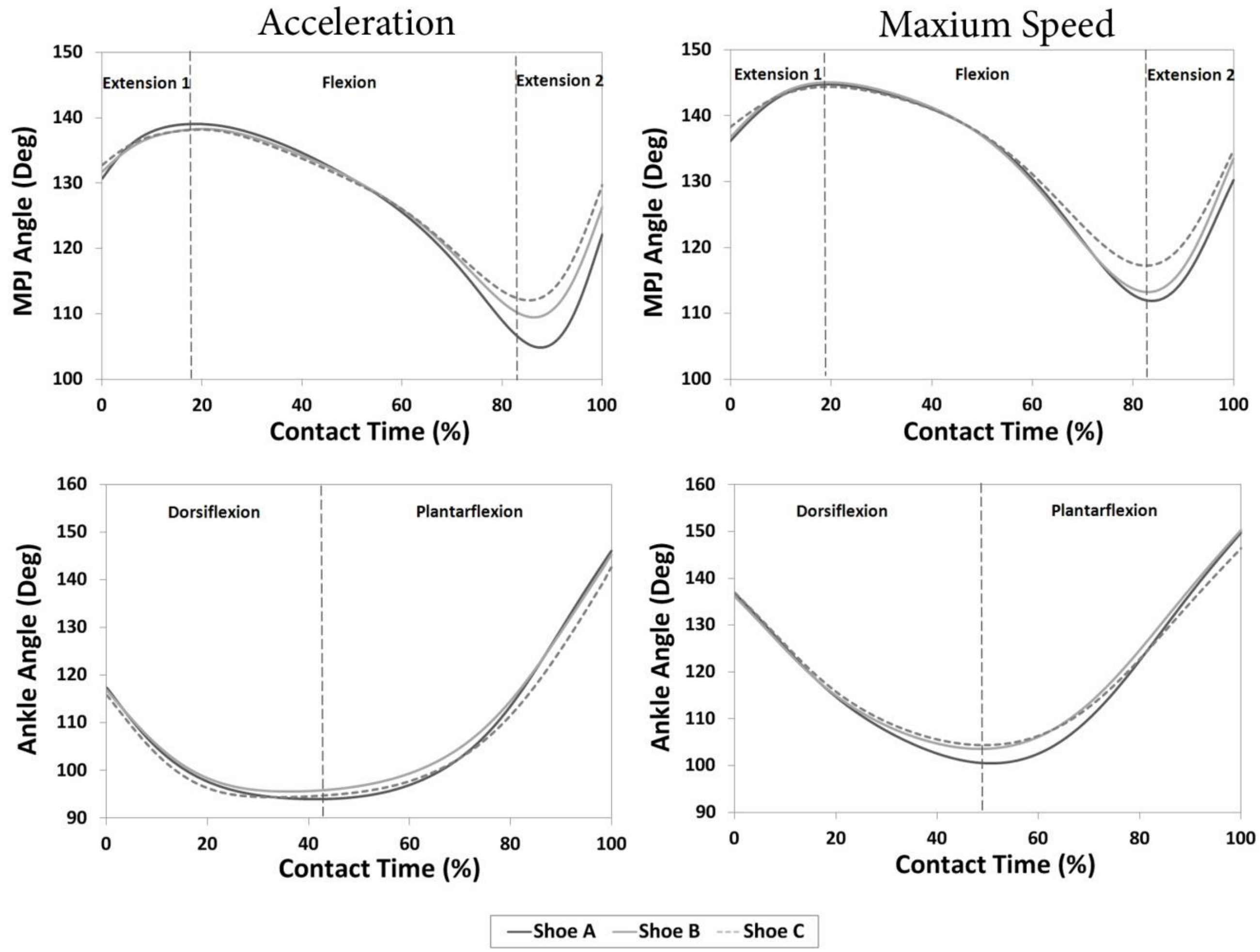


Figure 6.4 shows the mean angular range of motion of the MPJ and ankle for the group mean throughout stance for both the acceleration and maximal speed phases, respectively. In both the acceleration and maximum speed phases, the MPJ initially extends (Extension 1), then goes through a period of flexion, and extends again (Extension 2) prior to take-off. The group mean time series plots for the MPJ show a decrease in the angular range in the stiffer conditions compared to the least stiff condition in both the acceleration and maximal speed phases. In the acceleration and maximum speed phases, the ankle initially dorsiflexes, and then goes through a period of plantarflexion through to take-off.

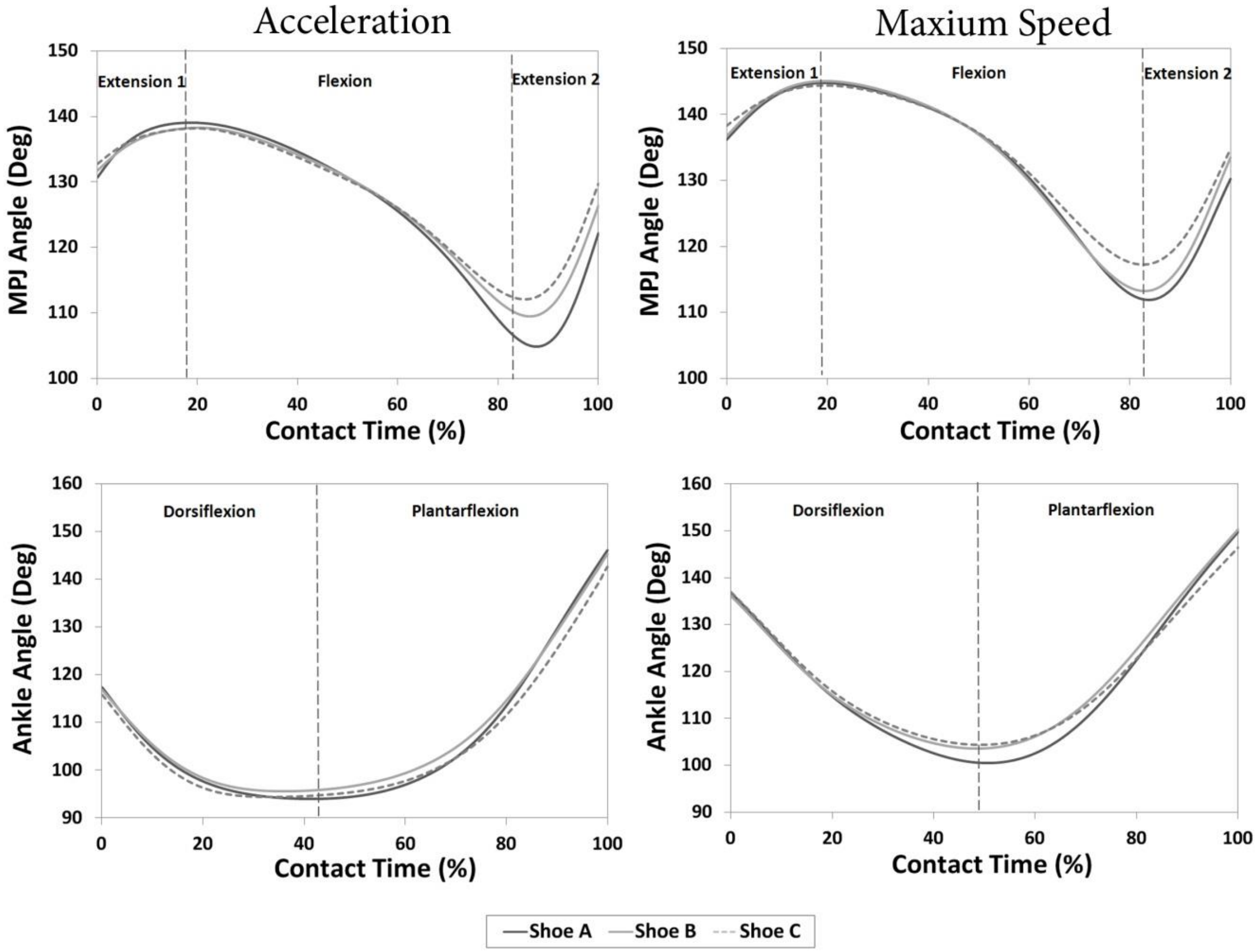


FIGURE 6.4: MEAN MPJ AND ANKLE ANGULAR RANGES THROUGH THE STANCE PHASE FOR ALL PARTICIPANTS IN FOOTWEAR CONDITIONS SHOE A, B AND C IN BOTH THE ACCELERATION (5M) AND MAXIMAL SPEED (45M) PHASE

The mean MPJ angular range of motion in the acceleration phase for all individual participants and the group mean are presented in Table 6.2

TABLE 6.2: MEAN MPJ ANGULAR RANGE IN EXTENSION 1/FLEXION/EXTENSION2 DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE ACCELERATION PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		MPJ Extension 1			MPJ Flexion			MPJ Extension 2		
		Shoe A	Shoe B	Shoe C	Shoe A	Shoe B	Shoe C	Shoe A	Shoe B	Shoe C
1	(Deg)	11.3	7.4	7.8	31.2	26.5	24.1	18.9	21.0	20.4
	(SD)	3.8	1.3	2.0	4.0	3.1	3.5	3.1	2.8	2.4
2	(Deg)	11.0	9.8	7.0 *	40.3	33.7 *	27.6 *	16.8	17.0	16.3
	(SD)	1.3	3.7	0.2	0.7	2.5	1.9	8.3	3.7	4.8
3	(Deg)	7.6	7.5	5.2	33.8	32.4 *	28.1 *	12.4	10.9	12.7
	(SD)	0.7	0.9	0.5	0.1	0.2	1.6	2.1	1.0	2.8
4	(Deg)	5.2	2.5	3.4	35.4	26.7	27.8	23.3	18.8	23.4
	(SD)	2.3	2.5	0.3	7.4	2.5	2.3	9.9	3.7	0.8
Mean	(Deg)	8.8	6.7 *	5.8 *	35.2	29.6 *	26.9 *	17.9	17.5	18.2
	(SD)	3.3	3.6	2.0	5.0	4.0	2.7	7.0	4.5	5.0

The mean MPJ peak angle in the initial phase of extension (Extension 1) was reduced in stiffer footwear conditions compared to Shoe A, reaching significance for P2 in Shoe C and the group mean in both Shoe B and Shoe C. The mean MPJ peak flexion was also reduced in stiffer footwear conditions compared to Shoe A, reaching significance for P2 in Shoe B and Shoe C, P3 in Shoe B and Shoe C, and the group mean, in Shoe B and Shoe C. There were no significant differences or trends in the amount of extension at the MPJ prior to toe-off (Extension 2) in the different shoe conditions.

Mean peak ankle dorsiflexion and plantarflexion angular ranges of motion for all the participants and the group mean in the acceleration phase are presented in Table 6.3.

TABLE 6.3: MEAN ANKLE ANGULAR RANGE IN FLEXION AND EXTENSION DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE ACCELERATION PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		**Ankle Dorsiflexion**			**Ankle Plantarflexion**		
		Shoe A	**Shoe B**	**Shoe C**	**Shoe A**	**Shoe B**	**Shoe C**
1	**(Deg)**	**23.1**	**20.7**	**20.0**	**44.8**	**42.0**	**40.6**
	(SD)	**2.2**	**1.5**	**2.3**	**3.2**	**3.0**	**2.4**
2	**(Deg)**	**23.0**	**20.6**	**21.7**	**58.3**	**54.9**	**50.4** *
	(SD)	**1.4**	**2.6**	**1.1**	**0.9**	**3.1**	**0.9**
3	**(Deg)**	**28.0**	**29.5**	**29.3**	**55.0**	**52.7**	**51.9**
	(SD)	**1.2**	**3.0**	**2.4**	**2.0**	**1.0**	**0.5**
4	**(Deg)**	**18.5**	**19.5**	**18.8**	**58.3**	**53.4**	**54.3**
	(SD)	**3.2**	**1.9**	**1.3**	**5.4**	**2.8**	**3.7**
Mean	**(Deg)**	**23.2**	**22.6**	**22.5**	**54.1**	**50.6** *	**49.3** *
	(SD)	**4.0**	**4.2**	**4.6**	**6.4**	**6.0**	**5.8**

There was no significant difference in the mean ankle peak dorsiflexion in the different shoe conditions. However, the mean ankle peak dorsiflexion angle was reduced in stiffer footwear conditions compared to Shoe A, reaching significance for P2 in Shoe C, and the group mean in both Shoe B and Shoe C.

Mean MPJ angular range of motion for all participants and the group mean in the maximum speed phase are presented in Table 6.4.

TABLE 6.4: MEAN MPJ ANGULAR RANGE IN EXTENSION 1/FLEXION/EXTENSION2 DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE MAXIMUM SPEED PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		**MPJ Extension 1**			**MPJ Flexion**			**MPJ Extension 2**		
		Shoe A	**Shoe B**	**Shoe C**	**Shoe A**	**Shoe B**	**Shoe C**	**Shoe A**	**Shoe B**	**Shoe C**
1	**(Deg)**	**5.4**	**5.8**	**3.3**	**29.6**	**29.8**	**23.4** *	**17.2**	**17.3**	**13.7**
	(SD)	**1.1**	**1.7**	**0.7**	**1.2**	**1.7**	**0.9**	**1.5**	**2.9**	**3.2**
2	**(Deg)**	**16.2**	**14.0**	**10.5**	**37.6**	**37.6**	**31.3**	**20.0**	**23.5**	**18.5**
	(SD)	**2.4**	**2.3**	**0.8**	**3.2**	**4.4**	**1.4**	**0.0**	**1.8**	**1.2**
3	**(Deg)**	**9.8**	**7.9**	**6.5**	**36.8**	**32.4**	**29.8**	**17.0**	**20.6**	**18.4**
	(SD)	**1.8**	**0.3**	**0.3**	**2.0**	**0.7**	**0.9**	**0.6**	**1.0**	**2.4**
4	**(Deg)**	**5.3**	**5.3**	**5.5**	**29.2**	**27.3**	**24.2**	**21.0**	**20.7**	**21.7**
	(SD)	**0.8**	**2.8**	**0.4**	**1.6**	**2.8**	**4.4**	**5.5**	**1.3**	**4.3**
Mean	**(Deg)**	**9.2**	**8.2**	**6.5**	**33.3**	**31.8**	**27.2** *	**18.8**	**20.5**	**18.1**
	(SD)	**4.6**	**4.2**	**2.9**	**4.4**	**4.8**	**4.0**	**2.6**	**3.0**	**3.7**

There was a trend of reduced mean peak MPJ extension angle in the initial phase of extension (Extension1) in stiffer footwear conditions compared to Shoe A for all participants except for P4, although there was no significant difference for any of the participants or the group mean in the different footwear conditions. The mean peak MPJ flexion angle was also reduced in stiffer footwear conditions compared to Shoe A, reaching significance for P1 and the group mean in Shoe C. There was no significant difference or trends among the participants in the amount of extension at the MPJ prior to toe-off (Extension2) in the different shoe conditions.

Mean peak ankle dorsiflexion and plantarflexion angles for all the participants and the group mean in the maximum speed phase are presented in Table 6.5.

TABLE 6.5: MEAN ANKLE ANGULAR RANGE IN DORSIFLEXION AND PLANTARFLEXION DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE MAXIMUM SPEED PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		**Ankle Plantarflexion**			**Ankle Dorsiflexion**		
		Shoe A	**Shoe B**	**Shoe C**	**Shoe A**	**Shoe B**	**Shoe C**
1	**(Deg)**	**34.4**	**28.6**	**28.9**	**43.1**	**43.7**	**39.2** *
	(SD)	**2.3**	**1.7**	**0.2**	**1.8**	**3.8**	**3.3**
2	**(Deg)**	**34.6**	**32.7**	**33.6**	**48.6**	**51.5**	**44.1**
	(SD)	**3.2**	**3.4**	**4.1**	**5.6**	**0.9**	**4.0**
3	**(Deg)**	**43.4**	**41.5**	**42.5**	**54.3**	**48.7**	**45.4**
	(SD)	**3.3**	**2.2**	**0.8**	**2.0**	**1.5**	**1.7**
4	**(Deg)**	**25.5**	**29.0**	**24.1**	**47.8**	**43.4**	**41.3**
	(SD)	**3.5**	**1.9**	**2.7**	**4.1**	**2.8**	**8.9**
Mean	**(Deg)**	**34.5**	**33.0**	**32.3**	**48.4**	**46.8**	**42.5** *
	(SD)	**7.1**	**5.0**	**7.2**	**5.3**	**4.4**	**4.6**

There were no significant differences or any apparent trends in the mean peak ankle dorsiflexion with changes to the footwear conditions. However, the mean peak plantarflexion is reduced in stiffer footwear conditions compared to Shoe A, reaching significance for P1 and the group mean in Shoe C.

Graphical data for the group mean MPJ and ankle angular velocities during the acceleration and maximum speed phases are shown in . In both the acceleration and maximum speed phases, the MPJ angular velocity initially decreases, from plantarflexion upon touchdown, to a peak angular velocity in dorsiflexion achieved between 60 to 80% of the stance phase, before rising steeply to reach a peak angular velocity in plantarflexion before take-off. In both the acceleration and maximum speed phases, the ankle angular velocity rises throughout stance, from the peak angular velocity in dorsiflexion at touchdown to the peak plantarflexion achieved just prior to take-off.

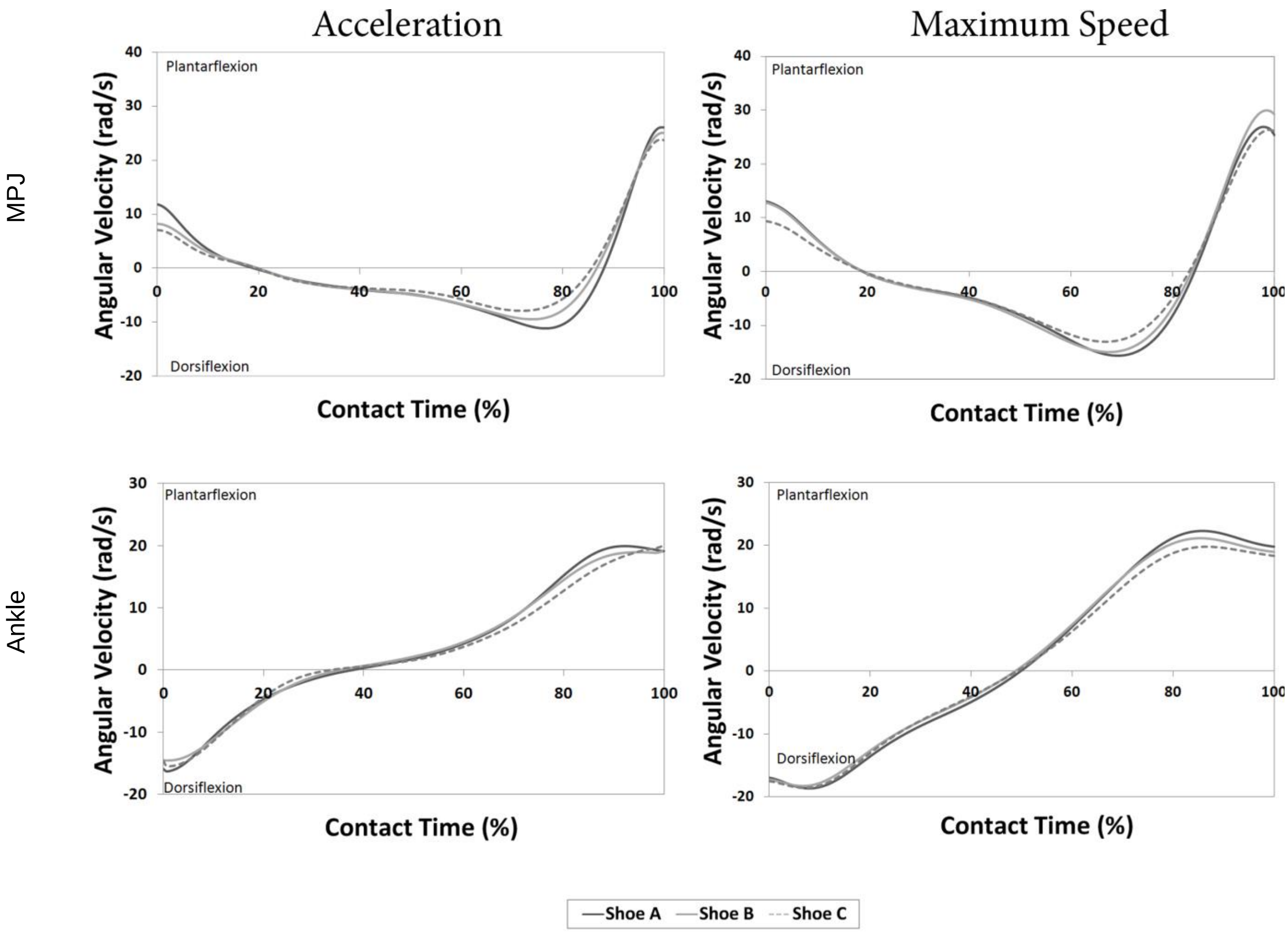


FIGURE 6.5: MEAN MPJ AND ANKLE ANGULAR VELOCITY THROUGH THE STANCE PHASE FOR ALL SUBJECTS IN FOOTWEAR CONDITIONS SHOE A, B AND C IN BOTH THE ACCELERATION (5M) AND MAXIMAL SPEED (45M) PHASES

Mean peak MPJ angular velocities in dorsiflexion and plantarflexion for all participants and the group mean in the acceleration phase are presented in Table 6.6.

TABLE 6.6: MEAN PEAK MPJ ANGULAR VELOCITY IN DORSIFLEXION AND PLANTARFLEXION DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE ACCELERATION PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		**Max Dorsiflexion**			**Max Plantarflexion**		
		Shoe A	**Shoe B**	**Shoe C**	**Shoe A**	**Shoe B**	**Shoe C**
1	**(rad/s)**	**-12.0**	**-9.3**	**-8.6**	**31.3**	**27.7**	**27.3**
	(SD)	**1.0**	**1.5**	**2.9**	**2.8**	**4.3**	**4.7**
2	**(rad/s)**	**-12.1**	**-10.9**	**-7.4** *	**27.5**	**27.9**	**23.7**
	(SD)	**1.0**	**2.1**	**1.0**	**9.9**	**4.8**	**4.9**
3	**(rad/s)**	**-15.1**	**-14.0**	**-11.9** *	**21.1**	**18.6**	**19.5**
	(SD)	**0.3**	**0.3**	**0.9**	**2.4**	**1.3**	**3.6**
4	**(rad/s)**	**-7.8**	**-7.5**	**-6.5** *	**25.1**	**24.6**	**25.2**
	(SD)	**0.4**	**0.9**	**0.9**	**5.4**	**2.4**	**1.7**
Mean	**(rad/s)**	**-11.8**	**-10.1** *	**-8.6** *	**26.2**	**25.3**	**23.9**
	(SD)	**2.8**	**2.7**	**2.6**	**6.4**	**4.7**	**4.5**

The mean peak MPJ angular velocity in dorsiflexion was reduced in stiffer footwear conditions compared to Shoe A, reaching significance for P2, P3, and P4 in Shoe C and the group mean in both Shoe B and Shoe C. With regards to the mean peak MPJ angular velocity in plantarflexion, although there was a trend towards a decrease in the peak MPJ angular velocity plantarflexion achieved in Shoe C compared to Shoe A for P1, P2, P3, and the group mean there were no significant differences with changes to the footwear conditions.

Mean peak ankle angular velocities in dorsiflexion and plantarflexion for all the participants and the group mean in the acceleration phase are presented in Table 6.7.

TABLE 6.7: MEAN MAXIMUM ANKLE ANGULAR VELOCITY IN DORSIFLEXION AND PLANTARFLEXION DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE ACCELERATION PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		Max Dorsiflexion			Max Plantarflexion		
		Shoe A	Shoe B	Shoe C	Shoe A	Shoe B	Shoe C
1	(rad/s)	-18.6	-16.3	-16.2	18.4	21.8	22.3
	(SD)	2.2	1.4	1.4	1.5	9.1	9.0
2	(rad/s)	-17.9	-14.3	-17.0	23.5	22.0	21.4
	(SD)	0.8	2.3	0.7	1.8	0.7	0.8
3	(rad/s)	-15.5	-15.9	-16.4	21.7	20.4	24.3
	(SD)	2.6	1.8	0.4	0.5	0.1	7.8
4	(rad/s)	-13.6	-12.6	-12.4	20.1	20.4	22.0
	(SD)	3.1	3.0	0.5	2.6	0.8	1.1
Mean	(rad/s)	-16.4	-14.6	-15.5	20.9	21.2	22.5
	(SD)	2.9	2.5	2.0	2.5	4.2	5.2

There were no significant differences or any apparent trends in the mean peak ankle angular velocity with changes to the footwear conditions in either dorsi or plantarflexion.

Mean peak MPJ angular velocities in dorsiflexion and plantarflexion for all participants and the group mean in the maximum speed phase are presented in Table 6.8.

TABLE 6.8: MEAN MAXIMUM MPJ ANGULAR VELOCITY IN DORSIFLEXION AND PLANTARFLEXION DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE MAXIMUM SPEED PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		Max Dorsiflexion			Max Plantarflexion		
		Shoe A	Shoe B	Shoe C	Shoe A	Shoe B	Shoe C
1	(rads/s)	-15.2	-15.5	-12.8 *	26.0	27.2	21.3 *
	(SD)	0.4	1.1	0.1	1.5	2.1	1.8
2	(rads/s)	-17.1	-16.4	-13.6 *	30.7	33.6	28.5
	(SD)	0.0	1.5	0.8	1.0	1.4	1.1
3	(rads/s)	-17.1	-15.3	-14.6 *	26.2	31.3	28.4
	(SD)	0.3	0.5	0.1	0.6	0.6	2.6
4	(rads/s)	-13.7	-12.2	-11.1	26.5	26.7	28.1
	(SD)	0.2	1.6	2.1	6.5	2.7	4.5
Mean	(rads/s)	-15.8	-15.0	-13.2 *	27.1	29.8	26.4
	(SD)	1.4	1.9	1.5	3.0	3.4	3.9

The mean peak MPJ angular velocity in plantarflexion was reduced in stiffer footwear conditions compared to Shoe A, reaching significance for P1, P2, P3 and the group mean in Shoe C. With regards to the mean peak MPJ angular velocity in plantarflexion, although there was a significant reduction in Shoe C compared to Shoe A for P1, there were no significant differences or any apparent trends with changes to the footwear throughout the remainder of the participants and the group mean.

Mean peak ankle angular velocities in dorsiflexion and plantarflexion for all the participants and the group mean in the maximum speed phase are presented in Table 6.9.

TABLE 6.9: MEAN MINIMUM AND MAXIMUM ANKLE ANGULAR VELOCITY DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE MAXIMUM SPEED PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		Max Plantarflexion			Max Dorsiflexion		
		Shoe A	Shoe B	Shoe C	Shoe A	Shoe B	Shoe C
1	(rads/s)	-17.8	-15.8	-16.9	20.3	20.2	19.9
	(SD)	0.8	1.5	0.6	0.7	2.3	1.8
2	(rads/s)	-21.7	-22.7	-21.2	25.4	22.9	20.5
	(SD)	0.7	4.5	1.4	6.5	2.7	4.5
3	(rads/s)	-21.4	-19.3	-19.6	24.5	22.5	20.8
	(SD)	1.1	1.2	0.6	0.8	0.1	0.5
4	(rads/s)	-15.3	-17.6	-16.4	19.8	20.6	19.9
	(SD)	4.3	1.3	1.7	0.8	0.6	6.6
Mean	(rads/s)	-19.0	-18.8	-18.6	22.5	21.5	20.3
	(SD)	3.1	3.7	2.2	2.6	1.8	2.3

There were no significant differences or any apparent trends in the mean peak ankle angular velocity with changes to the footwear conditions in either dorsiflexion or plantarflexion.

6.4.2 KINETICS

Graphical data of the group mean MPJ and ankle moments during the acceleration and maximum speed phases are shown in Figure 6.6. In both the acceleration and maximum speed phases, the moments are extensor at the MPJ. The moments at the ankle in both the acceleration and maximal speed phases are also extensor throughout ground contact.

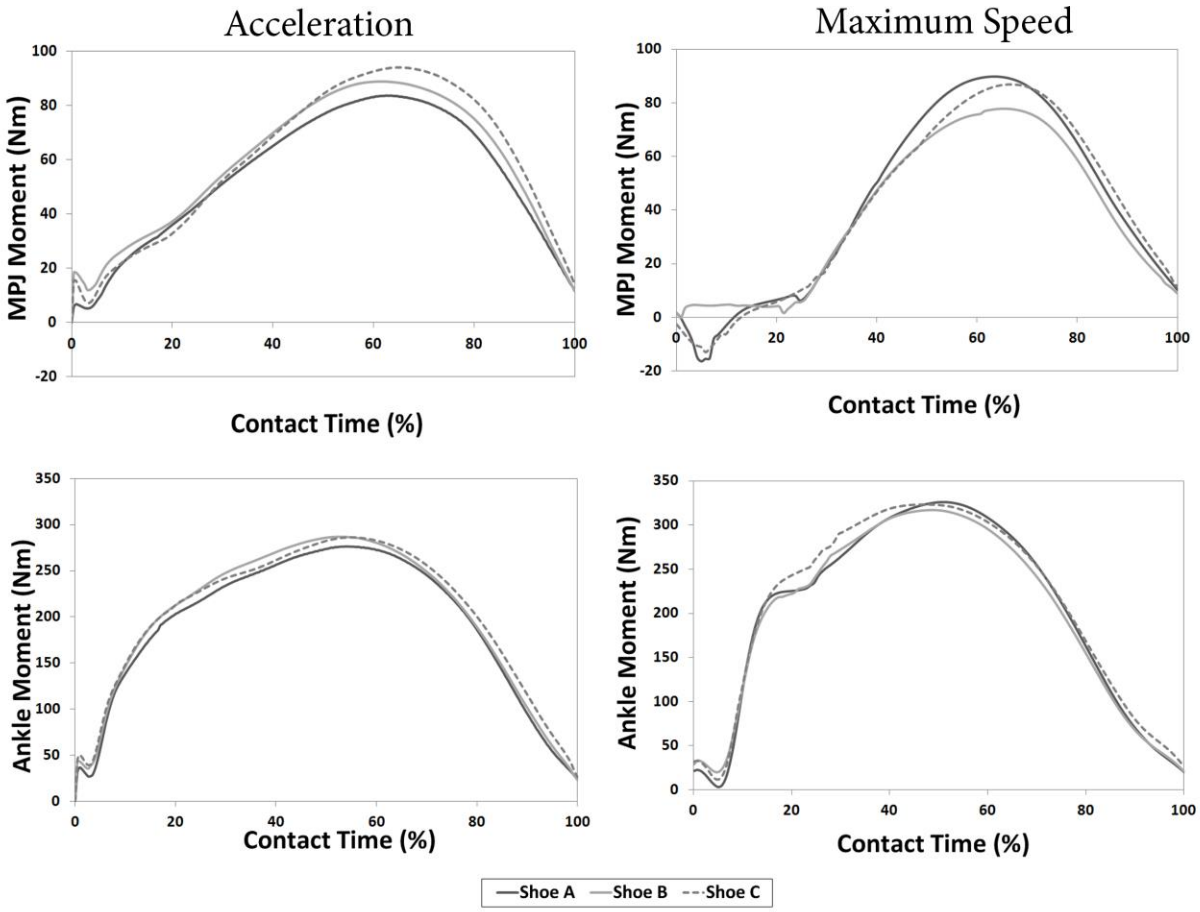


FIGURE 6.6: MEAN MPJ AND ANKLE MOMENTS THROUGH THE STANCE PHASE FOR ALL SUBJECTS IN FOOTWEAR CONDITIONS SHOE A, B AND C IN BOTH THE ACCELERATION (5M) AND MAXIMAL SPEED (45M) PHASES

Mean maximum moments for the MPJ and ankle in the acceleration phase are presented in Table 6.10.

TABLE 6.10: MEAN MPJ AND ANKLE MAXIMUM MOMENTS DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE ACCELERATION PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		**MPJ Maximum Moment**			**Ankle Maximum Moment**		
		Shoe A	**Shoe B**	**Shoe C**	**Shoe A**	**Shoe B**	**Shoe C**
1	**(Nm)**	**95.2**	**92.7**	**92.2**	**270.7**	**269.2**	**259.2**
	(SD)	**0.6**	**4.2**	**9.8**	**13.0**	**10.6**	**16.0**
2	**(Nm)**	**68.9**	**53.1**	**64.9**	**248.4**	**231.3**	**237.5**
	(SD)	**13.9**	**6.2**	**2.2**	**23.4**	**21.1**	**17.3**
3	**(Nm)**	**90.4**	**103.2**	**98.4**	**303.5**	**325.4**	**322.9**
	(SD)	**10.1**	**3.2**	**12.3**	**14.1**	**9.0**	**19.5**
4	**(Nm)**	**87.5**	**112.6**	**125.6** *	**286.4**	**341.2**	**335.5**
	(SD)	**12.8**	**6.6**	**9.9**	**47.8**	**14.7**	**13.3**
Mean	**(Nm)**	**85.5**	**90.4**	**95.3**	**277.2**	**291.8**	**288.8**
	(SD)	**11.5**	**24.9**	**24.9**	**32.1**	**48.6**	**45.5**

There was a significant increase in the mean maximum moment for P4 in Shoe C compared to Shoe A. The mean maximum MPJ moment for the group mean also shows an increase with increased bending stiffness of the footwear conditions, although not a significant difference. However, this trend appears to be heavily influenced by the results of P4. While P4 showed a significant increase in mean MPJ maximum moment in Shoe C compared to Shoe A, this trend is not observed in any of the other three participants. There is also no difference in the mean maximum ankle moment across all participants and the group mean.

Mean maximum moments for the MPJ and ankle in the maximum speed phase are presented in Table 6.11.

TABLE 6.11: MEAN MPJ AND ANKLE MAXIMUM MOMENTS DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE MAXIMUM SPEED PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		**MPJ Maximum Moment**			**Ankle Maximum Moment**		
		Shoe A	**Shoe B**	**Shoe C**	**Shoe A**	**Shoe B**	**Shoe C**
1	**(Nm)**	**108.7**	**72.5**	**84.8**	**359.6**	**338.6**	**357.7**
	(SD)	**4.4**	**20.4**	**6.2**	**7.2**	**20.8**	**9.2**
2	**(Nm)**	**77.1**	**95.3**	**99.7**	**287.1**	**320.1**	**335.4**
	(SD)	**17.4**	**4.1**	**0.8**	**25.1**	**22.5**	**9.1**
3	**(Nm)**	**96.1**	**93.4**	**95.1**	**334.8**	**318.8**	**315.7**
	(SD)	**7.5**	**8.2**	**3.5**	**8.3**	**12.6**	**2.7**
4	**(Nm)**	**84.7**	**61.6**	**72.6**	**329.2**	**303.2**	**300.7**
	(SD)	**31.5**	**42.9**	**27.0**	**38.5**	**31.4**	**7.1**
Mean	**(Nm)**	**91.6**	**80.7**	**88.1**	**327.7**	**320.2**	**327.4**
	(SD)	**17.8**	**22.9**	**15.4**	**31.1**	**22.2**	**15.2**

There were no significant changes or apparent trends in either MPJ or ankle maximum moments with changes to the footwear conditions for all individual participants or the group mean.

Graphical data of the group mean MPJ and ankle power during the acceleration and maximum speed phases are shown in

Figure 6.7. At the MPJ, in both the acceleration and maximal speed phases, power is negative for the majority of the stance phase, and then becomes positive for a short period in late stance before take-off. In the acceleration phase, it is observed that the peak negative MPJ power generation, while the

MPJ is in flexion, is reduced while peak positive power is increased in a stiffer shoe condition. In the maximum speed phase, it is observed that the peak negative MPJ power generation is again reduced in a stiffer shoe condition, however, the same increase in peak positive power generation with increased bending stiffness is not observed prior to take-off. At the ankle, in both the acceleration and maximal speed phases, power is initially negative, and then becomes positive for the remainder of the ground contact phase. In the maximum speed phase, it is observed that the stiffer shoe conditions generate less peak power throughout the final phase of power generation in comparison to the less stiff condition.

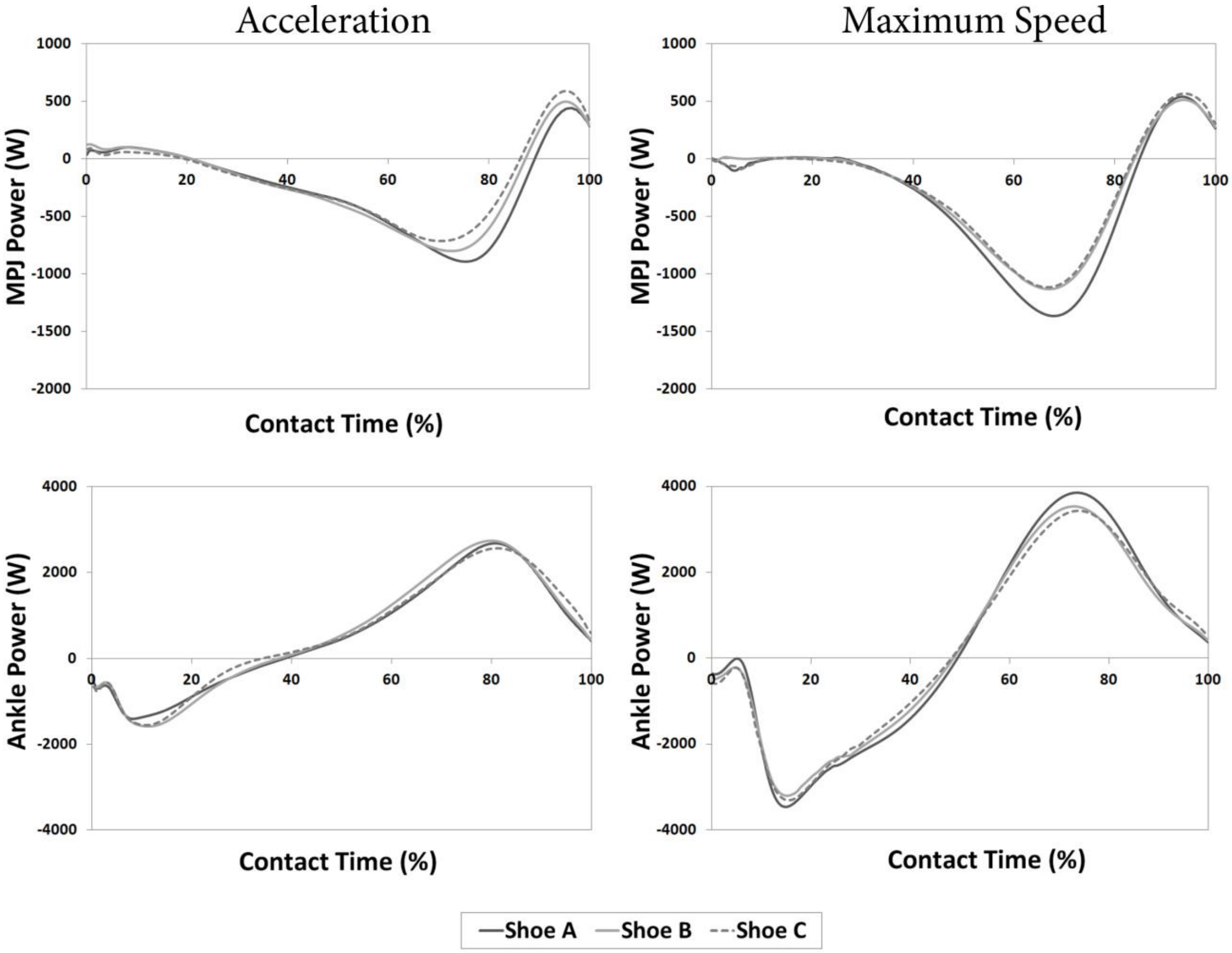


FIGURE 6.7: MEAN MPJ AND ANKLE POWER THROUGH THE STANCE PHASE FOR ALL SUBJECTS IN FOOTWEAR CONDITIONS SHOE A, B AND C IN BOTH THE ACCELERATION (5M) AND MAXIMAL SPEED (45M) PHASES

Mean minimum and maximum powers for the MPJ in the acceleration phase are presented in Table 6.12.

TABLE 6.12: MEAN MPJ MINIMUM AND MAXIMUM POWER DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE ACCELERATION PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		MPJ Minimum Power			MPJ Maximum Power		
		Shoe A	**Shoe B**	**Shoe C**	**Shoe A**	**Shoe B**	**Shoe C**
1	**(W)**	**-999.4**	**-826.7**	**-745.5**	**488.5**	**616.7**	**653.4**
	(SD)	**63.0**	**95.5**	**178.8**	**124.9**	**55.1**	**102.3**
2	**(W)**	**-744.4**	**-569.5**	**-477.3**	**476.1**	**342.3**	**502.0**
	(SD)	**169.6**	**142.5**	**80.8**	**106.1**	**10.9**	**117.5**
3	**(W)**	**-1239.6**	**-1301.7**	**-1092.9**	**385.8**	**355.2**	**478.3**
	(SD)	**107.6**	**71.9**	**84.4**	**47.8**	**19.6**	**118.0**
4	**(W)**	**-646.1**	**-802.2**	**-822.1**	**583.6**	**656.8**	**761.6**
	(SD)	**110.5**	**99.1**	**157.6**	**108.1**	**40.0**	**48.7**
Mean	**(W)**	**-907.4**	**-875.0**	**-784.5**	**483.5**	**492.7**	**598.8** *
	(SD)	**261.8**	**271.0**	**255.5**	**113.1**	**155.2**	**148.1**

A trend of reduced mean minimum MPJ power in stiffer shoe conditions is observed for P1, P2, P3 and the group mean, although there was no significant difference in the values between shoe conditions. The mean maximum MPJ power is significantly increased in the group mean in Shoe C compared to Shoe A. Across the individual participants, mean maximum MPJ power is increased in the stiffest footwear condition Shoe C compared to Shoe A for all the participants.

Mean minimum and maximum powers for the ankle in the acceleration phase are presented in Table 6.13.

TABLE 6.13: MEAN ANKLE MINIMUM AND MAXIMUM POWER DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE ACCELERATION PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		Ankle Minimum Power			Ankle Maximum Power		
		Shoe A	Shoe B	Shoe C	Shoe A	Shoe B	Shoe C
1	(W)	-2077.6	-1962.8	-1922.8	2581.4	2167.7	2227.4
	(SD)	224.6	253.4	111.1	74.8	204.8	189.5
2	(W)	-1489.0	-1261.3	-1286.8	3150.8	2673.7	2610.2
	(SD)	141.2	116.7	162.8	442.6	340.3	368.1
3	(W)	-1503.9	-1666.8	-1676.3	3630.3	3508.8	3346.7
	(SD)	66.4	100.1	139.4	203.2	188.5	224.2
4	(W)	-2190.5	-1593.6	-1767.1	1571.4	2828.5	2389.7
	(SD)	290.8	391.2	336.0	376.0	159.3	373.0
Mean	(W)	-1815.2	-1621.1	-1663.3	2733.5	2794.7	2643.5
	(SD)	341.1	348.8	301.9	788.0	510.1	515.3

There were no significant differences in the mean ankle power minimum or maximum values for any of the participants or for the group mean.

Mean minimum and maximum MPJ powers in the maximum speed phase are presented in Table 6.14.

TABLE 6.14: MEAN MPJ MINIMUM AND MAXIMUM POWER DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE MAXIMUM SPEED PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		MPJ Minimum Power			MPJ Maximum Power		
		Shoe A	Shoe B	Shoe C	Shoe A	Shoe B	Shoe C
1	(W)	-1574.5	-1018.6	-1075.8	395.9	303.5	395.5
	(SD)	109.1	285.0	122.5	41.6	144.1	65.2
2	(W)	-1263.4	-1532.3	-1312.0	506.7	500.4	638.2
	(SD)	222.2	99.6	69.3	106.3	125.0	191.4
3	(W)	-1577.9	-1402.5	-1389.3	483.0	673.0	730.7
	(SD)	88.1	89.7	52.8	11.9	107.1	220.1
4	(W)	-1147.1	-658.7	-754.4	826.2	746.8	627.3
	(SD)	405.4	448.4	156.5	343.9	274.2	284.7
Mean	(W)	-1390.7	-1153.0	-1132.9	553.0	555.9	597.9
	(SD)	257.5	412.2	286.3	202.9	210.0	206.8

There were no significant differences in either minimum or maximum MPJ power generated for any of the participants or for the group mean. With regards to the minimum MPJ power, a trend of decreased power with increased bending stiffness is shown by in P1, P2, and P4

Mean minimum and maximum power for the ankle in the maximum speed phase is presented in Table 6.15.

TABLE 6.15: MEAN ANKLE MINIMUM AND MAXIMUM POWER DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE MAXIMUM SPEED PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		Ankle Minimum Power			Ankle Maximum Power		
		Shoe A	Shoe B	Shoe C	Shoe A	Shoe B	Shoe C
1	(W)	-4095.5	-3724.6	-3713.2	3897.2	3294.9	3156.8
	(SD)	213.2	89.4	107.4	68.8	55.7	78.9
2	(W)	-3471.2	-4242.4	-3815.0	3428.0	3940.4	3743.4
	(SD)	435.9	591.4	463.0	611.0	976.7	84.8
3	(W)	-4641.6	-3343.4	-3343.6	4481.2	4033.9	3866.9
	(SD)	794.5	577.7	80.2	27.0	151.6	114.4
4	(W)	-2779.7	-2794.4	-2617.6	4107.6	3017.2	2979.6
	(SD)	1277.3	504.3	575.2	844.9	132.1	577.8
Mean	(W)	-3747.0	-3526.2	-3372.4	3978.5	3571.6	3436.7
	(SD)	931.5	729.5	559.4	526.8	668.1	469.6

There were no significant differences in either minimum or maximum ankle power generated for any of the participants or for the group mean.

6.4.3 ENERGY

Graphical data showing the energy exchange for the group mean at the MPJ and ankle are presented in Figure 6.8. A phase of energy absorption and generation was observed at the MPJ and ankle. In the acceleration phase, there was a significant increase in the energy generated at the joint in Shoe C compared to Shoe A. There were no significant differences in the energy exchange at the MPJ in the maximal speed phase or at the ankle in either the acceleration or maximal speed phases for the group mean.

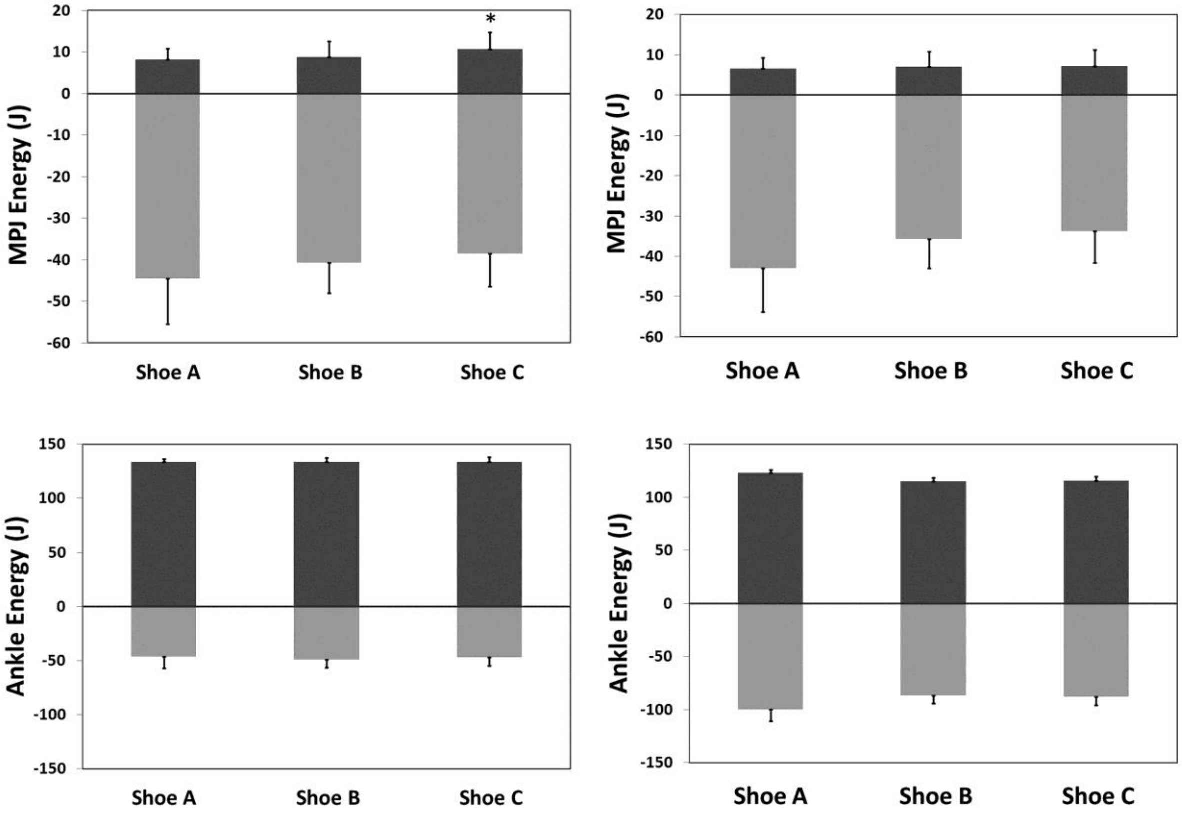


FIGURE 6.8: MPJ AND ANKLE ENERGY GENERATED (POSITIVE VALUE) AND ABSORBED (NEGATIVE VALUE) DURING THE STANCE PHASE IN THE ACCELERATION (5 M) AND MAXIMAL SPEED (45 M) PHASES (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

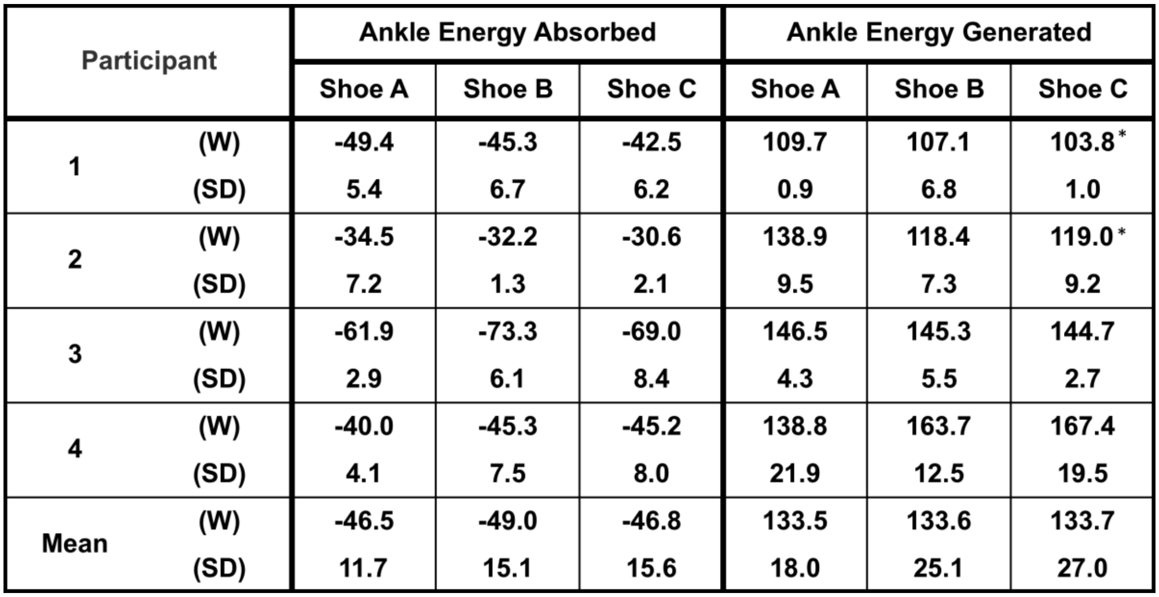
The mean MPJ energy generated and absorbed during ground contact in the acceleration phase are presented in Table 6.16. There was a trend towards a decrease in the MPJ energy absorbed at the MPJ in P1, P2, P3 and the group mean. However, P2 was the only participant to show a significant decrease in the MPJ energy absorbed in Shoe C compared to Shoe A. With regards to the MPJ energy generated, there was a trend in increased energy generated at the MPJ with increased bending stiffness through all of the participants. There was a significant increase in the energy generated at the joint for the group mean in Shoe C compared to Shoe A.

TABLE 6.16: MEAN MPJ ENERGY ABSORBED AND GENERATED DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE ACCELERATION PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		**MPJ Energy Absorbed**			**MPJ Energy Generated**		
		Shoe A	**Shoe B**	**Shoe C**	**Shoe A**	**Shoe B**	**Shoe C**
1	**(W)**	**-45.2**	**-38.5**	**-33.9**	**9.9**	**11.9**	**12.0**
	(SD)	**5.3**	**2.7**	**2.6**	**1.5**	**0.9**	**3.2**
2	**(W)**	**-39.9**	**-26.8**	**-24.5** *	**5.7**	**4.6**	**7.0**
	(SD)	**8.3**	**2.5**	**1.6**	**1.6**	**0.4**	**2.5**
3	**(W)**	**-47.4**	**-51.7**	**-43.9**	**5.8**	**6.7**	**7.2**
	(SD)	**4.4**	**1.5**	**6.0**	**0.6**	**3.3**	**2.2**
4	**(W)**	**-45.6**	**-46.0**	**-52.0**	**11.2**	**11.6**	**16.3**
	(SD)	**15.1**	**6.0**	**8.2**	**5.4**	**2.2**	**1.2**
Mean	**(W)**	**-44.5**	**-40.8**	**-38.6**	**8.1**	**8.7**	**10.6** *
	(SD)	**8.4**	**10.1**	**11.7**	**3.6**	**3.7**	**4.5**

The mean ankle energy generated and absorbed during ground contact in the acceleration phase are presented in Table 6.17. There were no trends or significant differences in the energy absorbed at the ankle between any of the shoe conditions. However, three of the four participants showed decrease in the energy generated in Shoe C compared to Shoe A, with significant differences shown in P1 and P2.

TABLE 6.17: MEAN ANKLE ENERGY ABSORBED AND GENERATED DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE ACCELERATION PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))



Participant		Ankle Energy Absorbed			Ankle Energy Generated		
		Shoe A	Shoe B	Shoe C	Shoe A	Shoe B	Shoe C
1	(W)	-49.4	-45.3	-42.5	109.7	107.1	103.8*
	(SD)	5.4	6.7	6.2	0.9	6.8	1.0
2	(W)	-34.5	-32.2	-30.6	138.9	118.4	119.0*
	(SD)	7.2	1.3	2.1	9.5	7.3	9.2
3	(W)	-61.9	-73.3	-69.0	146.5	145.3	144.7
	(SD)	2.9	6.1	8.4	4.3	5.5	2.7
4	(W)	-40.0	-45.3	-45.2	138.8	163.7	167.4
	(SD)	4.1	7.5	8.0	21.9	12.5	19.5
Mean	(W)	-46.5	-49.0	-46.8	133.5	133.6	133.7
	(SD)	11.7	15.1	15.6	18.0	25.1	27.0

The mean MPJ energy generated and absorbed during ground contact in the maximum speed phase are presented in Table 6.18. Two of the four participants showed a significant decrease in the energy absorbed at the MPJ with increase bending stiffness, for P3 in Shoe B and Shoe C compared to Shoe A, while P4 in Shoe B compared to Shoe A. There was no trend observed in the energy generated at the MPJ with increased bending stiffness. While P3 showed a significant increase in the MPJ energy generated in Shoe B compared to Shoe A, P4 showed a significant decrease in Shoe C compared to Shoe A.

TABLE 6.18: MEAN MPJ ENERGY ABSORBED AND GENERATED DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE MAXIMUM SPEED PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		MPJ Energy Absorbed			MPJ Energy Generated		
		Shoe A	Shoe B	Shoe C	Shoe A	Shoe B	Shoe C
1	(W)	-50.1	-31.1	-30.4	4.9	4.4	4.9
	(SD)	3.7	9.8	8.7	0.5	0.9	1.1
2	(W)	-38.9	-52.0	-45.5	5.2	5.9	7.9
	(SD)	14.3	5.8	1.7	1.3	1.1	1.9
3	(W)	-50.6	-43.7 *	-40.0 *	5.7	7.7 *	8.3
	(SD)	3.6	3.9	2.1	0.2	1.0	2.9
4	(W)	-32.1	-16.1 *	-19.1	10.7	10.0	7.9 *
	(SD)	14.5	15.0	7.4	4.6	4.6	3.2
Mean	(W)	-42.9	-35.7	-33.8	6.6	7.0	7.2
	(SD)	10.8	16.3	11.3	2.8	2.8	2.4

The mean ankle energy generated and absorbed during ground contact in the maximum speed phase are presented in Table 6.19. There were no clear trends of significant differences in the energy generated or absorbed at the ankle with increased bending stiffness.

TABLE 6.19: MEAN ANKLE ENERGY ABSORBED AND GENERATED DURING THE STANCE PHASE FOR EACH PARTICIPANT AND GROUP MEAN IN THE MAXIMUM SPEED PHASE (*INDICATES SIG DIFFERENCE FROM SHOE A CONDITION (P<0.1))

Participant		Ankle Energy Absorbed			Ankle Energy Generated		
		Shoe A	Shoe B	Shoe C	Shoe A	Shoe B	Shoe C
1	(W)	-116.1	-99.0	-103.7	112.5	97.4	92.2
	(SD)	9.8	11.8	9.9	3.1	3.8	3.7
2	(W)	-72.8	-85.2	-92.6	103.1	124.2	123.9
	(SD)	17.7	8.9	1.6	16.3	23.1	11.5
3	(W)	-125.3	-104.4	-106.2	139.4	126.9	121.9
	(SD)	11.6	11.9	2.3	5.7	4.5	6.6
4	(W)	-64.5	-65.8	-48.5	133.6	108.3	109.8
	(SD)	20.3	9.1	9.8	18.6	8.7	18.4
Mean	(W)	-94.7	-88.6	-87.8	122.2	114.2	112.0
	(SD)	29.6	15.5	25.4	17.8	17.1	14.3

The results of the power analysis are presented in Table 6.20. Kinematic and kinetic variables in the acceleration phase which showed a significant difference compared in Shoe C compared to Shoe A in the group mean were chosen for analysis. Although there were no significant differences in sprint times, a power analysis was conducted in order to inform the necessary sample size for further research.

TABLE 6.20: POWER ACHIEVED IN THIS RESEARCH AND PREDICTED SAMPLE SIZE (N) NEEDED TO ACHIEVE A POWER OF 0.8 FOR SELECT KINEMATIC, KINETIC AND SPRINT TIME VARIABLES

	Power	n
Variable	SA-SC	SA-SC
MPJ Flexion Range	0.97	3
Ankle Plantarflexion Range	0.36	11
MPJ Energy Generated	0.25	19
Sprint Times		
10 - 30 m	0.10	970
30 - 50 m	0.10	617

The kinematic variables achieved the highest levels of power in this research, while the sprint time variables achieved the lowest power. The sample sizes necessary to achieve a power of 0.8 for the kinematic and kinetic variables are much lower than those necessary for the sprint time variables.

6.5 DISCUSSION

6.5.1 PREVIOUS LITERATURE

The angular range of motion and the angular velocity patterns of the MPJ and ankle during both the acceleration and maximum speed phases throughout ground contact were similar in shape and amplitude to those presented in previous literature (Bezodis et al., 2011; Toon et al., 2009; Bezodis et al., 2008). The group mean shows that in Shoe A, the MPJ rotated through a range of motion of up to 35°, with mean peak angular velocities in dorsiflexion and plantarflexion of up to 16 rads/s and 30 rads/s, respectively, similar to previous results (Toon et al., 2009; Bezodis et al., 2011). The group mean shows that in Shoe A, the ankle rotated through a range of up to 23° in dorsiflexion and 54° in plantarflexion. Although the mean ankle angular range of motion were slightly higher than the 20° dorsiflexion and 40° plantarflexion reported by Stefanyshyn and Nigg (1998b), the angle angles are thought to be sufficiently comparable to be representative of commonly occurring movement of the ankle during sprinting. The mean peak ankle angular velocities measured in Shoe A in dorsiflexion and plantarflexion of up to 19 rads/s and 23 rads/s, respectively, were similar to previous literature (Bezodis et al., 2008).

The joint moment and power traces patterns during the acceleration and maximal speed phases throughout ground contact were similar in shape and magnitude to previous literature for both the MPJ and ankle. The group mean MPJ peak moment in Shoe A was 86 Nm in the acceleration phase and 92 Nm in the maximal speed phase, similar to previously reported ranges of 67 to 143 Nm in early acceleration phase (Bezodis et al., 2011) and 75 to 125 Nm in the late acceleration phase (Stefanyshyn and Nigg, 1997). The group mean peak ankle moments in Shoe A were 277 Nm in the acceleration phase and 328 Nm in the maximal speed phase, similar to previously reported ranges of 159 to 284 Nm in early acceleration (Bezodis et al., 2011) and 217 to 429 Nm in the maximal speed phase (Bezodis et al., 2008).

With regards to joint power values, the group mean MPJ peak power in dorsiflexion in Shoe A was -907 W in acceleration and -1391 W in the maximal speed phase. Previously reported ranges for peak MPJ dorsiflexion were similar, with Bezodis et al. (2011) reporting values between -500 to -1100 W in early acceleration and Stefanyshyn and Nigg (1997) reporting between -1000 to -2000 W in late acceleration. The group mean MPJ peak power in plantarflexion in Shoe A was 484 W for the acceleration phase and 553 W in the maximal speed phase. However, while Bezodis et al. (2011) report similar values for the peak MPJ power values in plantarflexion to those obtained in this research, ranging between 219 to 612 W in early acceleration, Stefanyshyn and Nigg (1997) report values less than 100 W in the late acceleration phase. This low value reported, however, is thought to be due to the previously mentioned low sampling rate and filtering frequency cut off values used by Stefanyshyn and Nigg (1997), which resulted in lower values of kinematics and kinetics in plantarflexion.

As for ankle power values, the group mean peak ankle power in dorsiflexion in Shoe A was -1815 W in the acceleration and -3747 W in the maximal speed phase while the peak power in plantarflexion was 2734 W in acceleration and 3979 W in the maximum speed phase. Previously reported values for peak ankle power were similar, with peak power in dorsiflexion reported between -700 to -

1000 W in early acceleration (Bezodis et al., 2011) and -2500 to -4500 (Bezodis et al., 2008) in maximal speed and peak power in plantarflexion between 1380 to 2433 W in the acceleration phase (Bezodis et al., 2011) and 2200 to 4000W (Bezodis et al., 2008) in the maximal speed phase.

Although the focus of this work has centred on improvement of sprinting performance, risk of injury is also of concern, as an injury may mean the end of the season for a sprinter or a loss to training time, which would result in a reduced sprinting performance. The injury rate in athletics is high, reported between 61 and 76 % (Bennell et al, 1999; D'Souza, 1994), with injuries primarily consisting of overuse injuries, such as tendinopathies and stress fractures. In addition, the majority of injuries occurred during training (60%) as opposed to in competition. With regards specifically to sprinting, 41% of injuries occurred below the knee (D'Souza, 1994). As this and previous work (Stefanyshyn and Nigg, 2000) have shown that changing the bending stiffness of sprint shoes can significantly affect the kinematics and kinetics at the MPJ and ankle for individuals, the effect of this changes on injury mechanics must also become a concern. While the effect of changes in bending stiffness did not result in injury in this work, indicating small injury risk in short term use of sprint shoes with increased stiffness, small increases in joint loading over the long term may increase overuse injury rates. The longitudinal effect of increased bending stiffness on injury rates in sprinters is unknown and should be an area of further study were stiff sprint shoes to be commercially available to the general public.

6.5.2 SPRINT PERFORMANCE

There were no significant changes in sprint times for either the individual participants or the group mean in either the acceleration or maximal speed phases with increased bending stiffness of the sprint shoes. However, this was not wholly unexpected due to the high levels of variation inherent to the timing system, the low sample size and the low number of trials performed. Although no changes in sprint performance were identified, it does not mean that there were not any changes, but that there were no changes confidently detected with the methodology used. This is highlighted by the low level of power achieved (0.1) in the sprint measures from 10 – 30 m and 30 – 50 m. While increasing the sample size would aid in increasing the power achieved, the predicted sample size necessary to increase the power to 0.8 in the current research is between 670 – 970 subjects. This is highly unrealistic when examining a population of elite sprinters. However, the kinematic and kinetic variables achieved much higher levels of power, between 0.25 and 0.97, along with much more realistic sample sizes necessary to achieve a power of 0.8. Therefore, the methodology must be considered carefully when deciding which variables to examine. In order to more confidently examine sprint performance variables, it is recommended to use a timing system with a lower typical error and coefficient of variation and significantly increase both the sample size and number of trials performed. However, increasing the sample size to the necessary subject numbers to achieve sufficient power may not be realistic. It is suggested that kinematic and kinetic variables be utilised as predictors of performance in future research.

6.5.3 KINEMATICS

In agreement with the hypothesis, increasing the bending stiffness of sprint shoes resulted in a significant reduction in the angular range of motion and the peak angular velocities at the MPJ for the group mean in both the acceleration and maximal speed phases. The observed decrease in the angular range and peak angular velocity at the MPJ with increased bending stiffness is consistent with previous literature (Toon, 2009; Smith et al., 2010). It was further observed that the decreases in the MPJ range of motion and angular velocity were specific to different phases throughout stance in both the acceleration and maximal speed phases. The reductions in angular range of motion were specific to the Extension 1 and Flexion phases of stance, while there were no changes in the Extension 2 phase prior to toe off. The observed decrease in peak MPJ angular velocity was also specific to the phase of dorsiflexion prior to toe-off, with no significant difference in plantarflexion phase upon touchdown.

With regards to the MPJ angular range of motion, while it was expected that increased bending stiffness would result in a decrease in the MPJ angular range of motion, it is of particular interest that this decrease in angular range was not observed across each of the phases during stance. There are confounding views on the effect of the reduction of the MPJ angular range of motion. On one hand, flexion at the MPJ has been associated with a significant absorption of energy (Scott and Winter, 1993; Stefanyshyn and Nigg, 2000) and therefore minimising this motion would result in a decrease in the energy absorbed at the joint. Conversely, Toon (2009) reasoned that a decrease in the MPJ angular range in flexion may reduce the effectiveness of the Windlass mechanism, which could affect the functionality of the foot during extension prior to toe off.

Without the rigidity in the longitudinal arch gained from the Windlass mechanism, two consequences may result: (1) energy may be wasted as compensatory muscle activation may be required to stabilise the foot in order to achieve the rigidity necessary for push off and (2) an optimal level of rigidity may not be achieved, reducing the effectiveness of the foot as a lever for propulsion. Since there was no change in the amount of extension of the MPJ prior to toe off, the suggestion is that the foot reached an acceptable level of rigidity for push off, indicating there is no difference in the effectiveness of the foot as a lever for propulsion with the amount of decreased angular range of motion in flexion achieved at this time. Otherwise, toe off would have occurred as more of a roll-over, with the toes remaining in a dorsiflexed position lacking the tension required to perform an active pushoff. It is unknown, however, if the foot itself is achieving sufficient tension through the Windlass mechanism or if, as suggested by Toon (2008), the increased bending stiffness of the sprint shoes may compensate for a loss of rigidity in the longitudinal arch. While achieving an increase in rigidity in the foot-shoe system may allow the participants to push off through the same range of motion with less dorsiflexion to activate the Windlass mechanism, it is unknown if energy is wasted through compensatory muscular activation in the foot.

The peak angular velocity at the MPJ for the group mean was reduced in dorsiflexion with increased bending stiffness while there was no change in the peak angular velocity in plantarflexion in both the acceleration and maximal speed phases. In addition, from the group mean results in Figure 6.5, it appears there was a shift in the timings of the occurrences of the peak angular velocities, with the peak angular velocity in dorsiflexion not only minimised with increased bending stiffness, but also occurring earlier in stance. Consequently, the MPJ transitioned into plantarflexion earlier in the stiffer shoe conditions, allowing the joint to remain in the plantarflexion phase for longer. As power is a function of the angular velocity at the joint, this results in not only a minimization of the amplitude but also the duration of the negative power phase and an increase in the duration of the positive power phase, where energy is generated at the joint.

In agreement with the hypothesis, increasing the bending stiffness of sprint shoes resulted in a significant reduction in the angular range of motion at the ankle for the group mean in both the acceleration and maximal speed phases. Similar to the behaviour of the MPJ, the reduction in the angular range of motion at the ankle was specific to the plantarflexion phase prior to toe-off while there was no difference in the initial phase of dorsiflexion upon touchdown. In opposition to the hypothesis, however, there was no significant difference in the peak angular velocities at the ankle for the group mean. While the effect of increasing the bending stiffness of sprint shoes on the ankle kinematics in sprinting has never been reported, the results obtained indicate that increasing the bending stiffness of sprint shoes can significantly affect the kinematics at the ankle in sprinting. As the ankle is a much larger contributor to the energy of the lower limb in sprinting compared to the MPJ, it should be considered in further investigations into increased bending stiffness and sprinting dynamics.

The lack of an observed change in the dorsiflexion at the ankle between the footwear conditions indicates that there is no change in the amount of lengthening of the triceps surae between initial touchdown and peak ankle dorsiflexion with increased bending stiffness of sprint shoes. A change in the length of the triceps surae would have implications for the stretch-shortening cycle (SSC). The SSC, characterised by an eccentric muscular contraction followed immediately by a concentric muscular contraction, has resulted in increased force production and power output from the muscles when compared to performing a concentric contraction alone (Komi and Bosco, 1978). A reduction in the peak dorsiflesion at the ankle would indicate less lengthening of the triceps surae under eccentric conditions. A reduction in the amplitude of eccentric loading has been shown to result in a reduction of the power output in the concentric phase (Cavagna, 1977).

While there was no change in the peak range of ankle dorsiflexion, however, there was a reduction in the amount of ankle plantarflexion with increased bending stiffness of sprint shoes. This indicates that there is a reduction in the amount of shortening of the ankle plantarflexors, which has implications considering the force-length relationship of the ankle plantarflexors. A change in the length of the ankle plantarflexors will shift the musculoskeletal properties of the muscle closer to or further from where the athlete has their peak power production (Hill, 1938; Katz, 1939).

Comparing the changes in kinematics at the MPJ and ankle in the different phases of sprinting, it is apparent that the bending stiffness has more of a controlling effect in the acceleration phase compared to the maximal speed phase. While there was decreased MPJ and ankle angular range of motion for the group mean in both the acceleration and maximal speed sprint phases with increased bending stiffness, in the acceleration phase there was a significant decrease in angular range of motion in both Shoe B and Shoe C compared to Shoe A, while in the maximal speed phase there was only a significant decrease in Shoe C compared to Shoe A. This was also evident for the peak angular velocity at the MPJ, with a significant decrease for the group mean in both Shoe B and Shoe C compared to Shoe A in the acceleration phase but only a significant difference in Shoe C compared to Shoe A in the maximal speed phase. This is in agreement with the hypothesis and is consistent with the previous literature of Toon (2009), who found that the effect of increased bending stiffness on the kinematics of the MPJ was larger during ground contact at 10 m versus 50 m comparing barefoot and shod sprinting. Toon (2009) reasoned that the difference in the composition of the GRF in the different phases may explain the observed differences in magnitude of change in the kinematics at the MPJ between the acceleration and maximum speed phases. While in the acceleration phase the horizontal component of force is dominant, in the maximal speed phase the resultant GRF increases compared to the acceleration phase, with relative contribution of the horizontal component of force reducing and the vertical component of the GRF increasing approximately ten-fold during braking and doubling during propulsion (Mero and Komi, 1986). The increase in magnitude of the vertical component of the GRF would impart a larger bending force on the shoe in the maximum speed phase, resulting in less of an effect of increased bending stiffness on the kinematics compared to the acceleration phase. It is evident that the appropriate levels of bending stiffness in the acceleration and maximal speed phases need to be considered separately as the effective stiffness is clearly different.

6.5.4 KINETICS

Contra to the hypothesis, increasing the bending stiffness of sprint shoes did not result in a significant increase in either the MPJ or ankle peak moments. While there were no significant changes in the peak MPJ moment in either the acceleration or maximal speed phases, the group mean results presented in Figure 6.6 for the acceleration phase indicate a trend towards increased MPJ moment with increased sprint shoe bending stiffness. However, examination of the individual participant data in Table 6.10 shows that this trend in the group mean is due to the dominance of the results of P4, who showed a significant increase in MPJ moment in Shoe C compared to Shoe A. None of the other participants exhibited this trend, minimizing the significance of the trend observed in the group mean.

Power generation at the MPJ and ankle were both initially negative, in the phase of energy absorption, and then increased to positive values, in the phase of energy generation, as shown in Figure 6.7. The results indicate that there were no significant differences in the peak negative or positive powers generated at the ankle in either the acceleration of maximal speed phases. There were, however, observed changes in the MPJ peak powers generated with increased bending stiffness. This, however, was specific to the acceleration phase, with no significant changes observed in the maximal speed phase. Specifically in the acceleration phase, increasing the bending stiffness of sprint shoes resulted in a significant increase in the positive peak power generated at the MPJ in the stiffest shoe condition for the group mean. This trend of increased power generation with increased bending stiffness was observed in all the participants. In addition, a trend of decreased peak negative power at the MPJ for the group mean was observed. Although there was not a significant difference in the decrease in the peak negative power with increased bending stiffness for the group mean, all but one participant showed decreased MPJ peak negative power in Shoe C compared to Shoe A, strengthening the validity of the trend in the group mean results.

Joint power is a function of the moment and the angular velocity at the joint. Therefore, changes in the power generated are due to a change in one or both of these variables. Examination the acceleration phase in Figure 6.6 and Figure 6.7 indicates that the peak negative power at the MPJ occurs at a similar time point in the stance phase as the maximum MPJ moment. Since there was no significant difference in the maximum moment generated with increased bending stiffness, the observed decrease in the negative peak MPJ power must be a result of the significant decrease in the angular velocity at the MPJ in the acceleration phase. This indicates that changes in the kinematics are more influential on the observed changes in peak negative power generation at the MPJ in the acceleration phase than the kinetics at the joint. However, the opposite is observed in the peak positive power at the MPJ. While there was a significant increase in the peak positive power generated at the MPJ with increased bending stiffness, there was no difference in the peak angular velocity at the joint during toe-off. It is reasoned that the increased power generation is therefore a consequence of higher moments throughout the final period of stance. As these values were not directly examined in this work, it is suggested that in future work, discrete values of the lower limb dynamics be examined at more points during ground contact rather than focusing solely on peak values throughout the stance phase. Nonetheless, the observed relationships indicate that the changes in kinetics with increased bending stiffness are more influential to the changes peak positive power generation during toe-off.

In addition to the observed changes to the magnitude of peak powers generated at the MPJ in the acceleration phase with increased bending stiffness, a shift in the timings of the occurrence of the peak powers was also apparent in the group mean results presented in Figure 6.7. As the phases of power are dictated by the angular velocity, the shifts in timings of the peak powers are a result of the previously discussed changes in the timing of the angular velocity. The results indicate that both the peak negative and peak positive powers occur earlier in the stance phase with increased bending stiffness of the sprint shoe. The result is that the time spent in the energy absorption phase is decreased, while the phase of positive power and the time spent in the energy generation phase is increased with increased bending stiffness of sprint shoes. In addition to the changes in the magnitude of the peak powers at the MPJ, the shift in the timing of the angular velocity resulted in decreased energy absorption and increased energy generation at the MPJ with increased sprint shoe bending stiffness.

In the maximal speed phase, increasing the bending stiffness of sprint shoes resulted in a trend of decreased peak negative power at the MPJ while there was no difference in the peak positive power produced for the group mean. Although there was not a significant decrease in the peak negative power with increased bending stiffness for the group mean, similar to the acceleration phase, all but one participant had decreased MPJ minimum power in Shoe C compared to Shoe A, strengthening the validity of the trend in the group mean results. Similar to the acceleration phase, as there was no difference in the maximum moment generated at the MPJ, the changes in peak negative power were due to changes in the angular velocity. The changes in the peak negative power resulted in a trend of decreased energy lost at the MPJ with increased bending stiffness, with a significant decrease in energy absorbed at the MPJ for two of the four participants. There was no change in the MPJ energy generated at the joint.

6.5.5 TRENDS

When examining the results of the group mean and the individual participants, the response patterns shown in the group mean were reflected among the majority of the individual participants throughout the kinematic variables. Where significant differences in the kinematic variables at the MPJ and ankle were observed, the trends in the individual participants generally followed the same trends as the group mean. This indicates that the kinematic responses observed in the group mean are possibly generalisable to the general population of elite sprinters, giving strength to the relationship between the changes in kinematic measures and sprint shoe bending stiffness as a general trend rather than an individual response.

However, when examining the results of the kinetic data, there is much less indication of consistent trends among the individual responses to increased bending stiffness. The trends in power seem to be more consistent through the individual responses than observed in the joint moments. However, this is most likely due to the power being calculated as a function of angular velocity. This indicates that kinetic responses are more individual, depending on the sprinters musculoskeletal properties and strategy for sprinting.

6.6 CONCLUSION

The kinematic and kinetic results obtained in this work were comparable to similar research, indicating that the kinematics and kinetics obtained was representative of normal sprinting performances. Although there are several limitations to this work, including the low number of participants and trials, the results of this investigation have demonstrated that changes in the kinematics and kinetics of the MPJ and ankle can be obtained through changes in the bending stiffness of footwear.

The effect of increased bending stiffness on sprinting performance remains ambiguous as there were no significant differences in sprinting performance with increased bending stiffness in either the acceleration of maximal speed phases. However this was not unexpected as it is difficult to accurately measure sprint times with commercially available timing systems. As previously mentioned, while it might be easier to elicit small changes in sprinting performance with footwear interventions, it is difficult to accurately and repeatedly measure these small changes. A measure of sprint time, however, may still a valuable tool in order to identify significantly large changes in performance.

Examination of the data set revealed that in agreement with the hypothesis, the effects of increasing the bending stiffness of sprint shoes on the kinematics and kinetics of the lower limb were more pronounced in the acceleration phase compared to the maximal speed phase. It is therefore suggested that the effect of bending stiffness on sprinting performance be examined in each phase and the different requirements considered for further research. It is also suggested that stiffer sprint shoes be utilised in the maximal speed phase in subsequent research as the conditions used in this work were not sufficiently different in stiffness to elicit the more obvious changes to the kinematics observed in the acceleration phase.

In support of the hypothesis, increasing the bending stiffness of sprint footwear resulted in a significant decrease in the angular range of motion and peak angular velocities at the MPJ in both the acceleration and maximum speed phases. The decreases in the angular range of motion at the MPJ, however, were specific to the initial phase of extension upon touchdown and the flexion phase while there was no change in the extension phase during toe-off. Although a reduction in the amount of flexion achieved may influence the effectiveness of the Windlass mechanism, as there was no change in the extension prior to toe off, it is indicated that the foot reached a sufficient level of stiffness in order to be an effective lever for push off. Furthermore, changes to the angular velocity were specific to the phase of dorsiflexion while there was no significant difference to the peak angular velocity in plantarfleixon. As changes to the kinematics in the different phases of ground contact will have different performance implications, it is suggested that subsequent research examine changes to these individual phases rather than quantifying just the absolute change during stance.

In addition to these changes in the magnitude of the kinematics at the MPJ, a shift in timing of the peak angular velocity in dorsiflexion as well as the transition between dorsi- and plantarflexion was observed. As the phases of positive and negative power are determined by the directionality of the angular velocity, these temporal changes mean that the phase of negative power was reduced while the phase of positive power was increased. It is suggested that further research examine the temporal changes in the kinematics at the joints in addition to changes in magnitude with increased bending stiffness of sprint footwear.

At the ankle, in support of the hypothesis, increasing the bending stiffness of sprint shoes resulted in a significant decrease to the angular range of motion at the joint. This observed decrease in the angular range of motion was specific to the plantarflexion phase during ground contact. However, in opposition to the hypothesis, there were no significant differences in the angular velocity at the ankle. As recent research has focused of the MPJ, as increasing the bending stiffness of sprint footwear has been shown to significantly alter the kinematics of the ankle, it is suggested that the ankle be examined in further research in addition to the MPJ. As the ankle is a larger contributor to the energy generated and absorbed by the lower limb in sprinting than the MPJ, it is argued that it has a greater potential to influence sprinting performance through footwear design than the MPJ.

Increasing the bending stiffness of sprint shoes did not result in an increase the maximum moments generated at either the MPJ or ankle as hypothesised. While increasing the bending stiffness resulted in a significant increase in the MPJ maximum moment for one participant, there were no differences or apparent trends among any of the other participants.

With regards to power generation at the joints, in agreement with the hypothesis, increasing the bending stiffness of sprint shoes resulted in significant changes to the peak powers at the MPJ in the acceleration phase. However, in opposition to the hypothesis, there were no changes at the MPJ in the maximum speed phase or at the ankle in either phase. In the acceleration phase, increasing the bending stiffness resulted in a trend of decreased peak negative power and a significant increase in the peak positive power at the MPJ. The decrease in the peak negative MPJ power with increased bending stiffness was a result of changes in kinematics while the increase in peak positive MPJ power was a result of changes in kinetics.

In addition to the changes in the magnitude of the peak powers at the MPJ, a shift in the timings of the occurrence of the peak powers resulted in reduced time spent in the negative power phase while increasing the phase of positive power generation with increased bending stiffness. In addition to the changes in the magnitude of the peak powers at the MPJ, the shift in the timing of the angular velocity resulted in decreased energy absorption and increased energy generation at the MPJ with increased sprint shoe bending stiffness.

From the results of this investigation, the effect of increased bending stiffness on the kinematics and the kinetics of the MPJ and ankle have been elucidated. In addition, some key methodological concerns for future research in this area have been highlighted, including the increased effect of sprint shoe bending stiffness in the acceleration phase compared to the maximal speed phase of sprinting as well as the importance of examining both the group mean and individual results.

Although it is still unclear whether sprinting performance can be improved with increase bending stiffness of sprint shoes generally across the population of elite sprinters, it is clear that changes in the kinematics of the lower limb are generally elicited by increasing the bending stiffness of sprint shoes. How sprinters accommodate this increased stiffness in terms of changes in kinetics and sprint performance in general seems to be specific to the particular sprinter. As it has been speculated that individual characteristics of the individual sprinters may influence the appropriate shoe stiffness for each sprinter to achieve their optimal performance (Stefanyshyn and Fusco, 2004), an examination of the characteristics of sprinters should be considered for further research. If particular characteristics of a sprinter could be identified as being associated with an optimal stiffness, for example force-length-velocity relationship of the plantarflexors or anthropometric measures, the levels of sprint shoe bending stiffness may potentially be prescribed in the future.

7 GENERAL DISCUSSIONS AND CONCLUSIONS

7.1 SUMMARY OF MAIN ACHIEVEMENTS AND FINDINGS

The purpose of this PhD research was to contribute to an increased understanding of the influence of the mechanical properties of sprint footwear on sprinting performance and lower extremity dynamics in sprinting. In particular, the influence of longitudinal bending stiffness on elite sprinters has been investigated. While the aim of this research was ultimately to examine biomechanical changes to human performance with changes to the bending stiffness of sprint shoes, in order to achieve this, sprint shoes in a range of bending stiffness with appropriate mechanical properties to facilitate maximal effort sprinting were constructed. In addition, an overarching aim addressed methodological concerns from previous research in this area throughout this work in order to inform methodologies undertaken in this and future research in this area.

The mechanical properties of current commercially available sprint shoes were evaluated. Of particular relevance was the traction generating properties and the level of longitudinal bending stiffness. The intention was to both validate the mechanical testing methodologies used and to benchmark the mechanical properties, both as a record of what currently exists in the market and to inform the subsequent construction of sprint shoes that were used in the human performance testing of this work.

A novel mechanical test apparatus and methodology were specifically designed to evaluate the traction generating properties of sprint shoes. Mechanical test procedures and benchmark data of this kind have not been reported in literature to date. Although limitations in the mechanical testing may undermine the external validity of the results obtained, the test rig and methodology were shown to be sufficiently repeatable and reproducible to be used in this and future work, providing an objective means for comparison between commercially available and bespoke sprint shoes.

With regards to current commercially available sprint shoes, a large disparity between the traction generating properties was observed, with a significant relationship shown between increased traction generated and increased number of pins on the sole unit. However, as even the lowest traction generating sprint shoes generate sufficient traction to prevent slipping in sprinting, the advantage of increased traction is questioned and notion of redundant traction is introduced. Human performance testing is recommended for further insights into the effects of increased traction generation on sprinting performance. With regards to informing future bespoke sprint shoe designs, a minimum level of traction generated by commercially available sprint shoes was identified in order to provide a minimum level of traction which bespoke sprint shoes should provide prior to being utilised in future human performance testing.

A novel method was introduced by Toon (2008) for the measurement of longitudinal bending stiffness of sprint shoes and was used in this research in order to be able to make direct comparisons between the mechanical properties of sprint shoes. Although previous research has shown improvements to sprinting performance with increased bending stiffness (Stefanyshyn and Fusco, 2004), the levels of bending stiffness of current commercially available sprint shoes measured in this work were comparable to those measured by Toon

(2008), indicating there are no trends detected towards the introduction of stiffer commercially available sprint shoes. This may be due to a lack of information on the changes to the dynamics of the lower limb with increases in longitudinal bending stiffness and the unknown potential for increased risk of injury. A longitudinal study on the injury potential with increased bending stiffness in sprint shoes is recommended for future research.

Although the methodology used in this research for the evaluation of the bending stiffness of sprint shoes was shown to be repeatable, there is little external validity to the measures. An aspect that has not been introduced is the notion that during ground contact, the shoe and foot will be acting as a system. With the foot itself being a rigid structure, it will introduce some stiffness into the system. In addition, during the ground contact in sprinting, the effective bending stiffness of the shoe will be continuously changing, as the point of application of the GRF is continuously moving as the foot-shoe moves through its range of motion. In future research, obtaining a more realistic effective bending stiffness for the foot and shoe system in sprinting is recommended in order to inform subsequent sprint shoe design.

A novel method for constructing sprint shoes in a range of bending stiffness, with sufficient traction in order to facilitate the investigation of the effects of increased bending stiffness on sprinting performance has been presented. The sprint shoe sole units were constructed using LS nylon-12. While Toon (2008) has shown that suitable levels of bending stiffness could be achieved utilising LS nylon-12 to construct sprint shoe sole units, the shoes lacked traction features necessary to facilitate a maximal effort sprint. An iterative process of concept design undertaken in this work resulted in a novel LS nylon-12 sprint sole unit with integrated traction features. Utilising the mechanical test rig and methodology developed in Chapter 2, these sprint shoe sole units have been shown to generate traction forces above the minimum threshold established from current commercially available sprint shoes. To complete the construction process, sprint shoe sole units were attached to the uppers of a New Balance SDS 1005 sprint spikes at their UK manufacturing facilities. A novel process for assembling the LS sole units with standard uppers was presented, producing durable shoes with a high quality finish.

An analysis of data collection and processing methods commonly used in recent literature for the examination of the kinematics and kinetics of the MPJ in sprinting was undertaken. Specifically, the effect of commonly used sampling rates (SR), filtering frequencies (*fc)*, and definition of the MPJ on the resultant MPJ kinematics and kinetics were examined in this work. Previous literature had shown the combined use of an SR of 200 Hz and *fc* of 8 Hz lead to underestimations of the kinematics at the joint, as well a lateral representation of the joint leading an underestimation of the angular range of motion compared to a medial representation (Smith and Lake, 2007). However, as Smith and Lake (2007) examined the combined effect of SR and *fc* on the resulting kinematics of the MPJ, the individual contribution was unknown, in addition to their effect on the kinematics of the MPJ.

In this research, the combined effect of commonly used *fc* (8 Hz), SR (200 Hz) and MPJ definition (5th MPJ) lead to significant differences in both the kinematics and kinetics at the MPJ in sprinting. With regards to the individual contribution of the data collection and processing variables, it was shown that all the commonly used values for commonly used f_c, *SR* and MPJ definition contributed to significant differences in the resulting MPJ kinematics, with f_c and MPJ definition resulting in the largest underestimation of MPJ kinematics. With regards to kinetics, only changes to the MPJ definition resulted in changes to the MPJ energy absorbed at the joint. This was attributed to the proximal position of the

5th MPJ and to the assumption made that the resultant joint moment at the MPJ was zero until the point of application of the ground reaction force acted distal to the joint, rather than the effect of changes to the MPJ angular range and angular velocity. It is recommended that the choice of data collection and processing variables should be carefully considered when examining the function of the MPJ in sprinting. Specifically, it is recommended that when examining the dynamics of the MPJ in sprinting, a residual analysis should be carried out in order to find an appropriate f_c and *SR* of at least 500 Hz should be utilised. With regards to the definition of the MPJ, it is recommended that MPJ kinematics should be based on a medial definition of the joint. With regards to kinetics, the MPJ should be represented as a transverse axis about the average if the 1st and 5th MPJ.

In Chapter 5, three pairs of sprint shoes, one control shoe (Shoe A) approximately equivalent to the stiffness of commercially available sprint shoes and two exceeding the stiffness of the control shoe by 4 (Shoe B) and 7 (Shoe C) times, respectively, were utilised to investigate the effect of increased bending stiffness on sprinting performance and step characteristics in a maximal effort 50 m sprint. The sprint times were evaluated for a 45 m sprint, at 15 m intervals within the sprint. The intervals were denoted as acceleration (5 – 20 m), mid-acceleration (20 – 35 m) and maximal speed (35 – 50 m) phases while step characteristics were evaluated in the maximal speed phase.

Methodological concerns were additionally addressed. Both a single subject and a group mean approach were utilised in order to highlight methodological concerns with using a group mean approach for analysis when the effect of increased bending stiffness on sprinting performance has been shown to be participant specific (Stefanyshyn and Fusco, 2004; Toon, 2008). The reliability of the measures of sprint performance and step characteristics were also examined, allowing for the identification of appropriate experimental designs for future studies in this area. Examination of the individual results indicated that there was little consistency or reliability between the trials completed by the subjects, calling into question the appropriateness of the application of a group mean analysis for this type of research. Both an examination of the group mean and individual responses to increased bending stiffness in sprinting is suggested in further work.

For the group mean results, increasing the bending stiffness of sprint shoes resulted in significant changes to both sprinting performance and step characteristics. A significant increase in sprint time of 1.1 % for the 45 m sprint in Shoe C compared to Shoe A was shown. In addition, the effect of increased bending stiffness was specific to the particular phase of the sprint, with no change to sprinting performance in the early acceleration phase (5 - 20 m), but a significant increase in sprint times in both the late acceleration (20 – 35 m) and maximal speed phases (35 – 50 m) in both Shoe B and Shoe C compared to Shoe A. In opposition to the hypothesis that the optimum level of stiffness would be subject specific, the level of stiffness for optimal performance for all of the participants in all of the phases was the least stiff condition. It is suggested that the shoe conditions in this chapter were too stiff for all of participants and suggested that less stiff shoes be used in subsequent research.

With regards to step characteristics, increasing the bending stiffness of sprint shoes lead to a significant decrease in ground contact time in both Shoe B and Shoe C compared to Shoe A. There has been no examination of the effects of increasing the bending stiffness of sprint shoes directly on step characteristics in previous research, and this provides elucidation of which mechanisms of the lower limb dynamics are affected in sprinting with increased bending stiffness. However, the potential implications of the current findings on sprint performance are not understood. Although this study saw both a decrease in ground contact time with an increase in sprint time with increased sprint shoe bending stiffness, the relationship between the two is not understood at this time and suggested for future research.

In order to further investigate the effects of increased longitudinal bending stiffness of sprint footwear on sprint performance and the dynamics of the lower limb, three new pairs of sprint shoes were constructed. This is the first study to examine the effect of increased bending stiffness on both sprint performance and the kinematics and kinetics of the MPJ and ankle simultaneously. The phases of acceleration and maximal speed were examined separately. The shoe conditions were less stiff than in the previous chapter, with one control shoe (Shoe A) approximately equivalent to the stiffness of commercially available sprint shoes and two exceeding the stiffness of the control shoe by 2 (Shoe B) and 3.5 (Shoe C) times, respectively.

In agreement with the hypothesis, the effects of increasing the bending stiffness of sprint shoes on the kinematics and kinetics of the lower limb were more pronounced in the acceleration phase compared to the maximal speed phase and it is therefore suggested that the requirements for sprint footwear in the different phases of sprinting be considered separately.

The effect of increased bending stiffness on sprinting performance remains ambiguous as there were no significant differences in sprinting performance with increased bending stiffness in either the acceleration of maximal speed phases. However this was not unexpected as it is difficult to accurately measure sprint times with commercially available timing systems. A measure of sprint time, however, may still a valuable tool in order to identify significantly large changes in performance, quickly highlighting highly inappropriate footwear stiffnesses resulting a large detriment to performance.

Significant reductions in the MPJ angular range of motion with increased bending stiffness were observed. These were specific to the Extension1 and Flexion phases, with no changes in Extension 2 prior to toe off. As there was no decrease in extension prior to toe off, it is reasoned that the reduced angular range of motion in flexion does not compromise the windlass mechanism. The observed decrease in peak MPJ angular velocity was also specific to the phase of dorsiflexion prior to toe-off, with no significant difference in plantarflexion phase upon touchdown. Also observed was a shift in the timings of the peak angular velocities, leading to a decrease in of the negative power phase and an increase in the positive power phase. It is suggested that further research examine the temporal changes in the kinematics at the joints in addition to changes in magnitude with increased bending stiffness of sprint footwear.

Increasing the bending stiffness of sprint shoes resulted in a significant decrease in the angular range of motion at the ankle, specifically in extension. Changes to the kinematics at the ankle with increased bending stiffness in sprinting have never been reported. As the ankle is a much larger contributor to the energy of the lower limb in sprinting compared to the MPJ, absorbing and generating approximately 2 and 17 times the energy, respectively, than the MPJ (Stefanyshyn and Nigg, 1997), it should be considered in further investigations into increased bending stiffness and sprinting dynamics.

7.2 FINAL CONCLUSIONS

The aims outlined in the introduction to address both performance drivers and methodology drivers have been addressed in this research. The primary performance focus of this research was the interaction between the longitudinal bending stiffness of sprint footwear, sprinting performance and lower limb dynamics. In order to address this, sprint shoes in a range of increasing bending stiffness were constructed and used in human performance sprint testing. Both sprint performance and lower limb dynamics were examined. With regards to addressing methodological concerns, two issues have been addressed. The first were gaps in the literature with regards to consistent, systematic research, which were addressed through the examination of the commonly used methodologies to examine the function of the MPJ in sprinting. In addition, both a group and single subject analysis have been undertaken in order to inform the methodologies of future research.

With regards to the specific objectives outlined:

- The development and evaluation of a novel mechanical test procedure for the evaluation of the traction generating properties of commercially available and future bespoke sprint shoe designs was achieved
- The quantification of mechanical properties (traction and bending stiffness) of current commercially available sprint spikes for the purposes of benchmarking and informing future bespoke sprint shoe designs was documented
- A novel construction method using LS nylon-12 to produce bespoke sprint footwear with suitable integrated traction in a range of longitudinal bending stiffnesses was presented
- Methodological concerns were addressed regarding the application of commonly used data collection and processing methods to the examination of MPJ kinematics and kinetics in sprinting

- Human performance testing was implemented, utilising novel methodologies to explore the effect of increasing the bending stiffness of sprint footwear on simple measures of sprinting performance, step characteristics, and lower limb dynamics
- Methodological concerns regarding single subject and group mean analysis of results were addressed

7.3 RECOMMENDATIONS FOR FUTURE WORK

With regards to benchmarking the mechanical properties of sprint shoes, human performance testing is recommended for the measurement of mechanical properties of traction and effective bending stiffness of sprint shoes in order to improve the external validity of the measures to further inform subsequent sprint shoe functionality.

A three dimensional analysis of the MPJ should be undertaken in order to find a method for modelling the joint in a manner that best represents the kinematics and kinetics across the five joints.

A detailed exploration into the minimum change in sprint shoe bending stiffness needed to elicit a biomechanical response from sprinters is recommended. Additional human performance testing should be carried out using small increases in bending stiffness between sprint shoe conditions.

Further testing using the current sprint shoes should focus on the injury implications of increasing bending stiffness of sprint shoes. As the findings of this research have shown that the dynamics of the ankle are significantly affected by shoe stiffness, further exploration in this area is required as changes in Achilles tendon loading are of concern.

Additional human performance testing using much greater sample sizes is recommended to more conclusively determine whether longitudinal bending stiffness affects sprinting performance.

Sprint shoe sole units for commercial use are typically manufactured using injection moulding. This process is very costly due to low volume manufacture, in addition to imposing design constraints upon the sole unit geometry. These factors have traditionally discouraged the production of bespoke, personalised sprint shoes. LS has been shown to be an alternative to this injection moulding process which offers several advantages. This tool-less process permits production of complex three-dimensional forms and enables cost effective low-volume manufacture. In addition, this work has shown that LS can produce sprint shoes with the desired mechanical properties. In terms of practical application, this allows the ability to produce bespoke sprint shoe sole units with mechanical properties tuned to the individual sprinter for optimal performance. Although the athlete’s particular characteristic to which to tune the stiffness for optimal performance has not yet been identified, the ideal in terms of commercial application would be to be able to perform a simple measure of a particular characteristic in a shoe store, and to have a bespoke sprint shoe with mechanical properties tuned to the athlete be constructed immediately.

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