PHD

Biomechanical investigations of bend running technique in athletic sprint events

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Award date:
2012

Awarding institution:
University of Bath

BIOMECHANICAL INVESTIGATIONS OF BEND RUNNING TECHNIQUE IN ATHLETIC SPRINT EVENTS

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A thesis submitted for the degree of Doctor of Philosophy

University of Bath

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May 2012

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ABSTRACT

Biomechanical Investigations of Bend Running Technique in Athletic Sprint Events

Sarah M. Churchill, University of Bath, 2012

For sprint events longer than 100 m, more than half the race is run on the bend, yet bend sprinting has received little attention in biomechanics literature. The aim of this thesis was to understand the effect of the bend on maximal effort sprint performance and technique, using bend radii and surfaces typical of outdoor competition.

Three empirical studies were undertaken with experienced bend sprinters. Initial 3D kinematics investigations revealed an approximately 5% velocity decrease on the bend compared to the straight. However, step characteristic changes contributing to this reduction were different for the left and right steps. For the left step there were significant decreases in step frequency ($p < 0.05$), due to increased ground contact time, which agreed with previously proposed theoretical models. For the right step, however, a significantly reduced flight time resulted in a significant reduction in step length ($p < 0.05$). Maintaining step length and an ‘active touchdown’ were closely related to an athlete’s ability to better maintain straight line velocity on the bend.

Generally, velocity decreased as bend radius decreased, with mean differences of up to 2.3% between lanes 8 and 2. However, changes to athletes’ technique due to different lanes were not conclusive.

Ground reaction forces revealed between-limb differences during bend sprinting. Furthermore, frontal plane forces were up to 2.6 times larger on the bend than on the straight.

Overall, asymmetries were identified between left and right steps for several performance, technique and force variables, suggesting that bend sprinting induces different functional roles between left and right legs, with the left step contributing more to turning to remain on the bend trajectory. The differences in kinematic and kinetic characteristics between the bend and straight, and between-limb asymmetries mean that athletes should apply the principle of specificity to bend sprinting training and conditioning, without sacrificing straight line technique.

PUBLICATIONS

Churchill, S. M., Salo, A. I. T. & Trewartha, G. (2011). The effect of the bend on technique and performance during maximal speed sprinting. *Portuguese Journal of Sport Sciences*, 11 (Suppl. 2), 471-474.

Churchill, S. M., Salo, A. I. T., Trewartha, G. & Bezodis, I. N. (In press). Force production during maximal effort sprinting on the bend. Accepted for *Proceedings of XXX International Symposium on Biomechanics in Sports.* Melbourne: Australian Catholic University.

Conference Presentations:

Churchill, S. M., Salo, A. I. T., Trewartha, G. & Bezodis, I. N. (2012) Comparison of force production in maximal sprinting between the bend and straight. *27th Meeting of the BASES Biomechanics Interest Group*, University of Ulster, UK.

Churchill, S. M., Salo, A. I. T., & Trewartha, G. (2011) The effect of running lane on performance and step characteristics during maximal effort sprinting. *26th Meeting of the BASES Biomechanics Interest Group,* University of Chichester, UK.

Churchill, S. M., Salo, A. I. T., & Trewartha, G. (2010) Performance and step characteristics during bend running. *25th Meeting of the BASES Biomechanics Interest Group,* University of Bath, UK.

ACKNOWLEDGEMENTS

I would like to express my thanks to a number of people:

First and foremost my supervisors, Dr Aki Salo and Dr Grant Trewartha, for all their time, help, support and advice. I have learnt so much from them both, and couldn't have done it without them.

Rob Ellchuk, Malcolm Arnold, James Hillier, Dan Cossins and their athletes, for always being interested and willing to help.

The staff at the Sports Training Village at the University of Bath and the National Indoor Athletics Centre at Cardiff Metropolitan University, for their help during data collections. Special thanks go to Rob Whalley for always accommodating my requests.

To everyone who gave up their time to help with a data collection, especially Andreas Wallbaum for all his technical assistance and Dr Ian Bezodis for his help with my final study.

To my friends and colleagues in the department, and my fellow post-grads, especially Neil, Jen, Karen and Becs, who have always been there when I have needed them. Thank you for all the support, coffee, movies, runs and chats.

To my family and friends who have always been there to lend an ear. Especially my Mum and Dad who have supported and encouraged me in everything I have done and to Ruan for all his support and a lot of patience.

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NOMENCLATURE AND DEFINITIONS

2D	Two dimensional
3D	Three dimensional
AP	Anteroposterior
BW	Body weight
CoM	Centre of mass
DLT	Direct linear transformation
GCS	Global coordinate system
GRF	Ground reaction force
LCS	Local coordinate system
LED	Light emitting diode
MTP	Metatarsophalangeal joint
ML	Mediolateral
PB	Personal best
ROM	Range of motion
TD	Touchdown
TO	Take off

Definitions of key terms used throughout the thesis

Absolute speed	An athlete's speed measured from the actual distance travelled by the centre of mass of the athlete regardless of whether or not the most effective path was taken
Directional step length	The distance component between the position of the MTP during consecutive contacts relative to the direction of travel of the athlete
Inward force	The force acting towards the inside of the bend
Lateral force	The force acting away from the midline of the body
Medial force	The force acting towards the midline of the body
Race line	An invisible line along which the official race distance is measured that is 0.20 m from the inside edge of the left-hand side track lane line
Race step length	The length of the race distance covered during one step

Race velocity	An athlete's velocity measured using the displacement along the official race line
Step contact factor	The proportion of total step time spent in ground contact, calculated as ground contact time divided by total step time

CHAPTER 1: INTRODUCTION

1.1. Research overview

Sprint events are an exciting part of track and field athletics, where the winning margins can be a fraction of a second. This means that even relatively small improvements in performance can have meaningful effects on an athlete's position in a race. For example, the difference between the silver and bronze medallist in the men's 200 m final at the 2011 International Association of Athletic Federations (IAAF) World Championships was just 0.10 s. At the 2008 Olympic Games the difference between silver and bronze medals was just 0.02 s in the men's 200 m final. Athletes and coaches are continually aiming to achieve a 'competitive edge' over opponents. As such, numerous biomechanical analyses of sprinting have been conducted with the aims of understanding and improving performance during sprint running. The majority of sprint studies have focussed on straight line sprinting. However, a standard outdoor track is such that for a 200 m race athletes start on the bend and complete more than half of the race on the bend before entering the 'home' straight. In 400 m sprints, athletes negotiate two bends at high speed. It is generally accepted that performance is reduced on the bend compared to the straight. Indeed, the world best time, of 19.41 s, for a 200 m run entirely along the straight, is held by Tyson Gay (Martin, 2010). Yet, Tyson Gay's personal best (PB) for a 200 m which includes a bend portion is 0.17 s slower than this, at 19.58 s (IAAF, 2012). The bend is an area for potential improvement in sprint performance, where even small improvements may make an important difference to an athlete's race time. Despite this, the bend component of sprinting has received relatively little attention in the biomechanics literature.

The few experimental studies of bend running have been limited to non-maximal effort running (~6.31 $m \cdot s^{-1}$; Hamill et al., 1987), or to the acceleration phase of sprinting (Stoner & Ben-Sira, 1979), have been performed on surfaces dissimilar to a track surface (Greene, 1985; Smith et al., 2006), or have been conducted using very small bend radii (Smith et al., 2006; Chang & Kram, 2007). Thus, they have not been representative of the maximal speed phase of sprinting, where the differences between bend and straight are likely to be largest, or under conditions typical of athletic sprint events. Furthermore, studies have generally been concerned with differences in performance, or force production on the bend compared to the straight, and not with any changes to technique that accompany changes in performance. In order to improve performance on the bend coaches and athletes need to understand how technique changes contribute to those changes in performance, and how they might be overcome.

Additional to differences between bend and straight, there are also differences between lanes when running on the bend. The distance run along the bend is the same for all athletes. However, the radius of the bend increases from the inside lanes to the outside lanes. It has been suggested that this places athletes in the innermost lanes at a disadvantage since the tighter bend is more difficult to negotiate. On an indoor 200 m track the level of disadvantage of running in lane 1 compared to lane 6 has been deemed so great that the IAAF have removed the 200 m event from the Indoor World Championships. However, the effect of lane allocation is not well understood outdoors, and the problem is exacerbated by seeding and psychological factors that might affect race results.

At very small radii and on concrete and grass surfaces, maximal effort sprint performance has been shown to decrease as bend radius decreases (Greene, 1985; Chang & Kram, 2007). However, to the author's knowledge no studies have properly assessed changes in performance or technique on the type of surface used in athletic sprint events and at radii typical of a standard outdoor track. Mathematical models of the effect of lane allocation on a 400 m outdoor track (e.g. Jain, 1980; Greene, 1985) support the proposition that athletes in the inner lanes are at a disadvantage compared to outer lanes, but have not reached a consensus on the level of disadvantage/advantage awarded by running in the inner/outer lanes. A mathematical model has been proposed, which aimed to explain why performance is impaired as radius decreases (Usherwood & Wilson, 2006). However, unfortunately, no experimental measures were made to back-up this model. Experimental studies, under conditions which eliminate psychological and tactical factors that would be present in a competition situation are required to further understand the effect of lane allocation on performance in sprinting.

1.2. Statement of purpose

The aim of this thesis was to understand the effect of the bend on maximal effort sprint performance and technique at bend radii and on surfaces typical of outdoor competition.

1.3. Research questions

To meet the aim of the thesis a number of research questions were formulated. Whilst it is generally accepted that velocity is lower on the bend than it is on the straight, specific changes to performance and the changes to technique on the bend compared to the straight are not fully understood. The limited experimental measures that have been made on bend running have been under conditions that are not applicable to athletes in athletic sprint events (Greene, 1985; Hamill et al., 1987; Smith et al., 2006; Chang & Kram, 2007). In order to improve bend running performance, it is important to understand how bend sprinting differs from straight line sprinting at radii and on surfaces experienced in race conditions. With this in mind the first research question was proposed:

i. **How do technique and performance change on the bend compared to the straight?**

Along with broad agreement that performance is poorer on the bend than the straight, it is also generally agreed that some athletes are better bend runners than others. In absolute terms the best bend runners are those who run the bend the fastest. However, conventional athletics wisdom acknowledges that some athletes have smaller differences between their straight line velocity and their velocity on the bend than others. These athletes might not necessarily be the fastest runners in absolute terms. By understanding the techniques employed by the fastest runners, and by those who have a closer match between velocities on the bend and on the straight, a greater insight into the techniques employed on the bend which might result in superior performance can be gained. This formed the basis for the second research question:

ii. **What effect does bend running have on technique and performance of athletes of different abilities running the same bend?**

Mathematical models have identified a disadvantage of being allocated the inner lanes in sprint races which include a bend portion (Jain, 1980; Greene, 1985; Usherwood & Wilson, 2006). However, experimental measures are required in order to understand the mechanisms by which performance is decreased and how these differ from lane to lane. Additionally, ecologically valid measurements are required under conditions that are free of the tactical and psychological and seeding factors that accompany race conditions. For these reasons, the third research question was proposed:

iii. **How do technique and performance change when athletes run bends of different radii?**

Many biomechanical studies of sprinting have been undertaken which measure the kinematics of athletes in order to inform as to which variables are associated with better performance (e.g. Kunz & Kaufmann, 1981; Mann, 1985; Mann & Herman, 1985). However, whilst a useful measure, and of interest to athletes and coaches, kinematic analyses are unable to fully explain the cause (kinetic) of differences in techniques. For this reason, analyses of the forces associated with better sprint performance have been undertaken in straight line sprinting (e.g. Mann, 1985; Mero & Komi, 1986; Mero, 1988; Hunter et al., 2005; Salo et al., 2005; Weyand et al., 2000; 2010; Morin et al., 2011a; In press). Additionally, force analyses have been conducted during maximal effort sprinting at very small radii (Chang & Kram, 2007). However, the literature is lacking information regarding force production during maximal effort sprinting under conditions that are applicable to competitive athletic sprint events. For this reason the following research question was developed:

iv. **Why are athletes unable to produce the same performance on the bend as they are able to on the straight and how are the better performances achieved on the bend?**

To answer this question, two sub-questions, a. and b., were developed:

a. **How does the requirement to follow the bend affect force production during sprinting?**

b. **What are the force characteristics of better performance during bend sprinting?**

These four main research questions (and two sub-questions) provided a focus for the thesis. Four biomechanical investigations were designed to address these research questions in order to meet the aim of the thesis.

1.4. Thesis outline

1.4.1. Chapter 2: Literature review

A review of the literature pertinent to the analysis of maximal effort sprinting on the bend is provided in Chapter 2. This includes literature regarding the kinematics and kinetics related to performance during maximal effort sprinting on both the straight and on the bend. Additionally, the effect of lane allocation on performance is discussed. Methodological issues relevant to the collection of biomechanical data of maximal effort sprinting on the bend are also addressed.

1.4.2. Chapter 3: The effect of the bend on technique and performance during maximal effort sprinting

This Chapter details a study of seven male and two female athletes running at maximal effort on the straight and on the bend (lane 2). Comparisons of performance descriptors and upper and lower body kinematic variables are made between the two conditions for both the left and right steps, to understand the differences between the bend and straight. Additionally, comparisons of left and right steps are made to assess the effect of the bend on symmetry.

1.4.3. Chapter 4: Relationships between performance and technique during bend sprinting in athletes of different abilities

The data collected for Chapter 3 is further analysed to understand the relationships between performance and technique during bend running. Correlations assess which variables are most closely related to the fastest performance on the bend for both the left and right steps. In order to understand the differences between athletes whose bend and straight line velocities are more, or less, similar correlations between changes in performance and changes in technique on the bend compared to the straight are made.

1.4.4. Chapter 5: The effect of running lane on technique and performance during bend sprinting

An investigation into the effect of the running lane on performance and technique is presented in Chapter 5. Nine male athletes ran at maximal effort in lanes 2, 5 and 8 of a standard outdoor track. To understand the differences between lanes, performance and upper and lower body kinematics were compared in each of the three lanes for both the left and right steps. Asymmetry between left and right steps within each lane was also assessed.

1.4.5. Chapter 6: Force production during maximal effort sprinting on the bend

Chapter 6 includes a study of the force production of seven male athletes running on the straight and on the bend, at a radius equivalent to lane 2 of a standard outdoor track. Performance descriptors are also compared between the bend and straight, in order to investigate the effect differences in force production on performance. Again, left and right steps are analysed separately and are also compared to each other within a condition. To understand the relationship between force production and performance, correlations between performance descriptors and force variables are also made.

1.4.6. Chapter 7: Discussion

A discussion of the main findings and conclusions of the thesis are presented in Chapter 7. The research questions presented in section 1.3 are addressed, and the methodological approach taken throughout the thesis discussed. The practical implications of the findings are suggested and areas for future research are proposed.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

This literature review details work conducted into the kinematics and kinetics associated with performance during maximal effort sprinting on the straight, as this give a basis upon which performance on the bend can be compared. The limited research already conducted into bend sprinting including kinematic variables, kinetic variables and the effect of lane allocation on these variables is also discussed. In addition, those data collection and processing issues that are particularly pertinent to the accurate analysis of bend sprinting are discussed, in order to aid the research design throughout the thesis.

2.2. Sprinting along the straight

2.2.1. Kinematics of straight line sprinting

It has been suggested that the kinematics of sprint performance can be analysed in two major categories: ‘direct performance descriptors’ and ‘upper and lower body kinematics’ (Mann & Herman, 1985). Direct performance descriptors are useful for understanding how the whole body is working towards performance, while upper and lower body kinematics indicate how individual body segments are contributing towards whole body performance (Mann, 1985).

Direct performance descriptors

The aim of a sprint race is for the competitor to cover the given horizontal distance in the shortest possible time; as such, horizontal velocity is ultimately the most important factor in terms of success. Horizontal velocity is the product of step length and step frequency which are themselves affected by a number of further determinants including ground contact time and flight time (Hay, 1993).

Studies have shown both step length and step frequency to increase as running speed increases (Luhtanen & Komi, 1978; Mero & Komi, 1986). In order to improve horizontal velocity, an increase in either step length or step frequency will have a beneficial effect as long as the increase in one factor does not result in an unacceptable decrease in the other (Mann, 1985). Ideally a sprinter will have a combination of large step length and a high step frequency, although research has shown that an increase in step frequency is the mechanism that has the greatest influence on improving performance at high speeds, on an individual level (Luhtanen & Komi, 1978; Mero & Komi, 1986; Weyand et al., 2000; Hunter et al., 2004a). Indeed, Mann (1985) suggested that it is an increase in step frequency, along with maintenance of an acceptable or above average step length that sets superior athletes apart from the rest.

A number of studies have found that as running speed increases, the length of time the foot spends in contact with the ground decreases (Luhtanen & Komi, 1978; Mann & Herman, 1985; Weyand et al., 2000; Kivi et al., 2002). The term 'duty factor' describes the proportion of stride time that the foot is in contact with the ground. As running speed increases, there is not only a decrease in absolute ground contact time, but also in the percentage of the gait cycle that ground contact occurs, i.e. the duty factor decreases (Mann & Hagy, 1980; Weyand et al., 2000). Weyand et al. (2000) found that when running at top speed, faster runners have a shorter ground contact time than slower runners, but the swing time remains constant for all runners at top speed, resulting in a decreased duty factor for faster runners and a superior step frequency.

The horizontal distance between the point of foot placement at touchdown and the centre of mass (CoM) is usually termed 'touchdown distance' and has been identified by a number of studies as having an important effect on sprint velocity. Touchdown distance is sometimes represented as an angle between the horizontal and a vector from the ankle or point of contact of the contact limb and the CoM (Deshon & Nelson, 1964; Kunz & Kaufmann, 1981; Hunter et al., 2005) or as a direct measurement of the horizontal distance between the point of contact and the CoM (Mann & Herman, 1985; Bushnell & Hunter, 2007). Studies have found a smaller touchdown distance (or larger angle) to be related to superior sprint performance (Deshon & Nelson, 1964; Kunz & Kaufmann, 1981; Mann & Herman, 1985). A smaller touchdown distance has also been shown to be related to shorter ground contact time which itself has been identified as an indicator of successful performance (Hunter et al., 2004a). It has been suggested that athletes should aim to reduce the touchdown distance by reducing the absolute forward velocity of the foot at touchdown (Mann, 1985; Hay, 1993) and by trying to ensure the foot is moving backwards as quickly as possible relative to the CoM (Mann & Herman, 1985).

Upper and lower body kinematics

Upper and lower body kinematics describe the movement patterns of athletes as they perform and, as such, describe the technique of sprinters. A number of studies have identified and analysed these technique variables in an attempt to establish which factors determine superior performance in sprinting (Deshon & Nelson, 1964; Mann & Hagy, 1980; Kunz & Kaufmann, 1981; Mann & Herman, 1985; Mann, 1985).

The level of success in sprinting is mainly affected by the performance of the lower body (Mann & Herman, 1985) and as such the role of the arms in sprinting has received relatively little attention. A number of upper and lower body kinematic variables for elite male 100 m runners were analysed during competitive situations for the United States Olympic Committee 'Elite Athlete Project' (Mann, 1985). Although the athletes were all considered elite, they were placed into three sub-groups: good, average and poor based on performance, in order that strengths and weaknesses during sprinting could be identified and related to performance. It was found that the range of motion (ROM) of the upper arm (shoulder) and lower arm (elbow) was greater in poorer athletes, indicating that poorer athletes were less economical in their arm motion. Mann and Herman (1985), however, found an opposite trend. They studied the first, second and eighth place finishers of the 1984 Olympic Games men's 200 m final and found the eighth placed athlete had a smaller upper arm ROM, a smaller lower arm ROM at the 125 m point and a similar lower arm ROM at the 180 m point compared to the gold medallist. The most successful athlete had a greater upper arm velocity, however it was concluded that this was due to the increased upper arm ROM of that athlete (Mann & Herman, 1985). It is possible that these apparently conflicting results are due to only three athletes being studied by Mann and Herman (1985). It is unclear what the criteria was for placement into the 'poor', 'average' and 'good' groups in the 'Elite Athlete Project' by Mann (1985) and as such it is difficult to establish which groups the first second and eighth placed runners in the study by Mann and Herman (1985) would have fallen into. When the arm ROM values from the study by Mann and Herman (1985) are examined in relation to the values reported by Mann (1985) as 'good', 'average' and ‘poor’ it can be seen that the first, second and eighth placed runners all had upper arm ROM values which would fall approximately within the ‘good’ group and lower arm ROM values that fall within the ‘poor’ group, suggesting that the upper body kinematics are not as closely related to successful performance as lower body kinematics. Indeed, it has been suggested that there is no evidence that the arms play a major part in dictating performance level (Mann & Herman, 1985) and that the role of the arms in sprinting is merely one of balancing movement (Mero et al., 1986).

Trunk angle in the sagittal plane has been suggested to be an indicator of sprint performance. In an analysis of three world-class American sprinters and sixteen national-level Swiss decathletes filmed over four steps at the 70 m mark during competitive 100 m races, trunk angle at touchdown was found to be greater i.e. there was more forward lean in the world class sprinters than the decathletes (Kunz & Kaufmann, 1981). The purpose of a forward lean during maximal speed sprinting is to counteract the moments caused by horizontal ground reaction forces and the effect of air resistance that would otherwise tend to rotate the athlete backwards about the transverse axis. Kunz and Kaufmann (1981) also found that the forward lean of the trunk contributed to a larger angle between the trunk and contact limb thigh at take off, which was itself associated with longer steps. As such, it is possible that forward trunk lean is both an effect of superior performance and aids superior performance.

Differences in hip, knee and ankle ROM in the sagittal plane have been analysed in walking running and sprinting for a mixed group of participants (sprinters, long distance runners and joggers; Mann & Hagy, 1980). At each joint, ROM increased as velocity increased. Mann (1985) identified three key events at which the hip angle indicates performance success for sprinting: at take off, at full extension and at full flexion. At each of the three events ‘good’ athletes were found to be less extended than ‘average’ or ‘poor’ athletes (Mann, 1985). This is in agreement with the study by Mann and Hagy (1980) who found that the increased hip ROM was due to increased flexion with a reduction in the degree of extension. Less extension at full hip extension was seen in the first and second placed athletes compared to the eighth placed athlete in the 1984 Olympic 200 m final (Mann and Herman, 1985). The results for hip angle at full flexion and take off were, however, found to be comparable between the three athletes, although this is perhaps unsurprising when the participants analysed in the study are considered. Only three athletes were compared and while there are clearly differences in the performance of these athletes, the fact that they all reached the final of the Olympic 200 m event shows that they were all world class athletes. Thus, it might be expected that they are comparable in at least some of their kinematics.

Along with the limb segment positions, the angular velocities of the lower limb segments have also been used as performance indicators. Peak hip flexion angular velocity during swing, extension angular velocity at touchdown and peak extension angular velocity during ground contact have been shown to be greater for 'good' athletes than 'average' or 'poor' athletes (Mann, 1985). A greater hip angular velocity during ground contact is supported by Mann and Herman (1985) who found the medal-winners to have greater hip angular velocities during ground contact than the eighth placed athlete, although all three athletes had comparable hip angular velocities at touchdown and during swing.

Similarly to the hip, there is an increase in the ROM at the knee as sprinting velocity increases (Mann & Hagy, 1980) and generally a reduction in the degree of extension. It has been shown that for better athletes the knee is more flexed both at take off (Mann, 1985; Bushnell & Hunter, 2007) and at full flexion (Mann, 1985). At touchdown, however, Mero and Komi (1985) found knee angle to be greater (i.e. the knee was more extended) in supramaximal sprinting than in maximal sprinting and suggested that this was because the extensor muscles were better positioned to exert force thus improving performance.

Knee angular velocity at touchdown has been identified as important to success. Mann (1985) showed that athletes considered to be 'poor' had an extension angular velocity of the knee at the moment of touchdown. On the other hand, better athletes were able to reposition their legs sufficiently during flight to enable a flexion angular velocity at the moment of touchdown. Overall, this reduced the braking forces experienced by the better athletes. This was supported by Mann and Herman (1985) who found the knee flexion angular velocity at touchdown of the gold medal winner to be greater than those of the second and eighth place athletes.

The pattern of movement at the ankle during sprinting is of initial dorsiflexion after touchdown until mid-stance, when it rapidly plantar flexes (Mann & Hagy, 1980). Shortly after take off the ankle begins to dorsiflex to a neutral position which it remains at for the majority of mid-swing before plantar flexing again until just prior to touchdown the ankle begins to dorsiflex in preparation for stance (Mann & Hagy, 1980).

Movement of the metatarsophalangeal joint (MTP) has often been overlooked in the sprint literature. However, Stefanyshyn and Nigg (1997) investigated the energy patterns of the MTP during the acceleration phase of sprinting and found that during the ground contact phase of sprinting the MTP absorbs large amounts of energy during mid-stance, while only a small amount is returned towards the end of stance. The authors went on to suggest that the large amount of energy absorption is uneconomical (Stefanyshyn & Nigg, 1997). Because of this, Krell and Stefanyshyn (2006) suggested that the MTP may play an important role in determining performance in sprinting and investigated the relationship between plantarflexion of the MTP and time taken to complete the 100 m in elite competition. The stance phase of male and female sprinters whose 100 m finish times were deemed to be of an elite standard (less than 10.9 s and 12.0 s for males and females, respectively) were recorded during the 2000 Summer Olympic Games at the 60 m mark of the 100 m races. Krell and Stefanyshyn (2006) hypothesised that increased performance would be associated with reduced peak plantarflexion angles at the MTP during the absorption phase, and greater posterior sole angles (i.e. the angle formed between the inferior surface of the foot and the horizontal) at touchdown and take off. No relationship between peak plantarflexion and sprint performance was found in male or female athletes. Female sprinters were found to have a significant negative relationship between time and posterior sole angle at touchdown (i.e. faster times were associated with larger posterior sole angles) supporting the initial hypothesis. Female athletes also exhibited a positive relationship between posterior sole angle at take off and 100 m time indicating faster females athletes had a smaller angle at take off. This was a finding opposite to the Krell and Stefanyshyn's (2006) initial hypothesis and it was proposed that a smaller posterior sole angle at take off may have increased stretch of the plantarflexors. It was suggested that this might have aided energy production in the ankle in the final stage of stance (Krell & Stefanyshyn, 2006).

Whilst no relationship was found between 100 m time and peak plantarflexion angle, there was a significant relationship showing faster performance was associated with maximum rates of MTP plantarflexion for the male competitors. It may appear strange that increased peak plantarflexion had been suggested as being bad for performance by Stefanyshyn and Nigg (1997), yet faster performance was associated with maximum rates of MTP plantarflexion (Krell & Stefanyshyn, 2006). However, it was highlighted by Krell and Stefanyshyn (2006) the fastest rates of MTP plantarflexion are not necessarily related to the peak MTP plantarflexion. In fact, peak plantarflexion and peak plantarflexion angular velocity may occur at different times during stance, with peak plantarflexion being associated with the phase in which absorption is occurring, while peak plantarflexion angular velocity may occur during the take off phase. Although Stefanyshyn and Nigg (1997) stated that in their study that there was little or no plantarflexion of the MTP at the end of stance at the 15 m mark of the acceleration phase of sprinting, Bezodis et al. (In press) showed there was in the region of 10-20° of MTP plantarflexion towards the end of the first stance phase of a maximal effort sprint. Furthermore, in the study by Bezodis et al. (In press) peak MTP plantarflexion angular velocity occurred towards the end of stance and not at the time of peak plantarflexion of the MTP. It should be noted, however, that the studies by Stefanyshyn and Nigg (1997) and Bezodis et al. (In press) were conducted at different phases of a sprint (15 m and first stance, respectively), which may account for the differences in results. Additionally, Stefanyshyn and Nigg (1997) described their participants as competitive sprinters but did not provide personal best times, and these athletes may not have been as high-calibre as the international-level athletes in the study by Bezodis et al. (In press).

Bezodis et al. (In press) investigated the effect of omitting the MTP joint (i.e. using a single segment foot) when calculating stance leg joint kinetics during the first step of a 30 m maximal sprint, using a multiple single-subject design. Three models representing the stance leg were compared, all of which included a thigh segment (hip to knee) and shank segment (knee to ankle). The models differed at the foot, where two models included a single segment foot (ankle to MTP or ankle to distal hallux) and one model included a rearfoot segment (ankle to MTP) and forefoot segment (MTP to distal hallux). In that study, MTP joint ROM was found to be approximately 30°, highlighting the substantial movement which occurs at this joint, and peak MTP joint moments ranged from 67 to 143 Nm, for the 3 athletes (Bezodis et al., In press). The results of the study by Bezodis et al. (In press) showed a large contribution of the MTP joint to energy absorption, supporting the results of Stefanyshyn and Nigg (1997). Furthermore, comparisons between the models found that when the MTP was omitted ankle joint extensor moments were significantly higher (35-57%, $p < 0.05$) and peak resultant knee extensor moments significantly lower (40-67%, $p < 0.05$) then when using a three segment model (Bezodis et al., In press). Together, these studies show the potential importance of inclusion of the MTP joint to both kinematic and kinetic analyses of sprinting.

A reduced angle between the thigh segments at touchdown has been suggested as an indicator of good performance and has been linked to reduced touchdown distance and ground contact time (Kunz & Kaufmann, 1981). Bushnell and Hunter (2007) measured the horizontal distance between the recovery knee and stance knee at touchdown (a measure that is illustrative of the thigh separation) and found sprinters to have a smaller distance between knees than either distance runners or non-runners during maximal speed running, further supporting the results of Kunz and Kaufmann (1981).

2.2.2. Kinetics of straight line sprinting

Most sprint kinetic studies have focused either on ground reaction force (GRF) variables (e.g. Mann, 1985; Mero & Komi, 1986; Mero, 1988; Weyand et al., 2000; Hunter et al., 2005; Salo et al., 2005; Morin et al., 2011a; In press) or on joint kinetics (e.g. Mann & Sprague, 1980; Johnson & Buckley, 2001; Bezodis et al., 2008). It has been suggested that measurement of the forces produced by an athlete during ground contact is the best direct measure of that athlete's leg strength and the quality of their mechanics (Mann, 1985). Indeed, such studies provide a valuable insight into the forces that cause the movement of the athlete as a whole.

During sprinting the largest component of the total GRF is the vertical GRF. Upon touchdown athletes must generate sufficient vertical force to arrest the downward movement, caused by gravity working to accelerate the CoM towards the ground, and produce upward movement to propel them into the next flight phase. In a group of young (23 ± 4 years) male sprinters running maximally (9.50 ± 0.42 $m \cdot s^{-1}$), mean peak vertical forces have been reported as approximately 3.35 times body weight (BW), with mean group values for average vertical force during contact as high as 2.07 BW (Korhonen et al., 2010). Mann (1985) found that for elite female 100 m, 200 m and 400 m athletes, the better athletes produced less vertical force than the poorer athletes, with values of approximately 1160 N and 1600 N for the good and poor athletes, respectively. It was suggested that this was because the better athletes produced sufficient force only to allow enough time for recovery of the legs and thus reduced the potentially fatiguing effects of high vertical forces.

Weyand et al. (2000), however, found different results. The vertical GRF was measured, at a number of speeds using a treadmill mounted force plate, for 33 participants during level treadmill running. Results showed that the average mass-specific force applied to the running surface to oppose gravity increased as speed increased and was greater for the faster runners at top speed than for the slower runners. Despite greater support forces being applied by the faster runners, it was found that effective vertical impulse (vertical impulse minus impulse due to body weight) was similar to the slower runners because the faster runners used shorter ground contact times. That is, the slower runners produced less force but over a greater contact time and vice versa (Weyand et al., 2000). The authors also found that for level treadmill running, when running at maximum speed, the swing time (0.373 ± 0.03 s) did not differ significantly between participants even though the actual maximum speed attained did differ. Regression analyses found that the majority of the difference in top speed attained was due to an increase in the amount of force applied to the ground during contact (Weyand et al., 2000). It was proposed that the limiting factor to running speed was the amount of force an athlete could exert against the ground during contact and not the length of swing time, which had been shown to be consistent for all runners at top speed.

It is possible that the differences between the study by Weyand et al. (2000) and that of Mann (1985) was due to differences in the measure of performance in those studies. Weyand et al. (2000) investigated force production at top speed, whereas

Mann (1985) categorised athletes in terms of overall performance. Indeed, Morin et al. (2011a; 2011b; In press) compared performances during a maximal effort 100 m sprint on a track to a number of mechanical variables measured during a 6 s maximal effort sprint on an instrumented treadmill. It was found that neither vertical nor resultant forces measured during maximal effort sprinting on a treadmill were significantly correlated with mean velocity during the 100 m sprint (Morin et al., 2011a; 2011b; In press). However, Morin et al. (2011a; 2011b) found vertical force measured at maximum velocity on the treadmill was significantly correlated with maximum velocity achieved on the track. Additionally, Morin et al. (In press) found vertical and resultant forces averaged over the entire acceleration phase to be significantly correlated only with maximal velocity achieved on the track.

Whist the results of Weyand et al. (2000) suggested that at top speed better athletes generate larger vertical forces rather than demonstrating a quicker repositioning of the recovery leg, more recently it has been suggested that the maximum force an athlete can exert is not the limiting factor in sprint performance (Weyand et al., 2010). Indeed, Weyand et al. (2010) found that greater peak forces can be exerted during one footed hopping locomotion than during maximum speed sprinting, thus, athletes do not generate their maximum force during sprinting. Overall, superior performance was achieved by the ability to apply ground forces at a greater rate (Weyand et al., 2010). Furthermore, studies have presented swing times of 0.295 s during over-ground sprinting (Bezodis et al., 2010a) and 0.297 s during treadmill sprinting (Morin et al., In press) which are considerably faster than the mean values of 0.373 s presented by Weyand et al. (2000), indicating that swing time can be markedly shorter for some athletes running at maximum speed, contradicting the suggestion by Weyand et al. (2000) that swing time is consistent between athletes. Indeed, the standard deviation of 0.03 s indicates there was variation within the study by Weyand et al. (2000) that would have meant a range of swing times in the region of ~0.300-0.430 s.

The anteroposterior (AP) GRF has also received a great deal of attention in sprint studies. Whilst it has been suggested that when running at maximal speed the vertical force produced is important to performance (Weyand et al., 2000; 2010), it has been shown that net AP force production and the technical application of AP force is more closely related to overall sprint performance than either vertical or total force production (Morin et al., 2011a; 2011b; In press). The studies by Morin et al. (2011a; 2011b; In press) found that the ratio of horizontal to total force was significantly correlated with mean velocity over the 100 m; athletes with a more anteriorly oriented GRF had a faster mean 100 m velocity (Morin et al., 2011a; 2011b). As velocity increased during the 6 s acceleration on the treadmill, the ratio of horizontal to total force decreased (Morin et al., 2011a; 2011b; In press). The level of decrease was quantified using an index of force application technique. This was calculated as the slope of the linear decrease in the ratio of horizontal to total force with increasing velocity. A steeper slope of the index of force application technique was linked to poorer performance in the 100 m sprint (Morin et al., 2011a; In press) and fatigue after multiple sprints (Morin et al., 2011b).

Upon touchdown and during the early part of stance the AP GRF acts posteriorly as a braking force, during maximal sprinting. Peak and average braking forces have been reported as approximately 1.42 BW and 0.40 BW, respectively in male sprinters at maximal velocity (Korhonen et al., 2010). Then, as the CoM moves over the point of ground contact and in front of it the GRF is anterior in direction and acts as a propulsive force. Korhonen et al. (2010) reported the peak and average values of approximately 0.74 BW and 0.41 BW, respectively, during the propulsive phase. The impulse generated during the braking and propulsive phases is of great interest in sprint studies, as it is the ratio of these impulses that determines whether an athlete increases or decreases their velocity during a ground contact. During constant velocity running the braking and propulsive impulses will be equal (ignoring the effect of air resistance). In order to increase velocity sprinters could reduce the braking impulse and/or increase the propulsive impulse. Mechanisms for reducing braking impulse include use of an active touchdown, i.e. deliberately trying to ensure the foot is not moving forwards at the moment of touchdown (Mann et al., 1984; 1985), reducing the touchdown distance (Slocum & Bowerman, 1962; Mann et al., 1984; 1985) and rapid hip extension during early contact (Mann, 1985). It has been suggested that propulsive impulse can be maximised by a greater mean hip extension angular velocity during stance (Hunter et al., 2005).

Techniques to minimise braking impulse and maximise propulsive impulse have been assessed by Hunter et al. (2005). Participants (31 males and 5 females; all participants in sports involving sprint running) were asked to perform 7-8 maximal effort 25 m sprints. Force data were collected at the 16 m mark and a number of variables were measured including braking and propulsive impulse. For each participant, a high braking and a low braking trial was selected from their fastest three trials and if the braking impulse (normalised by dividing by mass) differed by at least 0.010 $m \cdot s^{-1}$ the participant was included in the analysis. Similarly, high and low propulsion trials were selected for each participant (this time from all of their trials), and if the difference in impulse between these two trials was at least 0.015 $m \cdot s^{-1}$, the participant was included in the analysis. Hunter et al. (2005) found that in the low braking trials the horizontal velocity of the foot 0.017 s prior to touchdown was lower than in the high braking trials (2.12 and 2.43 $m \cdot s^{-1}$, respectively) supporting the recommendations that an active touchdown reduces braking impulse. Low braking trials were associated with a reduced touchdown distance. However, there were no significant differences between high and low braking trials for hip extension velocity or knee flexion velocity at touchdown. Of the proposed techniques aimed at maximising propulsion, it was found that only average hip angular velocity during stance was significantly positively related to high propulsion (Hunter et al., 2005).

The other horizontal component of GRF, the mediolateral (ML) GRF has received little attention in running and is generally ignored during sprinting, probably because it contributes so little to the overall resultant GRF and sprint kinematics when sprinting in a straight line, which has been the focus of the majority of sprint studies. Mediolateral GRFs have also tended to be very variable in nature making useful comparisons difficult (Munro et al., 1987). Cavanagh and Lafortune (1980) studied seventeen runners during slower running (~4.5 $m \cdot s^{-1}$) and found mean peak-to-peak amplitude of ML forces to be as low as 9% of peak vertical forces. The participants were categorised as midfoot and rearfoot strikes and ML amplitude values were reported as 0.35 BW and 0.12 BW, respectively. Further, vertical forces were reported as 2.7 BW and 2.8 BW for midfoot and rearfoot strikers, respectively (Cavanagh & Lafortune, 1980). In a study of 40 runners, running at their normal training pace (mean 3.83 $m \cdot s^{-1}$), McClay and Cavanagh (1994) found peak to peak amplitudes of ML forces to be around 0.27 BW, giving further evidence to suggest the contribution of force from the ML component in straight running is relatively small. It should be noted, however, that while this study used a relatively large cohort of participants, they were taken from an injured population and thus it may not appropriate to generalise the results. Payne (1983) reported peak ML forces of approximately 0.50 BW in a single runner sprinting at $9.2\ m\cdot s^{-1}$ with a typical ball-of-the-foot foot-strike pattern.

The combination of force data and kinematic data has enabled individual joint kinetics to be studied in order to understand how these contribute to overall sprint performance. A number of studies have investigated joint kinetics in various phases of sprint running, including the start (e.g. Mero et al., 2006; Bezodis, 2009), the acceleration phase (e.g. Johnson & Buckley, 2001; Belli et al., 2002; Hunter et al., 2004b) and the maximum velocity phase (e.g. Mann & Sprague, 1980; Mann, 1981; Vardaxis & Hoshizaki, 1989; Bezodis et al., 2008).

Mann and Sprague (1980) conducted a joint kinetic analysis during the maximal velocity phase of running with fifteen skilled sprinters ranging from collegiate level to world class performers. The average velocity of the runners was $9.49\ m\cdot s^{-1}$. Large hip extensor moments were generated by all athletes at touchdown, peaking between touchdown and the time when the foot was fixed (considered stationary on the ground). Mann (1981) and Mann and Sprague (1980) suggested that this large hip extensor moment is required to reduce the braking forces at touchdown. The peak hip extensor moment was followed by a reversal in direction so that shortly after the foot was fixed there was a hip flexor moment for the remaining part of stance (Mann & Sprague, 1980). In a study of four well-trained sprinters running at velocities between $9.06\ m\cdot s^{-1}$ and $10.37\ m\cdot s^{-1}$, Bezodis et al. (2008) also found a predominantly extensor moment of the hip during the first part of stance, although in that study a double peak extensor pattern was seen and the extensor dominance continued for approximately two thirds of the stance phase. During the stance phase of maximal speed sprinting, the hip has been shown to exhibit a double peaked power generation pattern for the majority of stance, the peaks of which were separated by short periods of power dissipation for some athletes (Bezodis et al., 2008). During late stance, until take off, the power pattern was then negative signifying power dissipation. Bezodis et al. (2008) also showed the muscles moving the hip joint be a net generator of energy during the stance phase of maximal speed sprinting.

During the first part of swing there has been shown to be continued hip flexor dominance (Mann & Sprague, 1980; Vardaxis & Hoshizaki, 1989) as the hip flexors contracted eccentrically to halt backward rotation and then concentrically to produce forward rotation of the thigh (Mann, 1981; Vardaxis & Hoshizaki, 1989). During the latter part of swing, however, as the foot descends, the hip extensors again became dominant (Mann & Sprague, 1980; Vardaxis & Hoshizaki, 1989) initially contracting eccentrically to halt the forward rotation of the thigh and then concentrically to produce backward rotation of the thigh prior to touchdown (Mann, 1981; Vardaxis & Hoshizaki, 1989).

Eight of the athletes studied by Mann and Sprague (1980) experienced large peak moments of the knee and ankle, as well as the hip, during foot strike. The large and sudden knee flexor moment experienced in these athletes was not as large, however, as that of the hip extensor moment, and it quickly reversed such that from the time of fixed foot and throughout stance the knee extensors were dominant. It has been suggested that the purpose of the initial knee flexor moment, similarly to the initial hip extensor moment, was to reduce the horizontal braking force experienced at touchdown (Mann & Sprague, 1980; Mann, 1981). Afterwards the knee extensors contract eccentrically to halt the downward motion of the body followed by concentric contraction to produce vertical and anterior horizontal velocity to propel the body into the next flight phase (Mann, 1981). The pattern of moments at the knee joint have shown some inconsistencies between studies, with, for example, a flexor-extensor-flexor-extensor-flexor pattern having been observed for the stance phase in the study by Bezodis et al. (2008). However, it has been suggested that the rapid changes between knee flexor and extensor moments during early stance may be due to filtering methods employed (Bezodis et al., 2011). It has been shown that filtering kinematic data at a lower cut-off frequency than the kinetic data introduces artificial peaks in knee joint moments (Bezodis et al., 2011). Bezodis et al. (2011) suggested that this was due to the lower cut-off frequency removing the impact-related high-frequency content of the kinematic data with the result of large joint moments calculated due to the inverse dynamics process. It is, therefore, possible that the inconsistencies between studies are due to differences in the methods employed by those studies.

In the study by Bezodis et al. (2008), similarly to the knee moments seen in that study, the power pattern of the knee was constantly changing direction throughout stance. Six phases, alternating from generation to dissipation of power, were identified and the second generation phase, which occurred shortly after touchdown, was shown to exhibit the largest peak. The net work performed at the knee has not been shown to be consistent, although in six of the eight trials in the study by Bezodis et al. (2008) the knee was found to be a net dissipater of energy. It was suggested that this showed that in maximal speed sprinting the knee played a larger role in weight acceptance and prevention of collapse of the joint than it did in positive power production (Bezodis et al., 2008).

The knee extensor dominance has been shown to be minimised at take off in order to prevent hyperextension of the knee at take off (Mann & Sprague, 1980). During the first half of swing, knee extensor dominance indicates eccentric contraction of the knee extensors working to halt the flexion angular velocity of the lower leg (Vardaxis & Hoshizaki, 1989). After knee flexion has been halted, concentric contraction of the knee extensors work to rotate the whole limb forward followed by a period of knee flexor dominance acting concentrically to flex the knee prior to touchdown (Mann, 1981).

Ankle joint moments have been shown to be more consistent between studies than hip and knee moments. Generally plantar flexor dominance has been observed throughout the stance phase of maximal speed sprinting, although some athletes have been shown to exhibit a small dorsiflexor moment shortly before take off (Mann & Sprague, 1980; Mann, 1981; Bezodis et al., 2008). The purpose of the action of the plantar flexors during the first part of stance is to eccentrically contract to halt the downward motion of the body and in the second part of stance plantar flexors contract concentrically to produce vertical and anterior horizontal velocity (Mann, 1981). Power patterns at the ankle have been shown to be that of power dissipation during the first half of stance with power generation during late stance until take off during maximal sprinting (Bezodis et al., 2008). The ankle has been shown to be a net dissipater of energy (Bezodis et al., 2008) which supports the suggestion of Mann and Sprague (1980) and Mann (1981) that the role of the ankle is more important for arresting the downward motion of the body during early stance than it is for propulsion into the next step during maximal effort sprinting. During swing negligible ankle moments were seen indicating little or no muscle activation or a balance between plantar flexors and dorsiflexors (Mann & Sprague, 1980). At the MTP, a plantarflexor moment has been shown throughout stance during the acceleration phase of sprinting and has been shown to be a net dissipater of energy (Stefanyshyn & Nigg, 1997; Bezodis et al., In press).

Research by Mann (1981) demonstrated a small contribution of the arms to performance. The elbow exhibited a flexor moment throughout the majority of the step cycle and the magnitude of the moment was small, peaking at approximately 20 Nm, primarily functioning to keep the arm flexed at the elbow. The shoulder moment values were slightly greater than the elbow, although still relatively small peaking at approximately 30 Nm. It was suggested that the lack of large muscle moments in the arms shows that athletes do not use their arms to set cadence in running, rather, the role of the arms' is to maintain balance during sprinting. Indeed, in a simulation study of muscle contribution to propulsion and support during running at a low velocity (3.96 $m \cdot s^{-1}$) the arms were found to play a negligible role in propulsion or support of the CoM (Hamner et al., 2010). However, the angular momentum of the arms was found to counteract the angular momentum of the legs about the longitudinal axis (Hamner et al., 2010). Despite the low velocity in the study by Hamner et al. (2010) it does provide support for the suggestion that the role of the arms in sprinting may be one of maintaining balance.

2.3. Sprinting around the bend

2.3.1. Effect of lane allocation on performance during bend running

In sprint races that include a bend portion, the distance run around the bend is equal for all athletes, but the bend radius is different for each lane, and reduces from the outside lane to the inside lane. In addition to differences between the bend and the straight, it is generally accepted that a reduction in bend radius has a detrimental effect on performance in sprint events. Anecdotal evidence has shown that athletes competing in sprint events that include a bend portion generally prefer not to run in the innermost lanes because of the detrimental effect of a tighter bend radius. Despite the potential advantage of being in the outer lanes, anecdotal evidence also suggests that athletes often prefer not to be in the outermost lanes as these lanes do not provide the possible psychological advantage of being able to see runners to 'chase down'. This is reflected in the lane allocation process in outdoor competitions, during which first round lanes are randomly assigned. Subsequent rounds are allocated based on the ranking of each athlete within the race, where the four highest ranked athletes are allocated lanes three to six at random, the fifth and sixth ranked athletes allocated lanes seven and eight at random, and the final two athletes allocated lanes one and two at random (IAAF, 2011).

Brickner (1995) compiled a list of 200 m and 400 m World Records by lane. The 200 m World Records for males and females are shown in Figure 2.1 and show that at the time of compilation the fastest world record was produced in lane 5 for both the men and women. Whilst an interesting exercise, there are of course a number of problems with this approach to assessing the effect of lane allocation on performance. These include the fact that the World Records were not achieved by the same athlete in each lane, thus the differences in time might simply be to the fact that different athletes achieved these times. Additionally, the conditions such as wind speed, wind direction and altitude, which have been shown to have an effect on sprint performance (Quinn, 2004) were unlikely to have been consistent for each of the records. Furthermore, differences in race times do not account for differences in tactics or psychological factors of athletes in different races and some of the races from which these records were taken would have used a seeding process which deliberately allocated the fasted athletes to the middle lanes. Thus, the pattern seen for the World Records by lane for the fastest times to be achieved in the middle lanes (Figure 2.1) is likely due to a number of variables and not necessarily due to biomechanical factors.

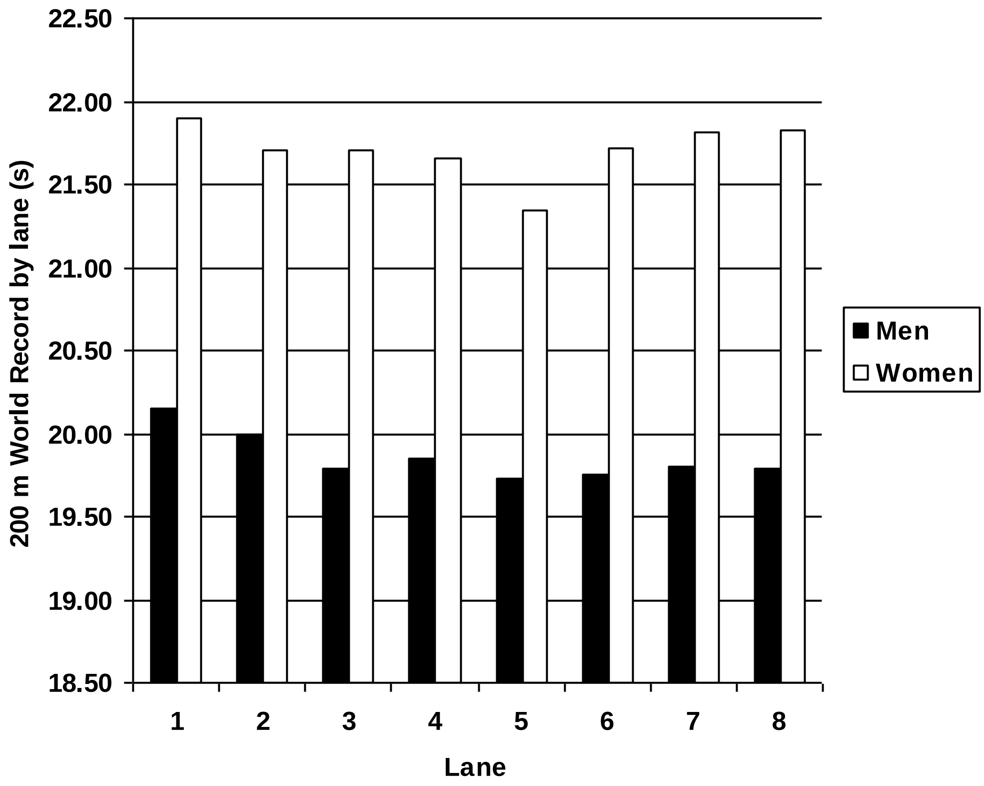


Figure 2.1. 200 m World Records by lane for men and women, as of 1st January 1995. Data from Brickner (1995).

In an attempt to understand the differences in performance between lanes due to biomechanical considerations, theoretical studies have been conducted. Jain (1980) attempted to quantify the discrepancies in race times between lanes in events that include a bend component. The author used the assumption that the difference between the time taken to run a set distance on a bend and a straight is inversely proportional to the radius of the curve. The average difference of 0.4 s between the records of 200 m times run on straight tracks compared to those on a curved track was obtained from Watman (1964) and the product of this value (0.4 s) and an average bend radius of 42.06 m provided a constant which could be used in the following equation (2.1) to calculate the time difference between lanes

$$t_m - t_n = K\left(\frac{1}{r_m} - \frac{1}{r_n}\right) \qquad (2.1)$$

where t_m and t_n are the times taken to run the given distance in the *m*th and *n*th lanes, K is the constant (16.824) and r_m and r_n are the radii of the *m*th and *n*th lanes, respectively. From this Jain (1980) concluded that difference in 200 m race times between the innermost and outermost lanes on a seven lane track could be as much as 0.069 s.

While 200 m sprints are undoubtedly faster when run on a straight track than on a track which includes a bend portion (Watman, 1964), it is not well explained how the value of 0.4 s, stated by Watman (1964) and subsequently used by Jain (1980), has been arrived at. World records in 1964 were 20.0 and 20.2 s for the men's 220 yd (not 200 m) on a straight track and on a track including a bend portion respectively, a difference of 0.2 s (Watman, 1964). Since the constant used by Jain (1980) is based on the difference of 0.4 s, any discrepancy in the calculation of differences between the bend and the straight records will affect the magnitude of the advantage/disadvantage calculated.

Greene (1985) proposed a model for sprint performance on a flat curve during maximal effort running. The model, describing the speed-radius relationship in a dimensionless format, was developed in order that a large number of participants with a variety of maximum running velocities could be tested experimentally and plotted on the same set of axes. It showed a speed-radius relationship i.e. as radius decreased maximum speed also decreased. The model proposed by Greene (1985) was compared to experimental data also collected as part of the study. There were two trials conducted. The first trial involved ten male participants running at maximal speed along curved paths of 25.9, 18.9, 11.0, 6.1, and 3.7 m radii on a grass surface. The second trial involved ten male and three female participants running maximally on a concrete surface along paths of 30.5, 24.4, 18.3, 12.2, 6.1, 3.1 m radii. Greene's (1985) experimental results confirmed the theoretically deduced speed-radius relationship, although agreement was stronger on the concrete surface which was attributed to the softness and erratic nature of the grass surface. It was suggested that there was a relationship between ground contact time and radius with ground contact time increasing as radius decreased. Flight time also showed a relationship with radius, decreasing as the radius decreased. Greene (1985) used the values quoted by Jain (1980) and applied them to the model. Greene's (1985) model suggested that the difference in race times between the innermost and outermost lanes on Jain's (1980) track was actually 0.123 s, approximately twice that quoted by Jain (1980).

Mathematical modelling of 400 m sprinting (Quinn, 2004) and 400 m hurdling (Quinn, 2010) has also found athletes in the inner lanes to be at a disadvantage to those in the outer lanes. It was suggested that under windless conditions on a standard outdoor track, the difference in times for a 400 m race (including two bend portions) between lane 8 and lane 1 of a standard outdoor track may be as much as 0.29 s for men and 0.22 s for women (Quinn, 2004). In 400 m hurdling it was suggested that the difference between lane 8 and lane 1 may be 0.23 s for men and 0.19 s for women (Quinn, 2010). It should be noted, however, that during 400 m hurdling, five of the ten hurdles are on the bend in lane 1, whereas on some tracks, six are on the bend in lane 8 (IAAF, 2008). The discrepancies between theoretical studies illustrates that, while the general trend was for those runners in the outer lanes were at an advantage, the magnitude of any advantage the outer lanes provide has not been agreed upon.

To the authors knowledge, the only study that has attempted to experimentally determine kinematic data detailing the effect of the bend on performance during maximal speed sprinting, on surfaces and at radii typical of athletic sprint events was by Ryan and Harrison (2003). Eight male sprinters (200 m PB times ranging from 20.67 s to 22.10 s) and five females sprinters (200 m PB: 24.06 s - 24.50 s) ran at maximum velocity along the bend at four different bend radii: indoor lanes 1 and 4 (radii of 10.5 m and 13.5 m, respectively) and outdoor lanes 1 and 8 (radii of 36.5 m and 45.04 m, respectively). While these surfaces and bend radii used in the study were typical of competitive situations, the validity of comparing lanes of an indoor track to an outdoor track must be questioned. Like most indoor tracks, the indoor track in the study by Ryan and Harrison (2003) was banked. This is so that the lateral force that athletes are required to exert to produce centripetal force is reduced and athletes do not have to lean inward to such an extent as would otherwise be required if the bend was flat. As such it is not appropriate to compare the kinematics of a banked bend with that of a flat bend. Furthermore, the study by Ryan and Harrison (2003) collected 50 Hz video data using a two dimensional (2D) panning protocol. Therefore, times could only be measured to the nearest 0.02 s, which may have concealed differences between lanes. Furthermore, several of the results in the study by Ryan and Harrison (2003) have been reported as means of left and right steps within a lane. This overlooks the potentially asymmetrical effect of bend running and may have masked important findings. Thus, limitations in the methodological approach taken in that study mean that even comparisons between the outdoor unbanked lanes are fallible.

2.3.2. Kinematic characteristics of bend running

Regarding technique and performance, in general there is a paucity of literature concerning bend running. Stoner and Ben-Sira (1979) conducted a comparison between bend sprinting and straight line sprinting in the acceleration phase. Nine subjects performed three sprint starts to 20 m on both the bend (radius: 37.72 m) and straight, and were filmed between the 8 m and 16 m marks by a camera set perpendicular to the 12 m mark. The time to 12 m (from movement onset, to eliminate reaction time from the measurement), average velocity over a step, step length, ground contact time and flight time for left and right steps were measured. Time to the 12 m mark was increased by ~0.02 s on the bend, although this difference did not quite reach statistical significance. Left and right step lengths were found to be significantly ($p < 0.05$) reduced by 0.03 and 0.09 m, respectively, on the bend compared to the straight. Left step velocity reduced significantly ($p < 0.05$) by 0.19 $m \cdot s^{-1}$ on the bend compared to the straight, but right step velocity was not significantly different between conditions. Of the ground contact times and flight times, only the right flight time was found to be significantly different on the bend compared to the straight, with the bend condition eliciting a shorter flight time. However, it was suggested that a faster sampling rate than the 148 Hz used would have enabled better time resolution and significant differences between conditions may have been found (Stoner & Ben-Sira, 1979). Step frequencies were not given, but these can be calculated from the mean velocities and step lengths provided. On the left, step frequency was slightly reduced on the bend at 4.26 Hz compared to 4.30 Hz on the straight. For the right step, step frequency increased on the bend to 4.36 Hz compared to 4.19 Hz on the straight, due to the reduced flight times. While the study by Stoner and Ben-Sira (1979) highlighted important differences between bend and straight sprinting and possible differences in the left and right steps on the bend, it is limited in that only direct performance descriptors were measured which do not provide an insight into the technique changes that occur on the bend. The study also only concentrated on the acceleration phase during which technique is different to that during maximal speed sprinting (Mero et al., 1992).

The study by Ryan and Harrison (2003) provides some kinematic data relating to bend running, and specifically radius effect, that is otherwise lacking in the literature, however, methodological limitations mean that the results should be treated with caution. Additional to the limitations mentioned previously, the study by Ryan and Harrison (2003) did not undertake any trials on the straight so a comparison of straight line and bend sprinting kinematics cannot be made, meaning there is still a lack of information regarding the difference between running on the bend compared to the straight. Additionally, the use of a 2D panning protocol used by Ryan and Harrison (2003) overlooks the three dimensional (3D) nature of bend running. While studies of sprinting along the straight have reasonably assumed the majority of motion to occur in the sagittal plane, the curvilinear motion of bend running means that it is likely that non-sagittal motion plays an important role that cannot be studied in a 2D analysis.

It is reasonable to assume, as a starting point, that those kinematic variables that are important to performance during sprinting along the straight are also important to sprinting around the bend. However, there are a number of other variables that have not been studied in straight line sprinting that are likely to be important factors in determining sprint performance on the bend. These include inward lean, upper body kinematics and hip abduction/adduction. While it has been suggested that upper body kinematics have little effect on sprint performance on the straight (Mann & Herman, 1985), during bend running athletes are continuously turning 'into' the bend. This action, along with alterations to body orientation and potential step asymmetry may mean upper body kinematics are different and have a larger effect on performance on the bend than on the straight. During bend sprinting athletes can be observed 'leaning into the bend'. This is due to athletes needing to apply a lateral force during ground contact. The corresponding ground reaction force provides the centripetal acceleration required for the athlete to follow the curved path. However, the presence of the centripetal force causes a moment that tends to rotate the trunk outwards about the anteroposterior axis. In order to balance the moments and prevent this rotation, athletes lean into the bend. The angle of lean is dependent on the magnitude of the centripetal force, which itself is dependent on the radius of the bend and the velocity of the runner (Grimshaw et al., 2007). While the presence of this inward lean is well acknowledged, to the author's knowledge, no studies have quantified it experimentally during sprinting on the bend.

Measurements of hip abduction/adduction have tended to be in an attempt to explain/predict/prevent injury, for example, in straight line running (Ferber et al., 2003; Heinert et al., 2008), cutting manoeuvres (Houck et al., 2006) and are standard measurement in walking gait analyses. Descriptions of differences in hip abduction/adduction during walking, running and sprinting have been made. The magnitude of hip abduction/adduction has shown to be greater in running and sprinting than in walking, and in general the hip has been shown to be adducted for the majority of stance and abducted during swing (Novacheck, 1998). Hip abduction/adduction has not traditionally been studied in relation to technique or performance success in sprint studies, probably because it has not been considered significant in an action that is generally regarded as occurring mainly in the sagittal plane. It has been suggested, however, that the action of joints in the frontal plane may play a much more significant role in bend running than in straight line running (Chang & Kram, 2007) and as such warrants further attention.

2.3.3. Kinetic characteristics of bend running

During bend running athletes must exert a lateral force during ground contact in order to generate the corresponding GRF which provides centripetal force allowing the curved path to be followed. This is clearly an additional force requirement to the vertical force required to halt the downward motion and produce upward motion of the body to propel them into the next step and almost certainly has an effect on joint kinetics when running on the bend.

The theoretical studies by Jain (1980) and Greene (1985) attempted to show the effect of bend radius on performance but gave little explanation as to why performance is reduced on a bend. Usherwood and Wilson (2006), however, developed a model aiming to explain the reason velocity is lower on the bend. The authors used the assumption that the swing time and the distance travelled by the CoM during stance were constant and the limiting factor to maximum speed is the amount of force that can be exerted by the stance limb during contact based on the research by Weyand et al. (2000). Usherwood and Wilson (2006) proposed that during straight line sprinting athletes exert the maximum limb force possible, in order to oppose and overcome the acceleration due to gravity and propel themselves into the next step. Thus, the need to generate centripetal acceleration during bend running places an additional requirement in terms of force generation. They suggested that since the limb force is constant and cannot be increased further, the only way this force requirement can be met is to increase the amount of time over which the force is applied, i.e. the ground contact time, thus providing the necessary impulse. It follows that, if swing time is constant but stance time increases (with no additional distance travelled by the CoM during stance) then velocity will decrease.

Usherwood and Wilson (2006) used their model to predict the results of the 2004 World Indoor Championships 200 m results. The times of the men's and women's 200 m heats, quarter-finals, semi-finals and finals in the 2004 Olympic Games (races run on a standard 400 m track) were taken to represent times to run a 'straight' 200 m and were input into the model in order to predict the indoor 200 m times. The model predicted time taken to run 200 m indoors as slower than outdoors and that there was a bias for the inner lanes to be at a disadvantage to the outer lanes. The actual results of the 2004 World Indoor Championships were then plotted by lane and race time visually compared to the model predicted times and it was concluded that a good agreement was found between the indoor final times for men, although slightly less so for women. For the other rounds there was a degree of scatter to the data, which may be explained by the fact that the model does not take into account tactics (it assumes all athletes are running maximally at all times), natural variation or the effect of having to ascend into and descend out of the bend in the outer lanes on a banked indoor track (Usherwood & Wilson, 2006). While Usherwood and Wilson (2006) acknowledged the use of outdoor 200 m times to represent straight times as an approximation, there was, unfortunately, no up-to-date race data for straight 200 m available. Even though the model uses a number of assumptions and simplifications, e.g. values for swing times and distance travelled by the CoM during stance taken from Weyand et al. (2000), it does provide evidence for increased duty factor to preserve limb force being a cause of reduction in speed when sprinting on a bend. Direct measurement of duty factor during bend running would, however, be needed to confirm this.

Chang and Kram (2007) measured ground reaction forces in maximal velocity running of five recreationally fit males on curved paths of very small radii (1, 2, 3, 4, and 6 m) and along a straight path. On the curved paths participants undertook trials both with and without a tether designed to provide external centripetal force to the subject. Chang and Kram (2007) found that during maximal speed running on curved paths, peak vertical GRF was reduced compared to the straight and decreased as radius decreased. During the untethered trials, at each radius the inside leg produced smaller peak vertical GRF than the outside leg suggesting an asymmetry between left and right. Even at lower running velocities, a reduced vertical force and asymmetry between the inside and outside leg was supported by Smith et al. (2006), who studied differences in vertical ground reaction forces during jogging (~4.4 $m \cdot s^{-1}$) and running (~5.4 $m \cdot s^{-1}$) on natural grass along a curved path with a 5 m radius. Also by Hamill et al. (1987), who also studied runners at a relatively slow velocity (~6.31 $m \cdot s^{-1}$), on a bend radius more typical of a track (31.5 m). Chang and Kram (2007) found that use of a tether to provide external centripetal force resulted in larger vertical ground reaction forces and increased symmetry in vertical forces generated by the inside and outside leg.

Mediolateral forces in straight line running are very small component of the resultant GRF (Cavanagh & Lafortune, 1980; McClay & Cavanagh, 1994). During running on a curved path the ML force component has been shown to be much more considerable (Hamill et al., 1987; Smith et al., 2006; Chang & Kram, 2007). Chang and Kram (2007) found mean peak ML GRFs to be significantly greater in untethered curved maximal sprints than in the straight maximal sprint, with peak values of around 400 N during straight line sprinting rising to around 800 N on the bend, acting in the direction of the centripetal force. Although peak ML values were greater for the curved trials compared to the straight trials, values were similar across different radii. Again, an asymmetry between left and right was seen with the right leg experiencing in the region of 200 N greater ML forces than the left. Even at slower velocities an increase in ML forces and an asymmetry between the inside and outside leg have been shown on curved paths (Hamill et al., 1987; Smith et al., 2006). However, there are discrepancies between whether the inside or outside leg generates larger ML forces. Similarly to the study by Chang and Kram (2007), the outside (right) leg was reported to produce larger ML forces on the bend during curved running ($5.4\ m \cdot s^{-1}$) on a natural turf surface with a radius of 5 m (Smith et al., 2006), whereas, Hamill et al. (1987) reported the inside leg to produce greater force than the outside during bend running at $\sim 6.5\ m \cdot s^{-1}$ on a radius and surface more typical of an outdoor trace (31.5 m).

Peak braking and propulsive forces have been found to be reduced during running on curves of small radii compared to the straight with the outside leg producing greater AP forces in both the braking and propulsive phases compared to the inside leg (Smith et al., 2006; Chang & Kram, 2007). Peak braking forces reduced from approximately 600 N by around 200-400 N and peak propulsive forces reduced from around 400 N by up to 200 N on radii of 1-6 m (Chang & Kram, 2007). Hamill et al. (1987), however, found no significant differences in AP forces during running on the bend, using a typical track bend radius, compared to the straight.

Chang and Kram (2007) also measured peak resultant GRF and found a general trend for it to be lower in curved trials compared to straight line trials and to decrease as radius decreased, although the difference between straight and curve only reached significance at radii of 1 m and 2 m. The authors presented this as evidence against the assumption used in theoretical models (Greene, 1985; Usherwood & Wilson, 2006) that during sprinting the maximum force generated on the straight can be generated on the bend.

While there have been some valuable insights into the forces experienced by athletes during bend running, methodological issues mean that gaps in the knowledge still remain. Studies to date have either been conducted on very small bend radii (Smith et al., 2006; Chang & Kram, 2007), on grass surfaces (Smith et al., 2006) or at low velocities (Hamill et al., 1987) and as such are not necessarily representative of the forces experienced by athletes running at maximal speed on a standard outdoor 400 m track.

2.4. Methodological considerations for biomechanical investigations of sprinting

2.4.1. Data collection

Data for the analysis of sprinting has been collected in a variety of situations including competition, training and laboratory settings. Data collected in competition is valuable since it is likely that these represent an athlete's maximal effort. Some researchers have been fortunate enough to have trackside access for data collection (Mann & Herman, 1985). However, it is unusual to have access in this way, and the opportunity to calibrate, measure, or mark the track is likely to be limited. Other studies have used video from television broadcasts (Eriksen et al., 2009; Salo et al., 2011). While this approach is not limited by track access, there is no control over camera positioning, and, again, calibration, measurements and marking of the track are impossible. Furthermore, video from television broadcasts allow only limited analyses to be undertaken. Additionally, repeated measures of an athlete may not be possible in a competition situation, unless competition heats, during which an athlete may not have wanted to/needed to run maximally, are included in the analysis.

Data collected in a training or laboratory setting offers researchers more control over the protocol. The majority of sprint studies are conducted in this way. It has been suggested that athletes willingness to participate in research may be low during the competition season (Kearney, 1999). However, this is the time of year when athletes are likely to be at their fastest. For this reason, collecting data in such a way that is as similar to an athlete's normal training routine as possible, whilst still providing the required level of control for the researcher, may be the best way to promote cooperation from the athletes. This would also contribute to the ecological validity of the study.

2.4.2. Obtainment of joint kinematic data

There are two main approaches to obtaining kinematic data in the form of joint angles from sprint trials: automated 3D motion capture and manual digitisation of video. A number of sprint studies have conducted sagittal view 2D analyses involving manual digitisation of joint centres to calculate angles (Mann & Hagy, 1980; Kunz & Kaufmann, 1981; Mann & Herman, 1985; Hamilton, 1993; Bushnell

& Hunter, 2007; Bezodis et al., In press) and in straight line sprinting this has generally been accepted due to the largely sagittal nature of the activity. If a 2D protocol is used on the bend, inward lean of the athlete would introduce out of plane errors in the analysis (Sih et al., 2001). Additionally, motion of the athlete in the frontal plane is likely to be of much greater importance in bend sprinting than in straight line sprinting (Chang & Kram, 2007) and as such warrants investigation that cannot be achieved with a 2D protocol.

Using two or more manually digitised camera views 3D coordinates of joint centres can be obtained by reconstructing the separate 2D coordinates using direct linear transformation (DLT; Abdel-Aziz & Karara, 1971). The unobtrusive nature of manual digitisation has the advantage over automated 3D motion capture systems which require either passive or active markers to be placed on the participant, although it is more time consuming in the data processing stage. Interventions such as attachment of markers is likely to be met with reluctance from athletes during the competitive season (Kearney, 1999) and the usual confinement of 3D motion capture systems to a laboratory mean that participants often do not have the distance required to achieve maximum velocity. For example, in the study by Mann and Hagy (1980), which was conducted in a gait analysis laboratory with a runway approximately 45.7 m long, the velocity of the male sprinters during the trial was approximately 7.5 $m \cdot s^{-1}$. Personal best times of the participants were not provided, but 7.5 $m \cdot s^{-1}$ is considerably slower than the velocities expected of elite male sprinters in competition and it is likely that the participants were not able (or willing) to achieve maximum velocity on such a short runway.

In 2D sagittal analyses the joint angles calculated are deemed to represent flexion/extension. If participants move out of plane, as is likely in bend sprinting, or perform alternative joint actions such as abduction/adduction, the assumption that the angle being measured represents flexion/extension should be met with caution. One advantage of 3D motion capture is the ability to resolve joint angles into three dimensions in terms of anatomically-relevant angles. Ordinarily, three dimensional reconstruction of joint centre locations from manual digitisation can be used to calculate joint angles as 3D vector angles, but it is not possible to discern from these vector angles how much flexion/extension, abduction/adduction or internal/external rotation there is at the joint. Yeadon (1990a), however, developed a method of obtaining orientation angles from 3D joint centre coordinates. Usually, at least three points are required on each segment in order for segment local coordinate systems and thus 3D orientation angles to be calculated (Nigg et al., 2007). When digitised joint centres are used, segments are usually defined with only two points as a vector from proximal joint centre to distal joint centre. In the absence of a third point on the segment of interest Yeadon's (1990a) method enables segment local coordinate systems to be created by using a third point from a distal segment. For example, the upper arm local coordinate system is defined using the shoulder elbow and wrist joint centres. This allows resolution of joint angles into flexion/extension, abduction/adduction and internal/external whilst using a relatively unobtrusive data collection.

2.4.3. Camera set-up

The accuracy of results calculated from 3D coordinate data can be affected by errors introduced during data collection and processing. The camera position, calibration and digitisation can all have large effects in terms of accuracy (Nigg et al., 2007) and, therefore, it is important that best practice is followed during the data collection and processing.

Direct linear transformation (Abdel-Aziz & Karara, 1971) allows the reconstruction of 3D coordinates by providing a linear relationship between a point's 3D coordinates and the 2D coordinates seen in a camera view. The orientation and position of the camera and the internal parameters of the system are defined by 11 DLT parameters. The DLT equations can be expressed as:

$$x_{ij} = \frac{a_{1j}x_i + a_{2j}y_i + a_{3j}z_i + a_{4j}}{a_{9j}x_i + a_{10j}y_i + a_{11j}z_i + 1}$$
$$y_{ij} = \frac{a_{5j}x_i + a_{6j}y_i + a_{7j}z_i + a_{8j}}{a_{9j}x_i + a_{10j}y_i + a_{11j}z_i + 1} \qquad (2.2)$$

where x_{ij} and y_{ij} are the two coordinates of a point i the 2D camera view image j, a_{1j}-a_{11j} are the 11 DLT parameters and x_i, y_i and z_i are the three coordinates of the point in the 3D space. Careful calibration provides known 3D coordinates of calibration points and the x and y coordinates of the digitised calibration image allow the 11 DLT parameters to be determined. Once the 11 DLT parameters have been determined, these can be used in the DLT equations to reconstruct the three dimensional coordinates of digitised points providing the same point is imaged by at least two cameras simultaneously. A 12th DLT parameter can also be included in the DLT equations to correct for lens distortion. However, in certain situations it has been found that overall an 11 parameter DLT produces lower reconstruction errors than a 12 parameter DLT, since improvements in one direction may be offset by increased error in other directions (Salo et al., 2006). Additionally, positioning cameras far from the region of interest and using the mid-part of zoom can minimise lens distortion errors (Salo et al., 2006).

In order for the 11 DLT parameters to be determined, a minimum of 6 calibration points are required. A study into DLT extrapolation accuracy by Wood and Marshall (1986) found that increasing the number of calibration points used for the DLT from 7 to 11 points and then to 30 points resulted in an increase in calibration accuracy. However, with such a large increase in calibration points from 11 to 30, it was unclear when the addition of further points ceased to be of benefit. Later, Chen et al. (1994) also investigated the effect of increasing the number of calibration points and found that calibration accuracy increased as the number of points increased from 8 to 16. Increasing the number of calibration points above 16 resulted in no further significant increases in calibration accuracy. The distribution of calibration points within the calibration volume was also studied and calibration accuracy was increased when the points were more evenly distributed within the calibration volume (Chen et al., 1994). This was in agreement with the study by Wood and Marshall (1986) who found a ‘cluster’ of 11 calibration points around the central vertical pole of their calibration object to be less accurate than the same number of calibration points evenly distributed around the calibration volume. Subsequently, Salo et al. (2006) suggested that calibration points should be as evenly distributed as possible in the camera views, rather than the actual calibration volume.

In the study by Chen et al. (1994) the calibration volume was 2.10 x 1.35 x 1.00 m. This volume is smaller than the area taken up by many biomechanical analyses. For larger areas of interest and in the absence of a larger calibration frame, which may be impractical, the DLT can be extrapolated beyond the control point (Salo et al., 2006), or a multiphase calibration conducted (Challis, 1995). Extrapolation beyond the control point volume has been associated with errors due to lens distortion and errors in digitising, although it has been shown that with extrapolation beyond the calibration errors are not increased dramatically, compared to those within the calibration volume, and may in some cases yield smaller reconstruction errors than seen within the calibration volume (Salo et al., 2006). Chen et al. (1994) found extrapolation errors to increase as the distance from the calibration volume increased. In order to mitigate against extrapolation errors in a larger field of view Challis (1995) developed a multiphase calibration which involved the recording of a calibration frame in its initial position and subsequently in further positions throughout the field of view, each time overlapping an area already recorded. While the results showed that the errors were smaller using the multiphase method, the calibration volume was still relatively small (3.6 m^3), and errors still increased as points moved further away from the original location of the frame. The alternative to extrapolation or multiphase calibration is to construct a calibration object that encompasses the whole area to be analysed such as in the study by McDonald and Dapena (1991) who used 64 points of known coordinates on 16 hurdles to calibrate a volume of approximately 150 m^3. Relative errors were found to be small and it was suggested that they were likely to be due to slight inaccuracies in placement of the control points and digitising errors, and would not affect the validity of the reconstructed 3D coordinates.

Camera set-up can have important implications for DLT accuracy. For biomechanical analysis of sporting situations it is common to use just two cameras for 3D motion analysis (McDonald & Dapena, 1991; Salo et al., 1997; Nolan & Patritti, 2008). In such a situation the optimisation of camera set-up is of great importance. The angle between the two cameras should be close to 90° in order to minimise the effect of digitising errors on reconstructed coordinates (Nigg et al., 2007), although there is little difference in errors seen when cameras are at an angle of between 60° and 120° (Pedotti & Ferrigno, 1995).

2.4.4. Gait event detection

In order to calculate many of the variables analysed in sprint studies, it is imperative to determine gait events such as touchdown and take off. Force plate data is often regarded as the 'gold standard' for event detection. Equipment such as foot switches (Hausdorff et al., 1995), linear accelerometers and angular velocity transducers (Jasiewicz et al., 2006), photocell contact mats (Viitasalo et al., 1997) and other devices, such as pressure transducers attached to footwear (Nilsson et al., 1985) have been used in walking and running studies. However, these other equipment may be impractical to use in a competition or training environment, and for those devices that are attached to the athlete, any encumbrance of an athlete in sprint studies is likely to be met with reluctance and may compromise the ecological validity of a study.

In the absence of force plate data, or other equipment based data, a number of studies have used kinematic data for the identification of events. These have generally used positional, velocity and/or acceleration data from markers on the feet (Hreljac & Marshall, 2000; O'Connor et al., 2007; Zeni Jr. et al., 2008; Leitch et al., 2011). Leitch et al. (2011) compared a number of marker based methods during over-ground and treadmill running. Evaluating a method which used AP position data of heel and toe markers (referenced to a sacrum marker) Leitch et al. (2011) found a mean error of 50 ms early for touchdown and 95 ms late for take off, in 100 over-ground running trials of self-selected pace when compared to force plate derived timings. A method which used the vertical velocity profile of a mid-foot point (halfway between heel and toe markers) was more accurate, with touchdown being predicted 15 ms early and take off 50 ms late (Leitch et al., 2011). Touchdown predicted from the time at which there was a peak in the heel vertical acceleration and a negative gradient in the position profile of the hallux, was 10 ms early compared to force plate detection (Leitch et al., 2011). Furthermore, take off predicted from the time when the hallux vertical acceleration profile demonstrated a peak and when the position of the hallux was below 70 mm was 2.5 ms early when compared to force plate event detection (Leitch et al., 2011).

A more accurate method has been advocated by Hreljac and Marshall (2000) which uses the acceleration profiles of the heel and toe to determine gait events in walking

(Hreljac & Marshall, 2000). Mean errors associated with this method, compared to force plate determined events, were relatively small, ranging from 4.7 to 5.8 ms. Whilst the above methods have been used in walking and studies of running at low velocities, the fact that sprinters land on the balls of their feet presents a problem with the direct use of these methods. In fact, Leitch et al. (2011) examined the effect of foot strike pattern on the accuracy of the methods in their study and found that the most accurate method was more accurate for rearfoot strikers than midfoot strikers because of the use of a rearfoot marker (the heel marker). Indeed, Bezodis et al. (2007) found that in sprinting, using peak vertical acceleration of markers on the forefoot produced relatively small errors in the region of 5 ms for touchdown and 7 ms for take off, depending on the marker used, demonstrating the importance of using a marker relevant to the action being analysed. In a study of maximal effort sprinting in the acceleration phase, Hunter (2004a) used the peak vertical acceleration of the head of the second MTP joint to detect touchdown and found it to predict this to within 4 ms (one frame of 240 Hz data) 93% of the instances. The errors reported by Bezodis et al. (2007) and Hunter et al. (2004a) were similar to errors expected from visual inspection of video at 200 Hz (Hreljac & Marshall, 2000).

Visual inspection of video to identify gait events can be as accurate as other non-equipment based methods (Hreljac & Marshall, 2000). Furthermore, the process can easily be incorporated into the digitisation process and does not require further processing post-digitising. The accuracy of visual identification of gait events relies upon a high enough video sampling rate and the high video quality, such as non-blurred images (Hreljac & Marshall, 2000). However, in the absence of force plate data, and providing the criteria for high video quality is met, visual inspection is a legitimate approach to identification of gait events and has often been used in sprint studies (e.g. Mann & Hagy, 1980; Mann & Herman, 1985; Bezodis et al., 2010a).

2.4.5. Force data collection

One of the main concerns for force data collection during sprinting is the obtainment of ‘clean’ force plate strikes. That is, that ground contact occurs entirely on the force plate area. A problem can occur if participants deliberately change their gait patterns in order to obtain a clean force plate strike. This is often referred to as force plate targeting.

In a study on the effect of force plate targeting in walking, Wearing et al. (2000) found no significant effects of targeting on the timing, variability or magnitude of ground reaction force parameters when measured in the time-domain and averaged over a number of trials. However, the same research group later found significant differences in the frequency domain between ground reaction force parameters when participants targeted the force plate, compared to when they did not (Wearing et al., 2003). Challis (2001) showed step length, timing of and magnitude of peak vertical impact force, and some lower leg kinematic variables were significantly affected by deliberate force plate targeting when running at approximately 3.2 $m \cdot s^{-1}$. It is likely that as velocity increases the effect of targeting will increase, due to step length generally increasing with velocity. Obviously, where step length is a variable of interest, as is the case in most sprint studies, any adjustment in this parameter may have an important effect on results obtained. Therefore, force plate targeting should be avoided.

Having a number of force plates in sequence may improve the chance of obtaining clean force plate strikes. Indeed, some sprint studies have used a sequence of force plates totalling up to 10 m in length (Mero & Komi, 1986; Belli et al., 2002; Salo et al., 2005; Korhonen et al., 2010). However, it is unusual to have such long force plate systems. A typical force plate is around 0.90 m, and it is rare to have a number of plates in sequence. In such situations it may be preferable not to inform participants of the location of force plates, or the desire for clean force plate strikes. Instead, the start position of the participant may be adjusted in order to facilitate clean strikes on the plate without participants deliberately targeting. This approach has been taken in previous sprint studies when using a single force plate (Johnson & Buckley, 2001; Hunter et al., 2004a; Bezodis et al., 2008).

In straight line sprint studies the direction of travel of athletes is generally assumed to be aligned with one of the horizontal axes of the force plate coordinate system. Thus, the forces resolved into their three directional components are assumed to be aligned with the three principle directions of movement of an athlete, anteroposterior, mediolateral and vertical. However, it has been suggested that in studies of movement other than those in a straight line, force data should be rotated to align it with the direction of travel of the participant to enable the force to be expressed relative to the body reference frame (Glaister et al., 2007). Glaister (2007) highlighted that in studies of walking turns, mean propulsive forces (relative to the force plate coordinate system) have been reported as 1.96 $N \cdot kg^{-1}$ for a 45° turn (Houck, 2003), approximately 1.00 $N \cdot kg^{-1}$ (based on the value for a typical peak and on the average mass of the participants) for a 60° turn (Patla et al., 1991) and negligible for a 90° turn (Taylor et al., 2005). Indeed, because of the 90° turn in the study by Taylor et al. (2005), the peak propulsive force normally observed on the force plate y-axis could be seen on the force plate x-axis, or in other words, in the new direction of travel. Thus, care should be taken when interpreting forces expressed relative to the force plate reference system when the movement is not aligned with that reference system. Indeed, Glaister et al. (2008) found that propulsive forces were large during a 90° walking turn, when the GRFs were rotated to the direction of travel of the participant. It is, therefore, important that studies of bend sprinting account for misalignment of the body with the force plate coordinate system if measuring ground reaction force variables.

2.4.6. Data conditioning

Signals that are measured in biomechanical research are usually affected by errors in the form of signal noise. The problem of noise in the data is exacerbated when the signal is differentiated, such as when velocity is obtained from displacement data, as the differentiation process amplifies errors (Winter, 2009). For this reason, data tends to be conditioned, or smoothed/filtered, before it can be used for subsequent analysis. Biomechanists aim to condition the data in such a way that minimises the effect of the error, whilst representing the true signal as accurately as possible (Woltring, 1985).

The errors may be systematic or random in nature. Systematic errors may be introduced to a signal in many ways, including image distortion, inaccuracies from faulty equipment, calibration errors and incorrect identification of body landmarks (Wood, 1982). Data conditioning is unlikely to help remove this sort of error (Wood, 1982). Instead these sources of error should be eliminated as far as possible by careful equipment set up, calibration and robust scientific data collection and processing protocols (McLaughlin et al., 1977). The presence of some random noise, however, is inevitable (Challis, 1999) and must be removed before the data is used for subsequent analysis. Sources of random error include electrical interference and random errors introduced during manual video digitisation (Wood, 1982). The most commonly used methods for data conditioning in the sprint literature include polynomial fitting (e.g. Mero & Komi, 1985; 1986; Mero, 1988; Bezodis et al., 2010b), spline fitting (e.g. Johnson & Buckley, 2001) and digital filtering (e.g. Belli et al., 2002; Hunter et al., 2004a; Mero et al., 2006; Bezodis et al., 2008; Weyand et al., 2010).

During polynomial fitting, a best-fit curve is used to represent the signal using a single equation, generally using a least squares approach as the criterion (Burkholder & Lieber, 1996). One of the benefits of using polynomial fitting is that the polynomial coefficients can be analytically differentiated to obtain higher order derivatives. However, it has been shown that local detail can be lost as polynomials can over-smooth the data (Zernicke et al., 1976; Pezzack et al., 1977; Burkholder & Lieber, 1996). As such, it has been suggested that polynomial fitting may not be suitable for data sets of varying complexity, such as those which include impacts (Wood, 1982). Polynomials have, however, been used to calculate the acceleration of a falling object and have closely matched the local gravitational acceleration (Vaughan, 1982), and it has been suggested that polynomial fitting may be better suited to non-repetitive data (Winter, 2009). Polynomial fitting has also been used in sprinting to smooth laser distance measurement data to represent the overall motion of athletes during the start of a race, whilst eliminating both noise and natural within-step fluctuations in the data, which may have affected the results when velocities were measured at specific distances from the start (Bezodis et al., 2010b).

Splines consist of a number of polynomials joined together at ‘knots’. They have the advantage over polynomials that they can adapt more readily to changes in curvature, therefore may be better for data sets that have curves of varying frequency content. Like polynomials, higher order derivatives are easily obtained from the spline function (Wood, 1982). Cubic splines have been found to better fit acceleration data in a simulated right leg kick than polynomials (Zernicke et al., 1976) and have been suggested to give a better representation of acceleration of the lower leg during running than polynomials (McLaughlin et al., 1977). In a comparison of vertical jump data smoothing, Wood and Jennings (1979) found a quintic spline to fit the data more appropriately than a cubic spline. Similarly, Burkholder and Lieber (1996) found a quintic spline to be a better method of smoothing than either simple polynomial fitting or stepwise polynomial fitting in a data set created to include the true signal and white noise.

Digital filters do not fit curves to the data. Instead, noise is reduced by limiting the frequency content of the data. Based on the assumption that the high frequency contact of the signal is predominantly from noise, low-pass digital filtering works by attenuating the high frequency components of that signal, whilst passing the low frequency components. The passing of data through a digital filter results in a phase lag, which requires a second pass of the filter in the opposite direction to remove the phase lag (Winter, 2009). The level of filtering is determined by the cut-off frequency above which the signal is attenuated. The choice of cut-off frequency will, therefore, affect the final signal obtained. A number of approaches to the determination of optimal cut-off have been suggested (Giakas & Baltzopoulos, 1997; Challis, 1999; Yu et al., 1999; Winter, 2009). A commonly used method in the sprint literature is a residual analysis. However, it is likely that when filtering coordinate data, different coordinates will have different optimal cut-off frequencies. Additionally, it has been suggested that the choice of cut-off depends on whether displacements, velocities or accelerations are of most interest to the researcher (Giakas & Baltzopoulos, 1997). Some sprint research has used a different cut-off frequency for different points in different directions (Hunter et al., 2004a; Bezodis et al., 2008), while others have chosen a single cut-off frequency which best suits most of the data (Belli et al., 2002; Kuitunen et al., 2002; Mero et al., 2006; Weyand et al., 2010).

Digital filters such as the Butterworth filter have been advocated for use in biomechanical analyses by Winter (2009). Indeed, Pezzack et al. (1977) compared derivatives calculated from raw displacement using finite differences, polynomial fitting and digital filtering followed by finite differences, and found digital filtering to give the best results. In that study, a mechanical device was used to produce displacement and acceleration data of different complexity, representative of those commonly found in human motion. In both movement patterns studied, digital filtering followed by finite differences differentiation was found to be superior to polynomial fitting (Pezzack et al., 1977). Higher order derivatives can be easily calculated after filtering using finite differences.

Unfortunately, data conditioning tends to have a detrimental effect on the signal at the start and end of the data set. This is often referred to as endpoint error. To avoid the problem of endpoint error, data is usually 'padded' or extra data collected. These additional data points can then be disregarded from the data after the conditioning process. Smith (1989) investigated a number of techniques designed to mitigate against endpoint error. Random computer generated noise was added to the data set of Pezzack et al. (1977) and a subset of the data used for the analysis. The data was padded by linear extrapolation of the first (or last) two points, duplication of the first (or last) point and by reflection of the first (or last) points using as many points as was required for padding. These methods were compared to using 'real' data points from the data set as if extra data had been included from digitising extra fields at the start or end of the fields of interest. It was found that reflection of the data points was the most effective padding method, with results being similar to those of the inclusion of additional real points from digitisation (Smith, 1989). The effect of the number of padding points was also investigated, and it was suggested that there was little improvement when more than 10 padding points were used, and if digitised data were to be used 10 extra points was sufficient to prevent endpoint effects (Smith, 1989). Conversely to the results of Smith (1989), Vint and Hinrichs (1996) found padding by linear extrapolation to be preferable to reflection when a subset of data from the data set provided by Pezzack et al. (1977) was conditioned using a Butterworth filter, a cubic spline, a quintic spline and Fourier series. Surprisingly, the quintic spline gave best result when left unpadded (Vint & Hinrichs, 1996). The differences between the two studies may have been due to the fact that, although subsets were taken from the same original data set, the points from which the data were taken were different. Subsequently it has been suggested that neither linear nor reflection extrapolation are the best methods for data padding (Giakas et al., 1998). Giakas et al. (1998) suggested a least squares method, which involved using coefficients of a 3^{rd} order polynomial fitted to the last 10 points of the data set to extrapolate by 20 points was a more robust method for data padding than linear extrapolation. Despite the differences between studies it seems that padding is generally preferable to no padding when real extra data is unavailable.

2.4.7. Inertia models

Most biomechanical analyses require the use of body segment inertia parameters, be it for determination of segment mass, segment or whole body CoM locations or segment principal moment of inertia values. Body segment inertia parameters have been determined from cadavers (Dempster, 1955; Clauser et al., 1969; Chandler et al., 1975), however, the number of cadavers used to create inertia models has generally been small and the population from which the cadaver data is drawn is typically unrepresentative of the participants in most biomechanical analyses of sporting activities. Additionally, segment CoM location reference points have not always coincided with joint centres, which are typically digitised in biomechanical studies. For this reason, Hinrichs (1990) made adjustments to the data of Clauser (1969) so that CoM locations were referenced to joint centre locations. Whilst this adjustment aligned the inertia data with a typical model of the human body used in digitising, it does not solve the problem that the inertia data obtained by Clauser (1969) is from a population that is likely to be very different from elite athletes.

Mathematical inertia models have been created, which have represented body segments as geometric solids in order to estimate inertia parameters (Hatze, 1980; Yeadon, 1990b). This allows participant-specific inertia data to be obtained. However, one of the drawbacks to this approach is that many anthropometric measurements of the participants must be taken. The model proposed Yeadon (1990b) requires a more realistic number of measures, at 95, than that of Hatze (1980), which requires 242 anthropometric measurements, taking up to 80 minutes to measure. However, even when only 95 measurements are needed, this is likely to take around 30 minutes per participant (Yeadon, 1990b). Therefore, participant-specific inertia models may not be attainable for a larger cohort of athletes or when athletes are reluctant to have their training sessions disturbed or prolonged.

Medical imaging techniques, such as gamma scanning (Zatsiorsky & Seluyanov, 1983; Zatsiorsky et al., 1990), dual energy x-ray absorptiometry (DXA; Durkin et al., 2002), and magnetic resonance imaging (MRI; Mungiole & Martin, 1990) may also provide a potential method of obtaining participant-specific inertia parameter. However, there are ethical considerations of exposing participants to potentially harmful radiation, the methods are relatively time consuming and thus may be met with reluctance from athletes. Furthermore, it is unlikely that these sorts of methods are available to most researchers conducting biomechanical investigations.

Whilst it may not be possible to use such methods for the obtainment of participant-specific inertia data, the data published from such investigations may be a viable alternative to cadaver data. Zatsiorsky et al. (1990) published body segment inertia parameters obtained from gamma scanning of 100 physically fit males and 15 national-level female athletes (swimmers and fencers). This data is from a much larger number of samples than most cadaver studies, and the population was much more like the populations used in the biomechanical analyses of sports, although, the reference landmarks do not correspond to joint centre locations. However, the inertia parameters provided by Zatsiorsky et al. (1990) have been adjusted by de Leva (1996) so that the reference landmarks correspond to the landmarks commonly used in biomechanical analyses. One exception is that the CoM location provided for the foot is referenced from the heel to the tip of the longest toe (de Leva, 1996), whereas many biomechanical models digitise from the lateral malleolus to the tip of the toe. Because of this, some sprint studies using the de Leva model have chosen to take the foot centre of mass from other sources such as Winter (1990; 2005) and have also made adjustments to the body inertia parameters in order to add the mass of the sprinting shoe to the foot (Hunter et al., 2004a; 2005; Bezodis et al., 2008).

2.5. Summary

A number of studies concerning straight line sprinting have been published, identifying performance descriptors and technique variables that contribute to performance, however such research into bend sprinting is very limited. A link between bend radius and performance has also been identified, however the reason for this relationship is not fully understood and the magnitude of the effect of bend radius has not been agreed upon. Potential changes to force production during bend sprinting and the additional force requirement of centripetal force generation have been identified, however, to date no empirical studies have been conducted to measure 3D kinematic and kinetic data during maximal speed running on bend radii typical of those experienced on a standard 400 m track.

CHAPTER 3: THE EFFECT OF THE BEND ON TECHNIQUE AND PERFORMANCE DURING MAXIMAL EFFORT SPRINTING

3.1. Introduction

During sprint events longer than 100 m on a standard outdoor track, athletes are required to run over half the race around the bend (IAAF, 2008), yet the technique and performance aspects of the bend sprinting component have generally been overlooked in biomechanics literature. A limited number of studies have been undertaken but these have been conducted using radii and surfaces which do not represent those found on a standard outdoor running track (Greene, 1985; Smith et al., 2006; Chang & Kram, 2007), or they have been concerned with sub-maximal running velocities (Stoner & Ben-Sira, 1979; Hamill et al., 1987; Smith et al., 2006). Additionally, these studies have tended to focus on performance descriptors, or force generation, without consideration of the technique variables which change from straight to bend and which may be of considerable interest to athletes and coaches. Maximal speed velocity has been shown to decrease on the bend at small radii (Chang & Kram, 2007) and on grass and concrete surfaces (Greene, 1985). Whilst it is generally accepted that there is a decrease in performance on the bend during sprinting, the technique changes that accompany this reduction in performance have not been fully investigated.

Understanding the changes to technique that occur on the bend compared to the straight will provide a strong foundation upon which further research can assess how different athletes perform and how better bend runners achieve better levels of performance. This knowledge can be used to inform coaching with the aim of improving athletes' performance. Therefore, the aim of the study was to understand the changes in performance and technique that occur during maximal effort bend sprinting compared to straight line sprinting.

3.2. Methods

3.2.1. Participants

Seven male and two female sprinters, all experienced in bend running, participated in the study. Mean age, mass, and height were 23.6 ± 1.9 years, 80.5 ± 9.2 kg, and 1.81 ± 0.07 m, respectively, for the male athletes, and 22.6 ± 0.3 years, 60.3 ± 2.2 kg, and 1.69 ± 0.02 m, respectively, for the female athletes. Personal best times for the 200 m ranged from 21.18 s to 23.9 s (hand-held timing) for the males and were 25.8 s (hand-held timing) for both females. Videotaping and subsequent analysis of athletes during normal training situations was approved by the local research ethics committee. All athletes provided written informed consent before taking part.

3.2.2. Data collection

Data were collected on a standard outdoor 400 m track at the University of Bath during the outdoor competitive season in the athletes' normal training sessions, when the athletes were undertaking speed training. For each athlete, data were collected on two occasions: on one occasion bend trials were completed and on the other straight trials were completed. On each occasion athletes completed a coach-prescribed, warm up before being asked to undertake three 60 m maximal effort sprints running in lane 2. Recovery time between trials was approximately eight minutes. For the bend trials the entire 60 m was around the bend and for the straight trials the entire 60 m was along the straight.

Two high speed video cameras (MotionPro HS-1, Redlake, USA) were used to record the athletes at the 40.00-47.50 m section of the 60 m, enabling two steps to be analysed. One camera was positioned 37.72 m away from the inside edge of lane 2 (which was the origin of the bend radius for bend trials) and provided a 'side view' while the other camera was positioned 30.00 m away from the centre of the side field of view and 1.50 m to the side and provided a 'front view' (Figure 3.1). The cameras were manually focussed, operated with a 200 Hz frame rate and shutter speed of 1/1000 s, and had an open iris with no gain.

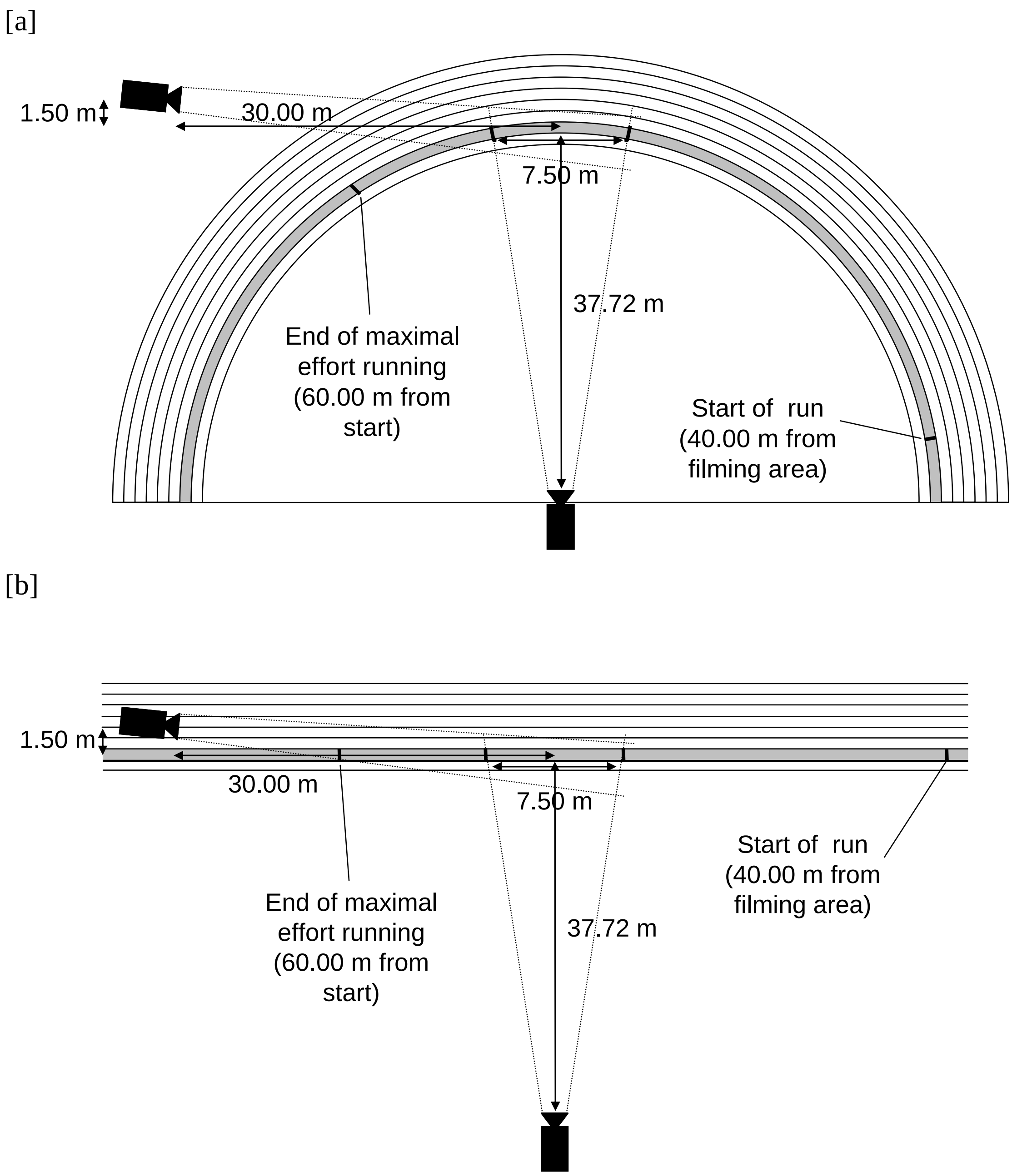
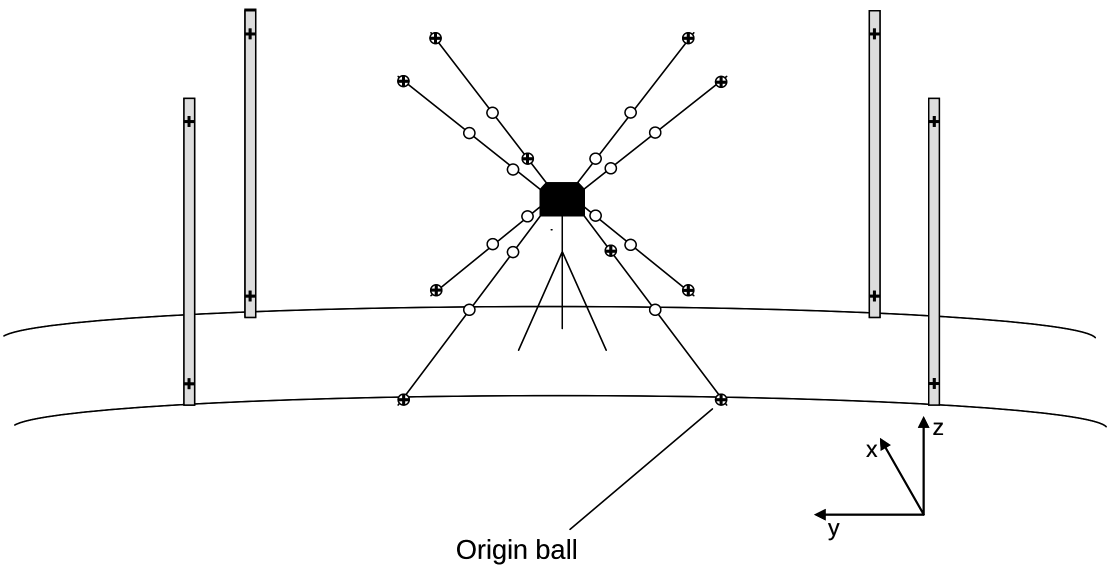


Figure 3.1. Camera set-up for [a] bend trials (not to scale) and [b] straight trials (not to scale).

An 18-point 3D calibration structure was recorded prior to the athletes' trials taking place. The structure consisted of a standard Peak Performance calibration frame (Peak Performance Technologies Inc., USA) at the centre of the field of view and four individual poles at the corners of the calibration volume (Figure 3.2). An effort was made to distribute the calibration points as evenly as possible throughout the calibration volume (Figure 3.2). The reference point for all calibration points was the origin ball (Figure 3.2). The height of the origin ball from the ground was measured for each testing session so that the locations of each calibration point relative to the origin ball could be calculated. The calibration volume was 6.5 m long, approximately 1.6 m wide (at widest) and approximately 2.0 m high (Figure 3.2). The global coordinate system (GCS) followed the right-hand rule and was aligned such that, within the filming area, athletes travelled primarily in the direction of the positive y-axis, the positive z-axis was vertically upwards and the positive x-axis was orthogonal to the other two axes (Figure 3.2).

[a]



[b]

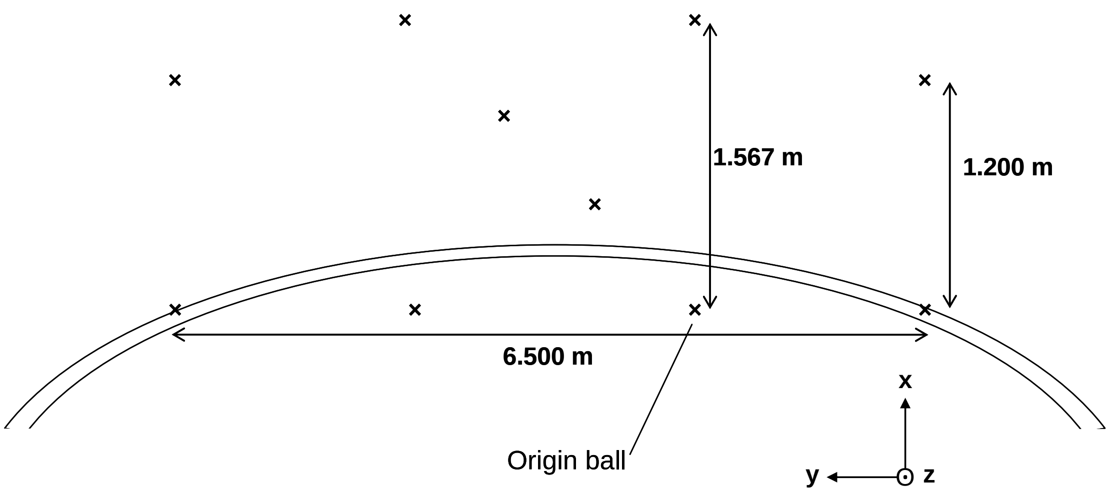


Figure 3.2. [a] Calibration set-up (not to scale). The 18 points digitised are denoted by a cross. Locations of each point were known relative to the origin ball.
[b] Plan view of calibration area (not to scale).

3.2.3. Data processing

All trials were manually digitised using Peak Motus software (Version 8.5, Vicon, Oxford, UK). In order that the data from two video streams could be synchronised, two sets of 20 LED displays were placed with one in each camera view during data collection. The LEDs were simultaneously triggered during each trial which caused the LEDs to illuminate sequentially at 1 ms intervals. From the number of lights illuminated in each camera view, the time of the LED trigger was established and entered into the digitising software as the common synchronisation point. Some athletes did not complete all three bend trials during the data collection, and for some athletes not all three bend trials could be digitised due to recording issues during the data collection or synchronisation problems. This resulted in two bend trials for two athletes and one bend trial for one other athlete being available for analysis. All other athletes had three bend trials available for digitising and all athletes had three straight trials available.

For each calibration, six video frames were digitised in each camera view to provide the relevant DLT parameters required for coordinate reconstruction (Abdel-Aziz & Karara, 1971). Translations were performed such that the GCS was moved from the origin ball of the calibration frame to the origin of the bend radius for the bend trials. For the straight trials the origin was translated in the y-direction such that the GCS origin was in the centre of the field of view in the y-direction, and lowered to track level in the z-direction. Video clips were cropped to include two complete steps plus 10 frames before the first touchdown of interest and 10 frames after the final touchdown of interest. This ensured the trial sequence was longer than the required data so as to mitigate against end-point errors in the data conditioning process (Smith, 1989). For the majority of trials, this allowed all points to be digitised for all frames. However, for some trials, some points were out of the field of view at the beginning or end of the trial. In these cases the missing points were not digitised and their positions were estimated using linear extrapolation based on the first (or last) four points when the point was in view. In all but one case the extrapolation yielded sensible coordinate positions. In the case in which the extrapolation was not satisfactory the missing points were digitised at the edge of the field of view giving more sensible coordinates. No trials had points missing in the frames of interest (frames for which kinematic data were calculated). Gait events (touchdown and take off) were determined by visual inspection of the video from the front view camera. Touchdown was defined as the first frame in which there was definitely contact with the track and take off was defined as the first frame in which there was definitely no contact with the track.

For running trials a 20-point model of the human body was digitised consisting of the top of the head, the joint centres of the neck, shoulders, elbows, wrists, hips, knees, ankles, second MTP joints and the tips of the middle finger and running spikes. An 11 parameter 3D-DLT (Abdel-Aziz & Karara, 1971) reconstruction enabled three dimensional coordinates to be calculated and then exported to a custom written Matlab script (v 7.9.0, The MathWorks, USA) for further processing. Raw 3D coordinates were filtered with a low-pass, 2^{nd} order, recursive Butterworth filter (effectively a 4^{th} order zero lag Butterworth filter; Winter, 2009) with a cut-off frequency of 20 Hz. The cut-off frequency was chosen based on cut-off frequencies used in a number of previous sprint studies ranging from 15 Hz to 24 Hz, with several using 20 Hz (Belli et al., 2002; Kuitunen et al., 2002; Krell & Stefanyshyn, 2006; Mero et al., 2006; Yu et al., 2008; Bezodis, 2009).

For calculation of segment CoM and whole body CoM positions, filtered coordinates were combined with body segment inertia data. Whole body CoM location was determined using the segmental approach (Winter, 1993). A 16-segment model of the human body was used: head, trunk, and left and right upper arms, forearms, hands, thighs, shanks, rearfeet and forefeet. Body segment inertia parameters, for all segments except the foot, were taken from de Leva (1996). Forefoot and rearfoot inertia data was taken from Bezodis (2009). The mass of a typical spiked sprinting shoe (0.2 kg; Hunter et al., 2004a) was added to the mass of the foot and all segment masses adjusted accordingly. From the filtered coordinates two virtual coordinates were also calculated: mid-hip (calculated as the halfway point between right and left hips) and mid-shoulder (calculated as the halfway point between right and left shoulders).

3.2.4. Calculation of variables

A number of direct performance descriptors and upper and lower body kinematics were calculated. Given the lack of information pertaining to the variables that contribute to bend sprinting performance, the variables chosen were those that have been identified as being important for straight line sprinting in the literature. Furthermore, because it is known that athletes are required to turn and lean inwards to follow the bend, a number of additional variables likely to be important in bend sprinting, such as frontal plane joint angles, were also measured. Variables were measured separately for left and right steps. A step was defined as touchdown of one foot to the next touchdown of the contralateral foot. Left and right steps were determined according to the leg that initiated the step; for example, left step refers to touchdown of the left foot to touchdown of the right foot at next ground contact.

Direct performance descriptors

Absolute speed and race velocity: Absolute speed was measured to assess the athlete's actual speed, regardless of whether or not the most effective path was taken, and was calculated as the horizontal speed of the CoM on the path that the CoM travelled. Resultant horizontal distance travelled by the CoM was calculated at each time point and a cumulative distance was determined. The finite difference technique (first central difference; Miller & Nelson, 1973) was used to calculate the horizontal speed of the CoM at each time point from the cumulative distance. The mean of the instantaneous speeds, from the first frame of ground contact to the frame prior to next touchdown, was calculated to give the absolute speed over the step.

Race velocity was measured to assess the athlete's performance in terms of race success. For straight trials race velocity was calculated relative to the global *y-axis*. The displacement of the CoM in the y-direction was subjected to first central difference calculations to give the horizontal velocity of the CoM in the y-direction at each time point. For bend trials, race velocity was measured relative to the curved race line (a line 0.20 m from the inside of the lane, along which race distance is measured; IAAF, 2011). At each time point, the angle (θ_i) between a vector extending from the origin to the horizontal CoM (x,y) position was calculated using a four quadrant inverse tangent, which provides the angle between the vector and the x-axis in the range $-\pi$ to π (equation 3.1)

$$\theta_i = \tan^{-1}\left(\frac{y}{x}\right) \tag{3.1}$$

The difference between the angles at two consecutive time points was used to calculate the race displacement covered between time points using equation 3.2:

$$\text{race displacement} = \theta_d r \tag{3.2}$$

where θ_d is the difference in the angles at two time points and r is the radius of the race line (37.92 m; Figure 3.3). Instantaneous velocities of the CoM relative to the race line were calculated using the first central difference method on the cumulative race displacement.

For both the bend and straight, race velocity was calculated as the mean of the instantaneous velocities, from the first frame of ground contact to the frame prior to next touchdown.

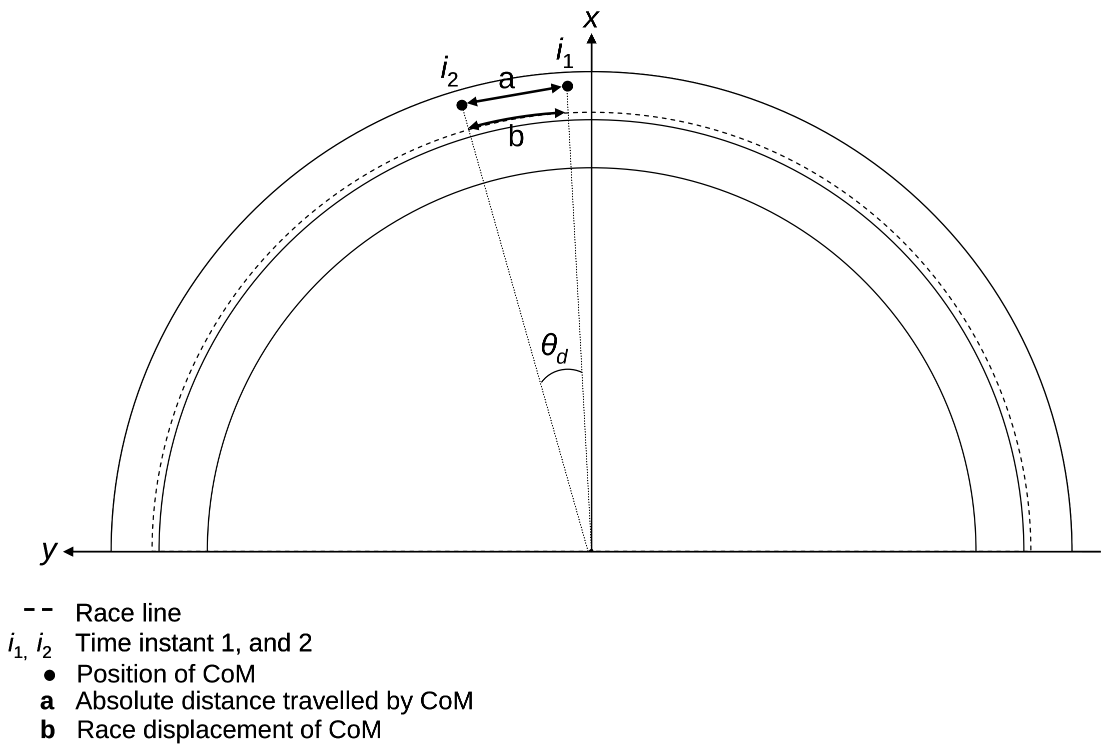


Figure 3.3. Calculation of absolute distance and race displacement on the bend. See text for method.

Directional and race step length: Directional step length was calculated relative to the direction of travel regardless of whether the direction of travel was along the race line. A step progression vector (which described the direction of travel over the entire step) was created from the horizontal position of the CoM at the ninth frame of contact (the same time as used for the MTP location, chosen to ensure that the MTP was stationary when it was used for step length measurements) to the horizontal position of the CoM eight frames after the first frame of next contact. These points were termed p_1 and p_2 respectively and the step progression vector was divided by its norm to create a unit vector (equation 3.3)

$$\overrightarrow{STEPPROG} = \frac{(\vec{p}_2 - \vec{p}_1)}{\|(\vec{p}_2 - \vec{p}_1)\|} \tag{3.3}$$

Directional step length was then calculated as the scalar projection of the vector from the horizontal position of the MTP of the contact foot during the first ground contact phase (GC1) to the horizontal position of the MTP of the contralateral foot during the next ground contact phase (GC2) onto the step progression vector (Figure 3.4). The location of the MTP was taken, again, at the ninth frame of contact to ensure the MTP location was stationary when it was used for step length measurements.

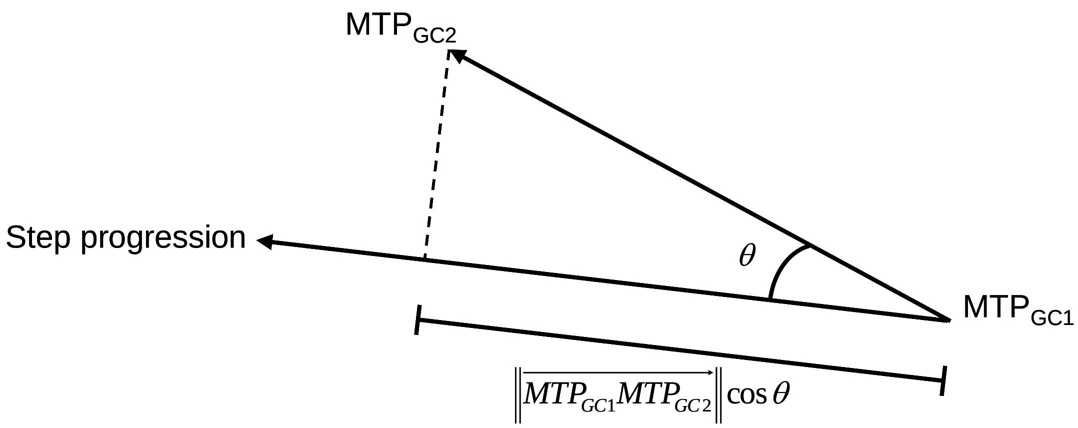


Figure 3.4. Calculation of directional step length shown in the transverse view. Directional step length is equal to the dot product of the step progression and MTP vectors.

Race step length was calculated as the length of the race distance covered by each step. For straight trials, the displacement between the y-coordinates of the MTP, when stationary during two consecutive contacts, was calculated. For bend trials, similarly to the method used to calculate race distance covered by the CoM for the race velocity calculations, the angle between the location of the MTP, when stationary during two consecutive contacts, was calculated. The arc length (race step length) was then calculated from this angle and the radius of the bend (equation 3.4)

$$\text{race step length} = \theta r \tag{3.4}$$

where θ is the angle between consecutive MTP positions and r is the radius of the race line (37.92 m).

Step frequency: Race velocity divided by race step length.

Ground contact time: Calculated as the time from touchdown (i.e. the first frame of ground contact) to take off (the first frame of flight).

Flight time: Total step time (touchdown to touchdown) minus ground contact time.

Step contact factor: The proportion of total step time spent in ground contact, calculated as ground contact time divided by total step time.

Touchdown distance: Calculated relative to the direction of travel of the athlete at touchdown. An instantaneous progression vector was calculated as a vector from the horizontal position of the CoM one frame before the instant of interest to the horizontal position of the CoM one frame after the instant of interest and divided by its norm to create a unit vector (equation 3.5).

$$\overrightarrow{prog_i} = \frac{(\overrightarrow{CoM_{i+1}} - \overrightarrow{CoM_{i-1}})}{\left\|(\overrightarrow{CoM_{i+1}} - \overrightarrow{CoM_{i-1}})\right\|} \tag{3.5}$$

A second horizontal vector from the body CoM to the MTP of the touchdown limb was created and the scalar projection of this vector onto the instantaneous progression vector at touchdown gave the touchdown distance in the AP direction (Figure 3.5).

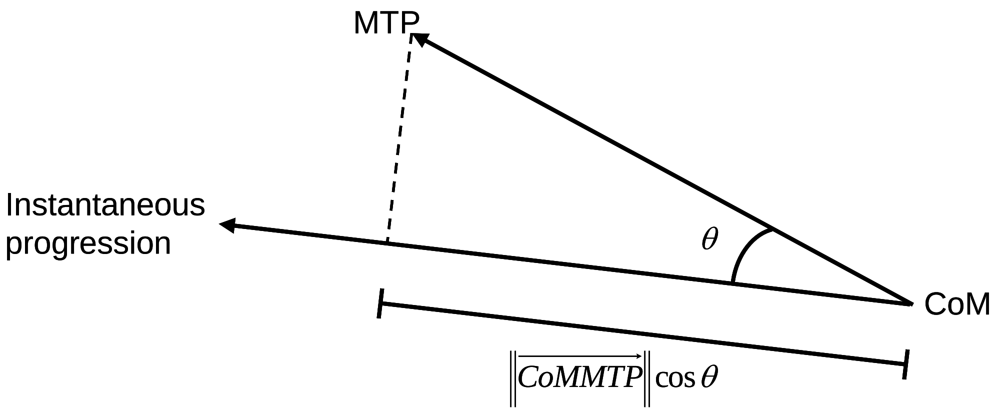


Figure 3.5. Calculation of touchdown distance shown in the transverse view. Touchdown distance is equal to the dot product of the instantaneous progression and the CoM-MTP vectors.

Turn of the CoM during ground contact: For the bend trials, as a measure of how much turning ‘into’ the bend an athlete achieved during each ground contact, the turn of the CoM was calculated. A raw CoM position was calculated from unfiltered 3D coordinates using the segmental approach (Winter, 1993). A linear trend line was fitted to the raw CoM x-displacement as a function of the raw CoM y-displacement for the three available flight phases. This gave the derivative of the polynomial which described the direction of the resultant horizontal displacement vectors for each flight phase (Figure 3.6). Raw data was available for 10 frames prior to the first touchdown and for all flight frames prior to the second and third touchdowns.

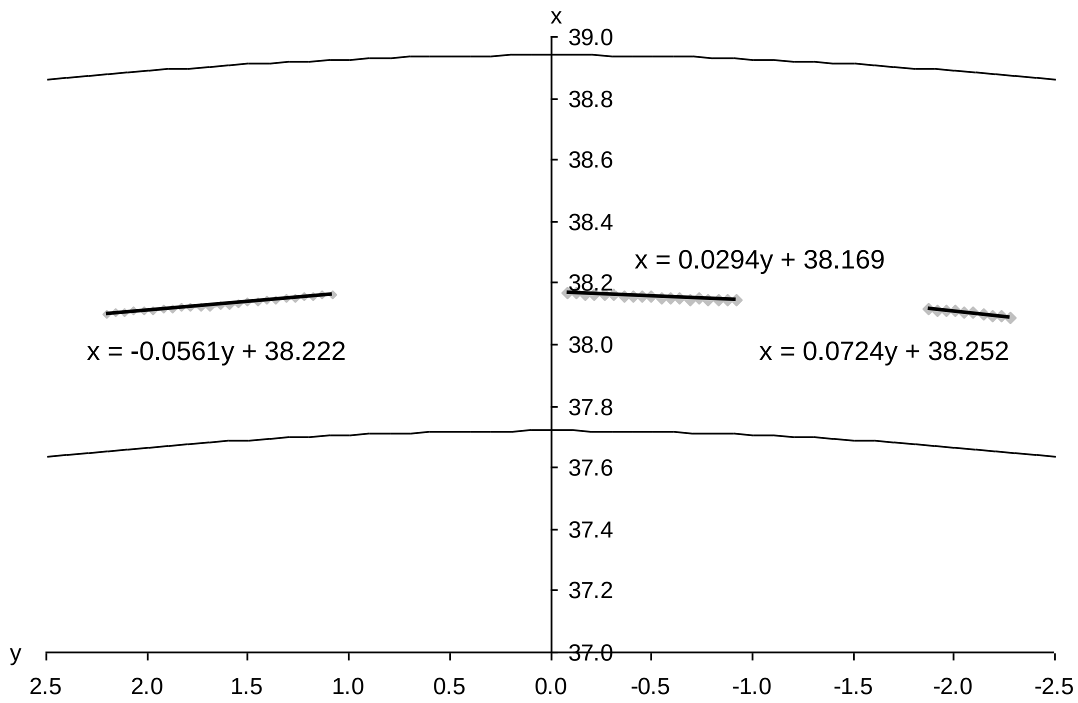


Figure 3.6. Displacement of CoM during each flight phase. Linear trend lines represent a CoM displacement vector for each flight phase.

The angle of each displacement vector was calculated using a four quadrant inverse tangent

$$\theta_F = \tan^{-1}\left(\frac{y}{x}\right) \tag{3.6}$$

where θ_F is the angle of the flight displacement vector relative to the x-axis, x is the x-coordinate of the vector and y is the y-coordinate of the vector. The angle of turn of the CoM during ground contact was calculated by subtracting the θ_F following the ground contact phase from the θ_F preceding the ground contact phase:

$$\text{Turn}\,1 = \theta_{F2} - \theta_{F1} \tag{3.7}$$

$$\text{Turn}\,2 = \theta_{F3} - \theta_{F2} \tag{3.8}$$

Upper and lower body kinematics

Foot horizontal velocity at touchdown: The resultant horizontal velocity of the foot was initially calculated from the horizontal displacement of the rearfoot CoM using the first central difference method. The velocity of the foot at touchdown, in the AP direction was then calculated as the scalar projection of the resultant horizontal velocity of the contact foot onto the instantaneous progression vector (calculated previously for the touchdown distance measurement; Figure 3.7).

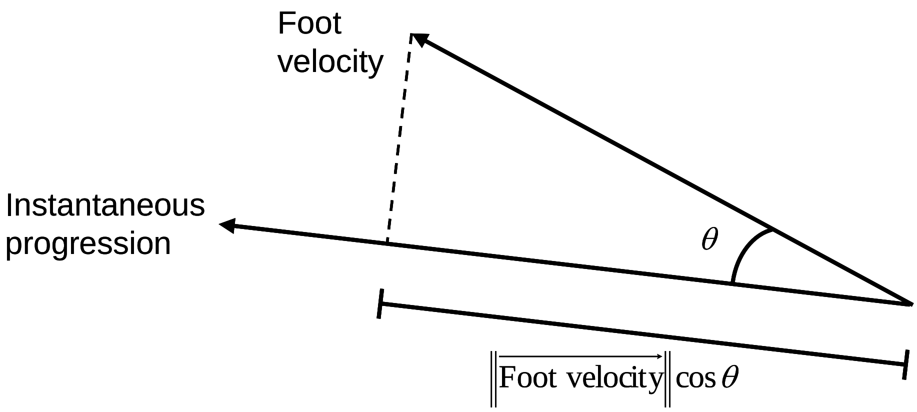


Figure 3.7. Calculation of foot horizontal velocity at touchdown shown in the transverse view. Foot horizontal velocity at touchdown is equal to the dot product of the instantaneous progression and the foot velocity vectors.

Foot horizontal velocity relative to CoM horizontal velocity at touchdown: The horizontal velocity of the CoM in the AP direction was calculated using the same method as for calculation of the foot horizontal velocity in the AP direction. The horizontal velocity of the rearfoot CoM relative to the body CoM was then calculated by subtracting the horizontal velocity of the body CoM in the AP direction from the horizontal velocity of the foot in the AP direction.

Foot vertical velocity at touchdown: Calculated from the vertical displacement of the rearfoot CoM using the first central difference method and taken at the first frame of contact.

Angles: For the purposes of joint angle calculations the same segments were defined as for the inertia model, with the exception of the trunk which was subdivided into two segments: the pelvis and thorax, which shared a common long axis (mid-hip to mid-shoulder) but whose orientations were calculated also, using the right hip and right shoulder for the pelvis and thorax, respectively. Joint angles calculated and events at which angles were recorded are given in Figure 3.8. In order to assess the whole body lean of the athletes, the angle of a vector between the relevant MTP and the CoM was also calculated. This allowed calculation of the angle of lean in the sagittal and frontal planes, termed body sagittal lean and body lateral lean, respectively (Figure 3.9). The range of motion (ROM) of the body sagittal lean from touchdown to take off and the body lateral lean at touchdown and take off were recorded.

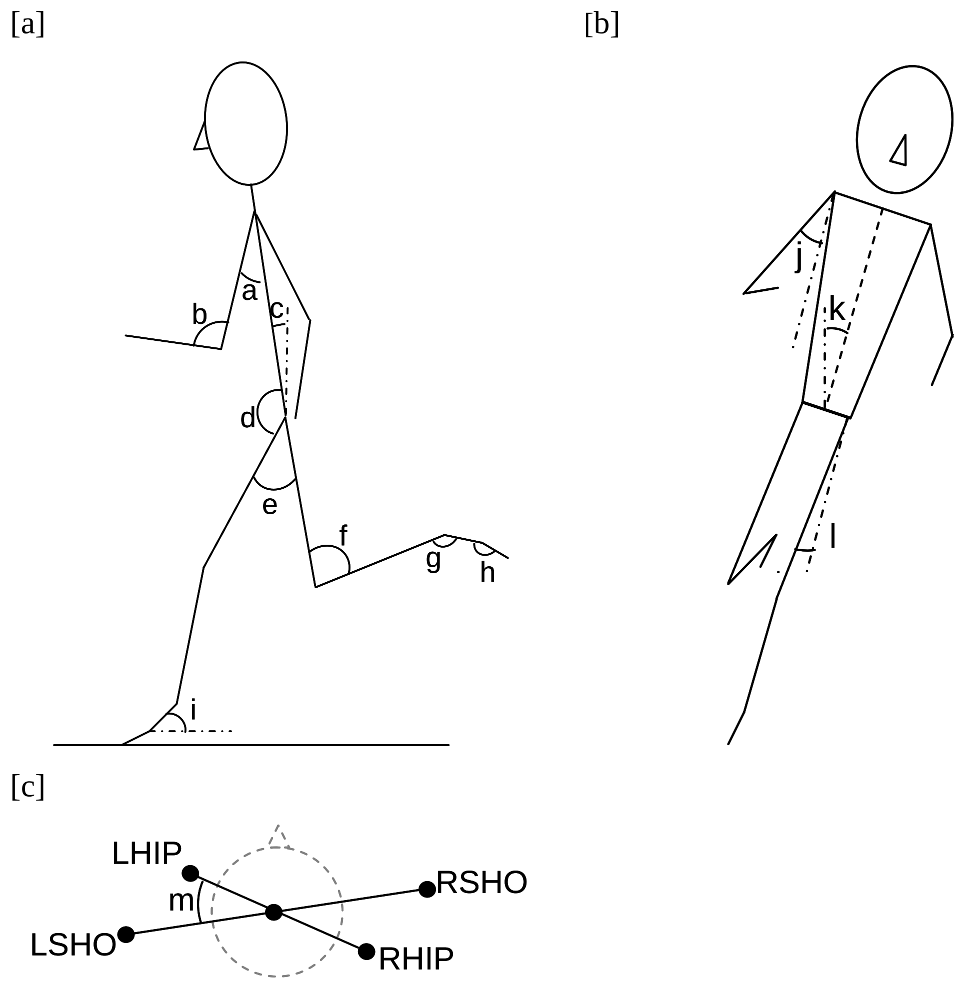


Figure 3.8. [a] Sagittal plane angles measured: a) Shoulder flexion/extension ROM; b) Elbow ROM; c) Trunk forward lean at touchdown (TD); d) Hip flexion/extension angle at take off (TO), at full flexion and full extension; e) thigh separation at TD; f) Knee angle at TO, full flexion, TD, and minimum and maximum angles during ground contact; g) Ankle angle at TD, minimum during contact, and at TO; h) MTP angle at TD, maximum during absorption phase, minimum during ground contact, and at TO; i) Rearfoot angle at TD, minimum during ground contact, and at TO.
[b] Frontal plane angles measured: j) shoulder abduction/adduction ROM; k) Trunk lateral lean at TD; l) Hip abduction/adduction at TD, at peak abduction, at peak adduction, and at TO.
[c] Transverse plane angles measured: m) maximum thorax rotation.
For angles measured at times other than TD and TO, the time at which they occurred was recorded. Minima and maxima values were used to calculate ranges of flexion/extension (and dorsiflexion/plantarflexion) during contact for the knee, ankle and MTP joints.

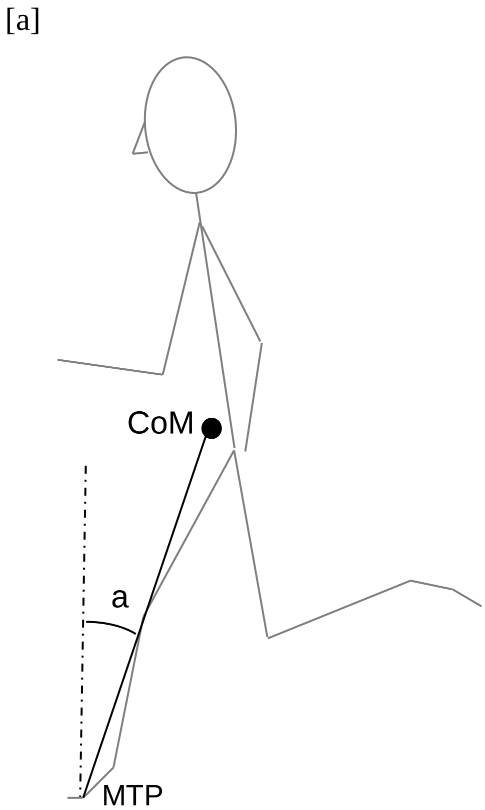


Figure 3.9. [a] Body sagittal lean angle and [b] body lateral lean angle.

Calculation of angles using 3D orientation angles was based on the methods outlined by Yeadon (1990a). For the calculation of the angles, the movement at a joint was defined as motion of the distal segment local coordinate system (LCS) relative to the reference (proximal segment) LCS. The root segment was the pelvis. For each set of angles the LCS of the distal segment was determined using three points termed p_1, p_2 and p_3 which each had coordinates in the GCS. See Table 3.1. for specific points used for each angle calculation. Firstly, a vector from p_1 to p_2 $(\vec{p}_2 - \vec{p}_1)$ was created and divided by its norm to create the first unit vector $\vec{k}'$.

$$\vec{k}' = \frac{(\vec{p}_2 - \vec{p}_1)}{\|(\vec{p}_2 - \vec{p}_1)\|} \tag{3.9}$$

A second vector was then defined from p_1 to p_3 $(\vec{p}_3 - \vec{p}_1)$ and along with vector $(\vec{p}_2 - \vec{p}_1)$ this created a plane; the cross product of these two vectors was calculated and divided by the norm of this operation which gave either unit vector $\vec{j}'$ or unit vector $\vec{i}'$, depending on the order of unit vector definition (Table 3.1).

$$\vec{j}' \text{or } \vec{i}' = \frac{(\vec{p}_2 - \vec{p}_1)\times(\vec{p}_3 - \vec{p}_1)}{\|(\vec{p}_2 - \vec{p}_1)\times(\vec{p}_3 - \vec{p}_1)\|} \tag{3.10}$$

For the calculation of shoulder angles the cross product calculation for the second unit vector was performed in the opposite order to ensure the correct orientation of the unit vector (equation 3.11).

$$\vec{i}' = \frac{(\vec{p}_3 - \vec{p}_1)\times(\vec{p}_2 - \vec{p}_1)}{\|(\vec{p}_3 - \vec{p}_1)\times(\vec{p}_2 - \vec{p}_1)\|} \tag{3.11}$$

The cross product of the first and second unit vectors to be determined gave the third unit vector:

$$\vec{i}' = \vec{j}' \times \vec{k}' \tag{3.12}$$

or

$$\vec{j}' = \vec{k}' \times \vec{i}' \tag{3.13}$$

The unit vectors of the distal LCS had coordinates relative to the origin of the LCS (p_1). In order to calculate the distal segment Rotational Transformation Matrix (RTM), unit vector matrices were constructed for each coordinate system.

$$[T_{REFERENCE}] = \begin{bmatrix} \vec{i}_x & \vec{i}_y & \vec{i}_z \\ \vec{j}_x & \vec{j}_y & \vec{j}_z \\ \vec{k}_x & \vec{k}_y & \vec{k}_z \end{bmatrix} \tag{3.14}$$

$$[T_{DISTAL}] = \begin{bmatrix} \vec{i}'_x & \vec{i}'_y & \vec{i}'_z \\ \vec{j}'_x & \vec{j}'_y & \vec{j}'_z \\ \vec{k}'_x & \vec{k}'_y & \vec{k}'_z \end{bmatrix} \tag{3.15}$$

The RTM [T_R] was the dot product of both unit vector matrices

$$[T_R] = [T_{DISTAL}][T_{REFERENCE}]^T \tag{3.16}$$

Which resulted in:

$$[T_R] = \begin{bmatrix} \vec{i}'\cdot\vec{i} & \vec{i}'\cdot\vec{j} & \vec{i}'\cdot\vec{k} \\ \vec{j}'\cdot\vec{i} & \vec{j}'\cdot\vec{j} & \vec{j}'\cdot\vec{k} \\ \vec{k}'\cdot\vec{i} & \vec{k}'\cdot j & \vec{k}'\cdot\vec{k} \end{bmatrix} \tag{3.17}$$

For an Xyz Cardan rotation, successive rotations about the x, y, and z axes, respectively, change a coordinate system from its initial orientation (aligned with the GCS or reference system) to its final orientation (non-aligned; Figure 3.10).

[a] [b] [c]

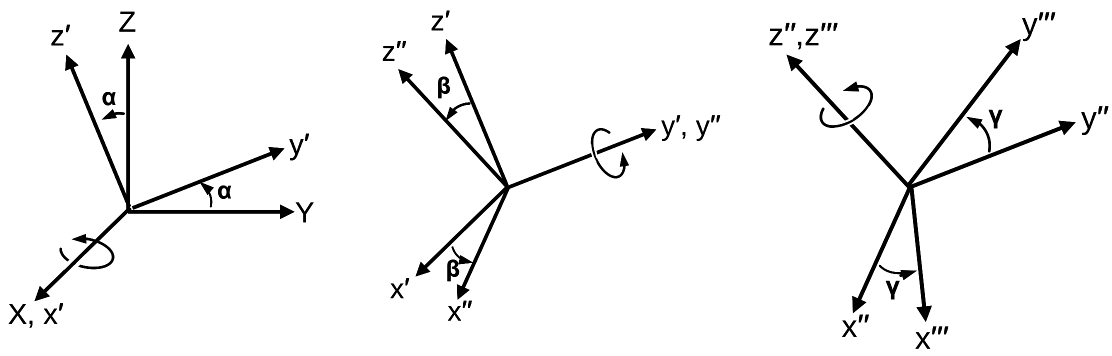


Figure 3.10. Positive Cardan rotations about [a] the x-axis (α) [b] the y-axis (β) and [c] the z-axis (γ).

For each rotation a direction cosine matrix can be defined:

$$[R_x] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix} \tag{3.18}$$

$$[R_y] = \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix} \tag{3.19}$$

$$[R_z] = \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3.20}$$

The relative orientation of one coordinate system about a second coordinate system, i.e. the final orientation relative to the initial orientation of the coordinate system, can be represented by a direction cosine matrix [R], which is the product of $[R_x]$, $[R_y]$ and $[R_z]$:

$$[R] = [R_z][R_y][R_x] \tag{3.21}$$

$$= \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix} \tag{3.22}$$

$$= \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\beta & \sin\alpha\sin\beta & -\cos\alpha\sin\beta \\ 0 & \cos\alpha & \sin\alpha \\ \sin\beta & -\sin\alpha\cos\beta & \cos\alpha\cos\beta \end{bmatrix} \tag{3.23}$$

$$= \begin{bmatrix} \cos\beta\cos\gamma & \cos\gamma\sin\beta\sin\alpha + \sin\gamma\cos\alpha & \sin\gamma\sin\alpha - \cos\gamma\sin\beta\cos\alpha \\ -\sin\gamma\cos\beta & \cos\alpha\cos\gamma - \sin\alpha\sin\beta\sin\gamma & \sin\gamma\sin\beta\cos\alpha + \cos\gamma\sin\alpha \\ \sin\beta & -\cos\beta\sin\alpha & \cos\alpha\cos\beta \end{bmatrix} \tag{3.24}$$

Element R_{31} of the direction cosine matrix is equivalent to T_{R31} of the RTM. It was therefore possible to calculate angle β:

$$\beta = \sin^{-1}(R_{31}) = \sin^{-1}(T_{R31}) \tag{3.25}$$

Once β was known α and γ could be calculated:

$$\alpha = \sin^{-1}\frac{-R_{32}}{\cos\beta} = \sin^{-1}\frac{-T_{R32}}{\cos\beta} \tag{3.26}$$

$$\gamma = \sin^{-1}\frac{-R_{21}}{\cos\beta} = \sin^{-1}\frac{-T_{R21}}{\cos\beta} \tag{3.27}$$

The angles calculated are those angles that take the coordinate systems from aligned to non-aligned: α represents the angle of rotation about the x-axis, β represents the angle of rotation about the y-axis and γ represents the angle of rotation about the z-axis. The anatomical explanations for each set of angles calculated are given in Table 3.1.

Table 3.1. Points used, order of unit vector calculation and resulting angles calculated using 3D orientation angles. Angles in bold are those used for subsequent analysis.

Angles	Distal LCS	Points used to define distal LCS			Order of unit vector definition			Reference LCS	α represents:	β represents:	γ represents:
		p1	p2	p3	1st	2nd	3rd				
Trunk	Pelvis	Mid-hip	Mid-shoulder	Right hip	$\vec{k}'$	$\vec{j}'$	$\vec{i}'$	GCS	**Trunk forward lean**	**Trunk lateral lean**	Pelvic rotation
Right hip	Right thigh	Right knee	Right hip	Right ankle	$\vec{k}'$	$\vec{i}'$	$\vec{j}'$	Pelvis	**Flexion/ extension** *	**Abduction/ adduction**	Internal/ external rotation
Left hip	Left thigh	Left knee	Left hip	Left ankle	$\vec{k}'$	$\vec{i}'$	$\vec{j}'$	Pelvis	**Flexion/ extension** *	**Abduction/ adduction**†	Internal/ external rotation
Thorax	Thorax	Mid-hip	Mid-shoulder	Right shoulder	$\vec{k}'$	$\vec{j}'$	$\vec{i}'$	Pelvis			**Long axis rotation relative to pelvis**
Right shoulder	Right upper arm	Right elbow	Right shoulder	Right wrist	$\vec{k}'$	$\vec{i}'$	$\vec{j}'$	Thorax	**Flexion/ extension**	**Abduction/ adduction**	Internal/ external rotation
Left shoulder	Left upper arm	Left Elbow	Left shoulder	Left wrist	$\vec{k}'$	$\vec{i}'$	$\vec{j}'$	Thorax	**Flexion/ extension**	**Abduction/ adduction**†	Internal/ external rotation
'Body'	Body	MTP**	CoM		$\vec{k}'$	$\vec{j}'$	$\vec{i}'$	Progression LCS	**Body sagittal lean**	**Body lateral lean**	

* To remain consistent with the majority of sprint studies the Cardan angles calculated for hip flexion/extension were offset by 180°

† Left hip and shoulder abduction/adduction angles were multiplied by -1 so as to standardise the angle sign and direction of motion.

** Body sagittal and lateral lean angles were calculated during left and right ground contacts; the MTP used for each step was the corresponding limb MTP. Body sagittal and lateral lean angles were expressed relative to the direction of travel, thus, in order that the body angle could be expressed relative to the progression of the athlete rather than the GCS, a progression LCS was calculated. The $\vec{k}$ unit vector of the progression LCS is equivalent to the $\vec{k}$ unit vector of the GCS. The $\vec{j}$ unit vector is equivalent to the instantaneous progression vector and the cross product of $\vec{j} \times \vec{k}$ gave $\vec{i}$.

It was not possible to obtain reliable orientation angles in three dimensions for the knee, ankle or MTP joints. The orientation angles method of Yeadon (1990a) uses a point on the distal segment in the definition of the proximal segment's LCS. It was, therefore, found that the *i* unit vector of the proximal segment and the *k* unit vector of the distal segment were not independent and were always orthogonal. This returned a value of zero for the rotation about the y-axis in the RTM when the dot product of the two vectors was performed and resulted in abduction/adduction angles of zero. For this reason 3D vector angles were used for the knee, ankle and MTP joints which would still provide more informative results than in previous studies where 2D projection angles have been used.

Right knee vector angles were calculated using the three points: right hip, right knee and right ankle, termed p_1, p_2 and p_3, respectively. Vectors from right knee to right hip and right knee to right ankle were created and the angle between the vectors calculated using the equation:

$$\theta = \cos^{-1}\left(\frac{(\vec{p}_1 - \vec{p}_2)\cdot(\vec{p}_3 - \vec{p}_2)}{\|(\vec{p}_1 - \vec{p}_2)\|\|(\vec{p}_3 - \vec{p}_2)\|}\right) \tag{3.28}$$

Left knee angles were calculated using left hip (p_1), left knee (p_2) and left ankle (p_3) and equation 3.28. Right and left ankle angles were calculated using the respective knee (p_1), ankle (p_2) and MTP (p_3) points (equation 3.28). Right and left MTP angles were calculated using the ankle, MTP and tip of spikes on the respective limbs used as points p_1, p_2 and p_3, respectively (equation 3.28).

The rearfoot angle was calculated as the angle that the rearfoot made with the ground. A rearfoot vector was calculated from the MTP to the ankle (p_1 and p_2, respectively). A ground vector was calculated by creating points p_3 and p_4 using the horizontal coordinates of the MTP and ankle, respectively, and with vertical coordinates given as zero. The vector angle between the two vectors was calculated as:

$$\theta = \cos^{-1}\left(\frac{(\vec{p}_2 - \vec{p}_1)\cdot(\vec{p}_4 - \vec{p}_3)}{\|(\vec{p}_2 - \vec{p}_1)\|\|(\vec{p}_4 - \vec{p}_3)\|}\right) \tag{3.29}$$

For the same reason outlined for the knee, ankle, and MTP angles, the elbow angles were calculated as 3D vector angles. Vector angles were calculated (equation 3.28) for the right and left elbows with the shoulder, elbow and wrist points on the respective limbs used as points p_1, p_2 and p_3, respectively.

Angular velocities: Angular velocities of the hip (flexion/extension), knee and MTP, were calculated from the angular displacements using the first central difference method and the times at which peaks occurred were recorded.

Rearfoot drop: Calculated as the difference between the rearfoot angle at touchdown and at its minimum value during contact.

Rearfoot lift: Calculated as the change in angle between the minimum rearfoot angle during contact and the rearfoot angle at take off.

Displacement of the wrists relative to the CoM: An upper body LCS was calculated with an origin at the body CoM so that the position of the wrists relative to the CoM (and direction of travel) could be calculated from their coordinates in the GCS. To define the upper body LCS, a vector from mid-hip (p_1) to mid-shoulder (p_2) was created and divided by its norm to create the first unit vector $\vec{k}'$:

$$\vec{k}' = \frac{(\vec{p}_2 - \vec{p}_1)}{\|(\vec{p}_2 - \vec{p}_1)\|} \tag{3.30}$$

In order that the position of the wrist was calculated relative to the direction of travel, the instantaneous progression vector was used as the *j* unit vector of the upper body LCS:

$$\vec{j}' = \frac{(\overrightarrow{CoM_{i+1}} - \overrightarrow{CoM_{i-1}})}{\|(\overrightarrow{CoM_{i+1}} - \overrightarrow{CoM_{i-1}})\|} \tag{3.31}$$

The cross product of $\vec{j}' \times \vec{k}'$ gave $\vec{i}'$:

$$\vec{i}' = \vec{j}' \times \vec{k}' \qquad (3.32)$$

Unit vector matrices were constructed for the upper body LCS and the GCS and an upper body RTM calculated from the dot product of both unit vector matrices:

$$[T_R] = [T_{UBOD}][T_{GCS}]^T \qquad (3.33)$$

The relative rotation of the upper body LCS in the GCS was calculated using the direction cosine matrix (equation 3.24) and the upper body RTM. To calculate the wrist coordinates in the upper body LCS, a translation was performed to account for the difference in location of the origins of the GCS and LCS. This was achieved by subtracting the coordinate values of the CoM from the wrist coordinate values in the x-, y- and z-directions:

$$[WRI_T] = [WRI_G] - [CoM_G] \qquad (3.34)$$

where $[WRI_T]$ is the column matrix of the translated wrist position, $[WRI_G]$ and $[CoM_G]$ are the column matrices of the positions, in the global coordinate system of the wrist and CoM, respectively. The position of the wrist in the LCS $[WRI_L]$ was then given by the equation:

$$[WRI_L] = [R][WRI_T] \qquad (3.35)$$

Thigh separation angle: The angle between the left and right thigh segments (hip to knee) at touchdown was calculated as a vector angle. In order that movement of the athlete out of alignment with the GCS could be accounted for, thigh separation was measured in the sagittal plane of the athlete. The sagittal plane of the athlete was defined by the *k* and *j* unit vectors of the body LCS (Table 3.1). A RTM representing the rotation of the body LCS in the GCS was calculated:

$$[T_R] = [T_{BOD}][T_{GCS}]^T \quad (3.36)$$

A translation was performed to account for the difference in location of the origins of the GCS and LCS. This was achieved by subtracting the coordinate values of the CoM from the hip and knee coordinate values in the x-, y- and z-directions. The position of the hip and knee in the LCS was then given by equations 3.37 and 3.38, respectively:

$$[HIP_L] = [R][HIP_G] \quad (3.37)$$

$$[KNE_L] = [R][KNE_G] \quad (3.38)$$

where $[HIP_L]$ and $[HIP_G]$ are the positions of the hip in the local and global coordinate systems, respectively; and $[KNE_L]$ and $[KNE_G]$ are the column matrices of the knee position in the local and global coordinate systems, respectively. $[R]$ is the direction cosine matrix. Using LCS coordinates right hip, right knee, left hip and left knee were termed points p_1, p_2, p_3 and p_4, respectively. Thigh separation was calculated as the angle between the thigh vectors (equation 3.29).

3.2.5. Reliability of digitising

In order to assess the reliability of digitising one of the bend trials and one of the straight trials of the same athlete was digitised a total of eight times. The repeat digitisations were completed at regular intervals throughout the whole digitising process, with redigitiations of the same condition trial a minimum of four days apart. Redigitised trials were processed in the same way as for all other trials and variables calculated for left and right steps separately. The mean and standard deviation of the eight trials within a condition were calculated for each variable. Furthermore, the coefficient of variation (CV) of the eight trials within a condition was calculated for each variable.

3.2.6. Statistical analysis

An individual mean value for each variable in each condition was calculated for each athlete from their available trials. Due to the two female athletes achieving relatively low velocities during the trials compared to the male athletes, statistical analyses were performed on only the male results. However, group mean values for the female athletes were calculated and female trends were also considered in relation to the male group results.

To measure the effect that the bend has on performance and technique, a number of comparisons were made using paired-samples t-tests (SPSS for Windows, v 14.0, SPSS Inc., USA). The following pairs were compared, for each variable: left on the bend to left on the straight and right on the bend to right on the straight in order to determine changes between the bend and straight. The presence of any asymmetries was assessed by comparing left on the bend to right on the bend and left on the straight to right on the straight, for each variable. Absolute values were used for comparison of left and right trunk lateral lean and body lateral lean on the straight. Race velocity was also compared to absolute speed for left and right, and race step length was compared to directional step length for left and right, for both bend and straight conditions. Significance was set at $p < 0.05$ for all t-tests.

The magnitude of the difference (the effect size) between bend and straight for left and right steps and between left and right on the bend was calculated for each variable using Cohen's *d* (Cohen, 1988). Relative magnitude of the effect was assessed based on Cohen's guidelines with *d* less than or equal to 0.20 representing a small difference, greater than 0.20 but less than 0.80 a moderate difference and *d* greater than or equal to 0.80 a large difference, between the two means.

3.3. Results

3.3.1. Direct performance descriptors

Race velocity and absolute speed were significantly slower on the bend compared to the straight for male athletes, with mean left step race velocity reducing from 9.86 $m \cdot s^{-1}$ to 9.39 $m \cdot s^{-1}$ ($p < 0.05$, $d = 0.92$) and mean right step race velocity reducing from 9.80 $m \cdot s^{-1}$ to 9.33 $m \cdot s^{-1}$ ($p < 0.01$, $d = 0.89$, Figure 3.11). The same trend was seen for females whose mean race velocity reduced from 8.34 $m \cdot s^{-1}$ for both steps on the straight to 8.00 $m \cdot s^{-1}$ and 7.98 $m \cdot s^{-1}$ for left and right, respectively, on the bend. No statistically significant differences were found between race velocity and absolute speed for males, although examination of individual results revealed that four of the seven male athletes had race velocities greater than absolute speeds for both left and right on the bend. Both females had race velocities lower than their absolute speeds.

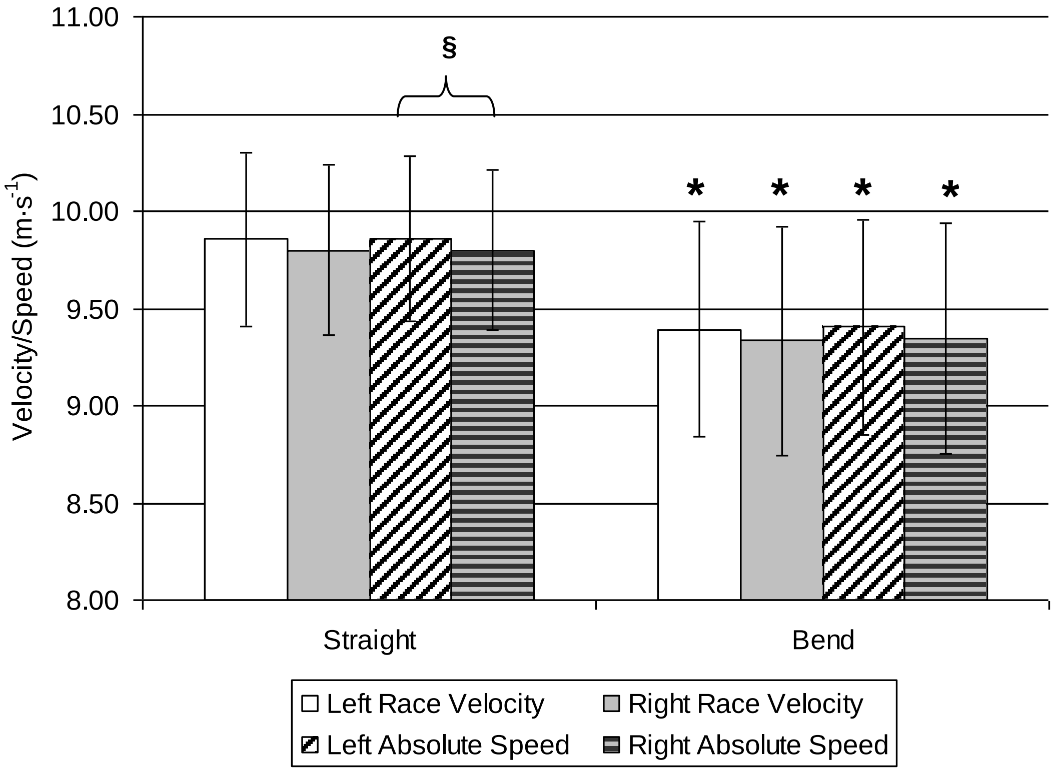


Figure 3.11. Left and right step group mean race velocity and absolute speed on the straight and bend for male athletes. ***** significantly different to straight ($p < 0.05$); § significantly different between left and right on the straight ($p < 0.05$).

For male athletes, directional step length reduced by 0.04 m (2.20 m to 2.16 m) and 0.08 m (2.20 m to 2.12 m) for left and right steps, respectively, on the bend compared to the straight, which represented a moderate sized effect of d = 0.37 for the left and d = 0.60 for the right steps. Race step length reduced by 0.06 m (2.20 m to 2.14 m; d = 0.51) and 0.10 m (2.20 m to 2.10 m; d = 0.79) for left and right steps, respectively, on the bend compared to the straight (Figure 3.12). Female athletes followed the same trend with mean race step length reducing from 1.99 m and 1.98 m to 1.96 m and 1.91 m for left and right steps, respectively. Race and directional step length were similar on the straight, but mean race step length was shorter on the bend than the directional step length, for both males and females.

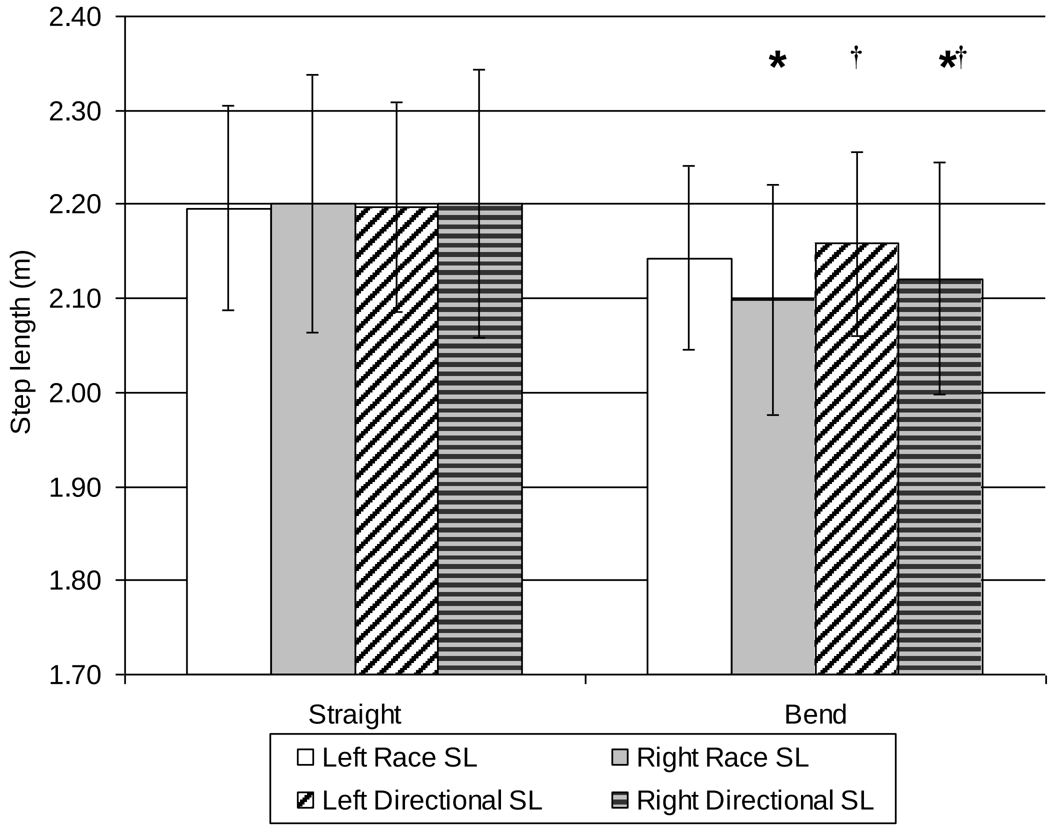


Figure 3.12. Left and right step group mean race and directional step length on the straight and bend for male athletes. ***** significantly different to straight ($p < 0.05$); † significantly different between race and directional step length on bend ($p < 0.05$).

Left step frequency was lower on the bend than on the straight for all but one participant (Figure 3.13). Mean values for the males' left step frequency reduced from 4.50 Hz on the straight to 4.39 Hz on the bend. This was found to be significantly different ($p < 0.05$, $d = 0.47$). There was no difference in male mean step frequency between the bend and straight on the right step with mean values of 4.46 Hz for both conditions ($p = 0.973$, $d = 0.00$). For females, mean right step frequency was only slightly lower on bend than the straight at 4.18 Hz compared to 4.22 Hz.

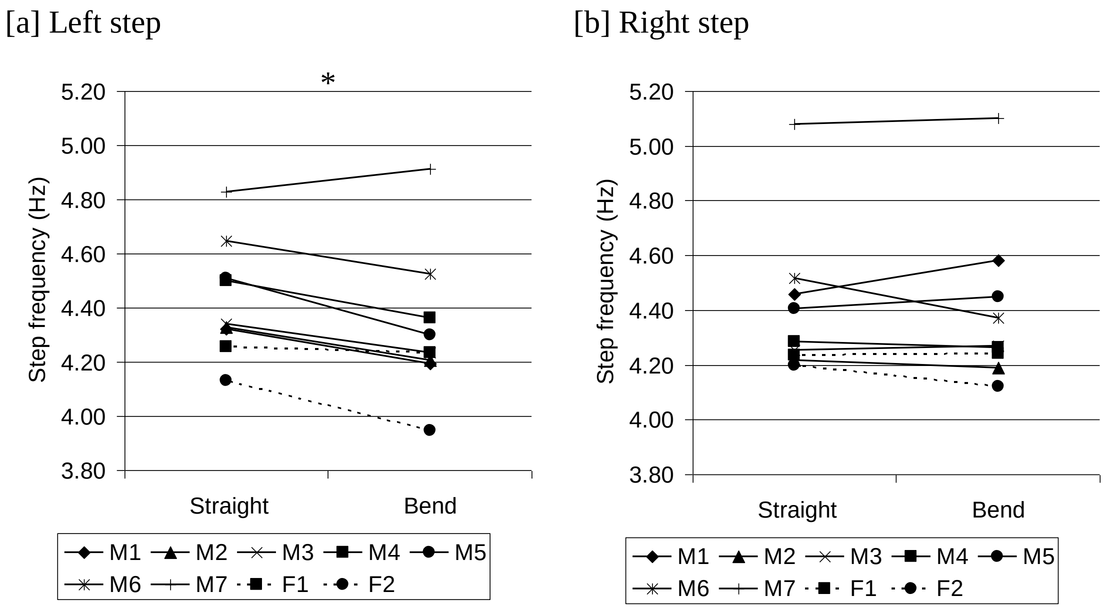


Figure 3.13. [a] Left and [b] right step frequency for all athletes on the straight and bend. Male athletes: M1-M7; female athletes: F1 and F2. For male athlete group mean data: * significantly different between bend and straight ($p < 0.05$).

All athletes showed an increase in left ground contact time from straight to bend (Figure 3.14). The mean left ground contact time of the males on the bend of 0.116 s was found to be significantly longer than the mean on the straight of 0.105 s ($p < 0.01$, $d = 2.97$) with female athletes also following the same trend (Figure 3.14). Mean values for the male athletes for right ground contact time were 0.105 s and 0.109 s for the straight and bend, respectively. The difference between male mean left and right ground contact times on the bend was also found to be significant ($p < 0.05$, $d = 1.70$). Mean flight time was similar between straight and bend for the left step at 0.115 s and 0.116 s, respectively, for the male athletes. There was, however, a significant decrease in flight time from 0.121 s on the straight to 0.112 s on the bend for the right step in the male athletes ($p < 0.05$, $d = 0.67$, Figure 3.14). Mean flight times for the two female athletes were 0.117 s and 0.114 s for left and right steps, respectively, on the straight, and 0.121 s and 0.110 s for left and right steps, respectively, on the bend. There were no significant differences between left and right within a condition for flight times. Generally, ground contact time expressed as the proportion of total step time (step contact factor) increased on the bend compared to the straight, with male means increasing from 0.478 to 0.501 for the left step and from 0.466 to 0.495 for the right steps. These differences were significant for both legs ($p < 0.05$, left $d = 1.54$, right $d = 1.23$, Figure 3.15).

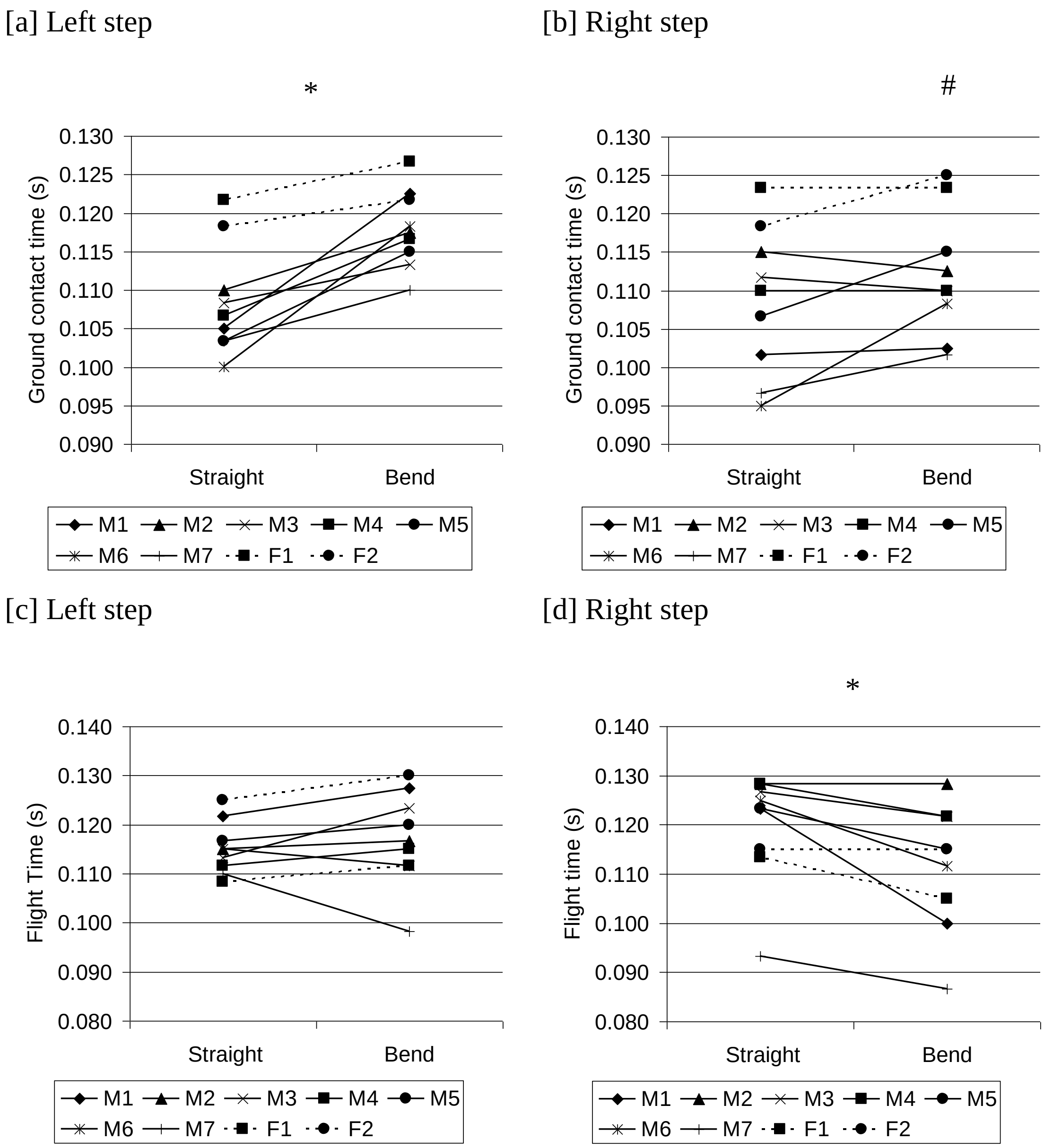


Figure 3.14. [a] Left and [b] right step ground contact time for all athletes on the straight and bend. [c] Left and [d] right step flight time for all athletes on the straight and bend. Male athletes: M1-M7; female athletes: F1 and F2. For male athlete group mean data: * significantly different between bend and straight ($p < 0.05$), # significantly different between left and right on the bend ($p < 0.05$).

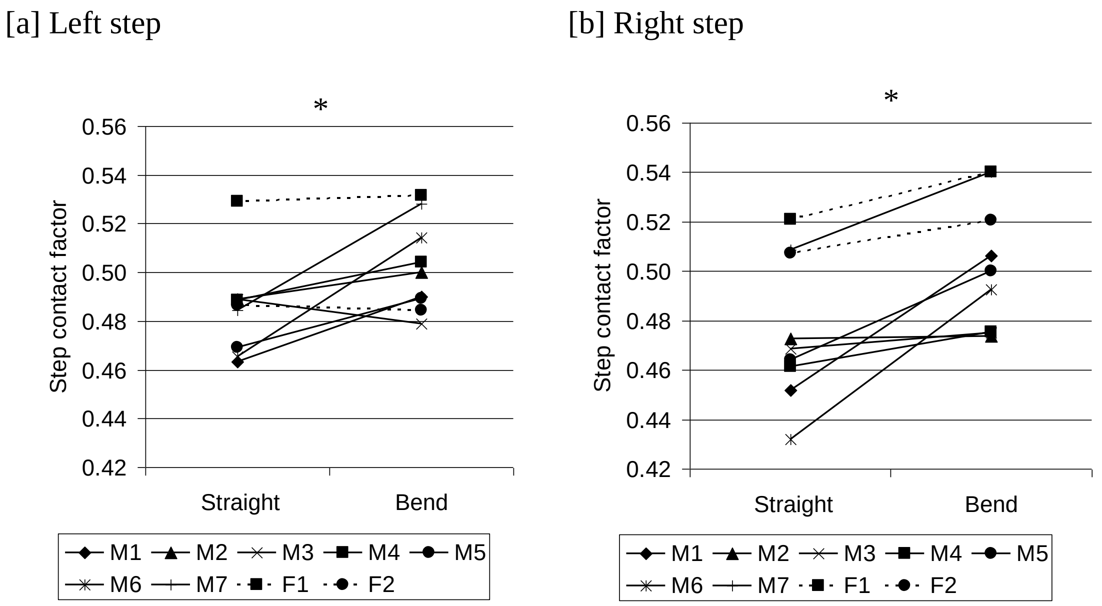


Figure 3.15. [a] Left and [b] right step contact factor for all athletes on the straight and bend. Male athletes: M1-M7; female athletes: F1 and F2. For male athlete group mean data: * significantly different between bend and straight ($p < 0.05$).

On the bend, more turning of the CoM occurred during left ground contact with mean values of 4.1° (± 0.7°) compared to 2.5° (± 0.8°) during right ground contact for males (significant at $p < 0.05$, $d = 2.12$) and 3.3° and 2.6° for females for left and right contacts, respectively.

An asymmetry between left and right steps was apparent on the bend in touchdown distance and body sagittal lean ROM, with the left step values being greater for both. The left step values were also statistically significantly larger on the bend compared to the straight for both of these variables (Table 3.2). There was significantly ($p < 0.05$) increased inward (more negative) body lateral lean at touchdown and take off for both steps on the bend, compared to the straight (Table 3.2) for the male athletes.

Table 3.2. Left and right step group mean values (± SD) and significant differences for male athletes, and group mean values for female athletes for touchdown distance and body lean kinematics on the straight and bend.

	Males								Females			
	Straight		Bend		Significant differences				Straight		Bend	
	Left	Right	Left	Right	Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right	Left	Right	Left	Right
Touchdown distance (m)	0.30 ± 0.04	0.31 ± 0.04	0.36 ± 0.04	0.30 ± 0.04		*	#		0.28	0.30	0.31	0.31
Body sagittal lean ROM (°)	51.1 ± 2.4	51.2 ± 2.7	57.2 ± 1.7	52.9 ± 2.7		#	§		53.8	54.3	55.2	54.9
Body lateral lean at TD (°)[1]	3.5 ± 1.2	-4.1 ± 0.8	-10.3 ± 2.3	-15.2 ± 1.6		#	§	§	2.0	-2.5	-6.9	-10.5
Body lateral lean at TO (°)[1]	3.4 ± 1.2	-4.4 ± 0.5	-8.2 ± 2.2	-14.1 ± 1.6	*	§	§	§	2.9	-3.2	-4.7	-10.0

***** Significant at $p < 0.05$; # significant at $p < 0.01$; § significant at $p < 0.001$

[1] Where left vs. right was compared on the straight, by paired samples t-test, absolute values were used for these variables

3.3.2. Upper and lower body kinematics

An asymmetry between left and right steps was present in the thigh separation at touchdown, where the separation was larger at left touchdown than right touchdown on the bend. Similarly to touchdown distance and body sagittal lean ROM, left step thigh separation was statistically significantly larger on the bend compared to the straight (Table 3.3), for the male athletes. There were no significant differences in male mean values for any of the foot velocity variables. However, there was a general trend for increased left foot horizontal velocity at touchdown and a less negative left foot horizontal velocity relative to the CoM at touchdown on the bend compared to the straight (Table 3.3).

Trunk forward lean reduced, i.e. it was less negative, at both left and right step touchdown from straight to bend and there was significantly increased inward (more negative) trunk lateral lean at touchdown for both steps on the bend in comparison to the straight for the male athletes ($p < 0.05$, Table 3.3).

Hip angles and angular velocities are given in Table 3.4. The left hip was significantly more adducted at touchdown and at peak adduction on the bend ($p < 0.05$) in comparison to the straight for the male athletes, and there was an asymmetry between left and right steps on the bend with the left hip being more adducted than the right at these times ($p < 0.01$, Figure 3.16).

Table 3.3. Left and right step group mean values (± SD) and significant differences for male athletes, and group mean values for female athletes for touchdown variables on the straight and bend.

	Males								Females			
	Straight		Bend		Significant differences				Straight		Bend	
	Left	Right	Left	Right	Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right	Left	Right	Left	Right
Thigh separation at TD (°)	17.2 ± 11.4	19.6 ± 5.6	25.5 ± 8.8	18.5 ± 5.8		*	*		28.8	31.5	30.8	27.5
Foot horizontal velocity at TD ($m \cdot s^{-1}$)	2.00 ± 0.62	2.06 ± 0.69	2.36 ± 0.73	2.02 ± 0.75					1.47	1.41	1.57	1.38
Foot horizontal velocity relative to the CoM at TD ($m \cdot s^{-1}$)	-7.62 ± 0.50	-7.76 ± 0.50	-6.89 ± 0.82	-7.25 ± 0.87					-6.77	-6.99	-6.48	-6.68
Foot vertical velocity at TD ($m \cdot s^{-1}$)	-2.12 ± 0.39	-2.21 ± 0.34	-2.07 ± 0.31	-2.05 ± 0.37					-1.34	-1.71	-1.43	-1.82
Trunk forward lean at TD (°)	-10.4 ± 2.2	-7.4 ± 0.8	-6.7 ± 1.7	-6.1 ± 0.9	*		#	*	-10.2	-8.3	-8.3	-5.5
Trunk lateral lean at TD (°)	-4.5 ± 2.1	2.8 ± 1.6	-12.8 ± 5.6	-9.9 ± 3.0			#	§	-2.0	2.1	-10.0	-5.5

* Significant at $p < 0.05$; # significant at $p < 0.01$; § significant at $p < 0.001$

Table 3.4. Left and right step group mean values (± SD) and significant differences for male athletes, and group mean values for female athletes for hip angles and angular velocities on the straight and bend.

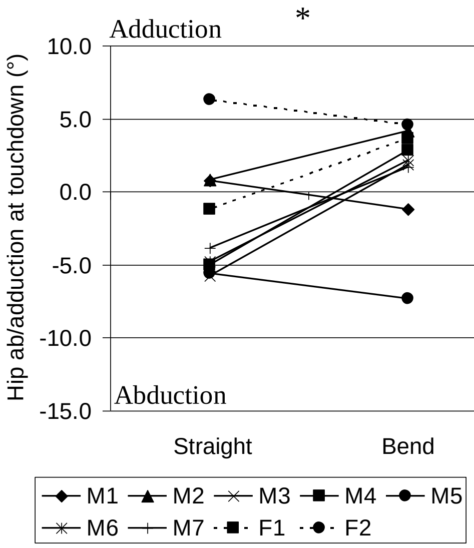
	Males								Females			
	Straight		Bend		Significant differences				Straight		Bend	
	Left	Right	Left	Right	Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right	Left	Right	Left	Right
Hip flexion/extension angle at TO (°)	207.6 ± 3.8	203.7 ± 6.8	209.7 ± 5.6	204.4 ± 3.1		*			210.5	210.3	213.6	209.8
Hip flexion/extension angle at full extension (°)	209.4 ± 5.2	205.1 ± 7.0	211.5 ± 4.8	206.8 ± 3.2	*	*			211.9	211.6	214.5	210.8
Time of hip full extension (% of step time)	53.2 ± 4.9	50.7 ± 3.1	54.8 ± 2.9	55.0 ± 1.9				#	53.9	55.7	53.5	57.0
Hip flexion/extension angle at full flexion (°)	103.9 ± 8.6	104.3 ± 7.7	101.7 ± 6.5	106.6 ± 6.7		#			109.9	108.7	110.6	110.1
Time of hip full flexion (% of contralateral limb step time)	49.9 ± 5.7	45.2 ± 6.5	48.0 ± 4.4	50.9 ± 5.2				*	55.4	52.4	54.8	55.1
Hip abduction/adduction angle at TD (°)	-3.4 ± 2.9	-5.5 ±1.9	0.6 ± 3.8	-7.1 ± 3.3		#	*		2.6	-3.0	4.1	-5.0
Hip peak abduction (°)	-6.3 ± 2.4	-7.5 ± 1.2	-4.8 ± 3.2	-8.9 ± 3.5					-1.8	-5.6	-4.5	-7.2
Time of hip peak abduction (% of contact)	56.3 ± 28.3	44.2 ± 31.5	88.7 ± 11.4	26.7 ± 28.4		#	*		52.9	51.4	80.7	31.3
Hip peak adduction (°)	4.1 ± 2.6	3.3 ± 3.7	10.6 ± 4.1	1.0 ± 3.5		§	#	*	9.7	6.9	13.7	3.0
Time of hip peak adduction (% of contact)	38.0 ± 10.1	47.7 ± 15.8	38.2 ± 7.1	55.5 ± 24.1					57.6	59.3	39.6	62.4
Hip abduction/adduction angle at TO (°)	-4.6 ± 2.4	-5.0 ± 2.2	-4.3 ± 3.0	-4.2 ± 3.9					0.4	-1.7	-4.1	-4.0

Table 3.4 - *continued*

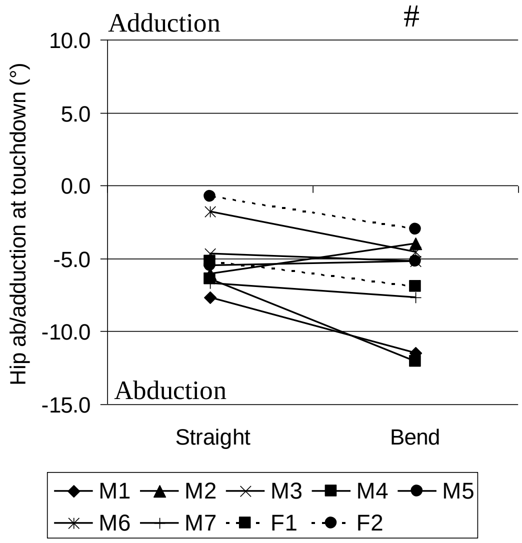
	Males								Females			
	Straight		Bend		Significant differences				Straight		Bend	
	Left	Right	Left	Right	Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right	Left	Right	Left	Right
Hip flexion/extension angular velocity at TD (°·s^{-1})	377 ± 114	440 ± 117	405 ± 106	348 ± 80					254	299	308	237
Hip peak extension angular velocity during contact (°·s^{-1})	951 ± 119	885 ± 152	853 ± 119	874 ± 132			*		931	854	874	904
Time of peak extension angular velocity (% of contact phase)	63.8 ± 11.8	63.9 ± 7.9	60.4 ± 10.3	64.9 ± 12.1					55.7	64.8	54.3	66.6
Peak hip flexion angular velocity during swing (°·s^{-1})	-974 ± 51	-898 ± 69	-1001 ± 83	-919 ± 91	#				-833	-750	-887	-759
Time of peak hip flexion angular velocity (% of contralateral limb contact)	21.1 ± 17.4	21.7 ± 21.8	23.7 ± 10.3	28.2 ± 19.2					15.9	15.5	21.3	18.3

***** Significant at $p < 0.05$; # significant at $p < 0.01$; § significant at $p < 0.001$

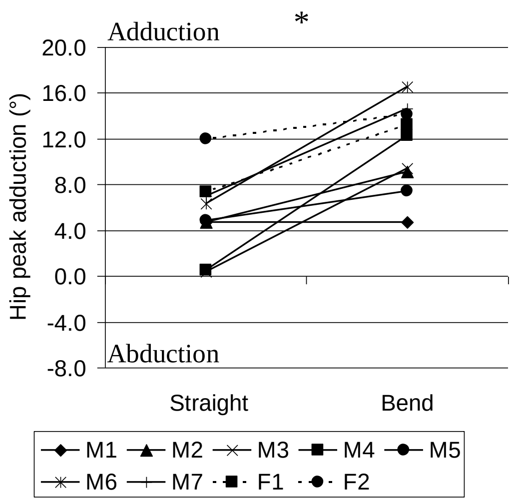
[a] Left step



[b] Right step



[c] Left step



[d] Right step

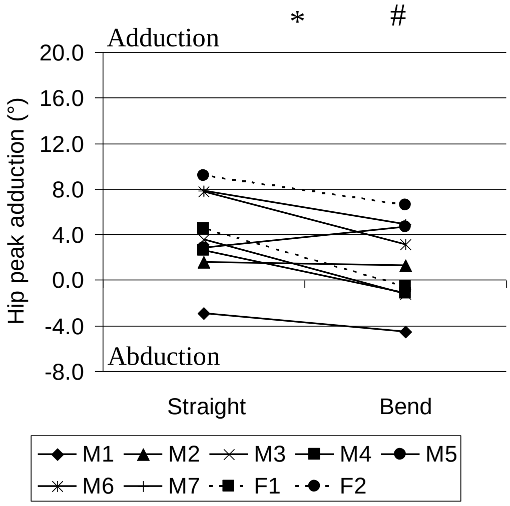


Figure 3.16. [a] Left and [b] right hip abduction/adduction angles at touchdown for all athletes on the straight and bend. [c] Left and [d] right hip peak adduction angles for all athletes on the straight and bend. Male athletes: M1-M7; female athletes: F1 and F2. For male athlete group mean data: * significantly different between bend and straight ($p < 0.05$), # significantly different between left and right steps on bend ($p < 0.01$).

For the male athletes knee angle at touchdown was significantly reduced (more flexed) on the bend for both the left ($p < 0.05$) and right steps ($p < 0.05$) compared to the straight and there was a significant asymmetry between left and right steps on the bend ($p < 0.05$, Table 3.5).

Ankle, MTP and rearfoot results are given in Table 3.6, Table 3.7, and Table 3.8, respectively. Left ankle angle at touchdown was significantly smaller, i.e. the ankle was more dorsiflexed at touchdown on the bend than on the straight for the males ($p < 0.05$). Minimum left ankle angle was significantly smaller on the bend compared to the straight and was significantly smaller than the right on the bend ($p < 0.01$). Left ankle range of plantarflexion was larger on the bend than on the straight ($p < 0.05$). Left rearfoot drop was significantly less on the bend compared to the straight and left was significantly smaller than the right on the bend for male athletes ($p < 0.05$).

There were generally few statistically significant results for upper body kinematics (Table 3.9), except for some differences between positions of the wrists. The left wrist was significantly further from the CoM (i.e. more to the left) at its closest in the ML direction on the bend compared to the straight. The right wrist was significantly closer to the CoM at its furthest back in the AP direction and both wrists were significantly closer to the CoM at their furthest forward in the AP direction on the bend compared to the straight ($p < 0.05$). Right wrist was also significantly higher at its lowest point in the vertical direction on the bend compared to the straight ($p < 0.05$).

Table 3.5. Left and right step group mean values (± SD) and significant differences for male athletes, and group mean values for female athletes for knee angles and angular velocities on the straight and bend.

	Males								Females			
	Straight		Bend		Significant differences				Straight		Bend	
	Left	Right	Left	Right	Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right	Left	Right	Left	Right
Knee angle at TD (°)	157.6 ± 4.4	160.6 ± 4.0	154.1 ± 3.5	157.5 ± 5.6		*	*	*	151.9	153.1	152.0	153.8
Knee angular velocity at TD ($°{\cdot}s^{-1}$)	-197 ± 152	-85 ± 192	-94 ± 120	-34 ± 142					-393	-347	-299	-277
Minimum knee angle during contact (°)	142.2 ± 7.0	144.4 ± 4.2	140.1 ± 4.7	140.9 ± 4.9					136.0	138.3	135.0	134.9
Time of minimum knee angle (% of contact)	46.2 ± 6.9	47.3 ± 5.1	48.5 ± 6.6	47.4 ± 3.2					36.1	42.8	39.6	41.7
Knee range of flexion (°)	15.5 ± 5.2	16.2 ± 5.2	14.0 ± 4.8	16.7 ± 3.5			*		15.9	14.7	17.0	19.0
Maximum knee angle during contact (°)	161.9 ± 5.5	162.5 ± 6.1	159.8 ± 6.7	162.3 ± 3.0					164.8	166.2	165.0	167.1
Time of maximum knee angle (% of contact)	94.1 ± 4.9	92.9 ± 5.5	94.6 ± 3.9	95.7 ± 4.9					95.2	94.5	93.9	94.7
Knee range of extension (°)	19.8 ± 8.2	18.1 ± 7.3	19.7 ± 6.8	21.5 ± 6.8				*	28.82	27.83	29.92	32.20
Knee angle at TO (°)	160.6 ± 4.9	161.0 ± 7.0	158.8 ± 6.2	161.6 ± 3.6					163.1	165.1	163.3	165.5
Knee angle at full flexion (°)	35.9 ± 6.9	37.6 ± 8.7	37.0 ± 6.2	41.1 ± 8.8					29.6	28.6	28.5	29.3
Time of knee full flexion (% of contralateral step time)	14.7 ± 3.7	11.3 ± 3.0	14.0 ± 3.5	14.0 ± 5.0					14.2	15.4	14.6	15.7

***** Significant at $p < 0.05$

Table 3.6. Left and right step group mean values (± SD) and significant differences for male athletes, and group mean values for female athletes for ankle angles on the straight and bend.

	Males								Females			
	Straight		Bend		Significant differences				Straight		Bend	
	Left	Right	Left	Right	Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right	Left	Right	Left	Right
Ankle angle at TD (°)	130.1 ± 5.9	132.9 ± 4.7	127.3 ± 5.1	130.4 ± 4.9			*		120.3	125.6	123.5	127.2
Minimum ankle angle during contact (°)	96.6 ± 3.6	97.9 ± 3.9	91.5 ± 2.8	97.2 ± 3.0		#	#		91.6	97.6	93.7	97.1
Time of minimum ankle angle (% of contact)	44.1 ± 1.7	45.3 ± 3.3	45.8 ± 3.3	45.7 ± 3.7					40.3	40.5	43.6	45.5
Ankle range of dorsiflexion (°)	33.5 ± 6.7	35.0 ± 4.0	35.9 ± 4.2	33.2 ± 4.7					28.6	28.0	29.8	30.1
Ankle angle at TO (°)	145.9 ± 3.3	151.0 ± 3.8	144.8 ± 4.3	149.8 ± 3.1	*	#			152.0	155.2	151.7	153.0
Ankle range of plantarflexion (°)	49.3 ± 2.5	53.1 ± 2.6	53.3 ± 3.2	52.6 ± 4.0	*		*		60.4	57.7	58.0	56.2

***** Significant at $p < 0.05$; # significant at $p < 0.01$

Table 3.7. Left and right step group mean values (± SD) and significant differences for male athletes, and group mean values for female athletes for MTP angles and angular velocities on the straight and bend.

	Males								Females			
	Straight		Bend		Significant differences				Straight		Bend	
	Left	Right	Left	Right	Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right	Left	Right	Left	Right
MTP angle at TD (°)	141.1 ± 9.6	137.1 ± 7.5	139.5 ± 8.1	138.0 ± 8.5	*				146.5	142.4	141.3	145.5
Maximum MTP angle during absorption phase (°)	154.1 ± 2.4	151.9 ± 4.6	152.0 ± 2.9	153.5 ± 4.0					157.6	152.6	151.5	151.8
Time of maximum MTP angle during absorption phase of contact (% of contact)	21.7 ± 7.6	23.4 ± 4.7	20.1 ± 8.1	26.0 ± 5.2					19.4	17.9	12.0	16.1
MTP range of plantarflexion during absorption phase (°)	13.0 ± 8.5	14.8 ± 8.3	12.5 ± 8.5	15.6 ± 5.6					11.1	10.2	10.2	6.3
Minimum MTP angle during contact (°)	117.9 ± 4.4	115.2 ± 3.8	115.7 ± 5.0	115.5 ± 1.6					111.4	113.0	111.7	114.3
Time of minimum MTP angle (% of contact)	78.3 ± 3.2	81.0 ± 2.6	80.8 ± 3.5	80.6 ± 4.1					81.3	80.0	78.5	82.6
MTP range of dorsiflexion (°)	36.2 ± 4.1	36.6 ± 4.0	36.2 ± 4.3	38.0 ± 4.2					46.3	39.6	39.8	37.5
MTP angle at TO (°)	144.9 ± 3.3	136.9 ± 6.0	141.8 ± 7.1	138.6 ± 7.5	#				138.8	138.0	140.6	136.5
MTP range of plantarflexion during extension phase (°)	27.0 ± 4.7	21.7 ± 4.6	26.1 ± 7.7	23.0 ± 8.0	§				27.4	25.0	28.8	22.2
Peak MTP plantarflexion angular velocity ($°\cdot s^{-1}$)	1790 ± 286	1450 ± 203	1561 ± 275	1495 ± 292	*				1706	1471	1578	1384

***** Significant at $p < 0.05$; # significant at $p < 0.01$; § significant at $p < 0.001$

Table 3.8. Left and right step group mean values (± SD) and significant differences for male athletes, and group mean values for female athletes for rearfoot angles on the straight and bend.

	Males								Females			
	Straight		Bend		Significant differences				Straight		Bend	
	Left	Right	Left	Right	Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right	Left	Right	Left	Right
Rearfoot angle at TD (°)	35.3 ± 3.8	37.7 ± 4.3	32.8 ± 3.6	35.6 ± 3.9					29.7	34.5	30.8	34.1
Minimum rearfoot angle during contact (°)	29.9 ± 2.1	30.9 ± 4.2	30.3 ± 2.5	28.4 ± 2.1					28.5	32.3	29.9	31.0
Time of minimum rearfoot angle (% of contact phase)	22.1 ± 7.4	23.2 ± 3.9	15.1 ± 9.4	24.8 ± 4.8		*			10.4	13.2	4.1	10.0
Rearfoot drop (°)	5.5 ± 3.0	6.8 ± 1.6	2.5 ± 1.9	7.3 ± 2.7		#	*		1.3	2.3	0.9	3.1
Rearfoot angle at TO (°)	108.5 ± 4.6	111.6 ± 2.3	113.4 ± 2.1	110.5 ± 3.7					113.9	114.6	116.2	112.1
Rearfoot lift (°)	78.7 ± 4.5	80.6 ± 3.1	83.1 ± 3.2	82.2 ± 4.0					85.4	82.3	86.3	81.1

***** Significant at $p < 0.05$; # significant at $p < 0.01$;

Table 3.9. Left and right step group mean values (± SD) and significant differences for male athletes, and group mean values for female athletes for upper body kinematics on the straight and bend.

	Males								Females			
	Straight		Bend		Significant differences				Straight		Bend	
	Left	Right	Left	Right	Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right	Left	Right	Left	Right
Maximum thorax rotation (°)	38.1 ± 3.3	39.4 ± 3.0	38.9 ± 6.4	39.5 ± 4.0					35.9	39.1	40.2	49.0
Shoulder flexion/extension ROM (°)	89.9 ± 6.9	90.6 ± 10.9	84.8 ± 6.2	93.1 ± 13.7					93.4	90.2	88.1	92.4
Shoulder abduction/ adduction ROM (°)	34.6 ± 12.6	33.0 ± 7.3	32.4 ± 11.1	30.3 ± 6.3					25.9	27.2	29.3	28.4
Elbow ROM (°)	88.0 ± 11.1	96.5 ± 9.4	87.1 ± 11.9	93.6 ± 10.1					72.5	71.0	73.8	74.8
Minimum wrist position [relative to CoM] in ML direction (m)	0.080 ± 0.040	0.094 ± 0.032	0.100 ± 0.039	0.094 ± 0.036			#		0.116	0.107	0.125	0.039
Maximum wrist position [relative to CoM] in ML direction (m)	0.352 ± 0.076	0.392 ± 0.041	0.337 ± 0.061	0.387 ± 0.042					0.339	0.303	0.315	0.325

Table 3.9 - *continued*

	Males								Females			
	Straight		Bend		Significant differences				Straight		Bend	
	Left	Right	Left	Right	Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right	Left	Right	Left	Right
Minimum wrist position [relative to CoM] in AP direction (m)	-0.312 ± 0.012	-0.318 ± 0.069	-0.306 ± 0.021	-0.291 ± 0.073				*	-0.279	-0.256	-0.326	-0.202
Maximum wrist position [relative to CoM] in AP direction (m)	0.314 ± 0.029	0.313 ± 0.020	0.297 ± 0.039	0.298 ± 0.024			*	*	0.327	0.330	0.328	0.322
Minimum wrist position [relative to CoM] in vertical direction (m)	-0.088 ± 0.031	-0.101 ± 0.030	-0.078 ± 0.021	-0.083 ± 0.031				*	-0.089	-0.098	-0.087	-0.086
Maximum wrist position [relative to CoM] in vertical direction (m)	0.353 ± 0.020	0.345 ± 0.049	0.332 ± 0.016	0.347 ± 0.064					0.299	0.311	0.278	0.328

***** Significant at $p < 0.05$; # significant at $p < 0.01$;
ML: mediolateral; AP: anteroposterior

3.3.3. Reliability of digitising

Coefficient of variation (CV) of the main direct performance descriptors (absolute speed, race velocity, directional step length, race step length and step frequency) for the eight redigitisations of the bend and straight trial was low at 0.8 % or below. The standard deviation of angle variables varied from 0.2 to 8.7°. The larger standard deviations tended to be found for the angles for which the shortest segments were used in the calculation, such as MTP angles. Coefficient of variation for angle variables ranged from 0.5 to 535.8 %, however examination of the standard deviations of the angle data showed that often the seemingly large CV was due to the mean value being close to zero. The standard deviation and CVs for angular velocity variables varied from 37 to 447°·s^{-1} and 5.7 to 41.3%, respectively. For timing variables expressed as a percentage of contact/step time the standard deviations varied from 0.0 to 29.2%, with CVs between 0.0 to 77.1%. For full reliability data see Appendix.

3.4. Discussion

The purpose of the study was to understand the changes to performance that occur during maximal speed sprinting on the bend (compared to the straight) and how differences in technique on the bend contribute to these changes in performance. This study is the first to show experimentally that performance is decreased during the maximal speed phase on the bend compared to the straight at bend radii typical of those used in athletic sprint events. There was a 4.7% reduction in absolute speed from 9.86 m·s^{-1} and 9.80 m·s^{-1} on the straight to 9.40 m·s^{-1} and 9.34 m·s^{-1} on the bend for the left and right steps, respectively. Since absolute speed measures the actual performance of the athlete regardless of the path of travel, this is important because it showed that there was a real decrease in performance on the bend and that reductions in race times are not simply due to athletes following paths that are longer than the race line. Race velocity on the bend was also reduced by 4.8% for both left and right steps compared to the straight as a consequence. For the male group no statistically significant difference was seen between race velocity and absolute speed measures. However, as has been seen in previous studies, group data can mask individual trends (Dixon & Kerwin, 2002). When race velocity and absolute speed were compared on an individual level, it was found that four of the nine athletes produced race velocities faster than their absolute speeds on the bend indicating the CoM of those athletes followed a path inside, and thus shorter than the race line.

Since velocity is the product of step length and step frequency, the reductions in race velocity and absolute speed seen on the bend must have been due to a reduction in step length and/or step frequency. On the left step, the reduction in velocity was due to a combination of significant 0.11 Hz reduction in step frequency ($p < 0.05$, Figure 3.13) and a 0.04 m reduction in directional step length, which was not found to be significant but for which the effect size was found to be moderate ($d = 0.37$) on the bend in comparison to the straight.

According to the theoretical model of Usherwood and Wilson (2006), velocity on the bend is reduced because of increased ground contact time required to meet the additional force requirements of centripetal force generation on the bend. The results of the present study initially appear to support this theory for the left step, with a mean increase in ground contact time of 0.007 s on the bend for males and with the two females following the same trend. This increased ground contact time in turn had the effect of reducing left step frequency and thus had a detrimental effect on velocity. However, there were also other technique changes that occurred during bend running which likely contributed to the increase in ground contact time. The results for the male athletes showed that there was an increase in left touchdown distance and body sagittal lean ROM on the bend compared to the straight (Table 3.2), which have both been shown to be related to increased ground contact time in straight line running (Hunter et al., 2004a). The differences between left touchdown distance and body sagittal lean were not as large for the two females, perhaps due to their relatively low sprinting velocities, but the general trend was the same (Table 3.2). The increase in distance between the point of ground contact at touchdown and the CoM also resulted in the increased left step thigh separation at touchdown seen on the bend in both males and females (Table 3.3).

The use of an active touchdown has been advocated in sprinting (Mann, 1985) since this reduces the touchdown distance, braking forces experienced, and ground contact time. In the present study, although not statistically significant, the mean left foot horizontal velocity at touchdown was $0.36 \text{ m}\cdot\text{s}^{-1}$ greater on the bend than on the straight for males (a moderate effect size, d = 0.54), and 0.10 $m \cdot s^{-1}$ greater for females. For both males and females this had the effect of producing a more detrimental (less negative) left foot horizontal velocity relative to the CoM meaning the foot was moving forward faster than the CoM at a greater rate than on the straight. The knee flexion angular velocity at touchdown was slower on the bend for both left and right limbs. Whilst it was not found to be statistically significant, the effect size was reasonably large (d = 0.76) and moderate (d = 0.30) for the left and right steps, respectively. Mann (1985) stated that a faster flexion angular velocity of the shank segment at touchdown meant that athletes were better able to recover their limbs and so reduced the braking forces experienced at touchdown. It is likely that the slower knee flexion angular velocities and increased left foot horizontal velocity seen in the present study would have increased the braking forces experienced by the athletes at left touchdown and thus potentially reduced the velocity of the left step.

During the right step there was no difference in mean right step frequencies between the bend and straight for the males. Instead performance decreased due to a significant reduction in right race and directional step lengths of 0.10 m and 0.08 m, respectively (p <0.05, Figure 3.12). This is consistent with the findings of Stoner and Ben-Sira (1979) who found that mean right step length was approximately 0.09 m shorter on the bend compared to the straight during the acceleration phase of sprinting, for a group of nine college athletes. The decreases in race and directional step lengths was due to a statistically significant 0.009 s reduction in flight time for the right step from straight to bend (p <0.05). This is, again, in agreement with the findings of Stoner and Ben-Sira (1979) who found similar left flight times on the bend and straight, but significantly shorter right flight times on the bend compared to the straight. This suggests that the athletes were not able to generate the required vertical and propulsive impulse during ground contact, possibly due to the requirement to generate centripetal force in order to follow the curved path. The greater reduction in right step length might suggest that more centripetal force is generated during the right ground contact. Indeed, in their study of very small bend radii (1-6 m) Chang and Kram (2007) found the right leg (outside leg) generated in the region of 100-200 N larger peak lateral forces than the left. The turn of the CoM results in the present study are therefore somewhat contradictory, since more turning of the CoM was achieved during the left step than the right. However, Hamill et al.

(1987) found larger peak lateral forces and impulses were generated with the left leg than the right during running at approximately 6.31 $m \cdot s^{-1}$ on a bend of 31.5 m radius. This is much more like the radius used in the present study. It is possible that during sprinting on radii typical of athletic events, it is the left leg (inside leg) that generates a larger lateral impulse thus contributing more to turning. Further studies measuring mediolateral ground reaction forces and impulses, during sprinting at such radii, are required to confirm this.

There was increased inward (more negative) body lateral lean at touchdown and take off and trunk lean at touchdown (Tables 3.2-3.3) on the bend compared to the straight. Generally, this inward lean caused the left hip to be more adducted at touchdown and at peak adduction (Figure 3.16). For the male athletes the left hip was also less abducted at peak abduction and, although this was not statistically significant, the effect size was moderate (d = 0.52, Table 3.4). At peak adduction the right hip was statistically significantly more abducted on the bend than the straight for the male athletes (Table 3.4). This tendency for the left hip to be more adducted and the right hip to be more abducted resulted in peak abduction occurring later for the left and earlier for the right on the bend compared to the straight. It has been suggested by Chang and Kram (2007) that the necessity to stabilise joints in the frontal plane during bend running may affect the ability of the athlete to exert extensor forces and may be a limiting factor for performance on the bend. The current study provides evidence for altered frontal plane kinematics during maximal speed bend running and the effect on force generation warrants further investigation.

Furthermore, studies have shown that alterations to hip muscular activity in the frontal plane can have an effect on the activity of muscles working in the sagittal plane (e.g. Earl et al., 2001; Coqueiro et al., 2005) and some muscles that are involved in abduction/adduction of the hip are also involved in flexion/extension of the hip or knee (Palastanga et al., 2006). It is, therefore, probable that the observed asymmetrical effect of the bend on sagittal plane hip angles were caused by the change in orientation of the hip in the frontal plane (Table 3.4).

On the bend the left hip flexion/extension angle was significantly more extended at take off and more flexed at full flexion compared to the right for the males

($p < 0.05$), and the pattern was the same for the females at take off (Table 3.4). It has been shown in previous research that as velocity increases from walking to sprinting, the hip is generally less extended and more flexed throughout the gait cycle (Mann & Hagy, 1980) and better sprint performance on the straight has been associated with reduced extension of the hip at take off and full extension and increased flexion at full flexion because better athletes minimise ground contact times and are better able to recover their legs more efficiently during swing (Mann, 1985). It is possible that the increased hip extension at take off contributed to the longer ground contact times observed for the left step when compared to the right step on the bend, although it might have contributed to the better maintenance of step length on the left than was seen on the right step on the bend. There was a statistically significant difference between left and right hip angles at full extension on the bend, but this was also the case on the straight and so it is difficult to know if there was a true asymmetrical effect of the bend in this variable. Additionally, the increased adduction of the left hip on the bend may have meant the limb was positioned in a less advantageous position to extend quickly causing the reduction in hip extension angular velocity during contact seen for the left on the bend (Table 3.4).

For the male athletes, the left and right knees were 3.5° and 3.1°, respectively, more flexed at touchdown on the bend then they were on the straight ($p < 0.05$, Table 3.5). Additionally, there was a significant asymmetry with the left knee 3.4° more flexed than the right knee at touchdown on the bend, for the male athletes ($p < 0.05$, Table 3.5). Mero and Komi (1985) found similar differences in mean knee angle at touchdown (4°) in supramaximal sprinting compared to maximal sprinting. It was suggested that a more extended knee at touchdown was advantageous in supramaximal sprinting since it positioned the joint such that the leg extensors could better exert the force required for superior performance (Mero & Komi, 1985). It is possible that the reduced extension of the knees seen on the bend in the present study prevented the leg extensors from producing the forces that were possible on the straight, and thus had a detrimental effect on performance.

The left ankle was significantly more dorsiflexed at touchdown on the bend than on the straight for males at 127.3 ± 5.1° compared to 130.1 ± 5.9° ($d = 0.50$, $p < 0.05$), however, the same trend was not shown for the two females. Mero and Komi (1985) found ankle angle at touchdown to be slightly (2°) larger (more plantarflexed) in supramaximal sprinting than in maximal sprinting. Although this difference, in the study by Mero and Komi (1985) was not statistically significant, it may suggest that a larger ankle angle at touchdown is beneficial to performance. In the current study there was a statistically significantly smaller (more dorsiflexed) left minimum ankle angle during contact on the bend or the males, which contributed to a larger left range of flexion (Table 3.6). Despite a significantly larger left range of extension ($d = 1.42$, $p < 0.05$), the left ankle angle at take off was smaller on the bend compared to the straight (Table 3.6). Females also had a slightly smaller mean left and right ankle angle at take off on the bend, but they did not follow the same trends for the ranges of flexion or extension seen in the male means (Table 3.6). A more plantarflexed ankle angle at take off has been suggested to improve performance by maximising propulsion into the next step (Hay, 1993), and the results of the present study partly support this. However, the differences between trends in males and females indicate that a variety of techniques may be utilised at the ankle and these differences may be related to the ability of the athletes to run the bend effectively.

There was a statistically significant 3° smaller left rearfoot drop on the bend compared to the straight ($p < 0.05$, Table 3.8). The male mean left rearfoot angle at touchdown on the bend was slightly smaller than the corresponding value on the straight, and the resulting drop from touchdown to minimum angle was therefore reduced and occurred significantly earlier than that of the right rearfoot on the bend (significant for the males, $p < 0.05$, Table 3.8). This may have been due to real differences in rearfoot angle, indeed, Krell and Stefanyshyn (2006) found larger angles at touchdown to be related to better performance in female sprinters. However, it may also have been due to the method of calculation of rearfoot angle and the effect that the inward lean of the athlete on the bend had on this calculation. The lean of the athlete meant that the angle between the rearfoot segment and the ground vector were not necessarily both in the sagittal plane of the athlete, as was the case in the study by Krell and Stefanyshyn (2006) and as such the calculation method might have meant a more acute angle was returned. This is a possible limitation of the rearfoot angle variable.

In straight line sprinting upper body kinematics have often been dismissed as being a poor indicator of performance (Mann & Herman, 1985; Mero et al., 1986). However, in the present study upper body variables were measured to assess whether the requirement for turning meant the upper body played a larger role during bend sprinting than straight line sprinting. Generally, there were few differences in the kinematics of the upper body on the bend compared to the straight (Table 3.9). The position of the wrist relative to the CoM was calculated as a measure of the involvement of the whole arm during sprinting. Statistically significant differences were found between bend and straight for the left wrist at its minimum distance in the ML direction, the right wrist minimum position relative to the CoM in the AP direction, and right and left wrists maximum positions relative to the CoM in the AP direction for the male athletes. This means that the left wrist was further from the midline (i.e. more to the left) on the bend than on the straight, the right wrist did not travel as far backward, and both wrists did not travel as far forward on the bend compared to the straight. All of these differences may have contributed to the athlete achieving the turning and/or lean required to follow the curved path.

There were some limitations to the present study. Unfortunately, as stated, some points were out of the field of view in the ten 'extra frames' at either side of the first and final touchdowns of interest. While extrapolation of these points yielded sensible, coordinates a slightly larger field of view would have mitigated against this without substantially compromising the digitisation accuracy. This is a consideration for future studies. However, no points were out of view on the actual frames of interest. Possible limitations in the calculation of rearfoot angle have already been mentioned, but another limitation of the angle calculation method is that it was not possible to reconstruct knee and ankle joint angles in three dimensions to correspond with anatomical axes of rotation as was possible for the hip and shoulder. It is likely that some measure of abduction/adduction at these joints would be of interest during bend sprinting and that is missing from the present study. However, the methods employed to obtain such angles (e.g. automated 3D motion capture) would mean that the ecological validity of the study would be compromised.

The choice of manual digitisation of video for collection of kinematic data enabled data collection with as little intrusion into athletes' training sessions as possible.

However, there are some limitations to this approach. Data were collected at a resolution of 1280 x 1024 pixels, and subsequently digitised at full resolution, with a 2x zoom factor. Thus a field of view 7.5 m long meant that the resolution of measurement was 0.0029 m. This may have introduced potential errors in the identification of landmarks. Whilst these potential errors would not have made large differences to joint angles calculated from longer segments such as the thigh and trunk, they may have had a greater effect on joint angles calculated from shorter segments such as MTP angle which was calculated from the forefoot and rearfoot segments. However, the digitisation process was carried out after extensive practise, and reliability was measured by redigitising both a bend and a straight trial eight times. The level of reliability was assessed by examination of coefficient of variation, and examination of the standard deviation for each variable in the eight redigitisations. Generally, reliability was deemed to be good, but larger ranges in values were indeed observed for the joints which used shorter segments in their calculation such as the MTP and rearfoot angles. However, since errors in digitisation are likely to be random in nature, any errors introduced from digitisation are likely to result in statistical significance being missed. Therefore, when statistical significance was found, it was deemed that these results could be accepted with reasonable confidence. Additionally, manual digitisation is a well-accepted method of obtaining kinematic data in the sprint literature, and the merits of maintaining ecological validity is an important issue.

Whilst the present study provides useful information as to the changes in technique caused by the bend in comparison to straight line sprinting, it does not provide an insight into the differences in techniques of athletes of different abilities running the same bend. Additionally, it does not further understanding as to how different bend radii affect performance in athletic sprint events. This is an important issue for athletes who are required to run at different bend radii depending on lane allocation in races. Further research is required to understand what changes occur to technique on bends of different radii typical of those experienced in athletic sprint events. Furthermore, in order to fully understand why the changes to technique occur on the bend, in comparison to the straight, further research is also required to understand the forces that act during bend running and how they contribute to the performance and technique changes seen in the present study.

Conclusion

The present study provides experimental evidence of decreased sprinting performance on the bend compared to the straight. This was due mainly to a decrease in step length on the right step resulting from a decrease in flight time and due to reduced step frequency on the left step because of an increase in ground contact time. The necessity to lean into the bend resulted in asymmetrical changes to technique. Changes in frontal plane kinematics likely affected sagittal plane kinematics. Additionally, it has been suggested that stabilisation in the frontal plane may affect athletes' ability to produce vertical and propulsive force (Chang & Kram, 2007) and it is likely that this was the case in the present study, although further investigations of force production during bend running are required.

From an athlete coaching perspective it appears that one of the biggest problems affecting forward velocity of athletes during bend sprinting is the increased left touchdown distance compared to the straight, and this might be an area in which improvements can be made. For example, exercises aimed at reducing touchdown distance should be undertaken on the bend and not just on the straight. These may include stepping down with a high foot carriage, rather than consciously trying to extend step length, with the aim of reducing the forward horizontal velocity of the foot (relative to the ground) as much as possible, such that it is moving backwards (relative to the CoM) with as high a magnitude as possible. Furthermore, strengthening the hip extensors to enable the foot to be pulled backward relative to the CoM at touchdown, whilst in the altered orientation induced by the lean may improve touchdown distance. Additionally, the asymmetrical nature of bend running, caused by the inward lean of the athlete, means that training for the bend should not only be different to that of the straight, but should also apply the training principle of specificity, meeting the different requirements for the left and right limbs. For example, athletes may need to improve their ability to withstand and generate forces whilst in the altered frontal plane orientation, which includes a tendency towards adduction of the left hip and abduction of the right hip, rather than focusing on training primarily in the sagittal plane. Whilst it may be prudent to ensure training meets the differing demands of the left and right limbs, care should be taken that asymmetries that may be detrimental to straight line performance are not introduced.

A reduction in performance and differences in technique have been identified on the bend compared to the straight. However, in order to fully understand how these technique changes are related to better or worse performance on the bend, it is necessary to understand differences in the technique of athletes of different abilities running the same bend.

CHAPTER 4: RELATIONSHIPS BETWEEN PERFORMANCE AND TECHNIQUE DURING BEND SPRINTING IN ATHLETES OF DIFFERENT ABILITIES

4.1. Introduction

The results of Chapter 3 have shown that sprinting performance is decreased on the bend compared to the straight. Additionally, technique has been shown to be different on the bend compared to the straight. However, it is generally accepted within the athletics community that some athletes are 'better bend runners' than others. The identification of performance descriptors and upper and lower body kinematics most closely related to better performance may give a greater insight into aspects of technique that may be worked on in order to improve performance on the bend. Given the number of technique variables which could potentially contribute to performance during a whole-body activity such as bend sprinting, it is unlikely this type of analysis will provide a simple picture. However, similar approaches have been taken in studies of straight line sprinting and have allowed important relationships between technique and better performance to be identified (e.g. Kunz & Kaufmann, 1981).

Since the goal of any sprint race is to cover the set distance in the shortest possible time, the best bend runners, in absolute terms, are those who run the fastest. Thus, understanding which kinematic variables are most closely related to the fastest performance on the bend may provide important information to athletes and coaches regarding areas of performance that might be improved. With this in mind, the first aim of the present study was to understand the technique variables which are most closely related to faster performance on the bend.

Whilst velocity is the ultimate measure of sprinting performance on the bend, it is commonly believed that the magnitude of the reduction in performance, from straight to bend, is different between athletes. The ability to achieve a similar velocity on the bend compared to the straight is not necessarily related to an athlete's maximum velocity on the straight. Understanding the technique changes in athletes who are better or less able to achieve a similar velocity on the bend compared to the straight may give an indication of technique variables that might be improved to help an athlete maintain their straight line velocity on the bend. Thus, the second aim of the study was to establish which technique characteristics are associated with the largest decrements in performance on the bend compared to the straight, such that this may identify potential areas for improvement of bend sprinting.

4.2. Methods

4.2.1. Participants, data collection and processing

The data set of the male athletes from Chapter 3 was used for this section. Thus, the methods were the same as for that chapter with the exception of the statistical analysis.

4.2.2. Statistical analysis

In order to establish how athletes of different abilities performed bend running differently, relationships between absolute speed and race velocity (as the prime indicators of performance) and technique variables of the respective side were assessed for the left and right steps on the bend, using Pearson's product-moment correlations. From the significant correlations a hierarchical 'map' of correlations contributing to absolute speed and race velocity was created. Thus, race velocity and absolute speed were top-level variables and those variables which were significantly correlated with race velocity/absolute speed became the second-level. Further correlations were performed between the second-level variables and those variables that were deemed possibly mechanically related. This process was repeated until a four-level map of the variables contributing to race velocity/absolute speed was developed, for both the left and right hand-side variables. The whole process was also repeated for right and left race and directional step length and step frequency as top-level variables (since they are the prime determinants of velocity) until a three-level map was created.

Since those athletes who are better able to maintain their velocity on the bend compared to the straight are not necessarily the fastest runners, the percentage reduction in race velocity from straight to bend and the changes in all other variables were also calculated. For all variables, except timing variables, change was calculated as the percentage change in that variable on the bend compared to the straight. For timing variables (already expressed as a percentage of step time or contact time), the difference between the bend and straight was calculated. Relationships between reductions in race velocity and changes in other variables were assessed using Pearson's product-moment correlations. Similarly to the absolute values, separate maps of correlations were created for the left and right hand-side variables. The reduction in race velocity was the top-level variable and variables significantly correlated to the reduction in race velocity became the second-level of the map. This process was repeated until a three-level map of the variables contributing to reductions in race velocity on the bend compared to the straight was developed for both the left- and right-hand side variables. For the situation where changes in step frequency or step length were not directly correlated with reductions in race velocity, the process was also repeated for changes in step frequency or step length as top-level variable until a two-level map of changes in variables that contributed to changes step frequency and step length was created.

Correlations between race velocity on the straight and the reduction in race velocity from straight to bend were also made for the left and right steps in order to assess whether there was a relationship between athletes' race velocity in absolute terms and their ability to achieve a similar velocity on the bend. For all Pearson product-moment correlations significance was set at $p < 0.05$.

4.3. Results

4.3.1. Relationships between performance and technique on the bend

Absolute speed/race velocity during the left step were negatively correlated with left body lateral lean at touchdown and at take off and left shoulder flexion/extension range of motion, but positively correlated with left rearfoot lift (Figure 4.1). The technique variables significantly correlated with left race and directional step length and left step frequency are shown in Figure 4.2. Both step frequency and race/directional step length were significantly correlated with thigh separation at left touchdown and peak MTP plantarflexion angular velocity, although the direction of the correlation was opposite between those variables and step frequency and directional step length.

For the right step, the time of peak right hip abduction (as a percentage of contact) and the time of minimum MTP angle (as a percentage of contact) were significantly positively correlated with absolute speed/race velocity (Figure 4.3). A significant negative interaction between right step frequency and right directional step length was observed (Figure 4.4). However the correlation between right step frequency and right race step length did not reach statistical significance (r = -0.732, p =0.062). There were four variables that were significantly correlated with both right step frequency and right directional step length. However, the negative interaction between step frequency and directional step length meant that the direction of the correlation was opposite between those variables and step frequency and directional step length. For example, step contact factor was positively correlated with step frequency and negatively correlated with directional step length for the right step on the bend (Figure 4.4).

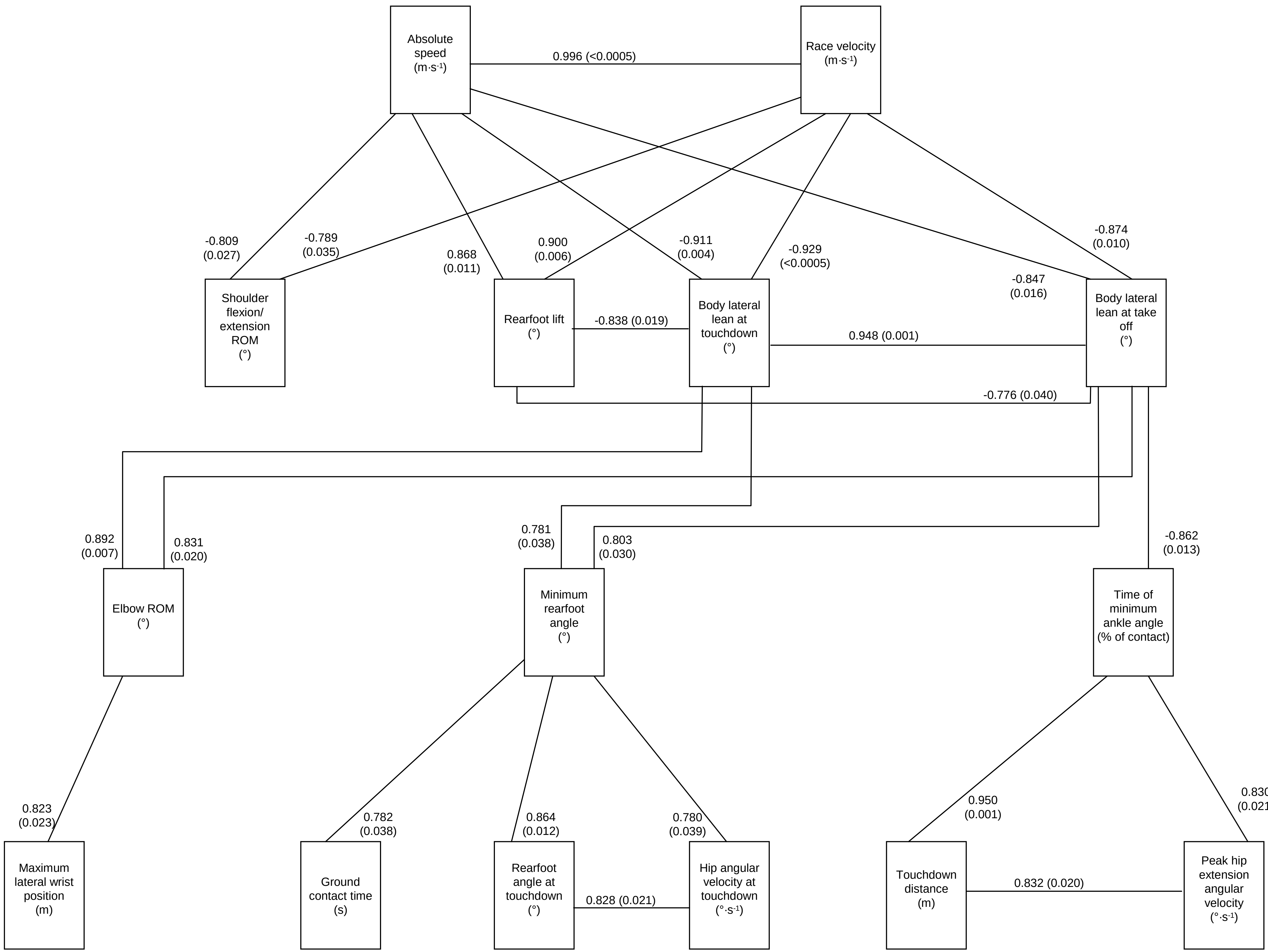


Figure 4.1. Map of significant Pearson correlations between left-hand side technique variables related to left absolute speed/race velocity on the bend. Correlation *r* value (and significance) is shown for each relationship.

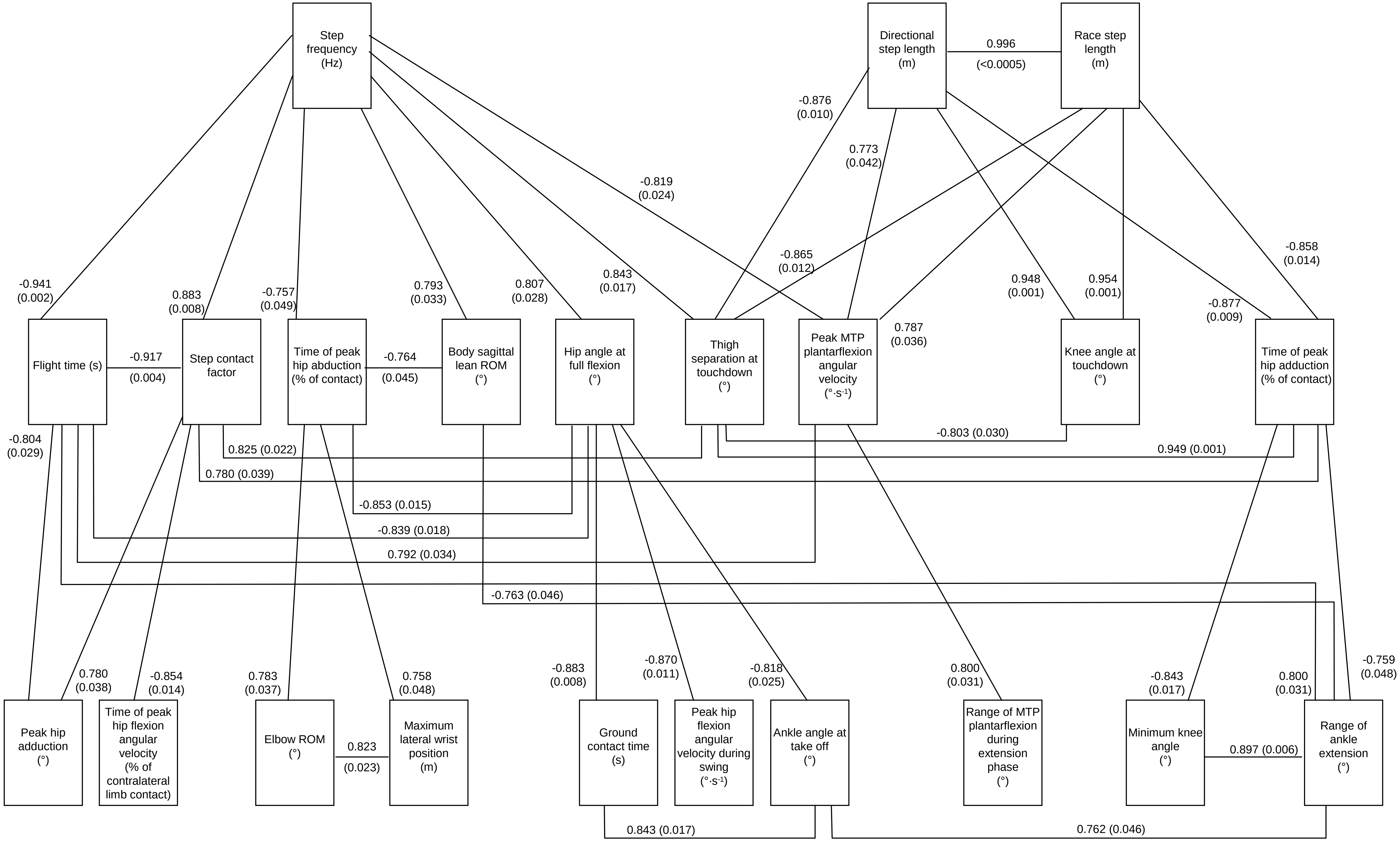


Figure 4.2. Map of significant Pearson correlations between left-hand side technique variables related to left step frequency and directional/race step length on the bend. Correlation *r* value (and significance) is shown for each relationship.

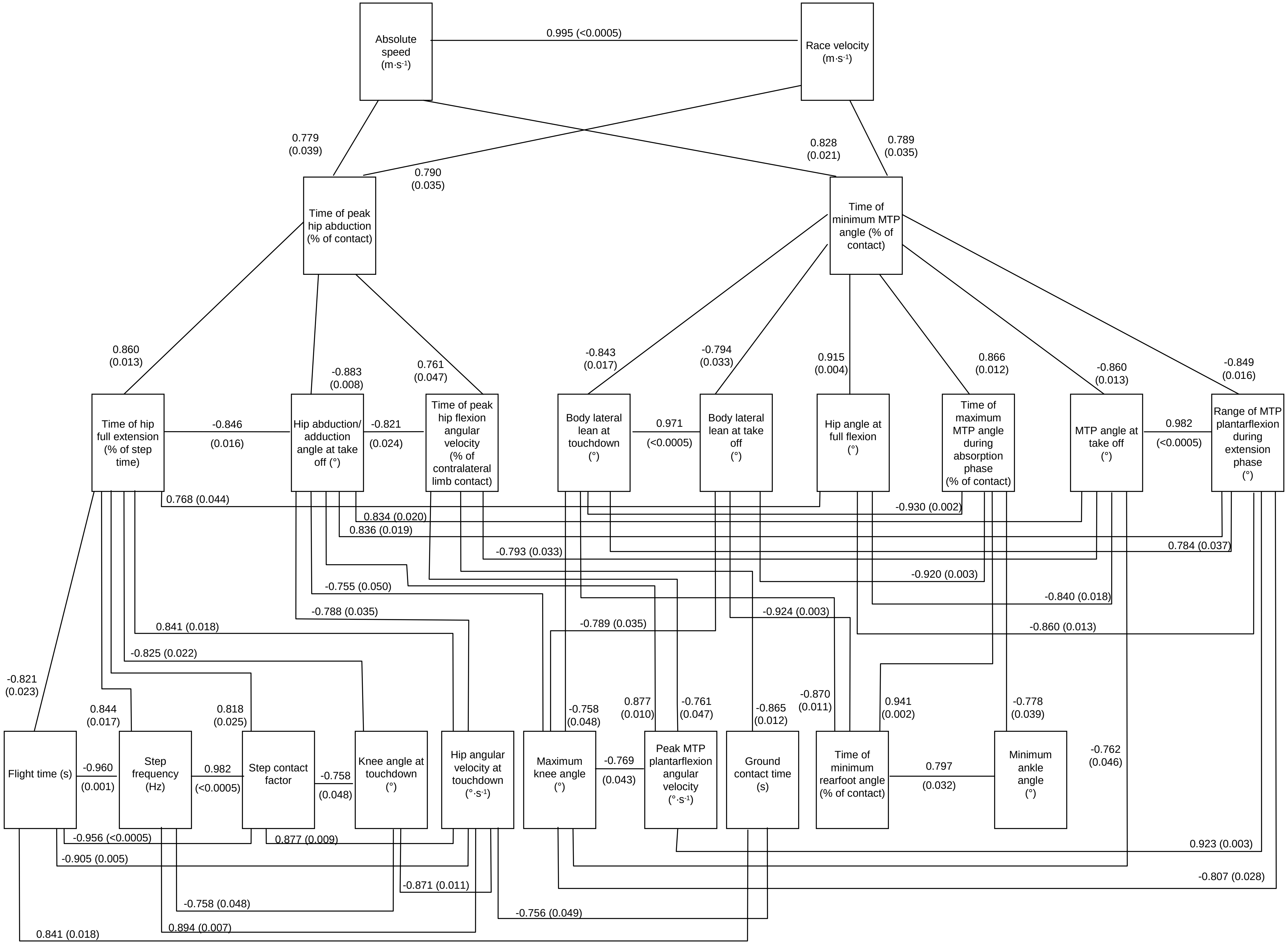


Figure 4.3. Map of significant Pearson correlations between right-hand side technique variables related to right absolute speed/race velocity on the bend. Correlation *r* value (and significance) is shown for each relationship.

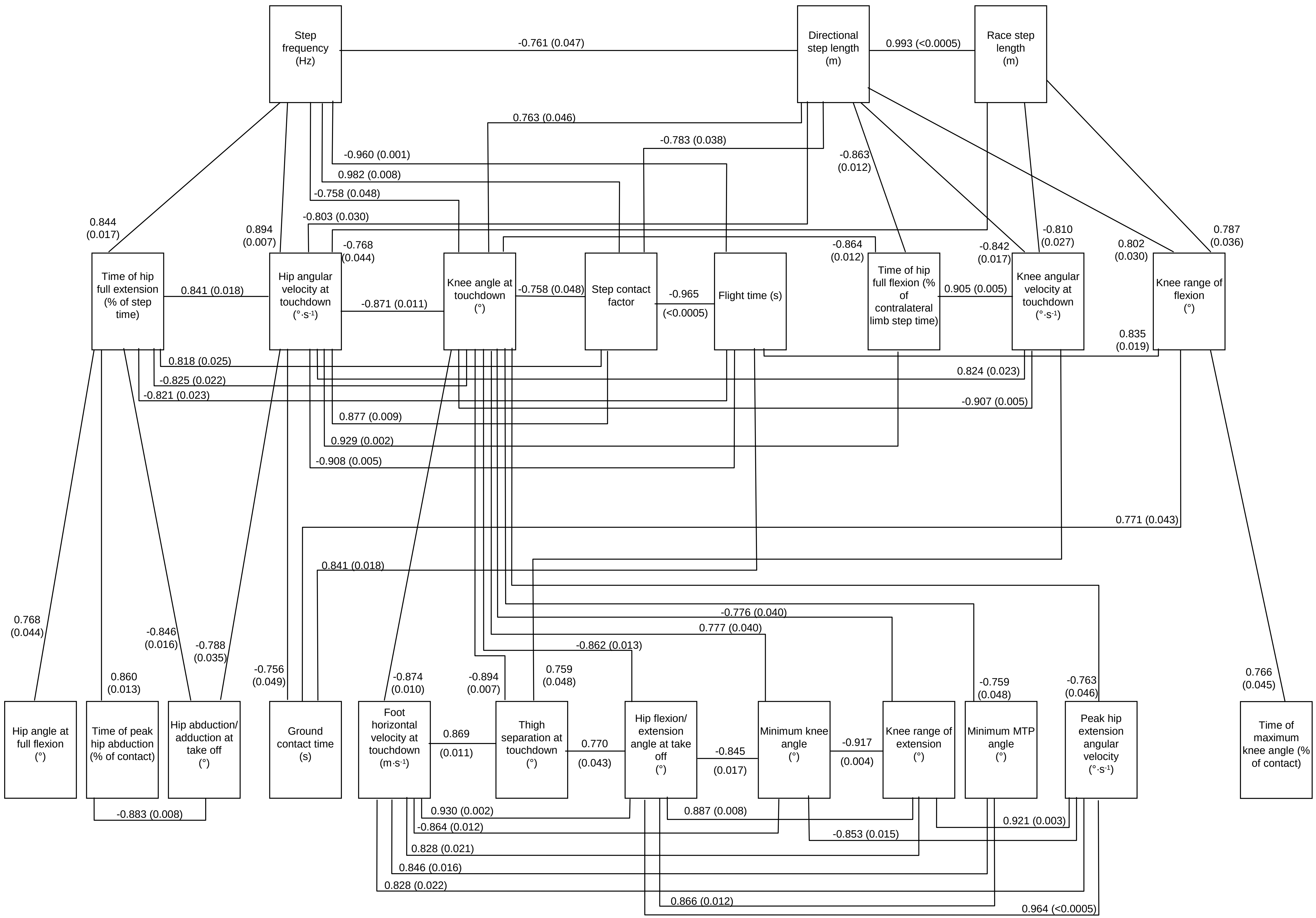


Figure 4.4. Map of significant Pearson correlations between right-hand side technique variables related to right step frequency and directional/race step length on the bend. Correlation *r* value (and significance) is shown for each relationship.

4.3.2. Relationships between changes in performance and changes in technique from straight to bend

All except one athlete exhibited reductions in left step race velocity ranging from 2.5% to 10.1% on the bend compared to the straight. The remaining athlete exhibited a 0.3% increase in left step race velocity on the bend compared to the straight. On the right step, all athletes reduced race velocity from straight to bend ranging from 0.9% to 7.9%. There were no statistically significant correlations between athletes' race velocity on the straight and the reduction in performance from the straight to the bend for either the left or right steps. This means that there was no relationship observed between how fast an athlete was on the straight and whether they could maintain their speed to be a greater or lesser extent.

For correlations between changes in performance indicators (race velocity, race and directional step length and step frequency) and technique variables, a positive correlation indicates that the most negative change in one variable is associated with the most negative change in the other variable and vice versa. For example, a positive correlation of $r = 0.863$ between the change in left race step length and a reduction in race velocity during the left step indicates that those athletes with the largest reductions in left race step length were those with the largest reductions in left step race velocity on the bend compared to the straight (Figure 4.5). On the other hand, a negative correlation, of $r = -0.816$, between change in the time of the minimum left MTP angle as a percentage of contact and a reduction in race velocity during the left step indicates that the largest increases in the time of the minimum left MTP angle as a percentage of contact (i.e. occurred at a later time) were associated with the largest reductions in left step race velocity on the bend compared to the straight (Figure 4.6). Correlation maps of statistically significant relationships between changes in performance indicators and technique variables for the left-hand side and right hand side are shown in Figures 4.7-4.9.

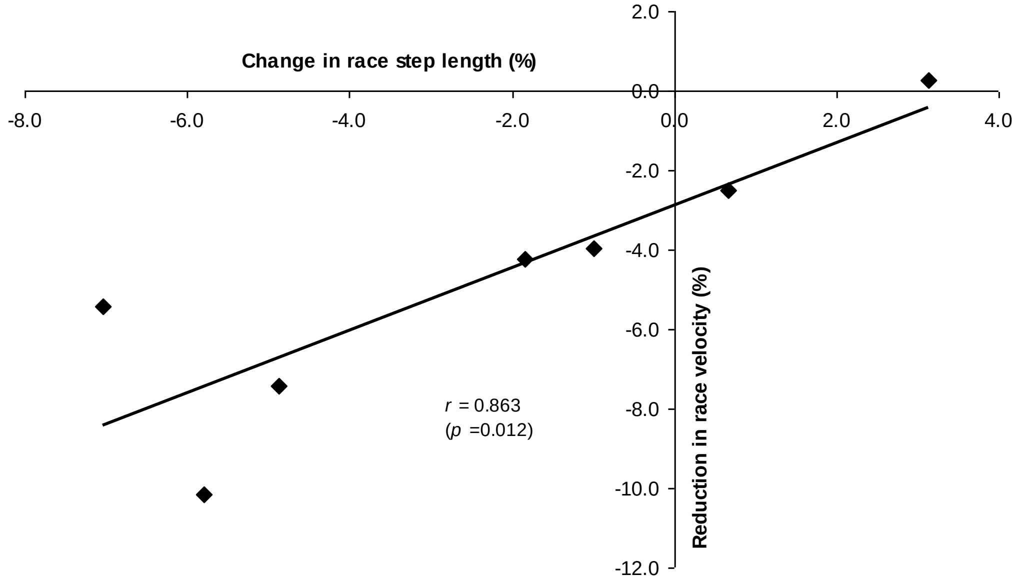


Figure 4.5. Relationship between the percentage change in race step length and the percentage reduction in race velocity during the left step on the bend compared to the straight.

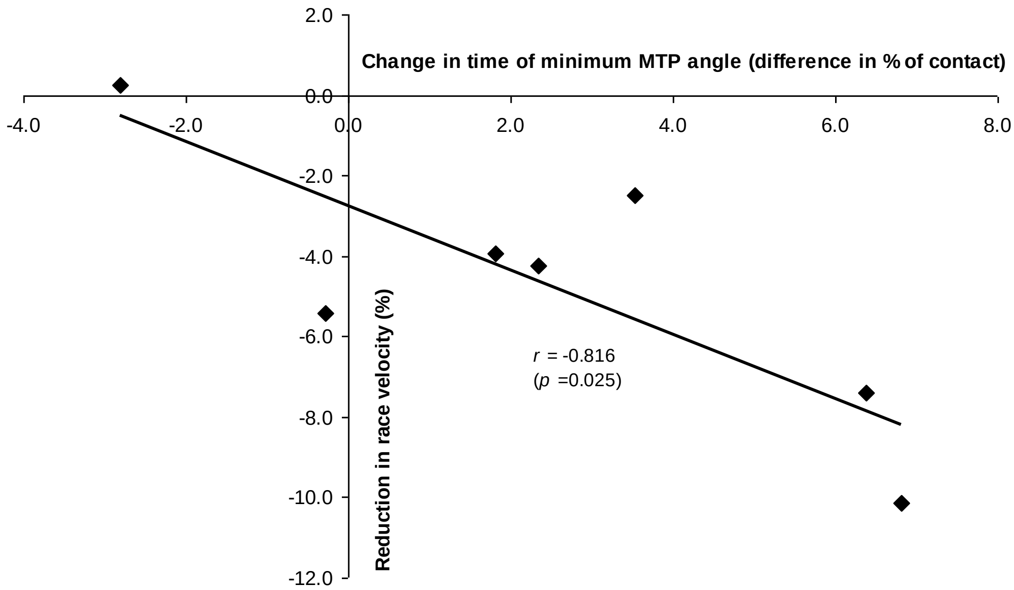


Figure 4.6. Relationship between the change in time of minimum MTP angle as a percentage of contact and the percentage reduction in race velocity during the left step on the bend compared to the straight.

Nine of the changes in technique variables from straight to bend were statistically significantly correlated with the reduction in left race velocity (Figure 4.7). These included positive correlations with changes in left race and directional step lengths. Thus, those changes in variables which were significantly correlated with changes in left race/direction step length on the bend compared to the straight are also shown in Figure 4.7. Additionally, seven further changes in left-hand side variables were found to be related to changes in left step frequency (Figure 4.8).

On the right, the changes in six technique variables were found to be statistically significantly related to the reduction in right race velocity from straight to bend. Similarly to the left, these included positive correlations with changes in right race and directional step lengths (Figure 4.9). Only one statistically significant correlation between right step frequency and any other change in a technique variable was found. This was a positive correlation between change in right step frequency and change in right MTP angle at touchdown, with an r value of 0.773 ($p = 0.042$).

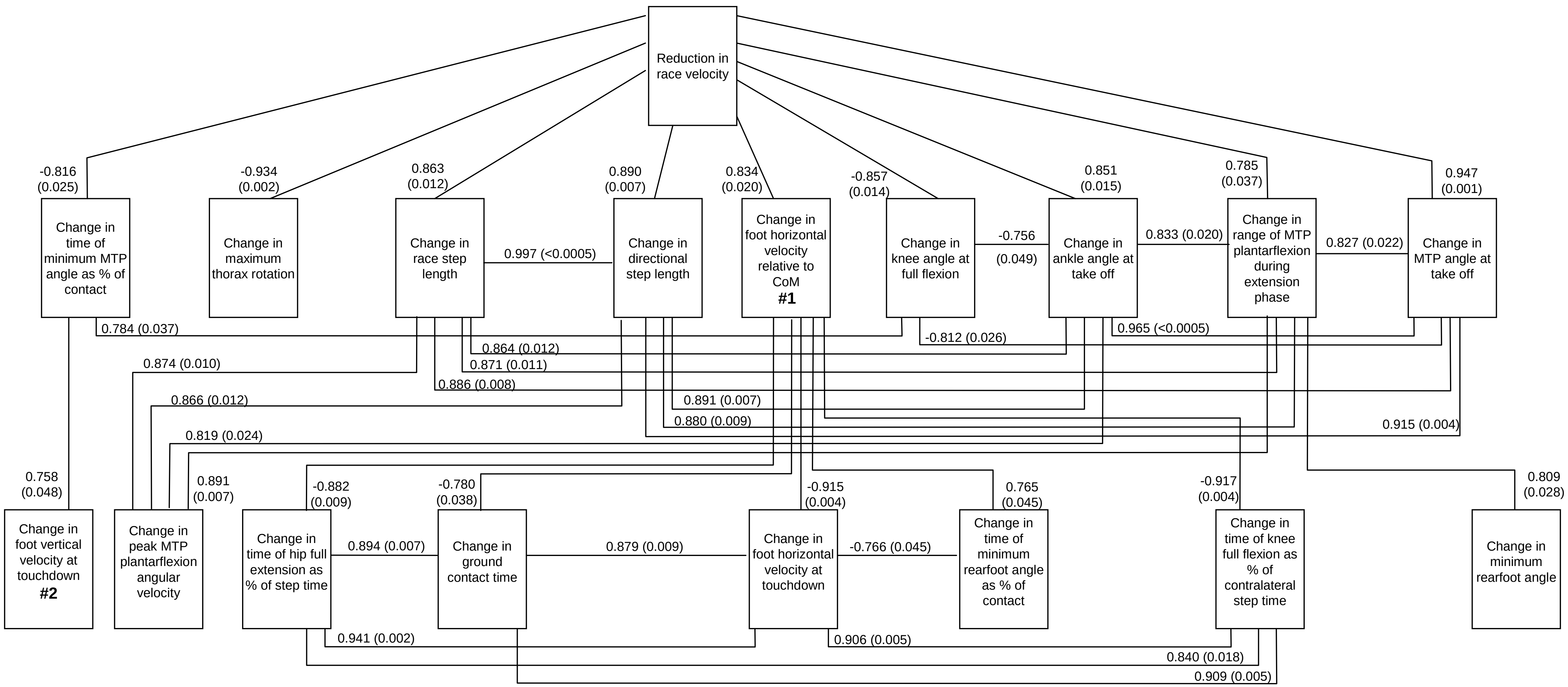


Figure 4.7. Map of significant Pearson correlations between left-hand side technique variable changes related to a reduction in left race velocity on the bend compared to the straight. Correlation *r* value (and significance) is shown for each relationship. See text for further explanation and interpretation of figure.

[#1] Foot horizontal velocity relative to the CoM is a negative value; therefore, a negative change in this variable indicates a less negative foot horizontal velocity

[#2] Foot vertical velocity is a negative value; therefore, a negative change in this variable indicates a less negative foot vertical velocity

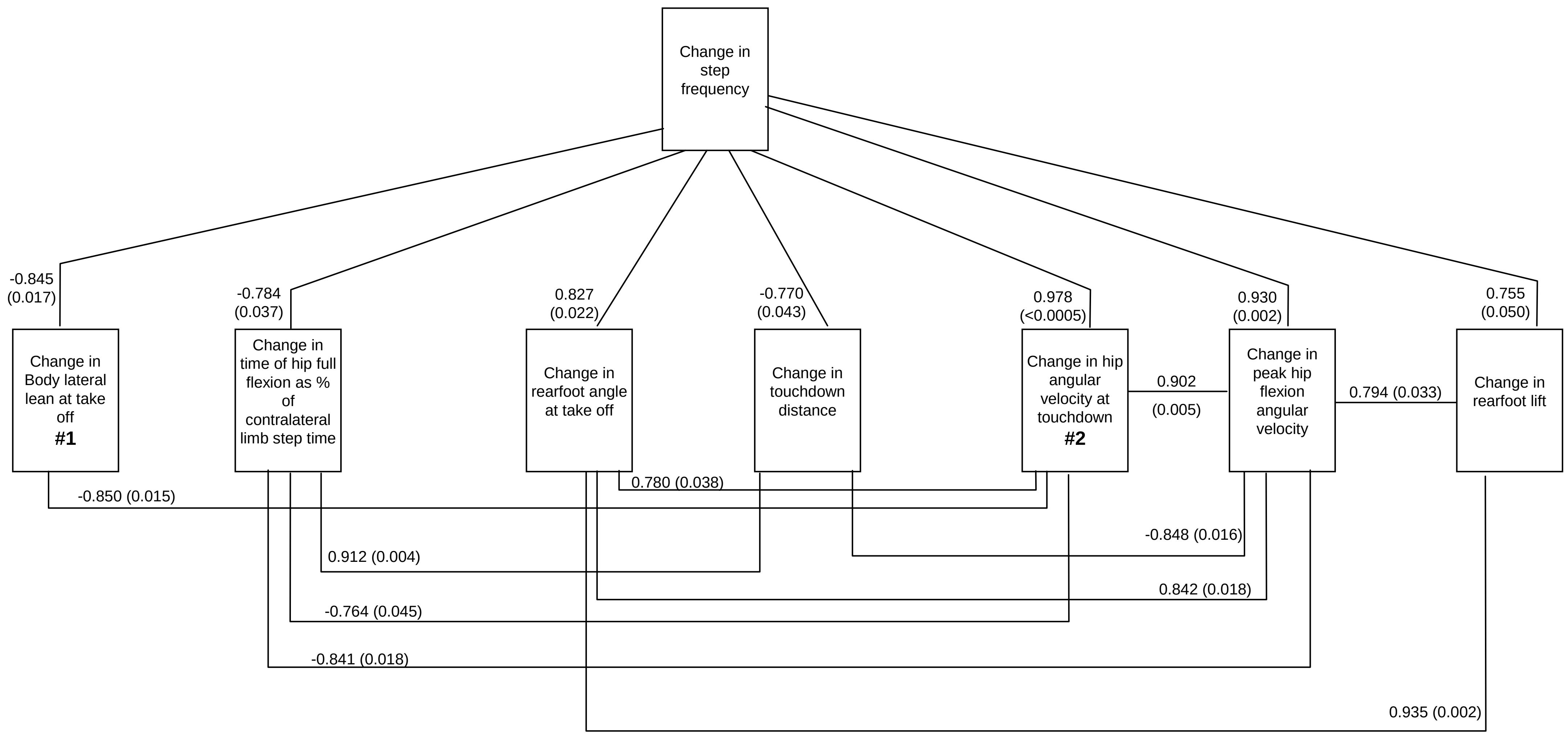


Figure 4.8. Map of significant Pearson correlations between left-hand side technique variable changes related to changes in left step frequency on the bend compared to the straight. Correlation *r* value (and significance) is shown for each relationship. See text for further explanation and interpretation of figure.

[#1] A negative change in this variable indicates greater inward lean
[#2] A negative change in this variable indicates decreased extension angular velocity

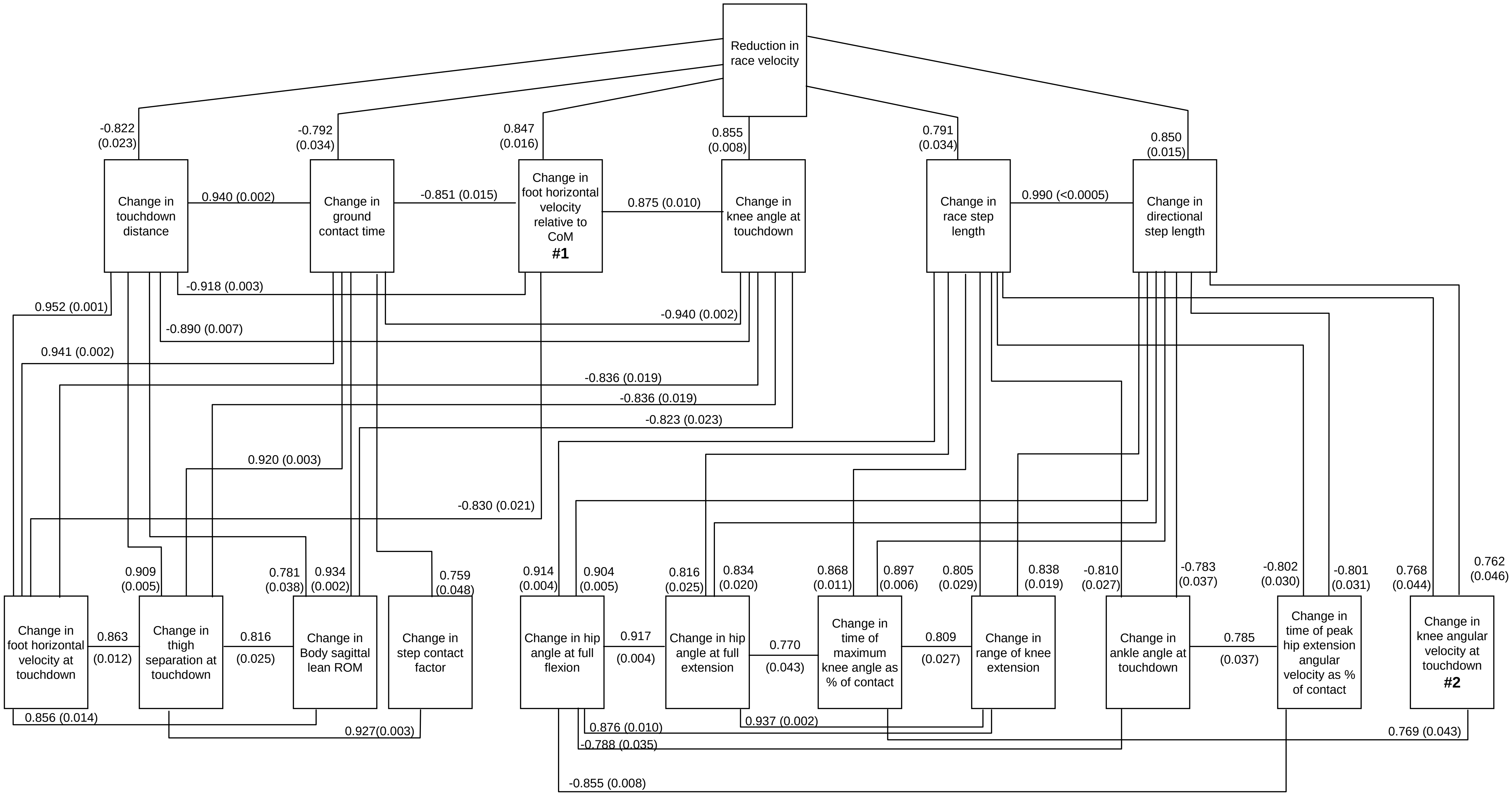


Figure 4.9. Map of significant Pearson correlations between right-hand side technique variable changes related to a reduction in right race velocity on the bend compared to the straight. Correlation *r* value (and significance) is shown for each relationship. See text for further explanation and interpretation of figure.

[#1] Foot horizontal velocity relative to CoM is a negative value; therefore, a negative change in this variable indicates a less negative foot horizontal velocity
[#2] A negative change in this variable indicates an increased extension angular velocity/decreased flexion angular velocity

4.4. Discussion

4.4.1. Relationships between performance and technique on the bend

The first aim of the current chapter was to understand the technique variables which are most closely related to faster performance on the bend. Consequently, correlations between performance and technique variables of athletes of different abilities on the bend were analysed. In general, athletes who were faster during the left step exhibited a greater inward (more negative) body lateral lean angle at left touchdown and left take off on the bend than slower athletes. This was evidenced by a negative relationship between absolute speed/race velocity with body lateral lean at touchdown and take off during the left step (Figure 4.1). Athletes must generate centripetal force in order to follow the curved path during bend running. Inward lean is required to counteract the moment caused by the centripetal force, which would otherwise rotate the trunk outwards about the AP axis. The relationship between greater inward lean and velocity on the bend may be for two reasons and is likely a combination of the two: firstly, the required centripetal force is dependent on the radius of the path, the square of the velocity that the athlete is travelling and the mass of the athlete. Thus, for the same mass, greater centripetal force is required for higher velocities, which would require greater inward lean. Secondly, inward lean places the contact foot more towards the outside of the bend than the CoM of the athlete. This placement of the foot is probably advantageous for centripetal force generation, which may allow athletes to travel at a greater velocity whilst still following the curved path and remaining within their lane. It is, therefore, possible that the greater inward lean of the faster runners is both the result of and beneficial for superior performance.

Of the upper body kinematic variables, the only relationships with absolute speed/race velocity were on the left step. Athletes who were faster during the left step exhibited a smaller left shoulder flexion/extension ROM (Figure 4.1). These athletes may have been more economical in their upper body motion than those athletes who were slower over the left step on the bend, which has also been suggested to be the case in straight line sprinting (Mann, 1985). There were relationships between body lateral lean at touchdown and take off with left elbow ROM which was itself related to maximum lateral left wrist position (Figure 4.1). It is possible that greater inward lean inhibits left arm motion, which may explain why there were significant correlations found for left-hand side but not right hand-side upper body variables. There is some conflict in the literature regarding the importance of upper body kinematics to sprint performance. However, the reason for inclusion of upper body variables in the present study was to investigate whether the requirement to turn during bend running meant the upper body played a more important role than in straight line sprinting. There were some significant differences found between bend and straight for some wrist position variables in Chapter 3 (Table 3.9). However, the lack of significant correlations for upper body variables with performance and/or other technique variables suggests that, similarly to straight line sprinting, it is likely that the role of upper body kinematics is more marginal than lower body kinematics in determining performance on the bend.

Neither left step length (race or directional) nor left step frequency returned a significant correlation with left race velocity or absolute speed. However, mathematically velocity is the product of step length and step frequency and athletes must improve one or both of these to improve performance. As such, it is important to understand the technique variables associated with each of these factors (step length and step frequency) during bend running. Athletes with a longer left race and directional step length had a more extended left knee at touchdown (Figure 4.2). It has been suggested that a more extended knee at touchdown results in better positioning of the extensor muscles to exert force (Mero & Komi, 1985). Thus, in the present study, the larger knee angle may have assisted in the greater force generation required to produce longer step lengths. A negative correlation was observed between left race and directional step length and thigh separation angle at left touchdown (Figure 4.2). This means that those athletes with a smaller thigh separation at touchdown produced a longer step length indicating that they were better able to recover their trailing leg, thus, enabling a longer left step.

Left directional step length and race step length were negatively correlated with the time of peak left hip adduction, which was itself positively correlated with minimum left knee angle (Figure 4.2). This shows that those athletes who experienced an earlier peak left hip adduction exhibited a larger (more extended) minimum left knee angle during the left stance phase. Chang and Kram (2007) suggested that one of the limiting factors to performance during bend running is the necessity to stabilise in the frontal plane. Additionally, it has already been mentioned that some muscles working in the frontal plane are also involved in sagittal plane motion (Palastanga et al., 2006) and alterations to the orientation of muscles in the frontal plane can affect the muscular activity of muscles working in the sagittal plane (Earl et al., 2001; Coqueiro et al., 2005). It is possible that the timing of motion in the frontal plane (in this case, the time of peak adduction) also had an effect on kinematics in the sagittal plane and may explain why those athletes who experienced peak adduction earlier exhibited a more extended minimum left knee angle during contact.

The longest left race and directional step lengths were associated with a higher peak left MTP plantarflexion angular velocity which was in turn related to a greater range of left MTP plantarflexion during the extension phase (Figure 4.2). Thus, the longest left step lengths on the bend were achieved, at least in part, by greater plantarflexion at the left MTP. It has been suggested that while increased extension may be beneficial for increasing step length, the extra time taken (i.e. an increase in ground contact time) may have a negative effect on step frequency (Mann, 1985). Indeed, in the present study there was a positive correlation between left race/directional step length and peak left MTP plantarflexion angular velocity, but the latter variable had a negative correlation with left step frequency. Whilst this initially appears to support Mann's (1985) suggestion that maximising extension (or plantarflexion) increases ground contact time and thus reduces step frequency, closer inspection shows left step frequency was not directly correlated with left ground contact time in the present study (Figure 4.2). Instead, a negative correlation between step frequency and flight time was observed (Figure 4.2). This suggests that whilst maximising plantarflexion has been linked to an increase in ground contact time in previous studies (Mann, 1985), in the present study rapid plantarflexion contributed to longer left flight time and thus reduced left step frequency (Figure 4.2). Therefore, an athlete wishing to increase step length on the bend must ensure that this is not at the expense of step frequency.

Previous research has suggested links between longer ground contact times and larger thigh separation at touchdown (Kunz & Kaufmann, 1981), greater body sagittal lean ROM during contact (Hunter et al., 2004a) and larger duty factor (the stride equivalent of the step contact factor measured in the present study; Usherwood

& Wilson, 2006). Therefore, it may seem unusual that larger values of thigh separation at left touchdown, body sagittal lean ROM during left contact and left step contact factor were related to higher left step frequencies in the present study (Figure 4.2). However, Figure 4.2 also shows that high left step frequencies were contributed to by short left flight times and not necessarily short left ground contact times in the present study. This gives further evidence that the effect of the bend is more complicated than simply an increase in ground contact time leading to decreases in step frequency and thus velocity, as was suggested by Usherwood and Wilson (2006).

Those athletes with the highest left step frequencies demonstrated the largest (least flexed) hip angles at full flexion, which was also related to greater peak left hip flexion angular velocities during swing. This allowed faster repositioning of the limb prior to next touchdown in what was a relatively shorter flight phase than that produced by athletes with a lower step frequency (Figure 4.2). Previous research has linked less flexion at full hip flexion with inferior performance (Mann & Hagy, 1980; Mann, 1985; Mann & Herman, 1985; Bushnell & Hunter, 2007). However, the relationship described presently is for hip flexion at full flexion with step frequency and not with the velocity of the athletes. As such, it is possible that while increased hip flexion has been related to increased velocity it is because it is beneficial for increased step length rather than increased step frequency. Indeed, in a study of treadmill sprinting, Kivi et al. (2002) found that while the degree of flexion at peak hip flexion increased as velocity increased from 70% to 90% of maximum, further increases in flexion as velocity increased were limited by the necessity to maintain step frequency.

For the right step on the bend, only the times of peak right hip abduction and minimum right MTP angle were significantly correlated with absolute speed and race velocity (Figure 4.3). The relatively few significant relationships found for right-hand side variables with right step absolute speed/race velocity suggest that the effect of the bend on the right step may have been more variable than its effect on the left step, therefore fewer significant correlations were returned.

There was a relatively later timing of minimum right MTP angle in the athletes who were fastest during the right step on the bend (Figure 4.3). Later minimum right MTP angle was also related to a reduced range of MTP plantarflexion in the extension phase and a smaller right MTP angle at take off. The smaller range of plantarflexion was probably contributed to by those athletes having a lower peak right MTP plantarflexion angular velocity (Figure 4.3). It is possible that the reduction in the degree of plantarflexion of the MTP during the push off phase resulted in a relative reduction in the time spent plantarflexing at that joint. Furthermore, the right MTP reached its maximum angle during the absorption phase later in those athletes with a later timing of minimum right MTP angle (Figure 4.3). An increase in the time taken for absorption and a reduction in the degree of plantarflexion would have had the effect of making the time of the minimum right MTP angle relatively later.

The fastest runners during the right step on the bend exhibited later peak right hip abduction which was also related to a later time of hip full extension (as a percentage of step time). The lateness of the latter variable may have been due to the shortening of the total step time because of the reduction in flight time (Figure 4.3). A later peak hip abduction also led to a more abducted hip at take off. Furthermore, there were a number of relationships between right hip abduction/adduction angle at take off and sagittal plane kinematics such as right hip angular velocity at touchdown, maximum right knee angle and peak right MTP plantarflexion angular velocity (Figure 4.3). This highlights the relationship that altering frontal plane kinematics has on sagittal plane kinematics.

There was a significant correlation showing a negative interaction between step frequency and directional step length on the bend for the right step (Figure 4.4). The relationship between right race step length and right step frequency did not, however, reach statistical significance (r = -0.736, p = 0.062). As a result of this negative interaction a number of variables were commonly correlated with right step frequency and right directional step length, but the sign of their correlations were opposite (Figure 4.4). This type of negative interaction has been observed in straight line sprinting (Hunter et al., 2004a), and appears to be present also in bend sprinting.

This means that athletes aiming to improve bend sprinting performance should be careful that an improvement in one area does not lead to deterioration in another.

Athletes with the highest right step frequencies had the largest right step contact factors and shortest right flight times (Figures 4.3-4.4). Furthermore, a short right flight time was also related to a short right ground contact time (Figure 4.4). This suggests that these athletes were unable to generate sufficient vertical impulse during contact to produce a long flight time. Consequently, the overall step frequency increased.

A negative correlation between right step frequency and right knee angle at touchdown (Figures 4.3-4.4) indicates that those athletes with a higher right step frequency exhibited a smaller right knee angle at touchdown. Conversely, positive correlations between right directional step length and right knee angle at touchdown (Figure 4.4) indicate that those athletes who exhibited a more extended knee angle at touchdown produced the longest right directional step on the bend. This further supports the fact that a more extended knee angle at touchdown, which has been postulated to be beneficial for performance, by favourably positioning the extensors for force generation (Mero & Komi, 1985), may be more beneficial for improving step length than step frequency.

Right knee angle at touchdown was also negatively correlated with foot horizontal velocity and thigh separation at right touchdown (Figure 4.4) indicating that athletes with a larger knee angle at touchdown also had a slower foot horizontal velocity and smaller thigh separation angle at touchdown, which are indicative of a more active touchdown (Kunz & Kaufmann, 1981; Mann, 1985). Furthermore, a greater (more negative) right knee flexion angular velocity at touchdown has previously been linked to superior performance on the straight, as it indicates the athlete has been able to sufficiently reposition their legs during swing to begin flexion prior to touchdown (Mann, 1985; Mann & Herman, 1985). In the present study the relationship between longer race/directional step lengths and greater (more negative) right knee flexion angular velocity at touchdown (Figure 4.4) is evidence that a more active touchdown strategy led to greater right step length production on the bend.

The athletes with the highest right step frequencies experienced later right hip full extension which itself was positively correlated with right hip angle at full flexion (Figures 4.3-4.4), indicating that later full extension had the effect of reducing the degree of flexion at full flexion, i.e. the angle was larger. Whilst it would normally be expected for better runners to have a more flexed hip at peak flexion (Mann & Hagy, 1980; Mann, 1985; Mann & Herman, 1985; Bushnell & Hunter, 2007) the relationship described was with step frequency and not absolute speed or race velocity. Thus, it seems that in the current study those athletes who had a higher right step frequency achieved this, at least in part, by a later but abbreviated right hip flexion and rapid right hip extension prior to next touchdown (Figures 4.3-4.4).

4.4.2. Relationships between changes in performance and changes in technique from straight to bend

In order to understand how some athletes are better able to achieve similar velocities on the bend compared to the straight, the relationships between changes in performance and changes in technique on the bend when compared to the straight were established (Figures 4.7-4.9).

During the left step, the athletes with the largest decreases in race velocity from the straight to the bend, were those who exhibited the largest decreases in left directional and race step length (Figure 4.7). The decreases in left race and directional step length were contributed to by those athletes having reduced plantarflexion of the left ankle at take off, reduced peak left MTP plantarflexion angular velocity and reduced range of plantarflexion of the left MTP during the extension phase and at take off (Figure 4.7). Therefore, those athletes whose velocity decreased the most on the bend compared to the straight appeared to have had an inhibited plantarflexion at the foot, perhaps because of the inward lean, and may be a potential area for some athletes to work on.

In those athletes with the largest decrease in left race velocity the left foot was also not moving backwards (relative to the CoM) at touchdown with as large a magnitude on the bend as it did on the straight. This is shown by the positive correlation between reduction in left step race velocity and change in left foot horizontal velocity relative to the CoM. The latter variable was also negatively correlated with change in left foot horizontal velocity at touchdown (Figure 4.7) meaning the foot also moved forward faster (relative to the ground) at touchdown on the bend compared to the straight. A greater velocity of the foot relative to the ground and a less negative velocity relative to the CoM at touchdown has been suggested as being detrimental to straight line sprinting as it indicates an athlete is less able to recover the foot before contact and employs a less active touchdown technique (Mann, 1985; Mann & Herman, 1985). It appears that those athletes with the largest decrease in left step race velocity on the bend compared to the straight exhibited a less active touchdown strategy. The less active touchdown of these athletes led to larger increases in ground contact time (Figure 4.7) which is in line with previous research on straight line sprinting (Hunter et al., 2004a). These results suggest that maintaining activeness of touchdown may be a potential area of focus in bend sprinting training.

Regarding upper body variables, those athletes with a larger decrease in left step performance had increased thorax rotation during the left step on the bend. This supports the Mann and Herman's (1985) findings that excessive motion of the upper body was detrimental to sprinting performance. However, similarly to the correlations between performance and technique in absolute terms discussed in section 4.4.1, the general lack of significant relationships between changes in upper body variables and reduced performance on the bend compared to the straight indicates changes in upper body kinematics are not closely related to an athlete's ability to maintain their straight line velocity on the bend.

The technique changes that contribute to altered left step frequency on the bend, compared to the straight, have been considered because of the importance of step frequency (along with left race and directional step length, which are shown in Figure 4.7) in the determination of velocity. Those athletes with the largest reductions in left step frequency experienced reduced peak left hip extension angular velocity on the bend in comparison to the straight (Figure 4.8). This suggests that these athletes were not able to produce as forceful hip extension on the bend as they were able to on the straight, probably because of the requirement to also generate centripetal force. This may have increased the time taken for extension which would contribute to decreasing left step frequency. Furthermore, these athletes had a reduced peak left hip flexion angular velocity during swing (Figure 4.8) indicating they were not able to reposition their legs as quickly as those athletes whose step frequency decreased less on the bend compared to the straight. An inability to quickly reposition the left leg during swing may also have reduced the activeness of touchdown contributing to the increased touchdown distance at left touchdown (Figure 4.8).

The largest reductions in right race velocity were associated with the largest reductions in right race and directional step lengths, which was likely due, at least in part, to the more negative change in the degree of extension of the right hip at full extension and range of right knee extension that these athletes underwent during the step. These athletes either reduced the extension of these variables or increased it to a smaller extent than those athletes whose right step length decreased the least on the bend compared to the straight. Peak right hip extension angular velocity was later in those athletes whose right race and directional step length reduced the most on the bend compared to the straight (Figure 4.9). Whilst it has been suggested that better athletes undergo less extension of the hip and knee (Mann, 1985), the correlations between changes in variables between the bend and the straight have been performed in order to identify differences in different athletes' ability to maintain velocity on the bend compared to the straight. As such, the change in hip and knee extension variables on the bend is relative to each athlete's own performance on the straight, rather than an absolute value and may be reflective of their ability to produce propulsive impulse on the bend. It is possible that the requirement for mediolateral force production on the bend inhibited hip and knee extension and generation of propulsive impulse.

Similarly to the left step, those athletes whose right race velocity decreased the most had a less active touchdown on the bend compared to the straight, as evidenced by greater right touchdown distance (Figure 4.9). Increased touchdown distance was itself associated with a more positive right foot horizontal velocity, a less negative right foot horizontal velocity relative to the CoM and larger thigh separation at right touchdown on the bend compared to the straight. Each of these variables has been linked to the activeness of touchdown in sprinting (Kunz & Kaufmann, 1981; Mann, 1985; Mann & Herman, 1985). The less active touchdown had the effect of increasing right ground contact time and body sagittal lean ROM during the right step. Increased right touchdown distance was also related to a reduced right knee angle at touchdown, i.e. the knee was more flexed at touchdown. This may have meant that the right knee was positioned in a less optimal orientation for force generation further reducing performance during the right ground contact phase, as has been suggested for straight line sprinting (Mero & Komi, 1985).

The only statistically significant relationship between change in right step frequency and another variable was with change in right MTP angle at touchdown ($r = 0.773$, $p = 0.042$). This was despite there being a number of correlations between reductions in race velocity during the right step and variables that would normally be associated with reductions in step frequency (e.g. increased right touchdown distance and right ground contact time; Figure 4.9). It is likely that reductions in right flight times meant that although right ground contact time may have increased, overall right step time was maintained. Thus, right step frequency was not correlated with these variables. This is in contrast with the model proposed by Usherwood and Wilson (2006), who postulated, based on research by Weyand et al. (2000) that swing times on the bend should be consistent for all athletes running at maximum velocity and decreases in velocity on the bend would be due to increased ground contact time resulting in reduced step frequency. For the right step it appears, from the current results that better bend runners were no more, or less, able to maintain right step frequency than less able bend runners, and in fact it is the ability to maintain step length that set these athletes apart.

One of the limitations of the study was the limited number of participants. Unfortunately, it was difficult to recruit competent bend sprinters for such a time consuming data collection. Drawing conclusions from correlations when a small sample size is used can be problematic. However, it has been shown that in the case where a small sample size is unavoidable, small samples can be used to detect relationships if that relationship in the whole population is strong (Lemons, 2009). This notwithstanding, if the relationship in the whole population is moderate or small, a small sample size is less likely to replicate the true population correlation (Lemons, 2009) meaning that the likelihood of obtaining statistically significant correlations may have been reduced by the small sample size in the present study. As well as the data from the seven male athletes, data were collected from two female athletes (see Chapter 3). However, the velocities of these athletes were relatively low. Inclusion of these athletes in the data set for the correlations would likely have reduced the homogeneity of the sample and it is known that when sample size is small, outliers have more influence over the regression line (Lemons, 2009). Thus, it was decided that a smaller, more homogenous, sample (males only) would allow more confident detection of strong correlations, albeit with the unavoidable chance that some moderate correlations would be missed.

Conclusion

The correlations between performance variables (absolute speed and race velocity) highlighted that those athletes who were fastest during the left step on the bend were those who leant inward to a greater extent. As such, one of the keys to superior bend running performance may be an athlete's ability to withstand and generate forces whilst in the altered frontal plane orientations elicited by the bend. This may be a consideration for training. Fewer significant correlations between right absolute speed/race velocity indicated that athlete technique during the right step on the bend may have been more variable than for the left step on the bend.

An athlete wishing to increase left step length on the bend may need to work on their ability to recover the right leg during swing, since this ability was subsequently linked to longer left step production. This may require specific training of the hip flexors to allow the thigh to be pulled through, whilst also leaning on the bend. For the right step, greater activeness of touchdown was linked to longer right step length production. It is possible that this is due to the requirement to lean affecting an athlete's ability to maintain sagittal plane kinematics. Athletes should, therefore, undertake exercises aimed at reducing touchdown distance on the bend and not just on the straight. As was suggested in Chapter 3, specifically training the hip extensors to be able to pull the leg backwards, whilst leaning to the left may be beneficial for reducing touchdown distance on the bend. The results showed that higher left and right step frequencies on the bend were achieved with shorter flight times and not necessarily shorter ground contact times. However, as is the case with straight line sprinting, care should be taken in any attempt to increase step length or step frequency, as a negative interaction between technique variables associated with these performance descriptors was evident.

An athlete's ability to achieve a velocity on the bend which is similar to their straight line velocity does not appear to be related to their straight line velocity. Therefore decreases in performance on the bend compared to the straight are not simply a function of the straight line velocity of an athlete. This provides support for the identification of technique variables that may enable improvement in bend sprinting.

For both the left and right steps, decreases in directional and race step lengths were directly related to decreases in race velocity on the bend compared to the straight. It appears, therefore, that the ability to maintain step length on the bend is a key area in order to prevent reductions in performance on the bend in comparison to the straight. For the left step, the reduction in step length was related to inhibited plantarflexion of the MTP and ankle during late stance, on the bend compared to the straight. It is likely that inward lean during bend running makes the left foot less stable, which reduces the ability to plantarflex. Strengthening the musculature of the foot, particularly with regards to stabilisation in the frontal plane may allow athletes to better achieve plantarflexion, which may allow left step length to be maintained whilst sprinting on the bend. During the right step the decrease in step length on the bend compared to the straight was related to a reduction in degree of extension of the right hip at full extension and knee range of extension. It is likely that the reduction in extension was related to the necessity to lean and stabilise in the frontal plane. Thus, athletes may need to strengthen the muscles which act to stabilise at these joints. Additionally, it may be beneficial to undertaking specific strengthening exercises of the hip and knee extensors whilst the athlete is in the same orientation induced by the inward lean of bend running.

Furthermore, maintaining activeness of touchdown appears to be an important factor in bend running as a less active touchdown was related to reduced left and right step race velocity. Again, this is possibly due to the requirement to lean affecting an athlete's ability to maintain sagittal plane kinematics and athletes should, therefore, undertake exercises aimed at reducing touchdown distance on the bend. Additionally, it is possible that those athletes who were better able to maintain their kinematics may have greater frontal plane strength, although such measurement was beyond the scope of this thesis.

The results of the current chapter, along with Chapter 3 have highlighted some important kinematic variables associated with bend sprinting performance, however only the straight and lane 2 of the bend were considered. In reality athletes perform bend sprinting in lanes of varying radii, and it is believed that bend radius may have a substantial effect on performance. Thus, it is important to consider how running in different lanes affects technique and performance during bend sprinting.

CHAPTER 5: THE EFFECT OF RUNNING LANE ON TECHNIQUE AND PERFORMANCE DURING BEND SPRINTING

5.1. Introduction

The results in Chapter 3 showed that athletes were not able to attain as high velocities on the bend as they were able to on the straight. Furthermore, the bend portion of the race might be an area for potential improvement of race times in sprint events longer than 100 m. Along with differences between bend and straight, there are potential differences between lanes during the bend portion of a race. The race distance around the bend is the same for all athletes within a race. The radius of the bend, however, increases from lane one to lane eight. It has been suggested that lane allocation may provide athletes in the outer lanes with an advantage over those athletes in the inner lanes (Jain, 1980; Greene, 1985). Indeed, it is well known that many athletes prefer not to run in the innermost lanes where the bend is tighter.

The magnitude of the advantage of being in lane seven as opposed to lane one for a 200 m race has been estimated as between 0.069 s (Jain, 1980) and 0.123 s (Greene, 1985) depending on differences in the mathematical models used. Empirical evidence at very small radii (1-6 m) has shown velocity to decrease as bend radius decreases (Chang & Kram, 2007). However, to the author's knowledge, there have been no robust experimental studies which have aimed to quantify the effect that lane allocation has on bend running performance on surfaces and at radii typical of those of athletic sprint events. Additionally, there is a paucity of literature regarding the changes to step characteristics and/or technique which contribute to changes in performance, when sprinting in lanes of different radii. Furthermore, there is a need for the effect of the lane on technique and performance to be investigated under conditions which do not introduce the psychological or tactical factors which would be present in a competition situation. With this in mind, the aim of the present study was to understand how the lane affects technique and performance during maximal effort bend sprinting in lanes with radii typical of those experienced in athletic sprint events.

5.2. Methods

5.2.1. Participants

Nine male athletes experienced in bend sprinting participated in the study. Mean age, mass, and height were: 21.5 ± 3.2 years, 79.4 ± 10.1 kg, and 1.82 ± 0.06 m, respectively. Personal best times for the 200 m ranged from 21.1 s to 22.6 s for eight of the athletes. The ninth athlete, who had no recent 200 m time, had a 400 m PB of 47.36 s. Examination of data for this athlete running in lane 2 in the present study ranked him 3rd fastest, indicating that his 200 m time would be well within the group mean. Videotaping and analysis of athletes during normal training situations was approved by the local research ethics committee. Written informed consent was obtained from all athletes prior to data collection taking place.

5.2.2. *Data collection*

Data were collected during the outdoor competitive season, in the participant's normal training sessions, when the athletes were undertaking speed training. Athletes completed a coach-directed warm up before undertaking two 60 m maximal effort sprints around the bend in each of lanes 2, 5, or 8 (radii: 37.72 m, 41.41 m and 45.10 m, respectively) on a standard outdoor 400 m track at the University of Bath. The order in which the lanes were run was mixed on different testing dates and athletes completed the whole 60 m around the bend. Recovery time between trials within a set was approximately eight minutes and approximately 15 minutes between lanes. For the majority of athletes all six trials were undertaken during a single training session. For two athletes, however, four trials were completed in one training session with the remaining two trials being completed in their next training session.

Two high speed video cameras (MotionPro HS-1, Redlake, USA) were used to record the athletes at the 40-48 m section of the 60 m, to enable two full steps to be recorded. 'Side view' and 'front view' cameras were positioned as for the bend trials in Chapter 3 (Figure 3.1, p50), although the field of view for the side camera was slightly extended to be 8 m wide. The position of the cameras was not changed between lanes but the 'front view' camera was adjusted in order that the centre of the lane of interest was in the centre of the field of view, and the zoom of the side view camera adjusted to maintain the 8 m wide field of view in the relevant lane. The cameras were manually focussed for each lane, operated with a 200 Hz frame rate and shutter speed of 1/1000 s, and had an open iris with no gain.

An 18-point 3D calibration was recorded prior to the athletes' trials taking place in each lane. The structure used was the same as for Chapter 3 (Figure 3.2, p51). For each new calibration, the locations of each calibration point were known relative to the origin ball, for which height from the ground was measured on each occasion. The GCS was defined in the same way as for the bend trials in Chapter 3, such that within the filming area athletes travelled primarily in the direction of the positive y-axis and with the positive z-axis vertically upwards. The positive x-axis was orthogonal to the other two axes following the right-hand convention.

5.2.3. Data processing

All trials were manually digitised using Vicon Motus software (Version 9.2, Vicon, Oxford, UK). For the majority of trials the two video cameras were genlocked such that the video streams were synchronised. On one data collection session the genlocking failed, in which case the two video streams were synchronised using two sets of 20 LED displays which were placed with one in each camera view during data collection. The LEDs were simultaneously triggered during each trial which caused the LEDs to illuminate sequentially at 1 ms intervals. From the number of lights illuminated in each camera view, the time of the LED trigger was established and entered into the digitising software as the common synchronisation point, permitting synchronisation between two views to within 1 ms.

For each calibration, six fields were digitised in each camera view to provide the 11 DLT parameters required for 3D reconstruction (Abdel-Aziz & Karara, 1971). Translations were performed such that the GCS was moved from the origin ball of the calibration frame to the bend radius origin. The trials were cropped to include two full steps plus 10 fields before the first touchdown of interest and 10 fields after the final touchdown of interest. This allowed all points to be digitised for all fields for the majority of trials. However, despite the 8 m field of view, some points were out of the field of view at the beginning or end of the trial for six trials. In these cases, the missing points were not digitised and their positions were estimated using linear extrapolation based on of the first (or last) four points when the point was in view. The extrapolation yielded sensible coordinate positions in all but two cases. In these cases, the missing points were digitised at the edge of the field of view giving more sensible coordinates. No trials had points missing in the fields of interest (fields for which kinematic data were calculated). Gait events (touchdown and take off) were determined by visual inspection of the video from the front view camera. Touchdown was defined as the first field in which there was definitely contact with the track and take off was defined as the first field in which there was definitely no contact with the track.

The same 20-point, 16-segment, model of the human body was digitised as in Chapter 3 and following 3D-DLT reconstruction (Abdel-Aziz & Karara, 1971) 3D coordinates were exported to a custom written Matlab script (v 7.9.0, The MathWorks, USA), for further processing. The coordinates were filtered with a low-pass 2nd order recursive Butterworth filter (effectively a 4th order zero lag Butterworth filter; Winter, 2009) with a cut-off frequency of 20 Hz. Filtered coordinates were combined with body segment inertia data, which had been adjusted from de Leva (1996) to incorporate a two segment foot (Bezodis, 2009) and include the mass (0.2 kg) of a typical spiked running shoe (Hunter et al., 2004a). Subsequently, segment and whole body CoM was calculated as outlined in Chapter 3.

5.2.4. Calculation of variables

To remain consistent with the previous chapters, the same direct performance descriptors and upper and lower body kinematics were calculated as in Chapter 3. They were calculated in the same way as for the bend trials in Chapter 3, with adjustments to radii in calculations as appropriate, and were as follows: Absolute speed; race velocity; directional step length; race step length; step frequency; ground contact time; flight time; step contact factor; touchdown distance; foot horizontal velocity at touchdown; foot horizontal velocity relative to CoM horizontal velocity at touchdown; foot vertical velocity at touchdown; body sagittal lean ROM; body lateral lean at touchdown and take off; shoulder flexion/extension ROM; elbow ROM; trunk forward lean at touchdown; hip flexion/extension angle at take off, at full flexion and full extension; thigh separation at touchdown; knee angle at take off, full flexion, touchdown and minimum and maximum angles during ground contact;

ankle angle at touchdown, minimum during contact, and at take off; MTP angle at touchdown, maximum during absorption phase, minimum during absorption phase, and at take off; rearfoot angle at touchdown, minimum during ground contact, and at take off; rearfoot drop and rearfoot lift; shoulder abduction/adduction ROM; trunk lateral lean at touchdown; hip abduction/adduction at peak abduction, at peak adduction, and at take off; maximum thorax rotation; turn of CoM during contact; displacement of the wrists relative to the CoM. When variable values were extracted at times other than touchdown and take off, the time at which they occurred was also recorded. Angular velocities of the hip (flexion/extension), knee and MTP, were also calculated from the angular displacements using the first central difference method and the times at which peaks occurred were recorded.

5.2.5. Statistical analysis

Individual mean values for each variable in each lane were calculated for all athletes. These means were then used in further statistical analysis carried out in SPSS for Windows software (v 14.0, SPSS Inc., USA). A repeated measures analysis of variance (ANOVA) was performed to measure the effect of the lane on each variable for the left and right steps separately. Where a main lane effect was found, pairwise comparisons were used to determine where the differences were and the level of significance of those differences. In order to reduce the chances of committing a Type II error, no adjustments for multiple comparisons were made. To assess the presence of any asymmetries within a lane, left step variables were compared to right step variables within that lane for each variable, using paired samples t-tests. Significance was set at $p < 0.05$. The magnitude of the difference (the effect size) between lanes and between left and right steps within a lane was calculated using Cohen's d (Cohen, 1988) for each variable. Relative magnitude of the effect was assessed based on Cohen's guidelines with d less than or equal to 0.20 representing a small difference, d greater than 0.20 but less than 0.80 a moderate difference and d greater than or equal to 0.80 a large difference, between the two means.

5.3. Results

There was a general trend for mean race velocity and absolute speed to decrease as bend radius decreased from lane 8 to lane 2 (Figure 5.1, Table 5.1). For absolute speed these decreases were statistically significant from lane 8 to lane 5 and from lane 8 to lane 2 for the left step ($p < 0.05$, Table 5.1). There was a decrease in mean race velocity of 2.1 % and 2.0 % from lane 8 to lane 5, for the left and right steps, respectively, which were found to be statistically significant ($p < 0.05$, Figure 5.1). From lane 8 to lane 2, the decrease in mean race velocity was 2.3 % and 2.0 % for the left and right steps, respectively, which was found to be statistically significant for the left step ($p < 0.05$, Figure 5.1). Effect sizes between lane 8 and lane 5 (left: $d = 0.42$; right: $d = 0.40$) and between lane 8 and lane 2 (left: $d = 0.42$; right: $d = 0.37$) were moderate for race velocity. The difference between race velocity in lane 5 and lane 2 elicited only small effect sizes (left: $d = 0.04$; right: $d = 0.01$). Similar values were found for absolute speed. For both race velocity and absolute speed, mean values for the left step were higher than for the right step within a lane, and these asymmetries were statistically significant in lanes 8 and 5 ($p < 0.05$, Table 5.1).

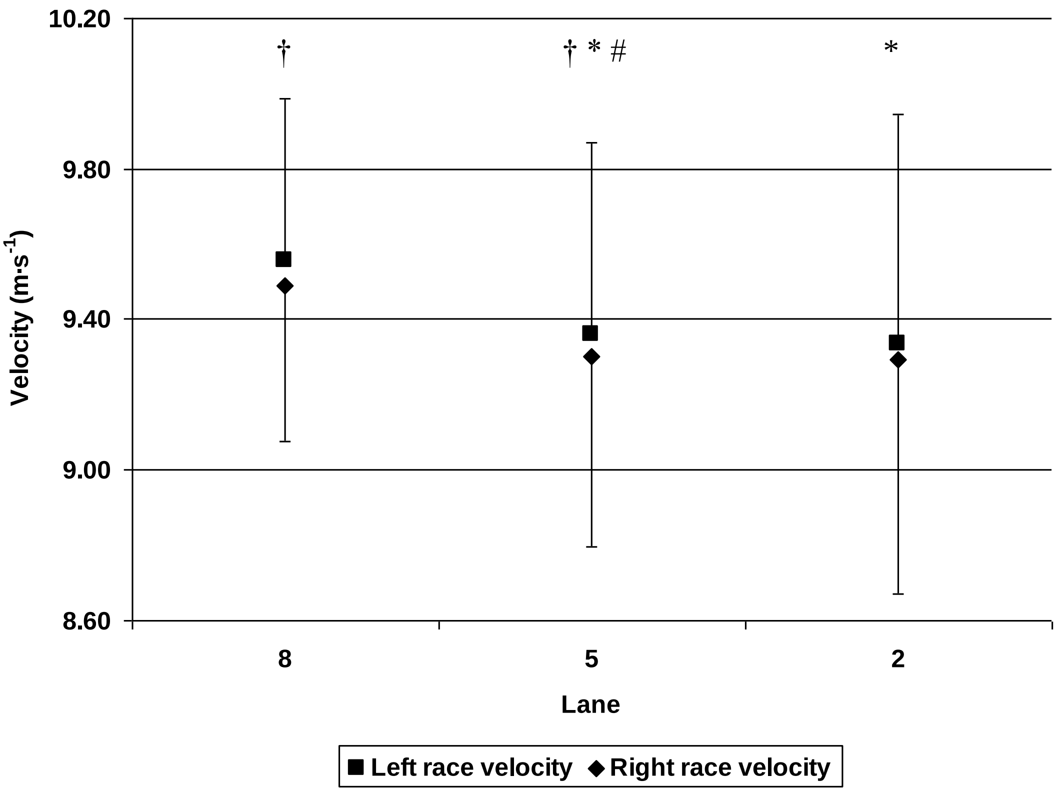


Figure 5.1. Left and right step group mean race velocity on the bend in lanes 8, 5, and 2. For clarity, only upper standard deviation bars are shown for the left step and lower bars shown for the right step. * left step significantly different to left step in lane 8 ($p < 0.05$), # right step significantly different to right step in lane 8 ($p < 0.05$)

[†] significantly different between left and right within lane (p < 0.05).

The shortest race and directional step lengths were seen in lane 5 for both the left and right steps (Table 5.1). Step frequencies for left and right steps within a lane were similar in all lanes. However, there was a general trend for step frequency to decrease as radius decreased, although the only significant difference was between lane 5 and 2 for the left step (p < 0.05, Table 5.1).

Mean ground contact time during the left step increased as bend radius decreased (significant between lane 8 and 2, p < 0.01, Table 5.1). During the right step, ground contact time was similar in all lanes, and statistically significant asymmetries between left and right ground contact time were present in all lanes (p < 0.01, Table 5.1). Mean step contact factor was greatest in lane 5 for both the left and right steps (Table 5.1). There were no statistically significant differences between lanes for step contact factor, but the effect sizes were moderate between lane 5 and lane 2 (d = 0.26), and between lane 5 and lane 8 (d = 0.036) on the left. For the right step, the size of the effect between step contact factor in lane 5 and the other lanes was small (lane 2: d = 0.15; lane 8: d = 0.17).

Significantly more turning of the CoM was achieved during the left ground contact phases compared to the right ground contact phase in all three lanes (p <0.01, Figure 5.2, Table 5.1). For the right step, there was significantly more turning of the CoM in lanes 5 (2.4°; p < 0.05, d = 1.04) and 2 (2.5°; p < 0.01, d = 1.44) compared to lane 8 (1.7°; Figure 5.2, Table 5.1). Moderate effect sizes were seen for the left step between lane 8 and lane 5 (d = 0.44) and between lane 8 and lane 2 (d = 0.44), and for the right step between lane 2 and lane 5 (d = 0.27). The effect size between lane 2 and lane 5 for the left step was small (d = 0.10).

Table 5.1. Left and right step group mean values (± SD) and significant differences for performance descriptors during bend running in lanes 8, 5, and 2.

	Lane 8		Lane 5		Lane 2		Significant differences								
	Left	Right	Left	Right	Left	Right	Left vs. right L8	Left vs. right L5	Left vs. right L2	L8 vs. L5 Left	L8 vs. L5 Right	L8 vs. L2 Left	L8 vs. L2 Right	L5 vs. L2 Left	L5 vs. L2 Right
Absolute speed ($m \cdot s^{-1}$)	9.58 ± 0.45	9.51 ± 0.43	9.40 ± 0.53	9.34 ± 0.53	9.35 ± 0.63	9.32 ± 0.65	*	*		*		*			
Directional step length (m)	2.15 ± 0.09	2.14 ± 0.11	2.13 ± 0.11	2.12 ± 0.10	2.17 ± 0.09	2.15 ± 0.12									
Race step length (m)	2.13 ± 0.08	2.12 ± 0.11	2.10 ± 0.11	2.10 ± 0.10	2.15 ± 0.09	2.13 ± 0.12								#	
Step frequency (Hz)	4.48 ± 0.19	4.48 ± 0.18	4.45 ± 0.21	4.43 ± 0.17	4.35 ± 0.25	4.36 ± 0.22								*	
Ground contact time (s)	0.116 ± 0.006	0.109 ± 0.006	0.119 ± 0.009	0.111 ± 0.009	0.121 ± 0.008	0.111 ± 0.008	#	#	§			#			
Flight time (s)	0.113 ± 0.009	0.109 ± 0.009	0.112 ± 0.010	0.109 ± 0.006	0.117 ± 0.012	0.111 ± 0.008									
Step contact factor	0.505 ± 0.027	0.499 ± 0.028	0.516 ± 0.031	0.504 ± 0.028	0.508 ± 0.031	0.500 ± 0.024		*							
Touchdown distance (m)	0.38 ± 0.04	0.34 ± 0.04	0.39 ± 0.04	0.33 ± 0.04	0.39 ± 0.03	0.32 ± 0.05	§	§	§						
Body sagittal lean ROM (°)	57.0 ± 3.2	53.6 ± 3.6	58.0 ± 3.0	53.9 ± 3.7	58.4 ± 3.2	53.4 ± 3.5	§	§	§						
Body lateral lean at TD (°)	-8.4 ± 1.5	-12.7 ± 2.4	-9.4 ± 2.2	-14.2 ± 1.8	-9.9 ± 2.5	-15.1 ± 1.9	#	§	§	*	*	*	#		*
Body lateral lean at TO (°)	-6.8 ± 1.1	-12.3 ± 2.2	-7.5 ± 1.7	-13.2 ± 1.8	-7.5 ± 2.0	-14.1 ± 2.0	§	§	§				#		
Turn of CoM (°)	4.0 ± 0.7	1.7 ± 0.6	4.4 ± 1.1	2.4 ± 0.6	4.3 ± 0.7	2.5 ± 0.4	§	#	#		*		#		

***** Significant at $p < 0.05$; # significant at $p < 0.01$; § significant at $p < 0.001$. L8: Lane 8; L5: Lane 5; L2: Lane 2

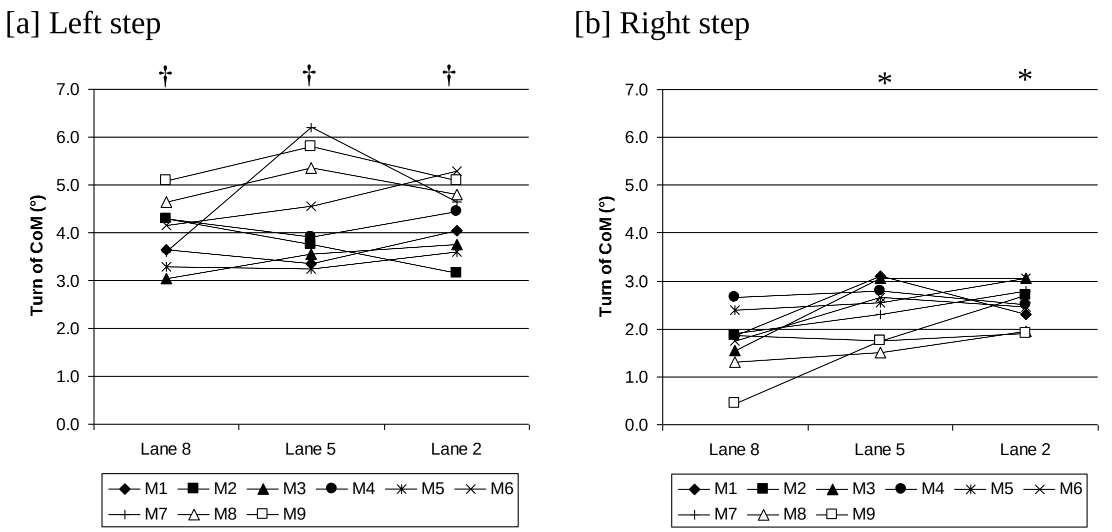


Figure 5.2. Turn of the CoM during [a] the left step and [b] the right step for all athletes in lanes 8, 5 and 2. Group data: † significantly different between left and right within lane (p < 0.01), * significantly different to lane 8 (p < 0.05).

Touchdown distance, thigh separation at touchdown, and body sagittal lean ROM were not statistically significantly affected by the lane, although statistically significant asymmetries between left and right within a lane were seen for all three variables (Tables 5.1-5.2). There was generally significantly increased inward (more negative) body lateral lean at touchdown as radius decreased for both the left and right steps (Figure 5.3, Table 5.1). There were few statistically significant differences between lanes for hip kinematics, although asymmetries within a lane were present for a number of variables (Table 5.3). Knee kinematics were also generally similar from lane to lane, with asymmetries between left and right step being seen for the maximum knee angle during contact in lane 2 and for the knee angle at take off in lane 5 and 2 (Table 5.4). There were no statistically significant lane effects for the ankle, MTP, or rearfoot kinematics (Tables 5.5-5.7). Generally upper body kinematics were similar in each lane, although shoulder abduction/adduction ROM in lane 8 was statistically significantly larger than in lanes 5 and 2 during the left step, and statistically significantly lower than in lane 5 during the right step (Table 5.8).

Table 5.2. Left and right step group mean values (± SD) and significant differences for touchdown variables during bend running in lanes 8, 5, and 2.

	Lane 8		Lane 5		Lane 2		Significant differences								
	Left	Right	Left	Right	Left	Right	Left vs. right L8	Left vs. right L5	Left vs. right L2	L8 vs. L5 Left	L8 vs. L5 Right	L8 vs. L2 Left	L8 vs. L2 Right	L5 vs. L2 Left	L5 vs. L2 Right
Thigh separation at TD (°)	25.1 ± 9.2	18.9 ± 11.1	25.5 ± 8.7	19.4 ± 9.8	27.1 ± 7.8	17.0 ± 9.3	*	*	#						
Foot horizontal velocity at TD ($m\cdot s^{-1}$)	2.66 ± 0.50	2.46 ± 0.77	2.53 ± 0.43	2.26 ± 0.72	2.34 ± 0.84	2.05 ± 0.92							*		
Foot horizontal velocity relative to the CoM at TD ($m\cdot s^{-1}$)	-6.90 ± 0.56	-7.04 ± 0.73	-6.85 ± 0.60	-7.11± 0.69	-6.97 ± 0.74	-7.27 ± 0.83									
Foot vertical velocity at TD ($m\cdot s^{-1}$)	-1.93 ± 0.20	-1.98 ± 0.17	-2.05 ± 0.23	-2.05 ± 0.15	-2.00 ± 0.24	-1.98 ± 0.23									
Trunk forward lean at TD (°)	-5.7 ± 4.1	-7.3 ± 2.5	-7.1 ± 4.0	-6.8 ± 2.9	-7.5 ± 3.2	-7.1 ± 1.7									
Trunk lateral lean at TD (°)	-13.5 ± 2.2	-7.5 ± 2.8	-13.2 ± 2.8	-8.1 ± 2.3	-13.7 ± 3.0	-8.7 ± 3.4	§	§	§						

***** Significant at $p < 0.05$; # significant at $p < 0.01$; § significant at $p < 0.001$. L8: Lane 8; L5: Lane 5; L2: Lane 2.

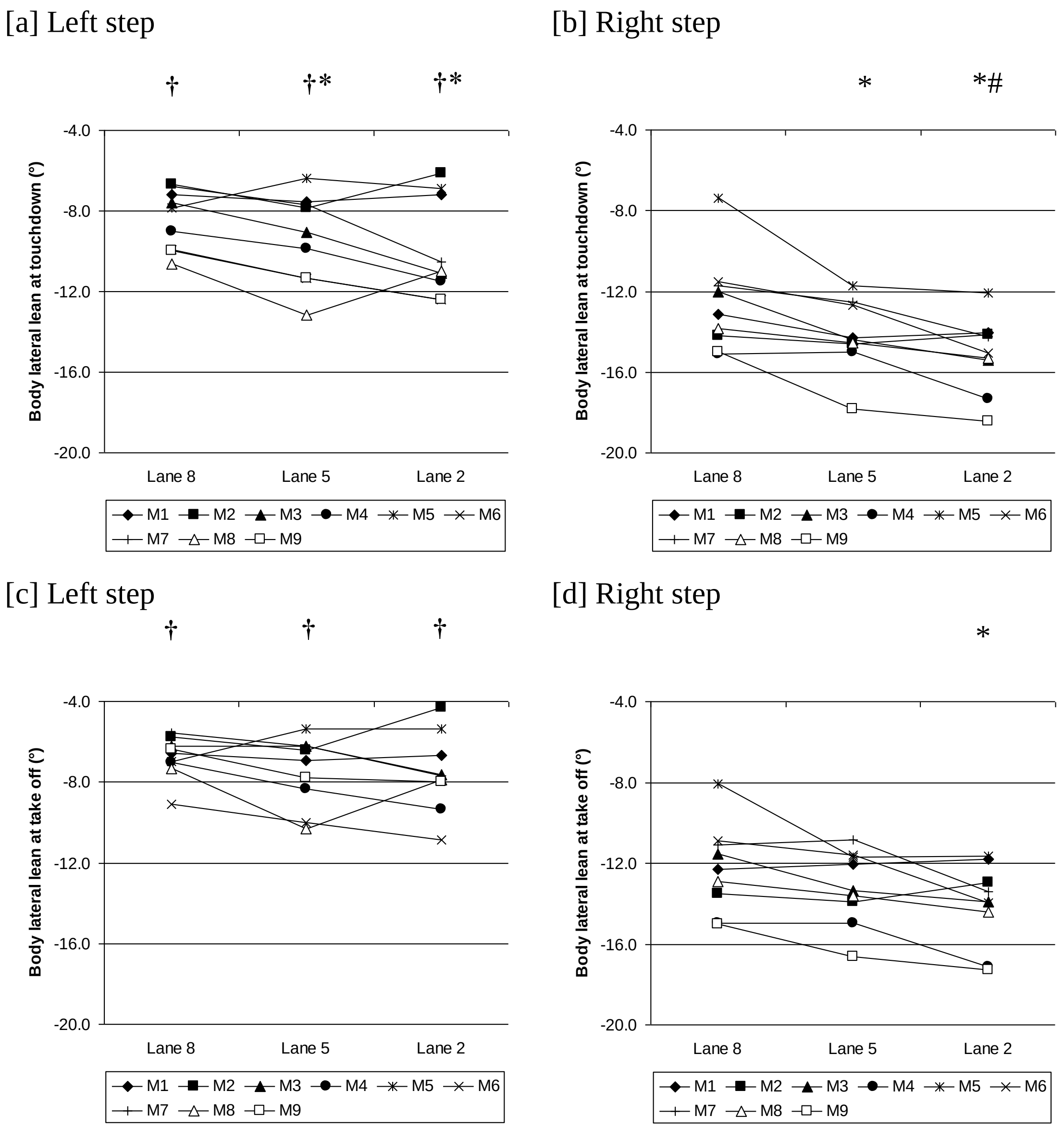


Figure 5.3. [a] Left and [b] right body lateral lean at touchdown for all athletes in lanes 8, 5 and 2. [c] Left and [d] right body lateral lean at take off for all athletes in lanes 8, 5 and 2. Group data: † significantly different between left and right within lane ($p < 0.01$), * significantly different to lane 8 ($p < 0.05$), # significantly different to lane 5 ($p < 0.05$).

Table 5.3. Left and right step group mean values (± SD) and significant differences for hip angles and angular velocities during bend running in lanes 8, 5, and 2.

	Lane 8		Lane 5		Lane 2		Significant differences								
	Left	Right	Left	Right	Left	Right	Left vs. right L8	Left vs. right L5	Left vs. right L2	L8 vs. L5 Left	L8 vs. L5 Right	L8 vs. L2 Left	L8 vs. L2 Right	L5 vs. L2 Left	L5 vs. L2 Right
Hip flexion/extension angle at TO (°)	210.3 ± 5.1	205.4 ± 3.5	210.4 ± 5.9	205.9 ± 4.7	211.6 ± 5.3	205.9 ± 4.5	#	*	#						
Hip flexion/extension angle at full extension (°)	211.4 ± 4.6	207.1 ± 3.7	211.5 ± 5.3	207.6 ± 4.5	212.6 ± 4.8	207.4 ± 4.7	#	*	#						
Time of hip full extension (% of step time)	52.9 ± 3.5	54.0 ± 4.0	54.2 ± 4.0	54.4 ± 3.4	53.6 ± 3.6	54.1 ± 3.7									
Hip flexion/extension angle at full flexion (°)	104.0 ± 5.6	110.2 ± 5.2	103.6 ± 5.9	110.7 ± 4.4	103.6 ± 4.9	110.1 ± 4.4	#	§	§						
Time of hip full flexion (% of contralateral limb step time)	48.1 ± 4.5	49.6 ± 4.9	48.9 ± 4.7	50.2 ± 4.6	47.7 ± 4.5	50.6 ± 5.0									
Hip abduction/adduction angle at TD (°)	-1.5 ± 3.0	-8.1 ± 5.3	0.4 ± 3.2	-8.0 ± 5.2	0.1 ± 3.2	-8.5 ± 5.1	#	§	#						
Hip peak abduction (°)	-7.8 ± 3.3	-9.5 ± 4.1	-7.6 ± 2.6	-9.7 ± 3.0	-7.8 ± 4.0	-11.1 ± 3.5									
Time of hip peak abduction (% of contact phase)	90.3 ± 14.0	21.1 ± 39.7	94.3 ± 5.2	26.1 ± 31.8	94.4 ± 4.1	50.1 ± 40.4	#	§	#						
Hip peak adduction (°)	9.1 ± 4.9	1.7 ± 3.9	10.8 ± 3.4	0.9 ± 3.2	10.4 ± 4.6	-0.1 ± 2.7	#	§	§						
Time of hip peak adduction (% of contact phase)	37.9 ± 5.3	44.8 ± 14.7	37.8 ± 4.3	45.1 ± 12.9	40.0 ± 2.3	44.4 ± 24.0									
Hip abduction/adduction angle at TO (°)	-7.3 ± 3.3	-4.2 ± 3.7	-6.9 ± 2.5	-5.9 ± 3.0	-7.2 ± 4.2	-7.6 ± 3.3							#		

Table 5.3. - *continued*

	Lane 8		Lane 5		Lane 2		Significant differences								
	Left	Right	Left	Right	Left	Right	Left vs. right L8	Left vs. right L5	Left vs. right L2	L8 vs. L5 Left	L8 vs. L5 Right	L8 vs. L2 Left	L8 vs. L2 Right	L5 vs. L2 Left	L5 vs. L2 Right
Hip flexion/extension angular velocity at TD (°·s^{-1})	437 ± 105	218 ± 157	414 ± 137	239 ± 175	397 ± 122	264 ± 129	*		*						
Hip peak extension angular velocity during contact (°·s^{-1})	910 ± 124	898 ± 89	898 ± 109	904 ± 108	894 ± 141	921 ± 124									
Time of peak extension angular velocity (% of contact phase)	67.1 ± 6.7	66.9 ± 11.6	58.5 ± 11.9	64.1 ± 9.9	60.2 ± 12.5	65.9 ± 11.4									
Peak hip flexion angular velocity during swing (°·s^{-1})	-948 ± 58	-876 ± 122	-979 ± 45	-885 ± 95	-932 ± 66	-887 ± 65		*							
Time of peak hip flexion angular velocity (% of contralateral limb contact phase)	18.8 ± 16.4	28.4 ± 11.6	13.8 ± 13.4	37.2 ± 16.1	12.6 ± 12.5	24.1 ± 19.3		*							

***** Significant at $p < 0.05$; # significant at $p < 0.01$; § significant at $p < 0.001$. L8: Lane 8; L5: Lane 5; L2: Lane 2.

Table 5.4. Left and right step group mean values (± SD) and significant differences for knee angles and angular velocities during bend running in lanes 8, 5, and 2.

	Lane 8		Lane 5		Lane 2		Significant differences								
	Left	Right	Left	Right	Left	Right	Left vs. right L8	Left vs. right L5	Left vs. right L2	L8 vs. L5 Left	L8 vs. L5 Right	L8 vs. L2 Left	L8 vs. L2 Right	L5 vs. L2 Left	L5 vs. L2 Right
Knee angle at TD (°)	155.1 ± 2.8	155.9 ± 5.6	156.6 ± 3.8	156.5 ± 4.2	155.9 ± 2.7	157.4 ± 3.1									
Knee angular velocity at TD ($°·s^{-1}$)	-113 ± 99	-152 ± 167	-75 ± 91	-184 ± 146	-120 ± 143	-208 ± 141									
Minimum knee angle during contact (°)	139.6 ± 5.3	140.0 ± 5.1	141.5 ± 7.1	141.3 ± 4.5	140.0 ± 5.8	142.4 ± 4.5							*		
Time of minimum knee angle (% of contact phase)	45.4 ± 5.6	44.3 ± 5.6	43.8 ± 8.4	41.6 ± 9.6	46.4 ± 3.7	42.2 ± 6.1									
Knee range of flexion (°)	15.5 ± 4.7	15.9 ± 4.5	15.0 ± 5.6	15.2 ± 5.0	15.9 ± 4.1	15.0 ± 3.5									
Maximum knee angle during contact (°)	161.0 ± 5.1	162.3 ± 3.5	161.7 ± 5.2	164.8 ± 3.5	161.9 ± 6.4	164.9 ± 3.8			*		*		*		
Time of maximum knee angle (% of contact phase)	95.0 ± 2.8	95.1 ± 3.6	92.0 ± 5.4	95.0 ± 4.6	94.1 ± 4.0	92.6 ± 5.3									
Knee range of extension (°)	21.4 ± 5.5	22.3 ± 6.0	20.2 ± 6.2	23.5 ± 5.7	21.9 ± 5.0	22.5 ± 6.1									
Knee angle at TO (°)	159.6 ± 4.9	161.2 ± 3.4	159.1 ± 4.4	163.2 ± 3.6	160.0 ± 5.2	163.1 ± 4.8		*	*				*		
Knee angle at full flexion (°)	40.4 ± 10.3	40.5 ± 6.9	39.7 ± 8.8	40.2 ± 7.5	38.8 ± 8.3	38.3 ± 7.6									
Time of knee full flexion (% of contralateral step time)	14.9 ± 4.7	16.6 ± 5.2	15.8 ± 5.1	16.8 ± 2.9	14.5 ± 6.1	15.4 ± 3.6									

***** Significant at $p < 0.05$. L8: Lane 8; L5: Lane 5; L2: Lane 2.

Table 5.5. Left and right step group mean values (± SD) and significant differences for ankle angles during bend running in lanes 8, 5, and 2.

	Lane 8		Lane 5		Lane 2		Significant differences								
	Left	Right	Left	Right	Left	Right	Left vs. right L8	Left vs. right L5	Left vs. right L2	L8 vs. L5 Left	L8 vs. L5 Right	L8 vs. L2 Left	L8 vs. L2 Right	L5 vs. L2 Left	L5 vs. L2 Right
Ankle angle at TD (°)	129.5 ± 4.1	132.8 ± 6.5	131.1 ± 4.7	132.8 ± 4.6	131.5 ± 5.0	133.8 ± 6.4									
Minimum ankle angle during contact (°)	91.6 ± 4.0	97.3 ± 3.7	92.7 ± 4.9	97.2 ± 3.6	91.8 ± 4.6	97.7 ± 2.9	#	#	#						
Time of minimum ankle angle (% of contact phase)	46.4 ± 2.9	45.4 ± 3.0	46.3 ± 3.3	46.2 ± 4.0	45.6 ± 2.9	46.5 ± 4.5									
Ankle range of dorsiflexion (°)	37.9 ± 1.5	35.5 ± 5.6	38.4 ± 3.4	35.6 ± 5.8	39.7 ± 2.8	36.1 ± 5.1			*						
Ankle angle at TO (°)	144.5 ± 4.6	147.7 ± 3.9	145.0 ± 5.8	148.6 ± 4.0	146.2 ± 3.9	150.0 ± 3.2									
Ankle range of plantarflexion (°)	52.9 ± 4.6	50.4 ± 6.4	52.4 ± 3.9	51.4 ± 5.4	54.4 ± 2.1	52.3 ± 4.8									

***** Significant at $p < 0.05$; [#] significant at $p < 0.01$. L8: Lane 8; L5: Lane 5; L2: Lane 2.

Table 5.6. Left and right step group mean values (± SD) and significant differences for MTP angles and angular velocities during bend running in lanes 8, 5, and 2.

	Lane 8		Lane 5		Lane 2		Significant differences								
	Left	Right	Left	Right	Left	Right	Left vs. right L8	Left vs. right L5	Left vs. right L2	L8 vs. L5 Left	L8 vs. L5 Right	L8 vs. L2 Left	L8 vs. L2 Right	L5 vs. L2 Left	L5 vs. L2 Right
MTP angle at TD (°)	135.8 ± 3.8	134.7 ± 4.6	133.1 ± 6.1	137.0 ± 5.8	134.8 ± 4.9	136.7 ± 6.6		*							
Maximum MTP angle during absorption phase of contact (°)	152.2 ± 3.3	152.9 ± 4.2	151.9 ± 3.9	154.7 ± 4.5	152.6 ± 4.7	154.3 ± 4.3									
Time of maximum MTP angle during absorption phase of contact (% of contact)	23.4 ± 4.2	26.4 ± 4.5	23.8 ± 5.0	27.3 ± 4.6	24.2 ± 5.3	26.9 ± 4.6									
MTP range of plantarflexion during absorption phase (°)	16.4 ± 3.4	18.2 ± 5.8	18.8 ± 5.6	17.7 ± 8.2	17.9 ± 5.4	17.6 ± 7.9									
Minimum MTP angle during contact (°)	118.0 ± 3.5	119.3 ± 3.8	118.6 ± 4.1	121.6 ± 5.0	117.6 ± 4.2	121.7 ± 6.8									
Time of minimum MTP angle (% of contact phase)	80.4 ± 4.0	79.6 ± 2.7	80.4 ± 1.2	81.4 ± 4.0	80.0 ± 1.8	80.6 ± 3.5									
MTP range of dorsiflexion (°)	34.2 ± 3.3	33.6 ± 5.4	33.3 ± 5.1	33.1 ± 6.5	35.1 ± 3.3	32.6 ± 8.4									
MTP angle at TO (°)	138.5 ± 5.0	138.9 ± 2.9	139.9 ± 4.3	139.3 ± 5.9	140.1 ± 4.4	139.4 ± 4.7									
MTP range of plantarflexion during extension phase (°)	20.5 ± 7.1	19.6 ± 5.2	21.3 ± 4.6	17.7 ± 7.3	22.5 ± 7.2	17.6 ± 7.6			#						
Peak MTP plantarflexion angular velocity ($°\cdot s^{-1}$)	1317 ± 292	1200 ± 347	1233 ± 244	1201 ± 348	1285 ± 378	1149 ± 446									

***** Significant at $p < 0.05$; # significant at $p < 0.01$. L8: Lane 8; L5: Lane 5; L2: Lane 2.

Table 5.7. Left and right step group mean values (± SD) and significant differences for rearfoot angles during bend running in lanes 8, 5, and 2.

	Lane 8		Lane 5		Lane 2		Significant differences								
	Left	Right	Left	Right	Left	Right	Left vs. right L8	Left vs. right L5	Left vs. right L2	L8 vs. L5 Left	L8 vs. L5 Right	L8 vs. L2 Left	L8 vs. L2 Right	L5 vs. L2 Left	L5 vs. L2 Right
Rearfoot angle at TD (°)	33.9 ± 4.3	37.1 ± 4.9	33.8 ± 4.7	37.3 ± 4.2	34.5 ± 4.5	38.1 ± 4.2			#						
Minimum rearfoot angle during contact (°)	30.9 ± 3.0	29.3 ± 3.1	30.3 ± 3.8	29.7 ± 3.3	30.5 ± 4.9	29.7 ± 3.0									
Time of minimum rearfoot angle (% of contact phase)	21.2 ± 5.4	25.3 ± 7.0	20.0 ± 6.7	28.6 ± 3.9	17.2 ± 9.0	27.3 ± 4.0	*	#	#						
Rearfoot drop (°)	3.0 ± 2.4	7.8 ± 3.7	3.5 ± 2.2	7.6 ± 3.3	4.0 ± 3.8	8.5 ± 3.4	#	#	§						
Rearfoot angle at TO (°)	112.2 ± 6.2	109.3 ± 5.6	112.8 ± 6.4	109.8 ± 4.1	113.6 ± 4.0	111.4 ± 3.8									
Rearfoot lift (°)	81.4 ± 6.6	80.0 ± 7.0	82.6 ± 6.1	80.1 ± 5.8	83.1 ± 4.6	81.7 ± 5.9									

***** Significant at $p < 0.05$; # significant at $p < 0.01$; § significant at $p < 0.001$. L8: Lane 8; L5: Lane 5; L2: Lane 2.

Table 5.8. Left and right step group mean values (± SD) and significant differences for upper body kinematics during bend running in lanes 8, 5, and 2.

	Lane 8		Lane 5		Lane 2		Significant differences								
	Left	Right	Left	Right	Left	Right	Left vs. right L8	Left vs. right L5	Left vs. right L2	L8 vs. L5 Left	L8 vs. L5 Right	L8 vs. L2 Left	L8 vs. L2 Right	L5 vs. L2 Left	L5 vs. L2 Right
Maximum thorax rotation (°)	36.9 ± 3.6	38.9 ± 8.0	38.9 ± 6.1	37.2 ± 6.2	37.1 ± 4.6	39.2 ± 5.9									
Shoulder flexion/extension ROM (°)	93.9 ± 11.4	91.8 ± 14.6	93.0 ± 9.7	88.8 ± 14.1	90.9 ± 13.5	90.8 ± 16.4									
Shoulder abduction/adduction ROM (°)	35.7 ± 6.4	27.5 ± 5.8	31.1 ± 7.0	31.1 ± 6.8	29.7 ± 7.4	30.1 ± 8.1	#			#	#	*			
Elbow ROM (°)	86.5 ± 8.1	110.8 ± 9.4	86.6 ± 8.5	108.2 ± 8.1	90.0 ± 6.9	106.5 ± 7.7	§	§	§						
Minimum wrist position [relative to CoM] in ML direction (m)	0.095 ± 0.028	0.095 ± 0.026	0.100 ± 0.027	0.086 ± 0.032	0.103 ± 0.020	0.088 ± 0.032									
Maximum wrist position [relative to CoM] in ML direction (m)	0.317 ± 0.037	0.362 ± 0.039	0.316 ± 0.036	0.362 ± 0.037	0.320 ± 0.045	0.366 ± 0.035	#	*	*						
Minimum wrist position [relative to CoM] in AP direction (m)	-0.301 ± 0.041	-0.304 ± 0.056	-0.309 ± 0.061	-0.285 ± 0.082	-0.309 ± 0.057	-0.287 ± 0.054									
Maximum wrist position [relative to CoM] in AP direction (m)	0.304 ± 0.036	0.297 ± 0.019	0.302 ± 0.044	0.298 ± 0.024	0.300 ± 0.037	0.299 ± 0.019									
Minimum wrist position [relative to CoM] in vertical direction (m)	-0.080 ± 0.042	-0.083 ± 0.026	-0.077 ± 0.038	-0.082 ± 0.028	-0.079 ± 0.031	-0.083 ± 0.021									
Maximum wrist position [relative to CoM] in vertical direction (m)	0.365 ± 0.045	0.355 ± 0.055	0.357 ± 0.047	0.360 ± 0.057	0.358 ± 0.043	0.365 ± 0.054									

***** Significant at $p < 0.05$; # significant at $p < 0.01$; § significant at $p < 0.001$. L8: Lane 8; L5: Lane 5; L2: Lane 2.

5.4. Discussion

The aim of the study was to understand how technique and performance are affected during maximal effort sprinting on the bend in different lanes with radii typical of those experienced in athletic sprint events. There was a 2.1% and 2.0% decrease in race velocity from lane 8 to lane 5 for the left and right steps, respectively. Compared to lane 8, there was a 2.3% and 2.0% decrease in race velocity in lane 2 for the left and right steps, respectively (Table 5.1). This trend is in agreement with mathematical models which have proposed athletes in the inner lanes are at a disadvantage since they are unable to achieve the velocities they otherwise would in outer lanes (Jain, 1980; Greene, 1985; Usherwood & Wilson, 2006). Comparison of the magnitude of the decrease in performance with previous studies and mathematical models of bend running are difficult because of differences in methodology and focus of those studies.

To the author's knowledge, the only experimental study which has reported velocities of athletes sprinting maximally at bend radii typical of those used in outdoor athletic events is that of Ryan and Harrison (2003). However, the results of that study should be considered with caution due to limitations in the methodology. For example, velocity was calculated as the product of step length and step frequency and methodological issues may have compromised the accuracy of these variables. Step frequency was calculated as the inverse of step time, which itself was calculated from 50 Hz video data. This, alongside any errors in the identification of the field of touchdown, may have reduced the accuracy to which it could be calculated. Additionally, step length was calculated at the distance between the toe markers at consecutive touchdowns, but the 2D nature of the study meant that the direction of travel of the athlete within a lane, the effect of step width, and the fact that athletes may have been running anywhere within the lane (the width of which is 1.22 m) were not accounted for. This may have introduced potential errors in step length calculation.

Mathematical models have tended to focus on the effect the bend radius has on race times, with differences in 200 m race times between lane 1 (radius 38.50 m) and lane 7 (radius 45.72 m) of an outdoor track suggested as 0.069 s (Jain, 1980) or 0.123 s (Greene, 1985) depending on the model used. With regards to the present study, the effect on 200 m race times of the percentage decreases in race velocity during the maximal speed phase of bend sprinting can be estimated using a number of assumptions and simplifications. On a standard outdoor track the distance run on the bend is approximately 115 m for all lanes (IAAF, 2008). If it is assumed that the lane draw has no effect on the time taken to run the final 85 m (along the straight), that the bend has no effect on velocity in the acceleration phase, and that the velocities measured in the present study are maintained for the entire bend from 40 m onwards, the effect of the bend on race time can be estimated. The average race velocity of the left and right steps in lane 8 was 9.53 $m \cdot s^{-1}$. This equates to a time of 7.87 s to cover the 75 m maximal speed phase on the bend (from 40 m to 115 m). The average race velocity over the left and right steps was 9.33 $m \cdot s^{-1}$ in lane 5 equating to a time of 8.04 s to cover the 75 m, and in lane 2 the average race velocity was 9.32 $m \cdot s^{-1}$ equating to a 75 m time of 8.05 s. Using these estimates, the difference in race times between lane 8 and lane 5 would be 0.170 s and between lane 8 and lane 2 it would be 0.180 s.

The estimated difference in race times above are larger than the predicted difference between lanes 1 and 7 given by Jain (1980) and Greene (1985), and as mentioned, does not take into account any affect that bend radius has on the acceleration phase, which would likely make the differences even larger, since Stoner and Ben-Sira (1979) found velocity to be reduced on the bend compared to the straight during the acceleration phase of sprinting. Additionally, since the velocity would be lower coming off the bend into the straight in the inner lanes, the straight line velocity would also be affected, further increasing the difference between the inside and outside lanes. It is acknowledged that none of the mathematical models takes into account tactics or psychological factors of a race, and it is likely that the magnitude of the effect of the bend will be different for different athletes, depending on their ability to run the bend effectively. This notwithstanding, it is interesting to consider the effect of the bend on race times, since this is the ultimate measure of performance for athletes.

Examination of the absolute speed and race velocity results in the present study suggests there is possibly a non-linear relationship in the effect of the lane on velocity (Figure 5.1, Table 5.1). The effect sizes for this variable also support this.

Moderate effect sizes were seen in the difference between lane 8 and lane 5 and between lane 8 and lane 2, but the difference between lane 5 and lane 2 was only small. The standard deviation of the absolute speed and race velocity showed that variability increased as bend radius decreased. This suggests that some athletes coped better than others with the demands of the tighter bend and gives further evidence to support the fact that some athletes are better than others at maintaining their velocity on the bend compared to the straight as seen in Chapter 4. This might be linked to an athlete's ability to sustain force when frontal plane kinematics are altered because of the lean. It should be borne in mind, however, that the present study comprised of only three lane conditions and nine athletes. More athletes, trials and lanes would need to be studied before firmer conclusions regarding linearity of the effect of the lane on velocity can be drawn.

There was a general trend for step frequency to decrease as radius decreased for both the left and right steps, where mean step frequency reduced from 4.48 Hz for both left and right steps in lane 8 to 4.35 Hz and 4.36 Hz, respectively, in lane 2 (Table 5.1). The mathematical model of Usherwood and Wilson (2006) suggested that the reason for a decrease in velocity as radius decreases is that step frequency decreases. It was postulated that the requirement to generate centripetal force on the bend meant that athletes would spend longer in ground contact, with flight times remaining constant. Thus, duty factor (the proportion of stride time spent in contact with the ground) would increase and overall step frequency would reduce. Examination of the step frequency results in the present study initially appears to support this suggestion. However, the ground contact time and step contact factor results suggest that Usherwood and Wilson's (2006) model, whilst a good predictor of race times, may be an oversimplification. Duty factor could not be calculated in the current study, as it would require three full steps to be recorded in order to obtain two full strides, which would have required such a large field of view that the digitisation accuracy would have been reduced to an unacceptable level. However, an artificial duty factor can be calculated by dividing ground contact time by the sum of ipsilateral flight time, contralateral ground contact time and contralateral flight time, although it is accepted that this is an approximation as the contralateral flight and contact times could come from a different stride. Artificial duty factor for the left stride was similar between lanes at 0.348, 0.359, and 0.356 for lanes 8, 5 and 2, respectively. Right stride artificial duty factors were lower than for the left, but were, again, similar between lanes at 0.322, 0.326 and 0.317 for lane 8, 5 and 2, respectively. Thus, the duty factor model did not fully explain changes in step frequency in the current study. In fact, there was an increase in ground contact time as bend radius decreased for the left step and ground contact times for the right step were similar between lanes, but flight times were not consistent and this affected step frequency (Table 5.1).

The shortest mean race and directional step lengths were seen in lane 5 for both the left and right steps with the longest steps seen in lane 2 (Table 5.1). The only significant difference for step length variables was between lane 5 and lane 2, where left race step length was 0.05 m longer in lane 2 than in lane 5 ($p < 0.01$). The significant increase in left race step length from lane 5 to lane 2 was accompanied by a significant decrease in step frequency ($p < 0.05$, Table 5.1). It is possible that when running in lane 2 the athletes may have tried to compensate for the tightness of the bend by increasing step length, but this had the detrimental effect of reducing step frequency, or vice versa. Negative interaction of this kind has been observed in straight line sprinting (Hunter et al., 2004a).

During bend running athletes need to alter their direction of motion in order to follow the curved path. As the radius is smaller in inner lanes than in the outer lanes, the amount of turning an athlete must achieve is consequently greater in the inner lanes than the outer lanes. There was less turning in lane 8 than in lanes 5 and 2 for both the right and left steps, although the only differences to reach statistical significant were for the right steps in lane 5 and 2, which were significantly greater than the right step in lane 8 ($p < 0.005$, Table 5.1). There were, however, statistically significant differences for the amount of turning achieved between the left and right ground contact phases in each lane studied (Table 5.1). Examination of individual results showed that for all athletes less turning was achieved during the right contact than the left in all lanes (Figure 5.2). This was consistent with the results of Chapter 3, where an asymmetry between turn of the CoM for the left and right ground contacts was seen in bend sprinting in lane 2, and suggests that this asymmetry is present regardless of bend radius. Normalisation to ground contact time reveals that the difference in turn of the centre of mass between left and right steps within a lane is not simply due to differences in ground contact time and indicates that there are functional differences in the centripetal force generation of the left and right steps.

Similarly to the results of Chapter 3, asymmetries in body lateral lean were accompanied by asymmetries in hip abduction/adduction angles. Statistically significant differences between left and right were seen in each lane for hip abduction/adduction at touchdown and at peak adduction, with the left hip being less abducted/more adducted at these events, compared to the right (Table 5.3). It has been suggested that the requirement for joint stabilisation in the frontal plane increases during bend running, compared to straight line running and that this may limit the leg extension force (Chang & Kram, 2007). The asymmetry between left and right increased as bend radius decreased in the present study (Table 5.3). It is possible, therefore, that at smaller radii, where there is increased inward lean (Table 5.1) there is an increased requirement for frontal plane stabilisation, and increased asymmetry between left and right which may reduce extensor forces, and thus performance, as radius decreases.

Touchdown distance, thigh separation at touchdown, and body sagittal lean ROM were not statistically significantly affected by lane, however, there were statistically significant asymmetries between left and right steps within each lane. This was true also for a number of other variables including a number of hip kinematic variables (Table 5.3), minimum ankle angle during contact (Table 5.5) and some rearfoot and upper body kinematics (Tables 5.7-5.8) where asymmetries were present between left and right steps at all radii. The results showed few statistically significant differences between lanes for the hip, knee and upper body kinematics, and none for the ankle, MTP and rearfoot kinematics. The results of Chapter 3 showed that the requirement to lean into the bend caused asymmetrical changes to technique. The results of the present study support this and show that these asymmetries are present even in the outer lane of a standard outdoor track. The negative changes to performance descriptors generally increase as radius decreases, but the same pattern does not seem to be true of upper and lower body kinematics. Athletes and coaches should apply the principle of specificity of training, and ensure that the demands of bend sprinting are met, paying particular attention to technique changes which occur on the bend compared to the straight, such as those brought about by the necessity to lean into the bend. The amount of inward lean increased as bend radius decreased, and this is likely to reduce an athlete's ability to generate vertical and propulsive force, because of the increased requirement to stabilise in the frontal plane, and may require lane specific training to meet these demands. However, the fact that technique appears to be similar in all lanes studied means that training effects of one lane are likely transferable to other lanes, meaning athletes do not necessarily need to 'over-train' in any particular lane, but, instead, should train in all lanes over the season.

One of the limitations of the study was that only two trials were undertaken in each lane. This was in order to obtain data from athletes in three different lanes during a single data collection. Averaging of two trials means that an anomalous result in one trial has a larger effect on the average than it would had more trials been averaged. Whilst it may have been desirable to have more trials, it was deemed following consultation with coaches that 6 maximal effort 60 m sprints was the most that could be asked of the athletes in a single training session before fatigue may have become a confounding variable. Examination of the results showed that results between trials in a particular lane were similar, thus, in the author's opinion, averaging of only two trials was not problematic.

Following the problems in Chapter 3, where certain landmarks were out of the field of view in the 'padding' video fields for some trials, the field of view was increased from the 7.5 m long used in Chapter 3 to 8.0 m long in the present study. Data were, again, collected at a resolution of 1280 x 1024 pixels, and subsequently digitised at full resolution, with a 2x zoom factor. In this study, a field of view 8.0 m long meant that the resolution of measurement was slightly larger at, 0.0031 m. Similarly to Chapter 3, this may have introduced potential errors in the identification of landmarks, which is a possible limitation of the study. However, it was deemed that the slight decrease in resolution of measurement was offset by the improvement in having all landmarks available for digitising in all fields in the majority of trials.

Conclusion

In general velocity has been shown to decrease as bend radius decreases, but this may not be a linear relationship. There was greater variability in velocities achieved as bend radius decreased, which may indicate athletes were differently able to meet the demands of the tighter bend radius. This may be related to their ability to withstand the increased force requirements of sprinting at a tighter bend radius. The results of the present study show that the effect of the bend during maximal speed sprinting was more complicated than mathematical models have previously suggested. There were changes to step frequency, but these were brought about by changes to ground contact time and flight time, and not just because of changes to ground contact time as has previously been suggested (Usherwood & Wilson, 2006). Inward lean increased as bend radius decreased, and this may affect an athlete's ability to generate vertical and propulsive force at tighter bend radii. Furthermore, there was an asymmetrical effect of the bend on a number of kinematics, but these were present in all lanes regardless of radii. This means training needs to be specific for bend running and training effects are likely transferable between lanes, but it would be good practice to train across all of the lanes over the course of a season.

Chapters 3-5 have provided valuable information about the kinematics of bend sprinting compared to the straight and also as bend radius changes, which were otherwise lacking in the literature. However, since forces cause movement, kinetic analyses are required in order to fully understand bend sprinting.

CHAPTER 6: FORCE PRODUCTION DURING MAXIMAL EFFORT SPRINTING ON THE BEND

6.1. Introduction

The force requirements of straight line sprinting have been well documented during the acceleration phase (e.g. Mero, 1988; Hunter et al., 2005; Salo et al., 2005) and the maximal speed phase (e.g. Mann, 1985; Mero & Komi, 1986; Weyand et al., 2000). There is, however, a paucity of literature concerning the forces produced during bend sprinting. This is despite a large proportion of 200 m and 400 m sprint events being run around the bend.

Athletes running the bend portion of a race must generate sufficient centripetal force in order to follow the curved path and remain within their lane. This places additional force demands on the athlete compared with straight line sprinting. It has been suggested that velocity on the bend is reduced, relative to the straight, because athletes have to increase the time spent in ground contact in order to meet these additional requirements (Usherwood & Wilson, 2006). The model of Usherwood and Wilson (2006) assumed that athletes running on the bend would be able to generate the same absolute maximum force on the straight, however, no experimental measures were made of the forces produced. Empirical research into maximal speed sprinting on bends of very small radii (1-6 m) has, in fact, found athletes to be unable to achieve the resultant and vertical forces on the bend that they were capable of during straight line sprinting (Chang & Kram, 2007). Even during slower running (approximately 6.31 $m \cdot s^{-1}$) on larger radii typical of an athletics track, vertical force production has been observed to be reduced compared to straight line running (Hamill et al., 1987). There have been, to the author's knowledge, no studies of force production during maximal effort sprinting on the bend on surfaces and at radii typical of athletic sprint events. With this in mind, the first aim of this study was to understand the changes that occur to force production which may contribute to changes seen in direct performance descriptors (Chapter 3) while running at maximal effort on the bend compared to the straight.

In addition to understanding what forces are produced during sprinting, previous research into straight line sprinting has attempted to identify the force requirements associated with superior sprint performance (e.g. Mann, 1985; Morin et al., 2011a; In press). The lack of research into force production during bend sprinting means that it is not known how force production on the bend is related to better bend sprinting performance. This would be valuable information to coaches and athletes. Therefore, the second aim of this study was to understand the relationships between force production and faster performance during maximal effort bend sprinting.

6.2. Methods

6.2.1. Participants

Seven male sprinters, all experienced in bend running, participated in the study. Mean age, mass, and height were 22.6 ± 4.2 years, 70.7 ± 9.2 kg, and 1.76 ± 0.06 m, respectively. Personal best times for the 200 m ranged from 20.89 s to 22.90 s. Videotaping and analysis of athletes during normal training situations was approved by the local research ethics committee. All athletes provided written informed consent before taking part.

6.2.2. Data collection

Data were collected during the indoor competitive season, in the athletes' normal speed-training sessions, at the National Indoor Athletics Centre (NIAC), Cardiff. In total there were two data collection sessions. Athletes completed a coach-prescribed warm up before undertaking up to six maximal effort sprints of 60 m in length, some of which were run on the bend and some along the straight. Markings were made on the track surface to replicate lane 2 of the bend of a standard outdoor track (i.e. not banked; radius: 37.72 m). For the bend trials, the whole run was completed around the bend, and for the straight trials the whole run was completed along the straight. Two 0.90 m by 0.60 m force plates (9287BA, Kistler Instruments Ltd, Switzerland) operating at 1000 Hz were located in an area where the bend and straight lanes overlapped (Figure 6.1). The force plates were situated in customised housings and were isolated from the track foundations and surrounding track surface. The force plates were covered with a piece of firmly-secured synthetic track surface which was flush with the surface of the rest of the track. Trials were recorded with two fixed video cameras (HVR-Z5E, Sony Corporation, Japan) operating at 200 Hz. The field of view of these cameras was set to cover a distance 6.60 m long in order that a whole step starting from touchdown on the force plate could be recorded. One camera was positioned 30.00 m away from the inside edge of the lane, in line with the centre of the force plates, and was slightly panned to provide a 'side view' covering 4.2 m in front of, and 2.4 m behind, the centre of the force plates. The other camera was positioned 32.00 m away from the centre force plate area and 1.50 m to the side and provided a 'front view' (Figure 6.1). The cameras were manually focussed and operated with a shutter speed of 1/600 s. Aperture details for each data collection session are given in Table 6.1.

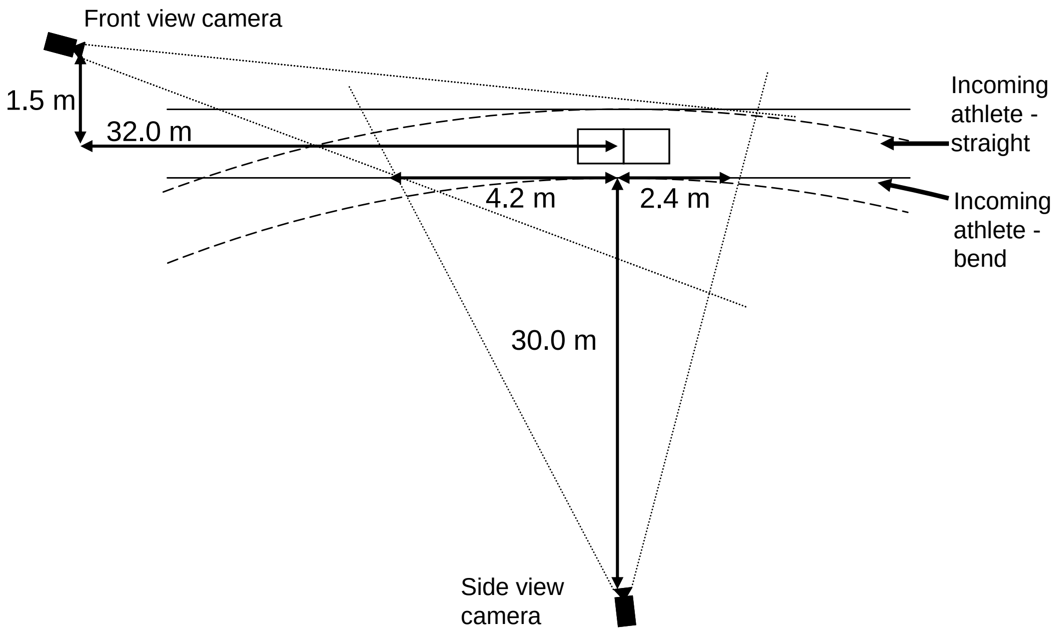


Figure 6.1. Camera set-up for bend and straight trials (not to scale).

Table 6.1. Aperture F-stop number (and dB of gain) for the front and side cameras in each data collection session.

	Data collection 1	Data collection 2
Side camera	2.4 (12)	2.6 (0)
Front camera	2.8 (12)	3.1 (9)

On each data collection session, an 18-point 3D calibration structure was recorded prior to athlete trials taking place. The structure used was the same as for Chapter 3 (Figure 3.2, p51). The calibration volume was 6.0 m long, approximately 1.6 m wide (at widest; Figure 6.2) and approximately 2.0 m high. The global coordinate system

(GCS) was such that the positive y-axis was aligned with the positive y-axis of the force plates, the positive x-axis was to the right and positive z-axis was vertically upwards.

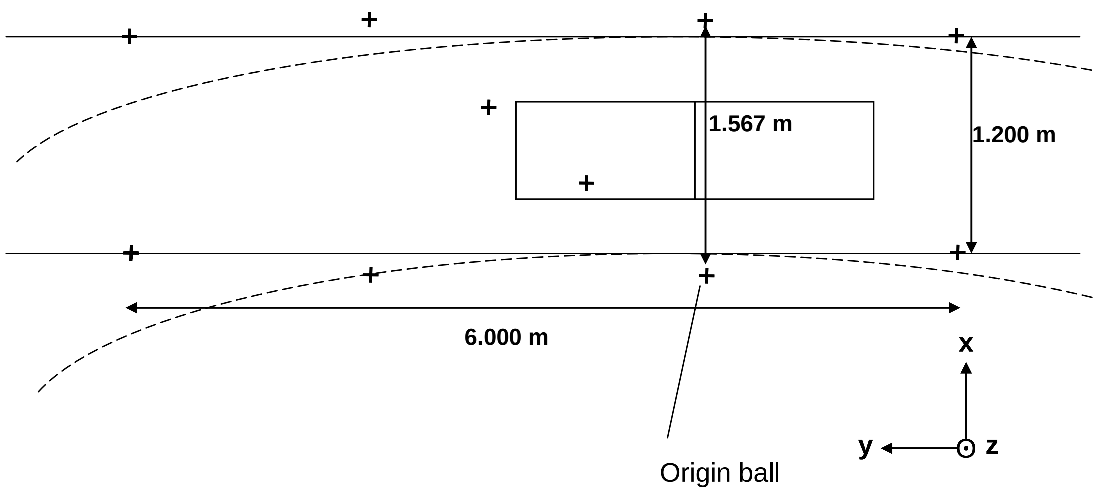


Figure 6.2. Plan view of calibration (not to scale).

All athletes undertook bend trials before straight trials, since it is information about the forces during bend running at radii and surfaces typical of athletic events that is missing from the literature. Therefore, from the six possible runs (due to coach-imposed restrictions and potential fatigue from maximal effort sprinting) from each athlete, obtaining force data from successful bend trials was most important. A successful trial was defined as having the athlete contact the force plate (one or both) with the foot entirely within the force plate area and in which it did not appear that the step pattern had been altered to do so. In order to reduce the chances of force plate targeting, athletes were not informed of the location of the force plates, nor were they easily visible. The start position of the athletes was 42.5 m before the camera field of view and was adjusted by up to 2.5 m in either direction, to facilitate obtainment of successful force plate strikes. This ensured that all athletes had at least 40 m run-up before the filming area. Athletes were instructed not to slow down until they reached a finishing point ~13 m after the filming area. Force data collection was started when athletes were approximately 10 m away from the filming area. The video data collections were manually triggered when the athletes reached the filming area. Once a successful left foot strike and a successful right foot strike had been obtained on the bend, the athlete then undertook straight trials, in order to obtain a foot strike from both feet on the straight. From the maximum of six trials completed, all athletes produced one successful left and one successful right foot strike for both the bend and the straight conditions. Recovery time between trials was approximately eight minutes.

6.2.3. Data processing

All trials were manually digitised using Vicon Motus software (Version 9.2, Vicon, Oxford, UK). Six fields were digitised in each camera view for calibration trials to provide the 11 DLT parameters required (Abdel-Aziz & Karara, 1971). Translations were performed such that the origin of the GCS was lowered and moved from the origin ball of the calibration frame to the bend radius origin at floor level. Video clips of trials were cropped to include 10 fields before the touchdown on the force plate and 10 fields after the next touchdown. This ensured the trial sequence was longer than the required data so as to mitigate against end-point errors in the data conditioning process (Smith, 1989).

The two video streams were synchronised using two sets of 20 LED displays which were placed with one in each camera view during data collection. The LEDs were simultaneously triggered during each trial which caused the LEDs to illuminate sequentially at 1 ms intervals. The time of the LED trigger was established from the number of lights illuminated in each camera view and entered into the digitising software as the common synchronisation point for the video streams. Upon triggering the LEDs, a simultaneous analogue signal was recorded with the force data on a spare channel allowing synchronisation between the force data and video data.

The same 20-point, 16-segment, model of the human body was digitised as in Chapter 3. Following a 3D-DLT reconstruction (Abdel-Aziz & Karara, 1971) the raw 3D coordinates and the force data were exported to a custom written Matlab script (v 7.9.0, The MathWorks, USA) for further processing. Data were filtered with a low-pass, 2nd order, recursive Butterworth filter (Winter, 2009). A cut-off frequency of 20 Hz was used for coordinate data. Force data were filtered with a 150 Hz cut-off frequency, chosen based on previous sprint research under similar testing conditions (Bezodis, 2009). Segment and whole body CoM were calculated in the same way as in Chapter 3.

Gait events (touchdowns and take off) were determined using a combination of force plate and kinematic data. The first touchdown was established in two ways using separate methods. The first method identified touchdown from the force data and was defined as the point at which the vertical force rose and stayed above two standard deviations greater than the mean zero load vertical force. The zero load mean and standard deviations were determined from the first 0.8 s of unloaded vertical force data. Secondly, first touchdown was also determined from the peak vertical acceleration of the touchdown MTP point (Bezodis et al., 2007). The latter method was used only for the purpose of calculating step time. Take off was defined using the force data as the point at which the vertical force dropped and stayed below two standard deviations above the mean zero load level. The second touchdown, which occurred off the force plate and could not be determined from force data, was identified solely from the peak vertical acceleration of the touchdown MTP (Bezodis et al., 2007). To calculate touchdowns from video data, the MTP vertical coordinate data was up-sampled to 1000 Hz from its initial 200 Hz using a cubic spline interpolation. Vertical acceleration of the MTP was then calculated using the first central difference method (Miller & Nelson, 1973). The reason for using up-sampled data for definition of touchdowns from MTP data was so that the same level of accuracy was used for all gait event definitions. This was necessary where step time was used in the calculation of variables.

6.2.4. Calculation of variables

The following performance descriptors were calculated in the same was as for previous chapters, for left and right steps, under both bend and straight conditions: absolute speed, race velocity, directional step length, race step length, step frequency, touchdown distance, body lateral lean at touchdown and take off, body sagittal lean ROM, and turn of the CoM during contact.

Ground contact time, flight time and step contact factor were calculated from 1000 Hz data (force and vertical acceleration of the MTP). Ground contact time was the time from touchdown to take off, as identified using force plate data. Due to potential discrepancies in identification of touchdown between the force plate and MTP acceleration methods, step time was calculated using touchdowns identified from the MTP acceleration data. Flight time was calculated as step time minus ground contact time. Step contact factor was calculated as the proportion of total step time spent in ground contact.

A number of force variables were also calculated. These were chosen based on force variables that have been shown to be important to performance in the straight line sprinting literature and in the limited bend sprinting literature, as well as those variables that were identified as of most interest to coaches, following discussions with them. For straight trials, these variables were calculated using the force data aligned with the GCS. For the bend trials, the horizontal forces in the GCS were rotated relative to the direction of travel of the athlete based on the methods of Glaister et al. (2007) in the following way: an instantaneous progression vector was calculated as a vector from the horizontal position of the CoM one field before the instant of interest to the horizontal position of the CoM one field after the instant of interest. This vector described the direction of travel of the athlete in the AP direction. The angle between the progression vector and the y-axis of the force plate was then calculated. The forces relative to the body reference frame were then calculated from the GCS by rotating them using the direction cosine matrix:

$$\begin{bmatrix} Fx' \\ Fy' \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} Fx \\ Fy \end{bmatrix} \qquad (6.1)$$

Where Fx and Fy are the horizontal ground reaction forces in the GCS, θ is the angle between the body reference frame and the global reference frame, and Fx' and Fy' are the horizontal ground reaction forces relative to the direction of travel of the athlete.

The following force variables were then calculated using the rotated or non-rotated forces as appropriate and expressed relative to body weight (BW):

Peak braking force: The largest force in the posterior direction (Figure 6.3).
Peak propulsive force: The largest force in the anterior direction (Figure 6.3).
Peak medial force: Calculated for straight trials only. The largest force acting towards the midline of the body (Figure 6.3).
Peak lateral force: Calculated for straight trials only. The largest force acting away from the midline of the body (Figure 6.3).

Peak inward force: Calculated for bend trials only. The largest force acting towards the inside of the bend (Figure 6.3).

Peak vertical force: The peak force in the vertical direction (Figure 6.3).

Average vertical force during contact: Mean vertical force during contact.

Peak resultant force: The maximum of the resultant of the three components of the force (Figure 6.3).

Average resultant force: Mean resultant force during contact.

Numerical integration of the force data (Trapezium Rule) allowed impulse to be calculated in each direction and the following impulse variables were calculated, again using rotated or non-rotated forces as appropriate. Impulses were also divided by mass to provide relative impulses:

Braking impulse: The sum of the posterior impulse during contact.

Propulsive impulse: The sum of the anterior impulse during contact.

Vertical impulse: The vertical impulse during contact, after the removal of the impulse due to body weight.

Net mediolateral impulse: Calculated for straight trials only. The sum of the impulse acting medially and laterally during contact.

Net inward impulse: Calculated for bend trials only. The sum of the impulse acting towards and away from the inside of the bend during contact.

Duration of braking: The duration of contact for which there was a posterior impulse.

Duration of propulsion: The duration of contact for which there was an anterior impulse.

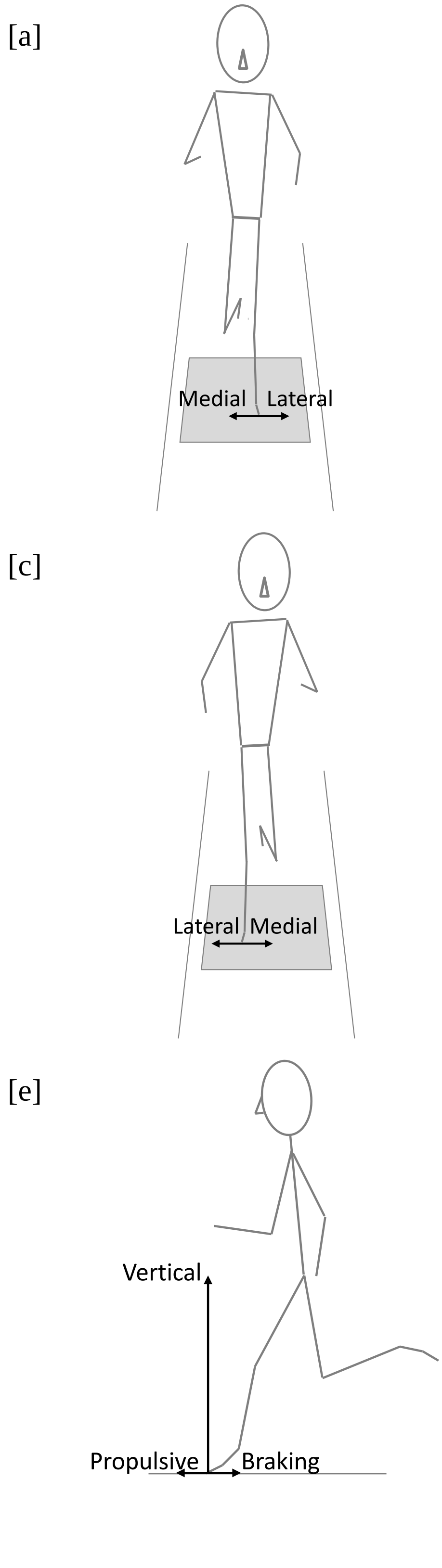


Figure 6.3. Directions of [a] medial and lateral forces during a left step on the straight, [b] inward force during a left step on the bend, [c] medial and lateral forces during a right step on the straight, [d] inward force during a right step on the bend, [e] vertical, propulsive and braking forces, and [f] resultant force.

Average frontal force-lean alignment angle during mid stance: This variable was calculated as a measure of the alignment between the force vector and the lean of the athlete during stance. A frontal force vector was calculated as the resultant of the vertical force and the mediolateral force. The rotated or non-rotated mediolateral force was used for the bend and straight trials, respectively. The angle between the body lateral lean vector and the frontal force vector was then calculated (Figure 6.4). To do this, force data at times corresponding to the 200 Hz lean data were used. The sign of the frontal force-lean alignment angle was then adjusted such that a negative angle signified that the frontal force vector was medial to the lean vector and a positive angle was lateral to the lean vector. Forces that were primarily mediolateral at the beginning and end of stance, i.e. when the contribution to the frontal force vector from vertical force was small, meant that very large frontal force-lean alignment angles would be returned at these times. These were not representative of the angles observed during the majority of stance. For this reason the average frontal force-lean alignment was measured during 60 ms of mid-stance only. Mid ground contact was identified and the mean of 30 ms of data (six fields) either side were calculated. Where an even number of data fields were present in contact, the ‘middle’ field was taken closer to the start of contact since the data for early stance was observed to be less problematic than late stance. Sixty milliseconds of mid-stance data represented a large proportion of stance for all athletes without any very large frontal force-lean alignment angles being included in the averaged data.

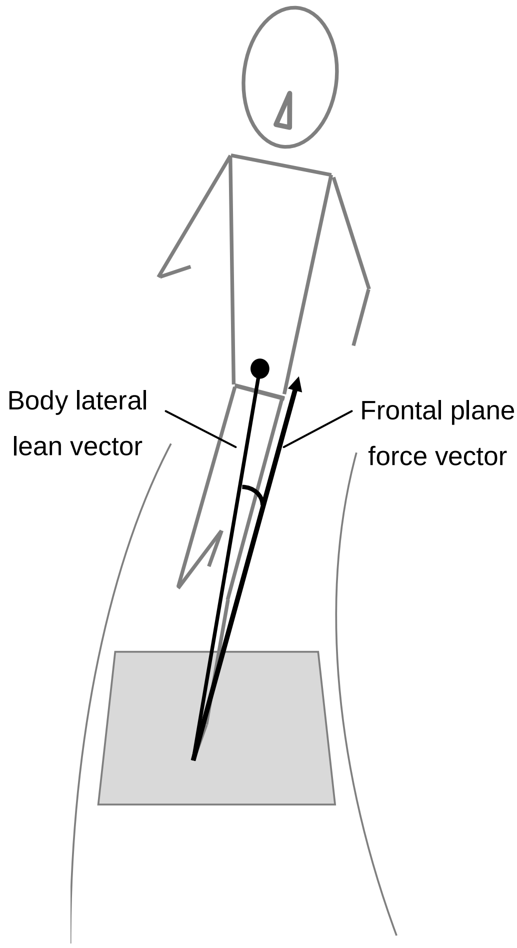


Figure 6.4. Frontal force-lean alignment angle. A positive angle indicates the force vector is acting laterally to the body lateral lean vector (depicted).

For one trial (a right step on the straight) the synchronisation unit did not trigger. For this trial, synchronisation had to be established manually based on the methods of Dapena and Chung (1988). The instants of touchdown and take off were visually identified to the nearest half field in each camera view. The identified field numbers in each camera view were then plotted against each other and a linear regression line fitted to the points. The equation of this line then gave the synchronisation offset of the two cameras which was entered into the digitising software to give the common synchronisation point for the video streams. The synchronisation between force data and kinematic data for this trial was also slightly different. As there was no LED trigger available for synchronisation, the synchronisation point was taken to be first touchdown. This was identified in the force data in the normal way and was assumed to correspond with the peak vertical acceleration of the MTP of the first touchdown limb in the up-sampled MTP acceleration data (Bezodis et al., 2007). All other calculations were then performed in the same way as for other trials.

The effect of any error in the offset of the alternatively-synchronised trial was investigated by processing the digitised trial with synchronisation offsets of 1 ms intervals, which is the level of accuracy attainable with the LED method, from zero lag to one full field lag between cameras. Thus, six possible synchronisation offsets were produced. Visual identification of the camera which was 'lagging behind' determined the direction of the offset. For these six sets of data, the performance descriptors and kinetic variables of interest were calculated. Inspection of these results showed that slight errors in the synchronisation had negligible effects on most of the results (Table 6.2). The largest difference was in touchdown distance where the range of results was 0.04 m. In reality, as this happened at the largest tested offset (5 ms), this synchronisation offset (one frame) would have been noticed by eye. It was deemed that, since this method was used for only one of seven trials for a right step on the straight, it would not substantially affect the group results and so the trial was included.

Table 6.2. The effect of alterations to synchronisation offset on values of outcome measures of one trial. Zero offset indicates the two cameras are operating at the selected synchronisation, with 1 ms intervals indicating an offset between cameras in intervals of 0.2 fields up to 5 ms intervals indicating a one field offset between cameras.

	Offset					
	zero	1 ms	2 ms	3 ms	4 ms	5 ms
Absolute speed ($m \cdot s^{-1}$)	8.99	8.99	8.99	8.99	8.99	8.99
Race velocity ($m \cdot s^{-1}$)	8.99	8.99	8.99	8.99	8.99	8.99
Directional step length (m)	2.12	2.12	2.12	2.12	2.12	2.12
Race step length (m)	2.12	2.12	2.12	2.12	2.12	2.12
Step frequency (Hz)	4.23	4.24	4.23	4.23	4.23	4.23
Ground contact time (s)	0.103	0.103	0.103	0.103	0.103	0.103
Flight time (s)	0.239	0.240	0.240	0.240	0.241	0.241
Step contact factor (%)	43.1	42.9	42.9	42.9	42.7	42.7
Touchdown distance (m)	0.28	0.29	0.30	0.31	0.31	0.32
Body sagittal lean ROM (°)	45.6	45.7	45.8	47.8	47.9	48.0
Body lateral lean at TD (°)	-2.0	-2.1	-2.1	-2.1	-2.1	-2.1
Body lateral lean at TO (°)	11.1	11.2	11.3	10.6	10.7	10.8
Peak braking force (BW)	1.75	1.75	1.75	1.75	1.75	1.75
Braking impulse (Ns)	19.2	19.2	19.2	19.2	19.2	19.2
Relative braking impulse ($m \cdot s^{-1}$)	0.3	0.3	0.3	0.3	0.3	0.3
Duration of braking (s)	0.048	0.048	0.048	0.048	0.048	0.048
Peak propulsive force (BW)	0.69	0.69	0.69	0.69	0.69	0.69
Propulsive impulse (Ns)	15.6	15.6	15.6	15.6	15.6	15.6
Relative propulsive impulse ($m \cdot s^{-1}$)	0.2	0.2	0.2	0.2	0.2	0.2
Duration of propulsion (s)	0.055	0.055	0.055	0.055	0.055	0.055
Peak vertical force (BW)	3.84	3.84	3.84	3.84	3.84	3.84
Average vertical force (BW)	2.09	2.09	2.09	2.09	2.09	2.09
Vertical impulse (Ns)	82.5	82.5	82.5	82.5	82.5	82.5
Relative vertical impulse ($m \cdot s^{-1}$)	1.1	1.1	1.1	1.1	1.1	1.1
Peak medial force (BW)	0.39	0.39	0.39	0.39	0.39	0.39
Peak lateral force (BW)	0.33	0.33	0.33	0.33	0.33	0.33
Net mediolateral impulse (Ns)	8.3	8.3	8.3	8.3	8.3	8.3
Relative mediolateral impulse ($m \cdot s^{-1}$)	0.1	0.1	0.1	0.1	0.1	0.1
Peak resultant force (BW)	3.87	3.87	3.87	3.87	3.87	3.87
Average resultant force (BW)	2.20	2.20	2.20	2.20	2.20	2.20
Average frontal force-lean alignment angle during mid-stance (°)	6.7	6.8	6.8	6.8	6.9	6.9

6.2.5. Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics software (v19.0, SPSS Inc., USA) and significance was set at $p < 0.05$. Paired samples t-tests were used to identify significant differences between left and right steps for variables within a condition, and between the straight and bend for the left and right steps. Absolute values were used for the comparison between left and right steps for body lateral lean at touchdown and take off on the straight. Additionally, net mediolateral impulse on the straight was compared to net inward impulse on the bend for left and right steps. For these comparisons only, the sign of the impulse for net mediolateral impulse was maintained in the global coordinate system rather than being expressed relative to the midline of the body. Effect sizes were calculated using Cohen's *d* (Cohen, 1988). Relative magnitude of the effect was assessed based on Cohen's guidelines with *d* less than or equal to 0.20 representing a small difference, *d* greater than 0.20 but less than 0.80 a moderate difference and *d* greater than or equal to 0.80 a large difference, between the two means. Pearson product-moment correlations were used to identify significant relationships between force variables and direct performance descriptors on the bend, for both the left and right steps.

6.3. Results

6.3.1. Changes to performance and force production during bend sprinting

Mean race velocity was significantly reduced from 9.56 and 9.51 $m \cdot s^{-1}$ on the straight to 9.34 and 9.29 $m \cdot s^{-1}$ on the bend for the left and right steps, respectively, with similar results for absolute speed ($p < 0.05$, Table 6.3). There was also a reduction in right race and directional step length. The mean right race step length reduced from 2.12 m on the straight to 2.02 m on the bend, which was found to be statistically significant, with similar values for directional step length (Table 6.3). There was a small reduction in left race and directional step length and in left step frequency from straight to bend. Although these differences did not reach statistical significance, the step length variables did yield moderate effect sizes (race step length: $p = 0.148$, $d = 0.67$; directional step length: $p = 0.347$, $d = 0.40$). Mean right step frequency increased from 4.49 Hz on the straight to 4.59 Hz on the bend. Again, this was not found to be statistically significant, but the effect size was moderate ($p = 0.225$, $d = 0.47$). A slight decrease in left step frequency and the increase in right step frequency on the bend did, however, result in a significant asymmetry between left and right on the bend, which was not seen on the straight ($p < 0.05$, Table 6.3). Statistically significant asymmetries between left and right on the bend were also seen in ground contact time, touchdown distance, body sagittal lean ROM and body lateral lean at both touchdown and take off ($p < 0.05$, Table 6.3). Differences in touchdown distance between the straight and bend were not statistically significant for either the left or right steps, however, effect sizes were moderate (left: $p = 0.103$, $d = 0.71$; right: $p = 0.082$, $d = 0.77$).

Mean turn of the CoM was 4.2° for the left step and 2.6° for the right step. The asymmetry between left and right in the amount of turning achieved on the bend was found to be significant ($p < 0.05$, Table 6.3).

A typical ground reaction force-time curve for the left and right steps on the bend and straight are given in Figure 6.5. For the group data, there was a statistically significant increase in braking impulse and the duration of braking for the left step on the bend when compared to the straight, and also a statistically significant asymmetry between left and right steps on the bend (Table 6.4). Mean peak inward force was 0.21 BW higher during the left step than the right step on the bend. Net inward impulse was also statistically significantly greater for the left step compared to the right step on the bend (Table 6.4). Net inward impulse on the bend was statistically significantly larger than net mediolateral impulse on the straight for both the left and right steps ($p < 0.001$).

Table 6.3. Left and right step mean values (± SD) and significant differences for performance descriptors on the straight and bend.

	Straight		Bend		Significant differences			
	Left	Right	Left	Right	Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right
Absolute speed ($m \cdot s^{-1}$)	9.56 ± 0.45	9.51 ± 0.47	9.35 ± 0.43	9.29 ± 0.47			*	§
Race velocity ($m \cdot s^{-1}$)	9.56 ± 0.46	9.51 ± 0.47	9.34 ± 0.43	9.29 ± 0.47			*	#
Directional step length (m)	2.14 ± 0.05	2.12 ± 0.07	2.12 ± 0.05	2.03 ± 0.08		*		*
Race step length (m)	2.14 ± 0.05	2.12 ± 0.08	2.11 ± 0.05	2.02 ± 0.07		*		*
Step frequency (Hz)	4.46 ± 0.23	4.49 ± 0.22	4.44 ± 0.25	4.59 ± 0.23		*		
Ground contact time (s)	0.107 ± 0.008	0.108 ± 0.008	0.117 ± 0.006	0.104 ± 0.005		§	#	
Flight time (s)	0.116 ± 0.019	0.120 ± 0.014	0.118 ± 0.011	0.108 ± 0.016				*
Step contact factor	0.482 ± 0.054	0.474 ± 0.046	0.498 ± 0.031	0.493 ± 0.043				
Touchdown distance (m)	0.37 ± 0.07	0.37 ± 0.06	0.41 ± 0.05	0.33 ± 0.05		§		
Body sagittal lean ROM (°)	53.1 ± 4.2	52.8 ± 4.9	57.9 ± 3.3	52.0 ± 3.7		§	#	
Body lateral lean at touchdown (°)[1]	3.3 ± 1.8	-2.6 ± 0.8	-9.1 ± 1.3	-14.2 ± 2.2		§	§	§
Body lateral lean at take off (°)[1]	3.6 ± 2.3	-2.9 ± 1.1	-7.8 ± 1.1	-13.2 ± 2.0		#	§	§
Turn of CoM (°)			4.2 ± 0.9	2.6 ± 0.7		*		

* Significant at $p < 0.05$; # significant at $p < 0.01$; § significant at $p < 0.001$

[1] Where left vs. right was compared on the straight, by paired samples t-test, absolute values were used for these variables

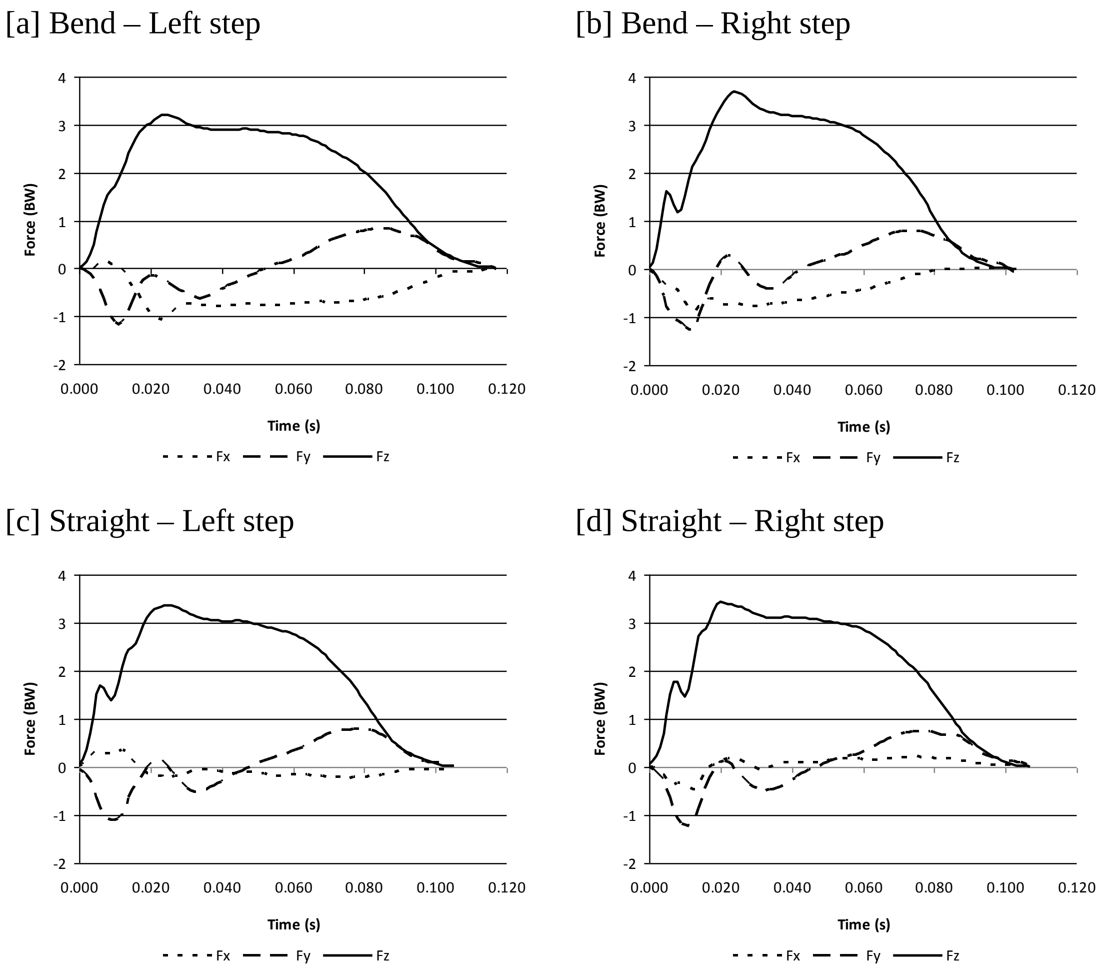


Figure 6.5. Ground reaction forces for one participant's left and right steps on the bend and straight. Negative Fx on the bend represents inward force; Negative and positive Fx for the left step on the straight represents lateral and medial force respectively; Negative and positive Fx for the right step on the straight represents medial and lateral force, respectively. Negative and positive Fy represents braking and propulsive force, respectively. Positive Fz represents upwards vertical force.

Table 6.4. Left and right step mean values (± SD) and significant differences for horizontal force variables on the straight and bend.

	Straight		Bend		Significant differences			
	Left	Right	Left	Right	Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right
Peak braking force (BW)	1.43 ± 0.39	1.31 ± 0.26	1.41 ± 0.34	1.31 ± 0.22				
Braking impulse (Ns)	14.0 ± 3.7	13.2 ± 3.8	16.6 ± 3.5	12.4 ± 2.8		#	*	
Relative braking impulse ($m \cdot s^{-1}$)	0.20 ± 0.04	0.18 ± 0.04	0.23 ± 0.02	0.17 ± 0.02		§	*	
Duration of braking (s)	0.046 ± 0.006	0.044 ± 0.007	0.052 ± 0.004	0.040 ± 0.004		§	#	
Peak propulsive force (BW)	0.81 ± 0.09	0.73 ± 0.07	0.76 ± 0.09	0.77 ± 0.07	*			
Propulsive impulse (Ns)	18.3 ± 3.7	16.8 ± 3.7	19.1 ± 2.8	18.7 ± 3.9				*
Relative propulsive impulse ($m \cdot s^{-1}$)	0.26 ± 0.02	0.24 ± 0.03	0.27 ± 0.02	0.26 ± 0.03				*
Duration of propulsion (s)	0.061 ± 0.004	0.064 ± 0.006	0.064 ± 0.003	0.064 ± 0.005			#	
Peak medial force (BW)	0.41 ± 0.11	0.41 ± 0.11						
Peak lateral force (BW)	0.22 ± 0.14	0.25 ± 0.06						
Net lateral impulse (Ns)	3.2 ± 5.0	5.3 ± 2.1						
Relative net lateral impulse ($m \cdot s^{-1}$)	0.05 ± 0.08	0.08 ± 0.03						
Peak inward force (BW)			1.07 ± 0.22	0.86 ± 0.25		*		
Net inward impulse (Ns)			39.9 ± 6.5	24.7 ± 5.8		#		
Relative net inward impulse ($m \cdot s^{-1}$)			0.56 ± 0.05	0.35 ± 0.06		#		

***** Significant at $p < 0.05$; [#] significant at $p < 0.01$; [§] significant at $p < 0.001$

Mean peak resultant force during the left step was 3.61 BW on the bend, which was significantly lower than the 3.82 BW observed on the straight ($p < 0.05$, Table 6.5). On the right, however, mean peak resultant force was greater on the bend than the straight at 4.19 BW compared to 3.66 BW. The standard deviation for the right step on the bend was, though, much larger than in the other instances of this variable (Table 6.5). This was due to one athlete producing a peak resultant force of just over seven times body weight during the right step on the bend, compared to a little over four times bodyweight for the right step on the straight.

Average frontal force-lean alignment during mid-stance was positive in all instances indicating the frontal force vector was lateral to the body lateral lean vector. There was a significant reduction in this angle from 4.8 ± 1.5° on the straight to 3.7 ± 1.6° on the bend for the left step ($p < 0.05$, $d = 0.73$). On the right step there was an increase from straight to bend with values of 5.6 ± 1.1° and 6.6 ± 1.5° for straight and bend, respectively, and although this was not found to be statistically significant ($p = 0.238$), the effect size was moderate ($d = 0.77$). The 2.9° difference in average frontal force-lean alignment angle between left and right steps on the bend was significant ($p < 0.01$, $d = 1.88$).

Table 6.5. Left and right step mean values (± SD) and significant differences for vertical and resultant force variables on the straight and bend.

	Straight		Bend		Significant differences			
	Left	Right	Left	Right	Left vs. right Straight	Left vs. right Bend	Straight vs. bend Left	Straight vs. bend Right
Peak vertical force (BW)	3.80 ± 0.52	3.64 ± 0.29	3.43 ± 0.41	4.13 ± 1.27			#	
Average vertical force (BW)	2.13 ± 0.25	2.05 ± 0.14	2.02 ± 0.20	2.09 ± 0.20			#	
Vertical impulse (Ns)	82.0 ± 18.2	76.9 ± 13.0	81.3 ± 17.4	78.4 ± 18.0				
Relative vertical impulse ($m \cdot s^{-1}$)	1.16 ± 0.21	1.09 ± 0.07	1.15 ± 0.20	1.11 ± 0.18				
Peak resultant force (BW)	3.82 ± 0.53	3.66 ± 0.29	3.61 ± 0.45	4.19 ± 1.29			*	
Average resultant force (BW)	2.23 ± 0.26	2.14 ± 0.15	2.18 ± 0.21	2.22 ± 0.20				

***** Significant at $p < 0.05$; [#] significant at $p < 0.01$

6.3.2. Relationships between performance and force production on the bend

Both left directional step length and left race step length were statistically significantly correlated with duration of propulsion and average vertical force (Figure 6.6, Table 6.6), as well as peak vertical force, peak resultant force and average resultant force (Table 6.6).

Left step frequency was significantly negatively correlated with relative vertical impulse (Figure 6.7, Table 6.6). Ground contact time, for the left step, was significantly positively correlated with duration of braking (Figure 6.8, Table 6.6) and with duration of propulsion (Table 6.6). Similarly, positive relationships were observed for flight time with average vertical force and with relative vertical impulse during the left step (Figure 6.9). There were also significant positive correlations between flight time for the left step with peak vertical force, vertical impulse, peak resultant force and average resultant force (Table 6.6). Conversely, left step contact factor was negatively correlated with average vertical force and relative vertical impulse (Figure 6.10, Table 6.6) and also with peak vertical force, vertical impulse, average resultant force and peak resultant force (Table 6.6).

There were statistically significant negative correlations for left touchdown distance with average vertical force and with relative vertical impulse (Figure 6.11), as well as with peak vertical force, peak resultant force and average resultant force (Table 6.6). Body lateral lean at left take off was statistically significantly positively correlated with peak vertical force as well as relative vertical impulse (Figure 6.12, Table 6.6). The turn of the CoM was positively correlated with relative propulsive impulse during the left step on the bend (Table 6.6).

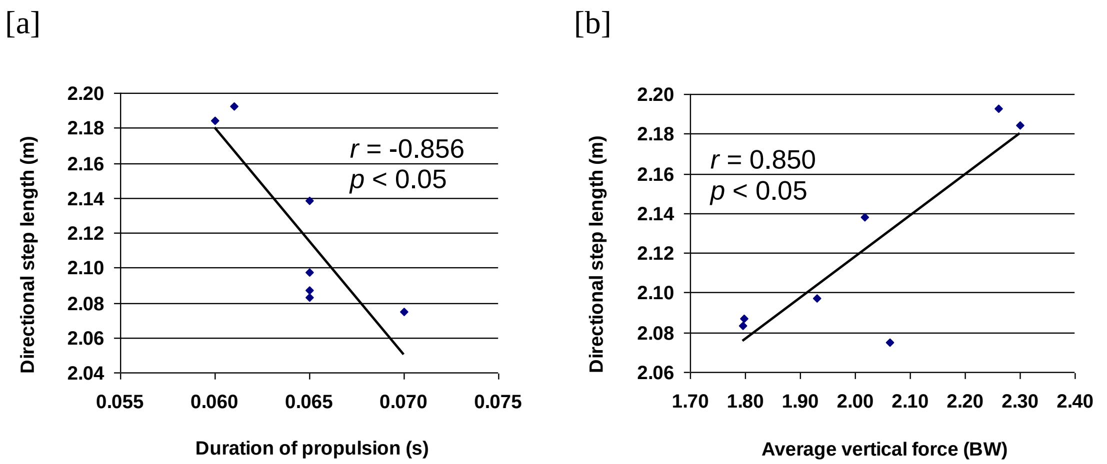


Figure 6.6. Relationship between [a] duration of propulsion, and [b] average vertical force with directional step length during the left step on the bend.

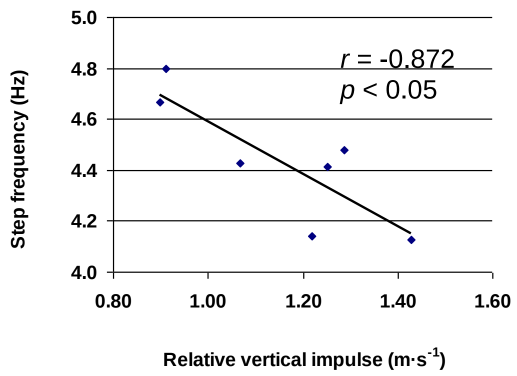


Figure 6.7. Relationship between relative vertical impulse and step frequency during the left step on the bend.

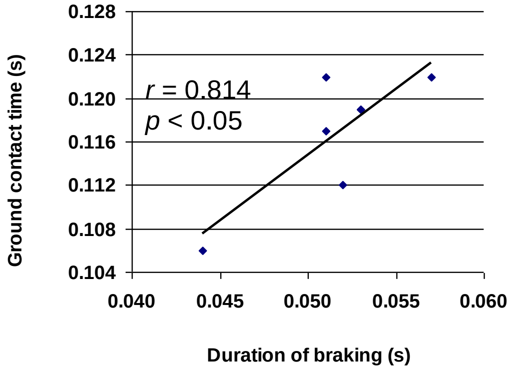


Figure 6.8. Relationship between duration of braking and ground contact time during the left step on the bend.

[a] [b]

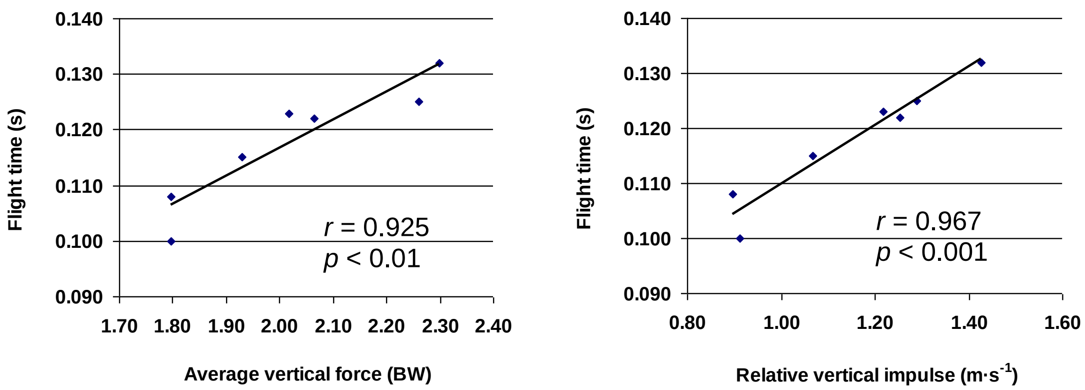


Figure 6.9. Relationship between [a] average vertical force, and [b] relative vertical impulse with flight time during the left step on the bend.

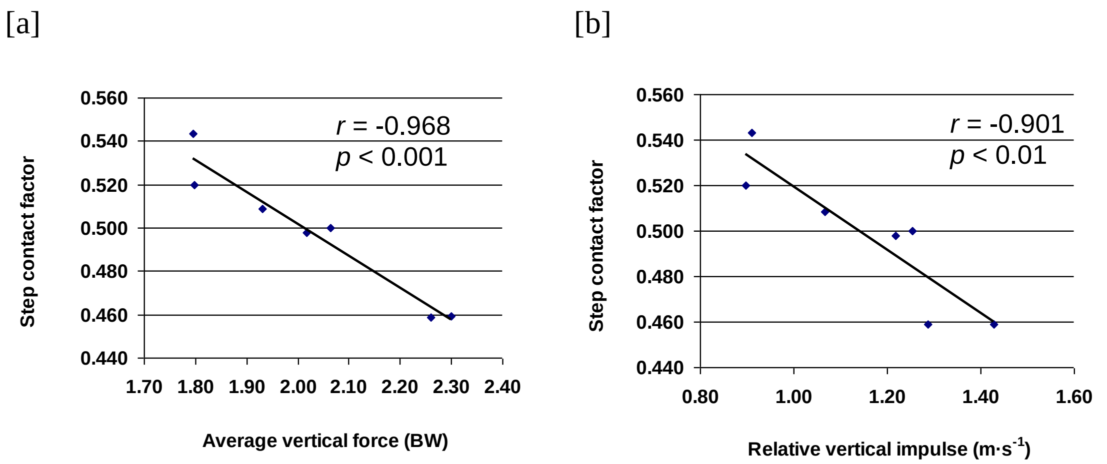


Figure 6.10. Relationship between [a] average vertical force, and [b] relative vertical impulse with step contact factor during the left step on the bend.

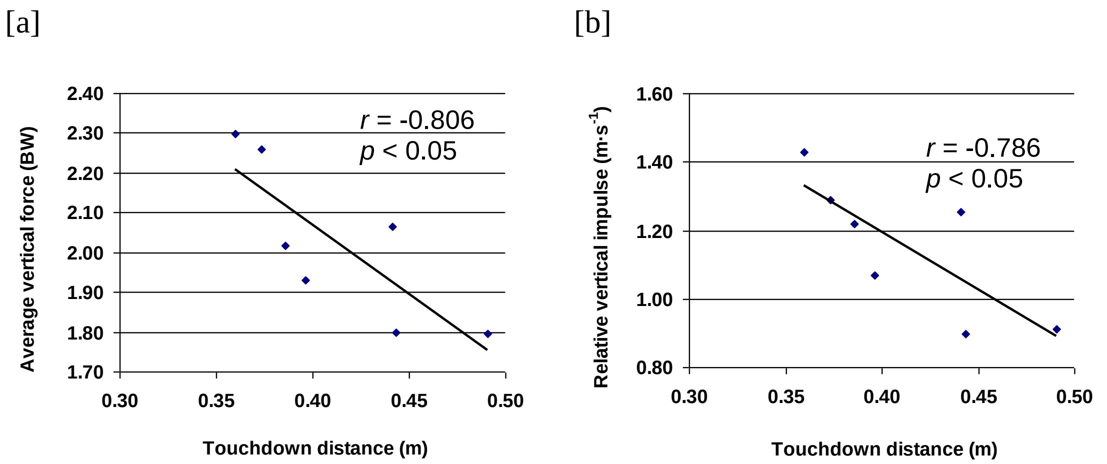


Figure 6.11. Relationship between touchdown distance with [a] average vertical force and [b] relative vertical impulse during the left step on the bend.

[a] [b]

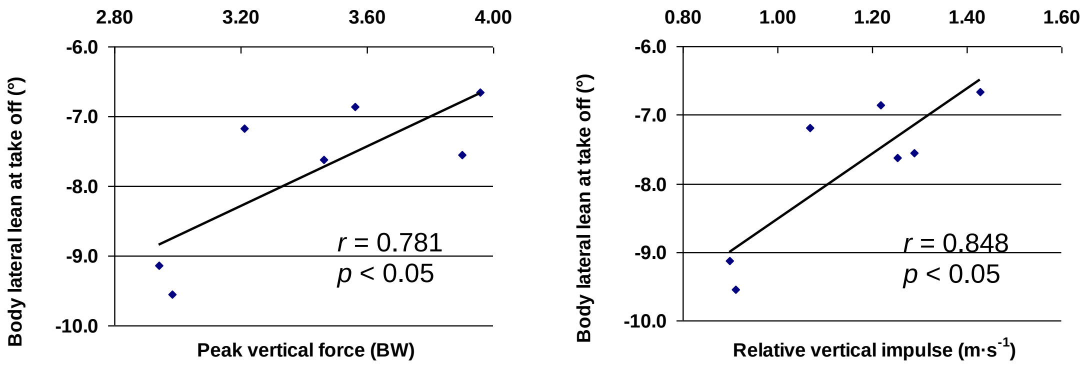


Figure 6.12. Relationship between [a] peak vertical force and [b] relative vertical impulse with body lateral lean at left take off during the left step on the bend.

Table 6.6. Correlation *r* values for performance descriptors with force variables for the left step on the bend (only significant correlations are shown).

	Directional step length (m)	Race step length (m)	Step frequency (Hz)	Ground contact time (s)	Flight time (s)	Step contact factor	Touchdown distance (m)	Body lateral lean at take off (°)	Turn of the CoM (°)
Duration of braking (s)				0.814 *					
Relative propulsive impulse ($m \cdot s^{-1}$)									0.842 *
Duration of propulsion (s)	-0.856 *	-0.873 *		0.816 *					
Peak vertical force (BW)	0.877 #	0.871 *			0.933 #	-0.954 #	-0.830 *	0.781 *	
Average vertical force (BW)	0.850 *	0.844 *			0.925 #	-0.968 §	-0.806 *		
Vertical impulse (Ns)					0.804 *	-0.895 #			
Relative vertical impulse ($m \cdot s^{-1}$)			-0.827 *		0.967 §	-0.901 #	-0.786 *	0.848 *	
Peak resultant force (BW)	0.838 *	0.827 *			0.921 #	-0.960 #	-0.795 *		
Average resultant force (BW)	0.855 *	0.850 *			0.895 #	-0.968 §	-0.788 *		

* Significant at $p < 0.05$; # significant at $p < 0.01$; § significant at $p < 0.001$

There were statistically significant positive correlations for absolute speed with peak propulsive force and with relative propulsive impulse during the right step on the bend (Figure 6.13, Table 6.7). The correlations between right step race velocity and these variables did not, however, reach statistical significance (with peak propulsive force $r = 0.743$, $p = 0.055$ and with relative propulsive impulse $r = 0.747$, $p = 0.053$).

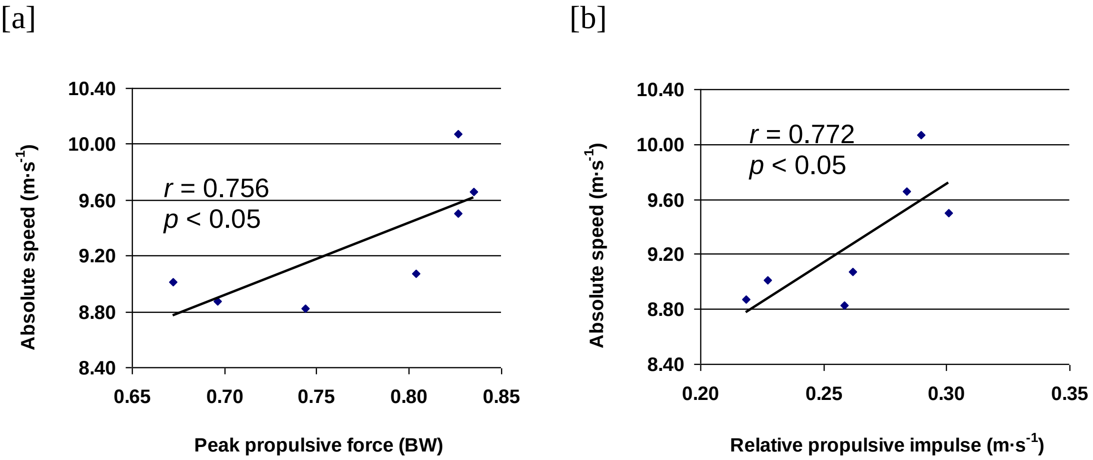


Figure 6.13. Relationship between [a] peak propulsive force and [b] relative propulsive impulse with absolute speed during the right step on the bend.

Step contact factor was significantly negatively correlated with average vertical force during the right step on the bend (Figure 6.14, Table 6.7). There was also a positive correlation between average vertical force and flight time during the right step which almost reached statistical significance ($r = 0.752$, $p = 0.051$). Body lateral lean at right touchdown was significantly negatively correlated with duration of propulsion, relative propulsive impulse, relative net inward impulse (Figure 6.15, Table 6.7), propulsive impulse and net inward impulse (Table 6.7). Body lateral lean at right step take off was statistically significantly negatively correlated with relative propulsive impulse, relative net inward impulse (Figure 6.16, Table 6.7) and also with absolute propulsive impulse and net inward impulse during the right step (Table 6.7).

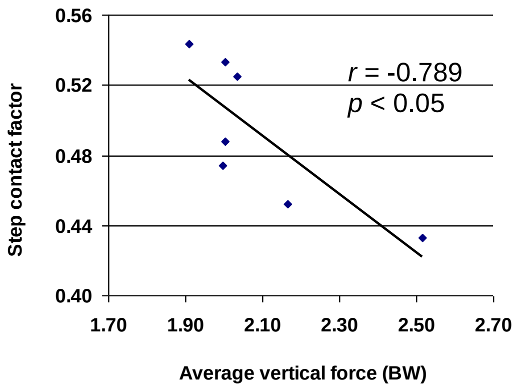


Figure 6.14. Relationship between average vertical force and step contact factor during the right step on the bend.

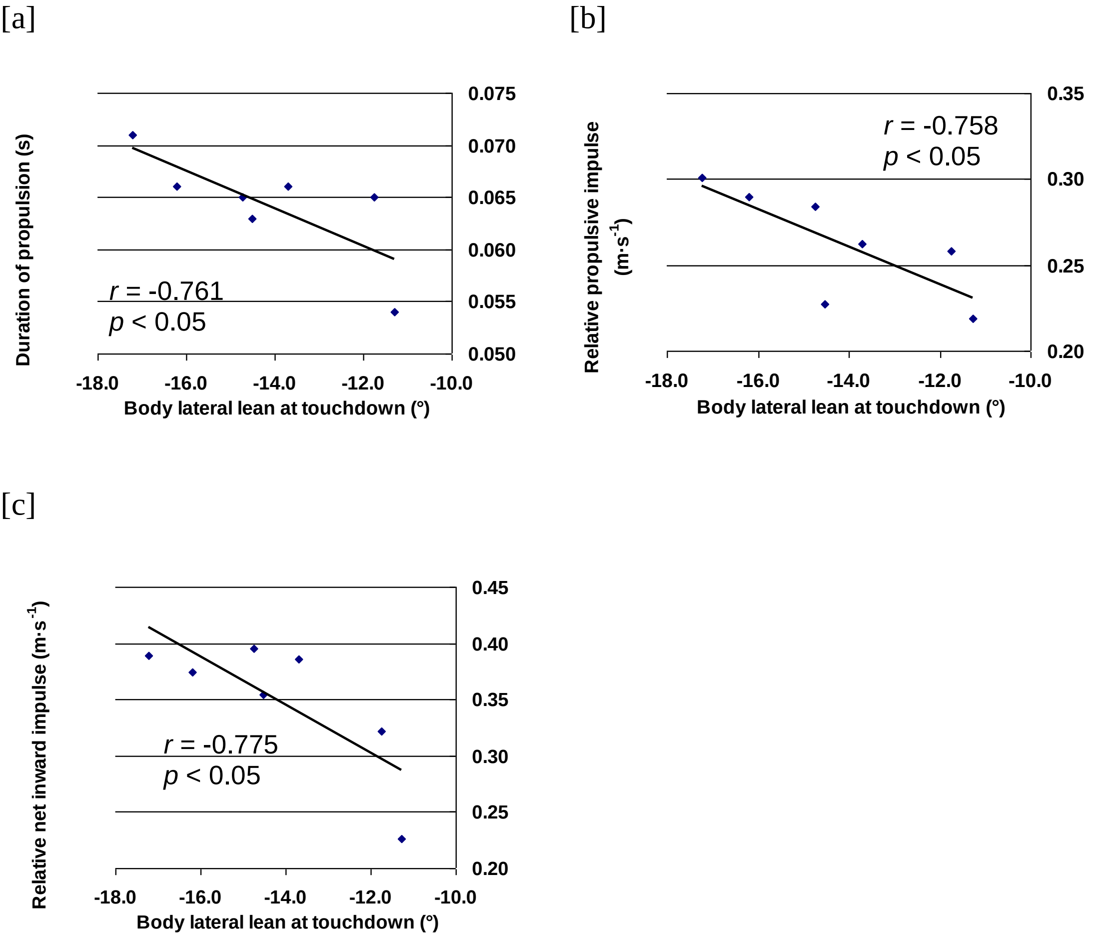


Figure 6.15. Relationship between body lateral lean at touchdown with [a] duration of propulsion, [b] relative propulsive impulse, and [c] relative net mediolateral impulse during the right step on the bend.

[a] [b]

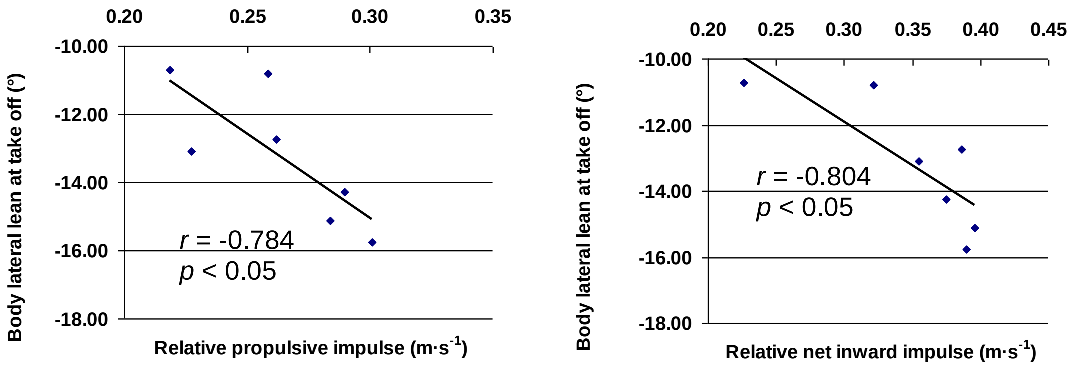


Figure 6.16. Relationship between [a] relative propulsive impulse and [b] relative net mediolateral impulse with body lateral lean at take off during the right step on the bend.

Table 6.7. Correlation *r* values for performance descriptors with force variables for the right step on the bend (only significant correlations are shown).

	Absolute speed ($m \cdot s^{-1}$)	Step contact factor	Body lateral lean at touchdown (°)	Body lateral lean at take off (°)
Peak propulsive force (BW)	0.756 *			
Propulsive impulse (Ns)			-0.788 *	-0.873 *
Relative propulsive impulse ($m \cdot s^{-1}$)	0.772 *		-0.758 *	-0.784 *
Duration of propulsion (s)			-0.761 *	
Net inward impulse (Ns)			-0.892 #	-0.978 §
Relative net inward impulse ($m \cdot s^{-1}$)			-0.775 *	-0.804 *
Average vertical force (BW)		-0.789 *		

* Significant at $p < 0.05$; # significant at $p < 0.01$; § significant at $p < 0.001$

6.4. Discussion

6.4.1. Changes to performance and force production during bend sprinting

The first aim of the study was to understand the changes that occur to force production which may contribute to changes seen in direct performance descriptors while running at maximal effort on the bend compared to the straight. Although performance descriptors from straight to bend have already been measured in Chapter 3, they were measured again in order that the forces measured could be associated with the particular performance of the athletes in the current study, and under the particular conditions for which forces were measured.

There was a statistically significant 2.2% and 2.3% decrease in mean absolute speed and race velocity, respectively, during the left step on the bend compared to the straight. During the right step on the bend, mean absolute speed and race velocity were both significantly reduced by 2.3% compared to the straight. These percentage decreases were smaller than those seen for the male athletes from straight to bend in Chapter 3, where a 4.8% decrease in race velocity was seen for the left and right steps. This was due to the athletes in the present study achieving a slower mean velocity on the straight than was achieved by the male athletes in Chapter 3, whereas similar velocities were achieved on the bend. It is possible that this was due to data collection occurring during the indoor competition season as opposed to the outdoor competition season as was the case in Chapter 3. It is also possible that this was due to the straight trials being undertaken after the bend trials meaning athletes may have been slightly fatigued for the straight trials. To mitigate against fatigue, athletes were given approximately eight minutes recovery time between trials. Furthermore, the coaches had agreed that each of the athletes should be able to complete six maximal effort 60 m sprints before fatigue became a problem. Nonetheless, it is possible the slower mean velocities on the straight may have potentially been due to slight fatigue. Despite these differences in mean velocities, changes in performance descriptors from straight to bend generally followed the same trends as were observed for the male athletes in Chapter 3.

Left step absolute speed and race velocity reduced due to a small decrease in mean left step length (directional and race) and mean left step frequency on the bend compared to the straight (Table 6.3). Whilst these differences did not reach statistical significance, the effect sizes for left directional and race step length were moderate ($d = 0.40$ and $d = 0.67$, respectively).

Unlike for the left step, right step absolute speed and race velocity decreased due to a significant 0.09 m and 0.10 m decrease in directional and race step length, respectively, from straight to bend (Table 6.3). The decrease in right race and directional step length was contributed to by the significant decrease in flight time observed on the bend compared to the straight ($p < 0.05$, Table 6.3).

Mean left step frequency decreased slightly (0.02 Hz) and right step frequency increased (0.10 Hz) on the bend compared to the straight resulting in a significant asymmetry between left and right on the bend which was not present on the straight ($p < 0.05$, Table 6.3). When compared to the straight, the small decrease in step frequency during the left step in the present study was due to a significant increase in ground contact time on the bend ($p < 0.001$, Table 6.3). The significant decrease in right step flight time, which contributed to the reduction in right step length, was responsible for the small increase in right step frequency, although this was not found to be significant.

Usherwood and Wilson (2006) suggested, based on the research of Weyand et al. (2000) that the maximum force an athlete is able to produce is achieved during straight line sprinting. As such, they postulated that ground contact time and the proportion of stride time spent in ground contact during bend running would be increased in order to generate the centripetal force that is required to follow the curved path. They suggested that swing time would remain constant, therefore, step frequency would decrease. However, in the present study step frequency did not decrease significantly for the left step and there was actually an increase in step frequency for the right step, although this did not reach statistical significance. There was partial support for Usherwood and Wilson's (2006) theory in that there was a significant increase in ground contact time on the bend compared to the straight for the left step. There was also a significant decrease in peak and average vertical force during the left step on the bend in comparison to the straight (Table 6.5). Vertical impulse was similar in both conditions. This suggests that while force generation in the vertical direction was diminished on the bend, athletes increased left ground contact time in order to allow sufficient vertical impulse generation.

Certain results, however, contradict or are not explained by the model of Usherwood and Wilson (2006). Along with the requirement for centripetal force generation, other changes from straight to bend were probably partly responsible for the increase in left ground contact time. In straight line sprinting greater touchdown distances and body sagittal lean ROM have been linked to increased ground contact times (Hunter et al., 2004a). Indeed, a statistically significant increase in body sagittal lean ROM was observed in the present study during the left step on the bend compared to the straight. Additionally, mean touchdown distance at left touchdown increased from 0.37 m on the straight to 0.41 m on the bend (Table 6.3). This difference was not found to be statistically significant ($p = 0.130$), but the effect size was moderate ($d = 0.71$), and similar (0.06 m) increases in left touchdown distance from straight to bend for the male athletes were found to be statistically significant in Chapter 3 ($p < 0.01$). It is, therefore, possible that the increased ground contact time observed during the left step on the bend compared to the straight was at least in part the result of changes in these variables and not simply due to athletes spending longer in ground contact to meet the additional centripetal force requirements of the bend. The changes to left step technique, such as increased touchdown distance which led to increased ground contact time and thus reduced step frequency, are factors not considered by the Usherwood and Wilson (2006) model.

For the right step, ground contact time was not significantly different. Instead, there was a significant decrease in flight time which had the effect of significantly reducing right race and directional step length (Table 6.3). The model of Usherwood and Wilson (2006) assumed that the left and right legs were affected by the bend in the same way and that changes would occur to ground contact time. It does not account for changes to flight time or step length. The results of the present study, along with the results of Chapters 3-5 show that the left and right steps are affected differently by the bend and as such the model of Usherwood and Wilson (2006) may partly explain changes to the left step, but doesn't explain the changes observed during the right step on the bend.

Athletes are required to adjust their direction of travel during bend running in order to follow the curved path and remain within their lanes. The only time that this can be achieved is during the ground contact phase, when athletes are able to generate centripetal force. In the present study, on average 1.6° more turning of the CoM was achieved during the left ground contact than during the right ground contact ($p < 0.05$). This was in line with previous chapters where the turn of the CoM during left contact was 4.1° and 4.3° in Chapters 3 and 5, respectively. For the right contact, the turns were 2.5° in both chapters when running in lane 2. Results of the present study showed that the greater turn during the left ground contact phase was due to a 15.2 Ns greater net inward impulse being generated during the left step in comparison to the right on the bend (Table 6.4). A longer mean ground contact time was observed during the left step than the right step on the bend (Table 6.3) and it is likely that this contributed to a larger inward impulse being generated. However, even if the inward impulse is normalised to time, inward impulse generated during the left ground contact was still greater. This suggests that there are functional differences between the left and right steps in terms of force generation during bend running with the left step contributing more to turning than the right step.

As well as greater inward impulses, greater peak inward force was observed during the left step than the right step (Table 6.4). These results contradict the results of the study by Chang and Kram (2007) who found the outer (right) leg generated greater peak inward forces during maximal effort sprinting on radii of up to 6 m, although they did not report impulse. Smith et al. (2006) also found the outside leg produced greater peak inward force during running (~5.4 $m \cdot s^{-1}$) on a curved path of 5 m radius on turf. It has been suggested that during bend running the outside leg performs an action similar to an open, or sidestep, cutting manoeuvre, whereas the inside leg performs a cross, or crossover, cutting manoeuvre (Rand & Ohtsuki, 2000). Cutting studies have reported larger vertical and mediolateral force production and greater muscle activation in open cutting manoeuvres than in cross cutting manoeuvres (Ohtsuki & Yanase, 1989; Rand & Ohtsuki, 2000). The tightness of the radii used in the studies by Chang and Kram (2007) and Smith et al. (2006) may account for the differences between those studies and the present study. It is possible that participants performed an action more like cutting at very tight radii rather than the turning achieved during sprinting on bend radii typical of an outdoor running track.

Additionally, those studies did not use experienced sprinters. Thus, the 'recreationally fit males' (Chang & Kram, 2007) and male soccer players (Smith et al., 2006) may have been more used to performing a cutting action, which appears to be different to the turning method employed by sprinters in athletic events.

It is difficult to directly compare peak mediolateral forces on the straight to the peak inward forces generated on the bend. This is because these forces are functionally different between the two conditions. On the straight the net mediolateral impulse over a number of steps should equal zero in order that the path of travel is a straight line (McClay & Cavanagh, 1994), whereas, in bend sprinting the mediolateral forces provide centripetal force in order to follow the curved path. However, in addition to the asymmetries in inward force and impulse production between left and right steps on the bend, there were large differences in the magnitude of peak forces produced in the frontal plane between the straight and bend. Mediolateral forces are generally overlooked in the sprint literature on the straight. This is due to their relatively low magnitude and due to the fact that they do not directly contribute to the goal of forward locomotion. Mediolateral forces of up to 0.35 BW have been reported in slower running of approximately 4.5 $m \cdot s^{-1}$ (Cavanagh & Lafortune, 1980) and of approximately 0.50 BW in a single runner sprinting at 9.2 $m \cdot s^{-1}$ (Payne, 1983). The magnitude of the mean peak medial force on the straight in the present study was similar to these reported values at 0.41 BW (Table 6.4). Mean peak inward forces measured on the bend were substantially larger, with magnitudes of 1.07 BW and 0.86 BW observed for the left and right steps, respectively (Table 6.4). These values were larger than the mean peak propulsive forces observed. These relatively large forces have potential implications for strength training for athletes. It has already been suggested that the ability to sustain forces in the frontal plane, whilst generating force in the sagittal plane, may be the limiting factor to bend running performance (Chang & Kram, 2007) and the present study supports this, showing the magnitude of inward force to be substantial. This, coupled with differences in frontal plane kinematics on the bend compared to the straight seen in Chapter 3, should be a factor for consideration in strength training for athletes.

It is likely that the inward lean of athletes running on the bend, and the alterations to frontal plane kinematics that ensue, result in different frontal plane joint moments on the bend when compared to the straight. Direct measurement of 3D joint moments was not possible in the present study, which is one of the limitations. The average frontal force-lean alignment angle during mid-stance was included in the present study as a rudimentary measure for changes in the way the force vector is directed through the body in the frontal plane, which may affect the frontal plane moments experienced by the athlete. This angle is a very basic measure and as such it would not be appropriate to infer what abduction or adduction moments might be occurring at the different joints. However, a change in this angle suggests there may have been a change in the frontal plane joint moments. Average frontal force-lean alignment angle during mid-stance was positive for each step in each condition indicating that the force vector was lateral to the body lean angle in each instance. The angle was significantly smaller for the left step on the bend compared to the straight ($p < 0.05$). This means alignment between the body lean angle and the resultant force vector in the frontal plane was closer on the bend. For the right step, there was a small increase in the angle from straight to bend meaning the force vector was more lateral to the body lean angle on the bend compared to the straight. This difference was not found to be statistically significant, but there was a moderate effect size ($d = 0.77$). Overall, there was a significant difference between left and right steps for this angle on the bend ($p < 0.01$) such that there was closer alignment between the force vector and the body lateral lean vector for the left step than was observed for the right step. This may explain differences seen in inward impulse production with the left leg possibly being better aligned for the generation of inward force.

Changes in the frontal force-lean alignment angle provide support for the supposition that the force vector in the frontal plane is directed differently through the body, which may alter frontal plane joint moments on the bend compared to the straight. Measurement of 3D joint moments is lacking in the literature and is a potential area for further investigation in order to establish if frontal plane joint moments are a limiting factor to bend running performance as has previously been suggested by Chang and Kram (2007).

Usherwood and Wilson's (2006) mathematical model assumed that athletes generated a maximum force on the bend equal to that generated on the straight, but the additional requirement for centripetal force generation meant that a longer time would be spent in ground contact. Chang and Kram (2007), however, suggested that athletes were not able to generate resultant forces as large as they could on the straight whilst they were running on the bend, although that study was conducted on bends of very small radii. The results of the present study appear to support the results of Chang and Kram (2007) for the left step, where a statistically significant reduction in peak resultant force was seen on the bend compared to the straight ($p < 0.05$, Table 6.5). The results for the right step, however, were more equivocal. Table 6.5 shows an increase in peak resultant force from 3.66 ± 0.29 BW on the straight to 4.19 ± 1.29 BW on the bend for the right step. The increase was, however, influenced by an exceptionally large peak resultant force produced during the right step on the bend by one athlete, of more than seven times body weight. When that athlete's results are removed, the mean peak resultant force for the right step on the straight is 3.58 ± 0.23 BW and on the bend 3.72 ± 0.37 BW. Numerically the value on the bend is slightly higher than that seen on the straight, but when tested with a paired samples t-test the difference between the straight and bend was not significant ($p = 0.440$).

Unfortunately, one of the limitations of the present study is that the number of trials was limited to a maximum of six per athlete in total. This was in order to ensure that the results were not compromised by fatigue and to ensure motivation was preserved throughout the data collection session. Furthermore, one of the main objectives of the testing session was that ecological validity be maintained and so it was important that training sessions were interfered with as little as possible, and after discussion with coaches it was deemed that six maximal effort sprints over 60 m was the maximum number of trials that could be asked of the athletes. However, this meant that only one successful foot strike on the force plate was achieved for each foot under each condition for each athlete, which meant that it is difficult to establish if apparently anomalous results are indeed that. Ideally multiple trials per foot per condition would be collected. Obtaining left and right steps from the same trial, such as was the case for the previous chapters, would enable more data to be collected with fewer trials. However, this is difficult to achieve when force data is required. Force data from multiple steps has been collected in sprinting (e.g. Mero & Komi, 1986; Belli et al., 2002; Korhonen et al., 2010; Morin et al., 2011a; In press). However, in those studies instrumented treadmills (Morin et al., 2011a; In press) or multiple force plate systems up to 10 m in length (Mero & Komi, 1986; Belli et al., 2002; Korhonen et al., 2010) were used. The use of an instrumented treadmill would not have been possible for bend running and force plate systems this long are rare. Another option would be to have collected bend and straight data on separate occasions, as was the case in Chapters 3 and 4. This would have facilitated the obtainment of multiple trials per foot per condition without risking fatiguing the athletes. However, athletes tend to be less willing to participate in research during the competition season (Kearney, 1999), as was the case in the present study, which made multiple testing sessions per athlete impractical. In an attempt to obtain data from the highest calibre athletes available and at a time when performance was likely to be highest meant compromising the number of trials attained.

The exceptionally large peak vertical and resultant forces produced by one athlete may have been due to a rather individualised technique. This athlete was running at the second highest velocity observed within that condition (9.66 $m \cdot s^{-1}$) and the ground contact time for that step was 0.097 s, which was the shortest ground contact time observed for the right step on the bend, and resulted in the second longest flight time and step length of the group for that condition. Additionally, that athlete produced higher forces than any other athlete in each of the conditions, even once normalised to body weight. It is likely that this athlete employs a technique which elicits large contact forces anyway, as it has been shown that faster sprinting is achieved with larger ground reaction forces produced in shorter ground contact times (Weyand et al., 2000; Weyand et al., 2010). It should be acknowledged that as part of the informed consent process athletes were aware that forces were being measured. Measures were taken to ensure athletes were unaware of the exact location of the force plate and they were not informed of the forces they had produced until after the testing session. Furthermore, all trials were observed for force plate targeting and/or changes to technique on approaching the force plate. Additionally, the athlete’s coach was present and reported nothing unusual about the trial and the run was also checked afterwards from the panning camera view which was used only for feedback purposes for athletes' coaches. However, Morin et al. (2009) showed that running patterns change with a participant’s increasing awareness of the parameters being measured and the time at which they are measured. Thus, it is possible that in the present study, knowing forces were being measured, the athlete in question deliberately drove the foot into the ground to produce large forces. However, with only one trial available for the right step on the bend, it is not possible to know whether this was an exceptional trial, or whether that athlete always employs a bend running technique during which the right step produces very large forces.

It is possible that during straight line sprinting athletes generate near optimal force in order to allow sufficient propulsion and flight. It has already been acknowledged that the forces produced in straight line sprinting are not necessarily the largest forces an athlete is able to produce and that larger forces can be produced during one footed hopping than are produced during maximal effort sprinting (Weyand et al., 2010). It is possible that changes in frontal plane kinematics and the requirement to generate centripetal force on the bend results in a reduction in the vertical force production, whilst facilitating the mediolateral force production during the left step. During the right step on the bend, propulsive and vertical force generation do not appear to be substantially compromised, and may even elicit larger force production than that seen on the straight, but in general, shorter flight times limit right step length and thus lead to a reduction in velocity. It is possible that powerful muscles, such as the gluteus maximus, which is involved in both hip extension and abduction (Palastanga et al., 2006), may have been in a more favourable position or length for force generation. Changes in force production of individual muscles or groups of muscles during bend sprinting would be an interesting topic for future studies, but is beyond the scope of this thesis.

It may appear unusual that there was a reduction in flight time, yet similar vertical impulses were generated, during the right step on the bend compared to the straight. However, the explanation may lie in the asymmetry of the steps on the bend. During the left step on the bend a significantly longer mean directional step length was produced than during the right step on the bend ($p < 0.05$). Mean left step flight time was also 10 ms longer than right flight time on the bend, although this difference did not reach statistical significance. Consequently, it is likely that upon touchdown of the right step a larger vertical impulse was required to halt the downward motion of the CoM, because of the longer preceding left flight phase. Thus, a smaller proportion of the total vertical impulse generated would have contributed to production of positive vertical velocity of the CoM, which would have resulted in a shorter right flight time. Conversely, during the left step on the bend the shorter preceding right flight time may have meant that less vertical impulse was required to halt the downward motion of the CoM. This would mean that more of the vertical impulse generated, in what was also a longer ground contact phase, produced positive vertical velocity and thus a longer flight time and step length.

One of the limitations in the present study was that a lower camera resolution (720 x 576 pixels) was available for data collection than had been available on the camera used for previous studies (1280 x 1024 pixels). As far as possible, this was mitigated against by using a smaller field of view (6.6 m). However, even after digitising at full resolution and using a 2x zoom factor, the resolution of digitising was 0.0046 m. While this resolution is lower than in the previous studies, it was unlikely to dramatically affect the results since the measurement of the performance descriptors are less sensitive to these small errors than upper and lower body kinematics which were measured in Chapters 3-5. Additionally, since any errors in digitisation are likely to be random in nature, they are unlikely to have had a dramatic effect on group means.

6.4.2. Relationships between performance and force production on the bend

As well as understanding how force production differs on the bend compared to the straight, the second aim of this study was to understand the relationships between force production and better performance during maximal effort bend running. For this reason, a number of correlations between performance descriptors and force variables were performed.

Peak and average vertical and resultant forces were significantly positively correlated with race and directional step lengths and flight time, but significantly negatively correlated with step contact factor, during the left step on the bend (Figure 6.6, Figures 6.6-6.7, Table 6.6) Additionally, vertical impulse and relative vertical impulse were significantly positively related to flight time and negatively correlated with step contact factor for the left step. These relationships indicate that athletes who exhibited the longest race and directional step length during the left step on the bend did so by generating larger vertical and resultant forces, causing the longest flight times. The longer flight times also meant that a smaller proportion of the total step time was spent in ground contact. A larger relative vertical impulse resulted in a longer flight time, but was negatively correlated with step frequency for the left step on the bend ($r = -0.872$, $p < 0.05$, Figure 6.7). This means that, while a larger vertical impulse was important for producing long left step lengths, the increase in flight time that followed resulted in a reduction in step frequency. This sort of negative interaction between step length and step frequency has been well documented in straight line sprinting (Hunter et al., 2004a) and appears to also be a factor in performance during bend sprinting.

Left touchdown distance was also significantly negatively correlated with left step vertical and resultant force variables and relative vertical impulse (Table 6.6). Interestingly, this indicates that those athletes who exhibited the longest touchdown distances were less able to generate resultant and vertical force during the contact phase. The relationship between touchdown distance and increased braking force on the straight has been well established in the literature (Hunter et al., 2005). It should be noted that braking forces have been suggested as necessary to prevent over-rotation of the body about the longitudinal axis during cutting manoeuvres (Jindrich et al., 2006). However, in the present study, no relationship was found between braking forces and the turn of the CoM, which suggests braking forces may not be as necessary at such small turn angles (approximately 4° for the left step, compared to the 30° and 60° cutting angles studied by Jindrich (2006)). Additionally, unlike cutting manoeuvres, turning is achieved over a series of steps during bend running, thus, any slight over rotation in one step can be mitigated against in the next step. Since the results of the present study suggest that increased touchdown distance may be detrimental to vertical force production on the bend further support is given to the recommendation that reducing the touchdown distance during the left step may be an area for improvement during bend running (Chapter 3).

There was a significant positive correlation for body lateral lean at take off with peak vertical force and relative vertical impulse during the left step ($r = 0.781$ and $r = 0.848$, respectively, $p < 0.05$, Figure 6.12, Table 6.6). This means that the most negative lean angles (the most inward lean) were associated with the lowest peak vertical force and relative vertical impulse generation. This is evidence that inward lean may reduce athletes' ability to produce vertical force during the left step, probably because of increased necessity to stabilise in the frontal plane when leaning into the bend (Chang & Kram, 2007).

Those athletes whose peak propulsive force and relative propulsive impulse were largest achieved the highest absolute speeds during the right step on the bend (p <0.05, Figure 6.13, Table 6.7). Right step race velocity showed similar correlations with these two force variables but did not quite reach statistical significance (with peak propulsive force: $r = 0.743$, $p = 0.055$; with relative propulsive impulse: $r = 0.747$, $p = 0.053$). There was also a link between inward lean and propulsive force production during the right step on the bend as athletes who exhibited more inward lean at touchdown exhibited a longer duration of propulsion, which likely contributed to the greater propulsive impulse and relative propulsive impulse. Additionally, more propulsive impulse and relative propulsive impulse was generated by those athletes with greater inward lean at both touchdown and take off during the right step. It is possible that the ability to lean into the bend whilst still generating propulsive impulse was what allowed those athletes to run faster. It is also likely that the fact they were able to achieve higher velocities contributed to greater lean angles being required at take off.

Larger (more negative value) body lateral lean angles at right touchdown and take off on the bend were also associated with more net inward impulse and relative net inward impulse, as evidenced by the negative correlations ($p < 0.05$, Table 6.7). It is likely that greater inward impulse requires athletes to lean inward more to counteract the moments cause by a larger centripetal force which would otherwise rotate the body outwards about the AP axis. It is also likely that during the right step a greater inward lean was more favourable for inward force, and thus impulse, generation than a lesser inward lean. That is, athletes may have been more able to exert forces in the outward direction, resulting in a larger GRF in the inward direction. Additionally, the fact that increased inward lean was associated with increased propulsive impulse generation, and thus faster performance may have meant these athletes were required to produce more inward impulse in order to turn effectively.

Overall, the relationship of inward lean with force generation appeared to be different between steps. For the left step, greater inward lean was associated with reduced ability to generate vertical force, which was detrimental to left step length production. On the right, however, the inward lean appeared to be beneficial for generating propulsive impulse and inward impulse. It is likely that the differing effects of the lean are due to the difference in orientation of the body in the frontal plane. For example, it was seen in Chapter 3 that there was a tendency for the left hip to be adducted and the right hip abducted during stance. It is also known that differences in frontal plane orientation can affect muscular activity and force production in the sagittal plane (Earl et al., 2001; Coqueiro et al., 2005) and that muscles do not work only in one plane (Palastanga et al., 2006), thus the differences in left and right leg orientations may account for the differing effects of lean on force generation.

The position of the foot during the push off may also have influenced the force generation during the left and right steps. Although not directly measured in the present study, Bojsen-Møller (1979) described the foot as being capable of using two alternative axes for push off: the transverse and oblique axes. The transverse axis runs through the first and second metatarsal heads, whereas the oblique axis runs through the second to the fifth metatarsal heads (Bojsen-Møller, 1979). The use of these two axes affects the congruency of the calcaneocuboid joint and the effectiveness of the windlass mechanism of the plantar aponeurosis, which in turn affect the stability of the foot and its effectiveness of propulsion. During push off about the transverse axis the calcaneocuboid joint is closely packed. Furthermore, there is a pre-tightening of the plantar aponeurosis and the relatively large radius of the first metatarsal head provides a larger drum about which the plantar aponeurosis is wound, which increases the effectiveness of the windlass mechanism (Bojsen-Møller, 1979). Conversely, when push off occurs about the oblique axis the calcaneocuboid joint is less closely packed, and the windlass mechanism is less effective due to the smaller radius of the second to fifth metatarsal heads (Bojsen-Møller, 1979). Thus, the transverse axis provides a stiffer, more stable foot for propulsion than the oblique axis (Bojsen-Møller, 1979). With regards to the present study, it is probable that increased inward lean of the athletes during bend running means that ground contact was more lateral for the left foot and more medial for the right foot. This would mean the left foot would be more likely to employ the oblique axis during the push off phase. This may account for the reduction in vertical force production with increased inward lean for the left step. In contrast, the right foot would be more likely to employ the transverse axis when inward lean increased, which may have contributed to greater propulsive force generation.

There was a significant negative correlation between right step contact factor and average vertical force production during the right ground contact ($r = -0.789$, $p < 0.05$, Figure 6.14, Table 6.7) indicating those athletes who generated less vertical force spent a greater proportion of the total step time in ground contact. This may be for two reasons. Firstly, it is possible that ground contact time was increased for those athletes who were less able to produce high vertical forces in order that sufficient vertical impulse could be generated. Indeed, it has been shown, in straight line sprinting, that better athletes were able to generate high forces in a short ground contact time (Weyand et al., 2010). Secondly, step contact factor may have increased because flight time was reduced due to a lower average vertical force generation eliciting a lower vertical impulse. The latter also seems likely since there was a positive correlation between average vertical force and flight time during the right step which was close to being statistically significant ($r = 0.752$, $p = 0.051$). This is likely to mean that, for those athletes, step length was shorter due to the reduced flight times which may have resulted from the poorer ability to generate vertical force during the step. Whilst there were fewer significant correlations between vertical force variables and performance descriptors on the right than there were on the left (Table 6.6-6.7) vertical force production is still important for the right step on the bend and those athletes who are unable to generate enough vertical impulse are likely to produce a shorter step length.

Conclusion

Race velocity and absolute speed were ~2.3 % lower on the bend than on the straight for both the left and right steps. This was due small decreases in race/directional step length and step frequency for the left step and significant decreases in race/directional step length for the right step on the bend compared to the straight. During the left step on the bend there was a significant decrease in peak and average vertical force as well as peak resultant force compared to the straight, whereas the bend did not appear to compromise force generation during the right step. However, there was a reduction in right flight time, suggesting that less of the vertical impulse generated during the right stance phase contributed to increasing positive vertical velocity of the CoM prior to take off. Thus, vertical force production during the right step may still be an area of interest for coaches and athletes.

Forces generated in the frontal plane were substantial during bend sprinting in comparison to straight line sprinting. Furthermore, there was an asymmetry between left and right, with the left step contributing more to inward impulse generation and thus turning. It has previously been suggested that the lean into the bend and the necessity to generate large mediolateral forces and impulse may result in increases in frontal plane moments which may compromise an athlete's ability to generate vertical and resultant forces (Chang & Kram, 2007). Inward lean during bend sprinting is inevitable and probably contributes to athletes being able to produce sufficient inward force to turn effectively and follow the curved path. Thus, athletes need to be able to generate the required vertical and propulsive forces whilst leaning and stabilising in the frontal plane, and training should reflect this. For example, athletes should ensure that they undertake maximal-speed training on the bend, in order that the high forces whilst leaning are not only experienced during a competition setting. This means that when the focus of the training is the bend, the starting positions should be such that the maximum speed phase occurs entirely on the bend. Additionally, the use of ropes/harnesses may allow athletes to be supported in a leaning position during strength training and/or plyometric training. Furthermore, the demands of the left and right steps on the bend appear to be functionally different, but care should be taken to avoid introducing asymmetries that might be detrimental to the straight line portion of the race.

Correlations showed that the ability to generate large resultant and vertical forces was associated with longer step length production during the left step on the bend. However, the longer flight time associated with the greater vertical impulse generated was associated with a lower left step frequency. Thus, athletes and coaches should take care that any attempt to improve one variable does not result in an unacceptable deterioration in another. During the right step on the bend the ability to continue to generate propulsive force/impulse whilst leaning into the bend was what set apart the better performers. Thus, this may be a potential area of focus of strength training for athletes.

CHAPTER 7: DISCUSSION

7.1. Introduction

The aim of this thesis was to understand the effect of the bend on maximal effort sprint performance and technique at bend radii and on surfaces typical of outdoor competition. A series of research questions were devised in Chapter 1 in order to meet this aim. These research questions directed the focus of the investigations outlined in Chapters 3-6. Consequently, these research questions are addressed and the main findings of this thesis are discussed in this chapter. Additionally, a discussion of the appropriateness of the methodological approach to meeting the thesis aim is provided, the practical implications of the research are highlighted, and suggestions for potential future investigations are provided.

7.2. Addressing the research questions

There is, in general, a paucity of biomechanical research into bend sprinting. Those studies, which have been previously undertaken, have not been representative of the conditions experienced by athletes running at maximal speed during athletic sprint events on an outdoor track. This led to the formulation of the first research question:

i. **How do technique and performance change on the bend compared to the straight?**

To answer this question, the study described in Chapter 3 was undertaken. Seven male and two female athletes, all experienced in bend running, undertook maximal effort 60 m sprints on the straight and on the bend in lane 2 of a standard outdoor track. Three dimensional coordinate reconstruction allowed a number of performance descriptors and upper and lower body kinematic variables to be calculated.

Mean left step race velocity reduced from 9.86 $m \cdot s^{-1}$ on the straight to 9.39 $m \cdot s^{-1}$ on the bend ($p < 0.05$) for the male athletes. Left step race velocity reduced because of a significant reduction in step frequency from 4.50 Hz on the straight to 4.39 Hz on the bend ($p < 0.05$). This was contributed to by a significant increase in ground contact time ($p < 0.01$) on the bend compared to the straight. The results for the left step are in line with the mathematical model proposed by Usherwood and Wilson (2006), which suggested the additional requirement for centripetal force generation would result in an increase in ground contact time, assuming athletes already generate their maximum force on the straight. However, there were also significant increases in touchdown distance and body sagittal lean ROM ($p < 0.01$) which have been shown to be related to increased ground contact time in straight line sprinting (Hunter et al., 2004a). It is likely that these changes in technique also contributed to the increased ground contact time on the bend compared to the straight and may have therefore contributed to the observed decrease in step frequency.

Mean right step race velocity reduced from 9.80 $m \cdot s^{-1}$ on the straight to 9.33 $m \cdot s^{-1}$ on the bend ($p < 0.01$) for the males. In contrast to the left step, this was due to a significant 0.10 m decrease in right race step length ($p < 0.05$) with no decrease in step frequency. This was caused by a significant decrease in flight time from 0.121 s on the straight to 0.112 s on the bend for the male athletes ($p < 0.05$). These are changes which are unaccounted for in the mathematical model of Usherwood and Wilson (2006).

The necessity for inward lean caused a number of technique changes in the frontal plane on the bend in comparison to straight line sprinting. These included a tendency for the left hip to be more adducted and the right hip to be more abducted during stance on the bend compared to the straight. It is likely that the changes in frontal plane kinematics also had an effect on sagittal plane kinematics, such as the statistically significant asymmetries between left and right steps on the bend observed in a number of sagittal plane kinematics including hip angle at take off and at full flexion, knee angle at touchdown and ankle angle at take off ($p < 0.05$). Asymmetries between left and right in many of the kinematic variables and the fact that the left step contributed more to turning than the right step indicate that the roles of the left and right steps may be functionally different in bend sprinting.

In order to build upon the knowledge gained from understanding the differences between the bend and straight in terms of performance and technique, it was desirable to understand how better bend sprinters perform bend running more effectively than poorer bend sprinters. This would allow a greater insight into the factors that contribute to better performance on the bend and thus may inform coaching. For this reason the second research question was proposed:

ii. **What effect does bend running have on technique and performance of athletes of different abilities running the same bend?**

For Chapter 4, the data collected in Chapter 3 was analysed to understand the relationships between performance and technique during bend running. The Pearson correlations showed that the faster left step performances on the bend were characterised by more inward lean. Thus, the ability to withstand and generate forces whilst leaning into the bend may be an indicator of superior bend running performance. For the right step, the relative lack of statistically significant relationships between absolute speed/race velocity and other kinematic variables may indicate that technique was more variable during the right step on the bend.

A smaller thigh separation at left touchdown was associated with longer left steps on the bend indicating that those athletes who were better able to recover their trailing leg prior to left touchdown, produced a longer step than those athletes with a larger thigh separation. For the right step on the bend a more extended right knee at touchdown was associated with longer step length production. A more extended right knee at touchdown was itself related to a more active touchdown strategy, based on the slower (less forward) foot horizontal velocity at touchdown, and a smaller thigh separation at right touchdown. Higher step frequencies were achieved with shorter flight times and not necessarily shorter ground contact times for both the left and right steps on the bend.

There was a negative interaction between right step frequency and right directional step length on the bend. Thus, the signs of the relationships of any variables commonly correlated with right step frequency and right directional step length were opposite. For example, right step contact factor was positively correlated with right step frequency but negatively correlated with right directional step length. A similar pattern was found for the left step, where there were a number of variables which were significantly correlated with both step frequency and race/directional step length, but the sign of the relationships were opposite. This has implications for training, where athletes and coaches should be careful that training to alter step length or step frequency does not result in an unacceptable deterioration in the other, and a potential decrease in velocity.

With regards to the factors that allowed athletes to better maintain their straight line velocity on the bend, the smallest decreases in performance were achieved by those athletes who exhibited the smallest decreases in step length on the bend compared to the straight for both the left and right steps. For both steps, this was contributed to by smaller reductions in some leg extension variables, such as plantarflexion of the ankle and MTP for the left step and hip extension at full extension and knee range of extension for the right step on the bend compared to the straight. Furthermore, those athletes whose left and right race velocities reduced the least on the bend compared to the straight were those who were better able to maintain a greater negative velocity of the foot relative to the CoM at touchdown. In other words, there was better maintenance of an active touchdown in these athletes. Thus, an active touchdown appears to be an important factor in bend running.

The fact that athletes are required to run the bends of different radii depending on lane allocation has led researchers to postulate that athletes in the inner lanes are at a disadvantage during bend running (Jain, 1980; Greene, 1985; Usherwood & Wilson, 2006). However, because the magnitude of any disadvantage has not been agreed upon, and because there had been no studies which have assessed the effect of the bend on technique and performance at different bend radii typical of athletic events, the third research question was developed:

iii. How do technique and performance change when athletes run bends of different radii?

The study detailed in Chapter 5 measured nine male athletes running at maximal effort in lanes 8, 5 and 2 of a standard outdoor track. Manual digitisation of video and 3D reconstruction allowed performance descriptors and upper and lower body kinematics to be measured in each of the lanes for the left and right steps.

There was a general trend for race velocity to reduce from lane 8 to lane 5 and then to lane 2. However, this relationship may not be linear. Mean race velocity decreased significantly by 2.1 % and 2.0 % from lane 8 to lane 5 for the left and right steps, respectively ($p < 0.05$). From lane 8 to lane 2, the mean race velocity was 2.3 % and 2.0 % lower for the left and right steps, respectively ($p < 0.05$). These results support mathematical models which have suggested the inner lanes to be at a disadvantage during sprinting (Jain, 1980; Greene, 1985; Usherwood & Wilson, 2006). The higher group variability in velocities achieved as bend radius decreased may be indicative of the fact that some athletes are better able to meet the demands of tighter radii than other athletes.

There were few significant differences between lanes for upper and lower body kinematics. This suggests these aspects of technique were similar regardless of which lane an athlete was in. However, there were a number of significant asymmetries between left and right within a lane for performance descriptors such as touchdown distance and body sagittal lean ROM, which were larger for the left step in all lanes ($p < 0.001$), and for a number of lower body kinematics. These included hip angle at take off and at full extension, where the left hip was significantly more extended than the right hip in each lane ($p < 0.05$). Furthermore, the left hip was significantly more flexed at full flexion than the right hip in each lane ($p < 0.05$). There were also significant asymmetries in frontal plane hip angles, where the left hip showed a tendency for greater adduction during stance, whereas the right hip showed a tendency towards abduction. These results are in line with the results of Chapter 3, and it is likely that the asymmetrical changes in frontal plane kinematics contributed to the asymmetries observed in sagittal plane kinematics in all lanes measured. In addition, in each lane studied significantly more turning was achieved during the left contact phase than the right ($p < 0.01$). These results support the proposition that there are functional differences between the left and right steps during maximal effort sprinting on the bend.

Chapters 3 to 5 had established that performance was decreased on the bend and a number of technique variables such as increased touchdown distance during the left step and reduced flight time on the right step were established as possible mechanisms for this decrease in performance. Furthermore, kinematic changes associated with running lane were identified. However, these studies did not yet establish the underlying cause of performance reductions. The necessity to produce centripetal force and a reduction in the ability to produce vertical and propulsive force had been suggested a limiting factor to bend running performance (Usherwood & Wilson, 2006; Chang & Kram, 2007). Thus, a kinetic analysis of bend sprinting was required to answer question iv:

iv. Why are athletes unable to produce the same performance on the bend as they are able to on the straight and how are the better performances achieved on the bend?

The ultimate reason for differences in bend and straight sprint performance is the fact that athletes must generate centripetal force in order to follow the curved path on the bend. Thus, sub-question, iv(a), was established in order to answer research question iv:

a. How does the requirement to follow the bend affect force production during sprinting?

Seven male athletes were analysed running along the straight and on the bend at a radius equivalent to lane 2 of a standard outdoor track. Race velocity decreased from 9.56 $m \cdot s^{-1}$ to 9.35 $m \cdot s^{-1}$ and 9.51 $m \cdot s^{-1}$ to 9.29 $m \cdot s^{-1}$ on the bend compared to the straight for the left and right steps, respectively.

During the left step on the bend, there was a significant decrease in peak vertical force from 3.80 BW on the straight to 3.43 BW on the bend ($p < 0.01$). Similarly, there were significant reductions in average vertical force and peak resultant force produced during stance for the left step on the bend compared to the straight. Vertical impulse, however, was similar between bend and straight conditions for the left step. This was due to a 10 ms increase in mean ground contact time from 0.107 s on the straight to 0.117 s on the bend for the left step. This supports the mathematical model of Usherwood and Wilson (2006).

For the right step, however, Usherwood and Wilson's (2006) model is not supported. There was no significant change in ground contact time, and in fact, numerically, mean ground contact time was actually shorter on the bend than the straight by 0.004 s. Indeed, the results indicated that with the exception of the necessity to generate inward force and impulse, right step vertical and propulsive force production was not substantially different on the bend compared to the straight. Right step velocity was reduced due to a decrease in right step length.

As expected, forces generated in the frontal plane were substantially larger on the bend than on the straight. For example, the largest peak frontal plane forces on the straight were the peak medial forces, which were 0.41 BW for both the left and right steps. On the bend, peak inward forces of 1.07 BW and 0.86 BW were observed for the left and right steps, respectively. Inward impulse was 39.9 Ns for the left step on the bend, which was found to be significantly larger than the 24.7 Ns inward impulse for the right step on the bend ($p < 0.01$). The differences in inward impulse generated caused significant differences in the turn of the CoM during the left and right steps on the bend, with the left step producing 1.4° more turning than the right step ($p < 0.05$). Even when normalised to account for the longer ground contact time, the left step still produced more inward impulse than the right step on the bend. This supports the proposition that the left and right steps are functionally different in bend sprinting.

In order to build upon the knowledge gained from comparing the bend to the straight, sub-question iv(b) was developed in order to answer the final part of research question iv:

b. What are the force characteristics of better performance during bend sprinting?

Correlations between performance descriptors and force variables were performed. The generation of resultant and vertical forces during the left step on the bend was associated with a number of performance descriptors. For example, peak and average vertical and resultant forces were significantly positively correlated with race and directional step lengths and flight time ($p < 0.05$), indicating that those athletes who produced the longest steps did so by producing large resultant and vertical forces, which resulted in longer flight.

However, whilst a larger vertical impulse was important for producing long left step lengths, the increase in flight time that followed resulted in a reduction in step frequency (significant negative relationship between relative vertical impulse and step frequency; $r = -0.872$, $p < 0.05$) during the left step on the bend. Thus, negative interaction between step length and step frequency, which has been observed in straight line sprinting (Hunter et al., 2004a), also appears to be a problem during bend running.

Those athletes who produced shorter touchdown distances were also better able to generate large resultant and vertical forces ($p < 0.05$) during the left step on the bend. It is likely that a shorter touchdown distance positioned those athletes more favourably for resultant and vertical force production, and further supports the proposition that reducing left touchdown distance is a potential area for improvement in bend sprinting.

A more negative (more inward) body lateral lean at left take off was associated with lower peak vertical force and relative vertical impulse during the left step ($r = 0.781$ and $r = 0.848$, respectively, $p < 0.05$). This is evidence that inward lean may reduce athletes' ability to produce vertical force during the left step, and may be because of increased necessity to stabilise in the frontal plane when leaning into the bend (Chang & Kram, 2007). However, inward lean during bend sprinting is inevitable and probably contributes to athletes being able to produce sufficient inward force to turn effectively and follow the curved path, therefore it is important that runners are able to generate sufficient vertical forces despite the lean, especially since Chapter 4 showed evidence of faster athletes exhibiting greater inward lean during the left step.

During the left step on the bend, inward lean was related to a reduced ability to generate vertical force, which may be detrimental to performance. However, for the right step inward lean was shown to be related to the generation of propulsive and inward impulse, thus appeared to have a beneficial effect on performance for the right step. For example, there was link between greater right step net inward impulse and a larger inward (more negative) body lateral lean angles at right touchdown (r = -0.892, $p < 0.01$) and at right take off (and r = -0.978, $p < 0.01$) on the bend. The relationship between inward impulse generation and lean is probably twofold: firstly, the greater inward impulse would have the effect of increasing the necessity for inward lean to counteract the moments caused by a larger centripetal force which would otherwise act to rotate the body outwards about the anteroposterior axis. Secondly, inward lean may have meant that the right foot was positioned favourably for inward impulse generation. Furthermore, the correlations showed that the athletes who leant into the bend more also generated more propulsive impulse. Additionally, the athletes who generated the largest relative propulsive impulse also exhibited the fastest absolute speed (r = 0.772, $p < 0.05$) during the right step on the bend. Thus, these athletes may have needed to produce more inward impulse in order to turn effectively and stay within the lane. It is likely that the effect of the lean was different between left and right steps because of the differences in frontal plane kinematics between limbs. For example, Chapter 3 and 5 showed a tendency towards adduction for the left hip and abduction for the right hip during stance.

The studies undertaken throughout the thesis have enabled the research questions to be answered. Chapters 3-5 have shown performance to decrease on the bend in comparison to the straight and also as a function of bend radius. Furthermore, step characteristics and technique variables have been shown to change both on the bend compared to the straight and in different lanes on the bend. The kinetic analyses undertaken in Chapter 6 have shown that force production differs on the bend compared to the straight and is different between left and right steps. Indeed, all of the studies presented in the thesis have highlighted asymmetries between left and right steps during bend sprinting. This is caused by the necessity to lean into the bend which places the left and right limbs in an altered frontal plane orientation, compared to straight line sprinting. This resulted in the left and right limbs being functionally different. That is, the limbs necessarily acted differently during bend sprinting, particularly in relation to their contribution to turning. As such, training for bend sprinting must be specific to bend sprinting, but care must be taken that asymmetries are not introduced into the straight line sprinting.

7.3. Discussion of the methodological approach

Three dimensional video analyses were undertaken for all studies conducted as part of this thesis. The video data were manually digitised and a 3D reconstruction of digitised landmarks performed. An approach, novel to sprint studies, to joint angle definition was taken (Yeadon, 1990a). This allowed joint angles to be resolved into 3D orientation angles for some of the joints. Previous sprint studies which have aimed to describe motion at a joint in terms of flexion/extension, abduction/adduction and/or internal/external rotation have used either a 2D sagittal plane protocol assuming joint angles to be flexion/extension (Mann & Hagy, 1980; Kunz & Kaufmann, 1981; Mann & Herman, 1985; Hamilton, 1993; Johnson & Buckley, 2001; Bezodis, 2009) or have used 3D automated motion capture technology to obtain 3D kinematics (Slawinski et al., 2010). In the studies presented in Chapters 3-6, the requirement for athletes to turn to follow the curved path of the bend would have resulted in out of plane errors had a 2D protocol been undertaken, which would have been unacceptable. Additionally, this would have resulted in the loss of valuable information from the studies, such as the angle of body lateral lean and hip abduction/adduction angles. Automated motion capture would have allowed these variables to have been calculated, as well as orientation angles for the knee and ankle joints, which would have likely been of interest in bend running. However, it is known that a greater level of interference, such as the attachment of markers for automated motion capture, is likely to result in athletes being less willing to participate in research (Kearney, 1999). Furthermore, the attachment of markers would have reduced the ecological validity of the studies.

The highest possible resolution of the video cameras available was used for each data collection. For the data collected and used in Chapters 3 and 4, a resolution of 1280 x 1024 pixels was used, which was digitised in Vicon Motus with a 2x zoom factor. The 7.5 m long field of view meant that the resolution of measurement was 0.0029 m. This compares favourably with the resolution of, for example, the study by Johnson and Buckley (2001). In that study a 4.5 m wide field of view and resolution of 640 x 512 was used (Johnson & Buckley, 2001). This means that the resolution of measurement was 0.0070 m. In the study detailed in Chapter 5, the field of view was extended to 8 m to prevent some of the body landmarks being out of the field of view during the extra 'padding' fields, which was one of the limitations of the data collected for Chapters 3 and 4 and which is discussed in Chapter 3. The resolution of measurement for the study in Chapter 5 decreased only slightly to 0.0031 m. In the final study (Chapter 6) the camera resolution was lower than in previous studies at 720 x 576 pixels. The 6.6 m field of view resulted in a 0.0046 m resolution of digitising (when a 2x zoom factor was used). Thus, it was deemed that the resolution of digitising was adequate in all studies conducted and that the benefits of the unobtrusive data collection merited the use of a manual digitisation protocol.

It has been suggested that one of the limitations to maximal speed velocity on the bend is the requirement to stabilise in the frontal plane (Chang & Kram, 2007). As such, the measurement of 3D joint moments and powers would have been interesting. Unfortunately, the joint centre-based methods used throughout the thesis to obtain 3D joint angles (Yeadon, 1990a) meant that a full 3D joint kinetics analysis was considered beyond the scope of this study.

There have been a limited number of participants in the studies in this thesis. Whilst it would have been desirable to recruit more athletes for each study, it is a common problem particularly as the calibre of athletes increases (Kearney, 1999). Additionally, the final study (Chapter 6) required force plates located in a facility large enough to allow 60 m of a lane of a bend with a radius of 37.72 m to be marked out. This often meant that athletes needed to travel further for that particular training session, which may have limited participation. However, in an attempt to recruit high calibre athletes, especially for the final study, who were experienced in bend running, a smaller sample size was deemed acceptable. Furthermore, despite the small number of participants, statistically significant results were still obtained in all studies.

Generally, throughout the thesis a group design has been undertaken. It has been suggested that this approach may mask individual differences in data (Dixon & Kerwin, 2002). For this reason, some sprint studies have taken the approach of conducting multiple single-participant analyses (Bezodis, 2009; Salo et al., 2011). However, to the author's knowledge, this is the first methodologically robust study that has investigated the biomechanics of athletes sprinting at maximal speed on the bend on a surface and at radii relevant to those of outdoor competition situations. Thus, a group design was employed in order that those kinematic and kinetic variables generally important to bend running performance could be identified. This type of group analysis, which was previously lacking from the literature, will allow a starting point by which athletes and coaches might identify where improvements can be made on the bend. Thus, although limited to identifying general trends, it was felt that, given the current state of knowledge, a group design was a legitimate approach to the analysis of bend sprinting.

Throughout the thesis, step frequency was calculated at the quotient of race velocity and race step length. Potentially, any of the three variables step length, step frequency, and velocity, can be calculated as long as the other two are known. Alternatively, some sprint studies have independently calculated each of the aforementioned variables from kinematic data (e.g. Mann & Herman, 1985). In this thesis, the chosen method was decided upon after consideration of the potential effects of errors in gait event detection upon step frequency calculation. It is possible for touchdown to occur immediately after a video frame. Therefore, at a 200 Hz frame rate, visual identification of touchdown may occur up to 5 ms later than its true occurrence. If step frequency is calculated as the inverse of a typical step time of 0.225 s, the result would be 4.44 Hz. If, however, an error in touchdown identification meant step time was recorded as 0.220 s, the resulting step frequency would be 4.55 Hz. Furthermore, gait events may be identified incorrectly. If the first touchdown was identified a frame late and second touchdown identified a frame early, step time might be recorded as 10 ms shorter. Conversely, first touchdown might be identified one frame early and second touchdown identified one frame late resulting in step time being recorded as 10 ms longer. The resulting step frequencies for the same step could, therefore, be calculated as 4.65 Hz or 4.26 Hz. Thus, it was decided that step frequency should be calculated from race velocity and race step length since it was deemed that this would be the most accurate method and is in line with the methods of previous sprint research (e.g. Bezodis et al., 2008).

One of the implications of the method chosen for step frequency calculation is that, throughout the study the inverse of the sum of ground contact time and flight time can be different to the step frequency presented. This discrepancy is acknowledged, and is due to potential errors in the calculations of the variables. It is not uncommon to find discrepancies of this nature in sprint studies.

7.4. Practical implications

There are a number of practical implications from the findings of this thesis, which may help to inform coaching practice. Firstly, the nature of bend running has been found to be substantially different to straight line sprinting both in terms of kinematic and kinetic characteristics. This means that, in order to improve performance on the bend athletes and coaches should ensure adequate attention is paid to sprint training and conditioning specific to the bend.

In particular, a potential area for improvement in bend sprinting may be employment of an active touchdown strategy. This includes ensuring the foot is moving forward at touchdown with as little forward velocity as possible (ideally it should move backwards relative to the ground, but this does not seem to be possible). Also, the horizontal velocity of the foot relative to the CoM should be as negative as possible, since a less active touchdown was shown to be related to shorter right step length production, and reductions in race velocity on the bend compared to the straight for both the left and right steps. For example, athletes may be encouraged to step down with a high foot-carriage, rather than consciously trying to extend the step length. Furthermore, a smaller thigh separation angle at left touchdown was linked to longer left step length production on the bend, indicating that those athletes who were better able to recover their right leg prior to left touchdown were then able to produce longer left steps. Thus, quick recovery of the right leg may be an area of focus in those athletes who wish to increase their left step lengths on the bend. Additionally, reducing the touchdown distance, especially at left touchdown, may improve bend sprinting performance by reducing left ground contact times, which were found to be increased on the bend compared to the straight which resulted in a decrease in left step frequency. Correlations revealed that reductions in step length on the bend compared to the straight were closely related to reductions in race velocity. Thus, training may focus on maintaining step length while bend sprinting. It should be noted that a number of negative interactions were identified during bend running, thus, it is important that care should be taken that any attempt to improve one aspect of an athlete’s technique does not result in an unacceptable decrease in another area.

The investigation into the effect of the lane on bend sprinting performance and technique revealed differences in step characteristics between lanes, although in general there were few significant differences in upper and lower body kinematics between lanes. This means that during training there will likely be the benefit of training effects being transferable between lanes, but it would be good practice to train in all of the lanes over the course of a season.

The distinguishing characteristics of bend running are the necessity to generate inward impulse in order to follow the curved path and lean into the bend in order that the centripetal force generated does not cause rotation about the anteroposterior axis. This means that athletes must be able to generate substantial mediolateral forces (up to approximately 1.1 BW) which are not required during straight line sprinting (where peak mediolateral forces of approximately 0.4 BW were generated). Furthermore, athletes must also generate the required vertical and propulsive forces whilst leaning and stabilising in the frontal plane. This is a requirement quite different to straight line sprinting. Thus, strength and conditioning training specific to the altered frontal plane orientation may improve an athlete's ability to withstand and generate the forces associated with bend sprinting. For example, this may include athletes undertaking plyometric training exercises, such as bounding, on the bend and not just on the straight. Additionally, it is possible that those athletes who have greater frontal plane strength are better bend runners, although such a measurement was beyond the scope of this thesis.

Throughout the investigations undertaken in this thesis, asymmetries between the left and right steps were identified in direct performance descriptors, upper and lower body kinematics, and kinetic variables. This meant that there were functional differences between the left and right steps during bend running. As such the principle of specificity of training should be employed so that the demands of what is fundamentally an asymmetrical movement can be met. This would include high speed training on the bend. This notwithstanding, care should be taken to ensure that asymmetries which could be detrimental to performance are not introduced into the straight line component of sprinting.

7.5. Future research

The studies conducted as part of this thesis have advanced the understanding of the biomechanics of maximal speed sprinting on the bend. However, there are a number of potential future studies outlined in this section that could be undertaken to further advance this knowledge.

As previously mentioned, it has been suggested that during bend running there is an increased requirement for stabilisation in the frontal plane (Chang & Kram, 2007). Furthermore, Chang and Kram (2007) suggested that muscles working to stabilise in the frontal plane may be limited in their ability to generate force in the sagittal plane. Throughout this thesis, the results have shown significant differences between the straight and bend in a number of frontal plane kinematics including body lateral lean at touchdown and take off and hip abduction/adduction angles during stance. Although it was not possible to measure changes in frontal plane kinematics of the knee and ankle joints using the methods employed in this thesis (see section 3.2.4 for discussion of this), it is reasonable to assume that there would be differences in frontal plane kinematics between the straight and bend at these joints too. Therefore, further study of 3D kinematics of the whole lower limb would be valuable. Furthermore, combining 3D kinematics with kinetic data would allow inverse dynamics analyses to calculate joint moments and powers in three dimensions. This would enhance the understanding of what limits force production on the bend. It is acknowledged that the methods required for this type of analysis would require 3D automated motion capture, which may compromise the ecological validity of such a study. However, in absence of less intrusive protocols, this may be a necessary compromise to further understand this topic.

Electromyographical (EMG) studies have often been undertaken in the sprint literature (Mero & Komi, 1986; Mero & Komi, 1987; Guissard et al., 1992; Nummela et al., 1994; Yu et al., 2008). However, to the author's knowledge, no such studies have been published concerning the bend portion of sprinting. Such a study would allow a greater understanding of muscle recruitment and activation during bend sprinting. In particular, muscles involved in both hip abduction/adduction and flexion/extension, such as the gluteus maximus, would be of interest, since it is possible that the changes in frontal plane kinematics may affect muscular function in the sagittal plane.

In this thesis, it was decided to conduct analyses of bend sprinting during the maximal speed phase. This was because it was deemed that this would be the phase upon which the bend would have the greatest effect. However, the other phases on the bend are likely to also be of interest to athletes and coaches, and may be potential areas for further study. The only previous study of bend running in the acceleration phase was conducted by Stoner and Ben-Sira (1979). However, that study was only concerned with performance descriptors. Thus, analyses of technique variables during the acceleration phase is still lacking in the literature.

Another area of interest is likely to be the effect that the bend has on sprint start performance. The start is unusual in that athletes may place their blocks in such a way as to minimise the curvature of the bend, allowing them to run as ‘straight’ as possible for the first few steps of the race. It would, therefore, be interesting to see what, if any, effect the bend has on start performance to see what the best strategy for block placement on the bend would be. It would also be interesting to compare start performance across lanes, where the potential distance for ‘straight’ running at the start of a race is reduced as bend radius decreases from the outer to inner lanes.

Finally, the results of Chapter 5 revealed a possibly non-linear relationship between bend radius and performance. It is possible that this is due to the force demands of bend running and that athletes are able to cope with the demands of decreases in bend radius up until a point, at which performance is substantially compromised and after which further decreases in performance are less dramatic. A study of the forces produced during bend sprinting at different radii, typical of an outdoor track may, thus, be an area for a future investigation.

7.6. Thesis conclusion

This thesis determined the effect of the bend on maximal effort sprint performance and technique using bend radii and surfaces typical of outdoor competition. Mean race velocity on the bend was found to be up to ~5% lower than on the straight. Furthermore, mean race velocity decreased as bend radius decreased by up to 2.3%

from lane 8 to lane 2. The changes in step characteristics associated with these reductions in performance were more complicated than had previously been suggested in mathematical models of bend running (Usherwood & Wilson, 2006). For the left step, the decrease in performance tended to be related to an increase in ground contact time contributing to a reduction in step frequency, as well as small reductions in step length. For the right step, reductions in performance tended to be related to a reduced step length resulting from a decrease in flight time.

Asymmetries between left and right steps during bend sprinting were prevalent throughout the studies in this thesis. These were caused by asymmetrical changes in frontal plane orientation induced by the necessity to lean inwards during bend sprinting. These asymmetries meant that the effect of the bend on kinematics and kinetics was often different between left and right steps. From a coaching point of view, this has important implications for training. Athletes should apply the principle of specificity to training, ensuring that adequate attention is paid to the bend component of sprinting. Additionally, training should be undertaken in each of the lanes on the bend across a period of training. Strength training should also consider the fact that during the bend portion of a race, forces are generated with the body in a different orientation to that of straight line sprinting. The ability to stabilise in the frontal plane, whilst generating the required sagittal plane forces likely plays an important role in bend sprinting performance. This notwithstanding, care should be taken to ensure asymmetries which could be detrimental to performance are not introduced into the straight line component of sprinting.

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APPENDIX: RELIABILITY DATA

Table A.1. Mean, standard deviation and coefficient of variation (CV) for left and right step performance descriptors from eight redigitisations of a bend trial and a straight trial.

	Bend				Straight			
	Mean ± SD		CV (%)		Mean ± SD		CV (%)	
	Left	Right	Left	Right	Left	Right	Left	Right
Absolute speed ($m \cdot s^{-1}$)	8.10 ± 0.02	8.11± 0.01	0.2	0.2	8.28 ± 0.01	8.35 ± 0.01	0.1	0.1
Race velocity ($m \cdot s^{-1}$)	8.05 ± 0.01	8.05 ± 0.01	0.2	0.2	8.28 ± 0.01	8.35 ± 0.01	0.1	0.2
Directional step length (m)	2.17 ± 0.02	1.95 ± 0.01	0.8	0.4	2.02 ± 0.01	1.98 ± 0.01	0.5	0.6
Race step length (m)	2.15 ± 0.02	1.93 ± 0.01	0.7	0.4	2.02 ± 0.01	1.98 ± 0.01	0.5	0.6
Step frequency (Hz)	3.75 ± 0.03	4.17 ± 0.02	0.8	0.4	4.11 ± 0.02	4.21 ± 0.03	0.4	0.7
Ground contact time (s)	0.120 ± 0.000	0.120 ± 0.000	0.0	0.0	0.115 ± 0.000	0.115 ± 0.000	0.0	0.0
Flight time (s)	0.145 ± 0.000	0.115 ± 0.000	0.0	0.0	0.130 ± 0.000	0.120 ± 0.000	0.0	0.0
Step contact factor	0.453 ± 0.000	0.511 ± 0.000	0.0	0.0	46.9 ± 0.0	48.9 ± 0.0	0.0	0.0
Touchdown distance (m)	0.29 ± 0.02	0.31 ± 0.01	5.1	2.1	0.31 ± 0.02	0.29 ± 0.01	6.5	4.9
Body sagittal lean ROM (°)	53.0 ± 0.7	53.4 ± 0.4	1.2	0.8	51.9 ± 0.4	51.4 ± 0.4	0.9	0.7
Body lateral lean at TD (°)	-5.6 ± 0.2	-10.9 ± 0.4	4.1	3.3	3.4 ± 0.3	-4.2 ± 0.2	9.1	4.8
Body lateral lean at TO (°)	-3.6 ± 0.3	-10.1 ± 0.3	7.0	2.9	3.8 ± 0.3	-4.6 ± 0.4	7.4	9.4
Turn of CoM (°)	2.8 ± 0.3	2.8 ± 0.6	9.2	20.8				

Table A.2. Mean, standard deviation and coefficient of variation (CV) for left and right step touchdown variables from eight redigitisations of a bend trial and a straight trial.

	Bend				Straight			
	Mean ± SD		CV (%)		Mean ± SD		CV (%)	
	Left	Right	Left	Right	Left	Right	Left	Right
Thigh separation at TD (°)	30.5 ± 1.1	26.2 ± 1.6	3.5	6.0	34.6 ± 2.5	33.4 ± 2.5	7.1	7.6
Foot horizontal velocity at TD ($m \cdot s^{-1}$)	0.97 ± 0.11	0.99 ± 0.21	11.6	21.7	1.44 ± 0.20	1.16 ± 0.21	13.9	18.3
Foot horizontal velocity relative to the CoM at TD ($m \cdot s^{-1}$)	-7.08 ± 0.24	-6.95 ± 0.28	3.4	4.1	-6.85 ± 0.29	-7.32 ± 0.27	4.2	3.7
Foot vertical velocity at TD ($m \cdot s^{-1}$)	-1.35 ± 0.18	-2.13 ± 0.13	13.2	5.9	-1.77 ± 0.21	-1.98 ± 0.18	12.0	8.9
Trunk forward lean at TD (°)	-7.6 ± 0.9	-5.9 ± 1.2	12.4	19.8	-11.8 ± 1.8	-10.2 ± 0.7	15.3	6.5
Trunk lateral lean at TD (°)	-8.0 ± 0.7	-7.1 ± 0.4	8.4	5.5	-0.2 ± 0.3	0.8 ± 1.1	176.7	141.0

Table A.3. Mean, standard deviation and coefficient of variation (CV) for left and right step hip angle variables from eight redigitisations of a bend trial and a straight trial.

	Bend				Straight			
	Mean ± SD		CV (%)		Mean ± SD		CV (%)	
	Left	Right	Left	Right	Left	Right	Left	Right
Hip flexion/extension angle at TO (°)	216.7 ± 1.3	208.1 ± 1.7	0.6	0.8	207.2 ± 1.6	208.7 ± 1.9	0.8	0.9
Hip flexion/extension angle at full extension (°)	217.3 ± 1.7	209.1 ± 2.0	0.8	1.0	207.2 ± 1.6	208.7 ± 1.9	0.9	0.8
Time of hip full extension (% of step time)	48.1 ± 2.3	55.6 ± 2.4	4.7	4.3	53.8 ± 1.1	54.8 ± 2.2	2.0	4.0
Hip flexion/extension angle at full flexion (°)	111.9 ± 1.1	105.9 ± 1.4	1.0	1.4	110.2 ± 1.8	107.4 ± 1.1	1.6	1.0
Time of hip full flexion (% of contralateral limb step time)	48.1 ± 3.9	52.8 ± 1.7	8.2	3.3	56.9 ± 3.2	51.5 ± 1.8	5.6	3.5
Hip abduction/adduction angle at TD (°)	5.5 ± 1.7	0.6 ± 2.5	31.4	416.3	5.5 ± 1.0	0.3 ± 1.3	18.1	535.8
Hip peak abduction (°)	-7.7 ± 2.2	-6.8 ± 1.8	28.8	26.1	-1.3 ± 2.0	-4.1 ± 2.3	156.4	54.8
Time of hip peak abduction (% of contact)	100.0 ± 0.0	96.4 ± 5.2	0.0	5.4	89.7 ± 29.2	98.4 ± 3.2	32.6	3.3
Hip peak adduction (°)	13.2 ± 1.4	7.0 ± 1.0	10.6	14.2	10.5 ± 1.3	9.2 ± 1.4	12.7	15.5
Time of hip peak adduction (% of contact)	41.1 ± 2.7	50.5 ± 2.7	6.5	5.3	49.5 ± 2.3	48.4 ± 4.9	4.5	10.1
Hip abduction/adduction angle at TO (°)	-7.7 ± 2.2	-6.5 ± 2.0	28.8	30.3	-1.2 ± 2.3	-4.0 ± 2.3	196.0	56.8

Table A.4. Mean, standard deviation and coefficient of variation (CV) for left and right step hip angular velocity variables from eight redigitisations of a bend trial and a straight trial.

	Bend				Straight			
	Mean ± SD		CV (%)		Mean ± SD		CV (%)	
	Left	Right	Left	Right	Left	Right	Left	Right
Hip flexion/extension angular velocity at TD (°·s^{-1})	380 ± 79	276 ± 114	20.8	41.3	303 ± 112	540 ± 90	37.0	16.7
Hip peak extension angular velocity during contact (°·s^{-1})	897 ± 84	803 ± 52	9.4	6.4	871 ± 50	819 ± 50	5.7	6.1
Time of peak extension angular velocity (% of contact phase)	45.8 ± 7.0	71.4 ± 7.2	15.4	10.1	61.4 ± 13.6	59.8 ± 5.6	22.2	9.3
Peak hip flexion angular velocity during swing (°·s^{-1})	-967 ± 68	-790 ± 55	7.1	7.0	-825 ± 98	-795 ± 53	11.9	6.7
Time of peak hip flexion angular velocity (% of contralateral limb contact)	10.4 ± 8.0	43.2 ± 14.9	77.1	34.5	28.3 ± 11.6	26.1 ± 15.8	41.1	60.4

Table A.5. Mean, standard deviation and coefficient of variation (CV) for left and right step knee angle and angular velocity variables from eight redigitisations of a bend trial and a straight trial.

	Bend				Straight			
	Mean ± SD		CV (%)		Mean ± SD		CV (%)	
	Left	Right	Left	Right	Left	Right	Left	Right
Knee angle at TD (°)	155.5 ± 2.1	156.8 ± 1.8	1.4	1.1	156.1 ± 1.8	157.3 ± 1.1	1.2	0.7
Knee angular velocity at TD ($°\cdot s^{-1}$)	-439 ± 53	-234 ± 79	12.1	33.7	-398 ± 49	-238 ± 37	12.4	15.7
Minimum knee angle during contact (°)	139.6 ± 1.7	141.6 ± 1.1	1.2	0.8	156.1 ± 1.8	157.3 ± 1.1	1.0	0.9
Time of minimum knee angle (% of contact)	35.9 ± 3.1	47.4 ± 3.1	8.6	6.5	42.4 ± 4.5	39.1 ± 8.7	10.6	22.2
Knee range of flexion (°)	15.9 ± 1.5	15.2 ± 2.5	9.7	16.6	16.2 ± 1.3	13.8 ± 1.9	7.9	13.7
Maximum knee angle during contact (°)	172.7 ± 1.8	168.8 ± 1.2	1.0	0.7	168.4 ± 1.5	170.7 ± 0.9	0.9	0.5
Time of maximum knee angle (% of contact)	93.8 ± 2.2	95.8 ± 2.2	2.4	2.3	98.4 ± 2.3	97.3 ± 2.3	2.3	2.3
Knee range of extension (°)	33.1 ± 2.8	27.2 ± 1.2	8.5	4.4	28.6 ± 1.7	27.2 ± 1.8	6.0	6.6
Knee angle at TO (°)	171.1 ± 2.0	168.2 ± 1.4	1.2	0.9	168.3 ± 1.2	170.5 ± 1.0	0.7	0.6
Knee angle at full flexion (°)	23.1 ± 2.9	24.6 ± 1.5	12.7	6.1	24.1 ± 1.1	24.8 ± 2.3	4.6	9.1
Time of knee full flexion (% of contralateral step time)	10.4 ± 1.4	14.4 ± 1.4	13.1	9.8	15.4 ± 1.5	17.9 ± 3.7	9.8	20.9

Table A.6. Mean, standard deviation and coefficient of variation (CV) for left and right step ankle angle variables from eight redigitisations of a bend trial and a straight trial.

	Bend				Straight			
	Mean ± SD		CV (%)		Mean ± SD		CV (%)	
	Left	Right	Left	Right	Left	Right	Left	Right
Ankle angle at TD (°)	125.7 ± 2.9	134.6 ± 1.5	2.3	1.2	125.0 ± 2.8	129.9 ± 2.0	2.3	1.6
Minimum ankle angle during contact (°)	96.5 ± 4.1	98.9 ± 2.4	4.2	2.5	94.2 ± 1.7	99.1 ± 1.7	1.8	1.8
Time of minimum ankle angle (% of contact)	41.7 ± 2.2	44.8 ± 2.9	5.3	6.6	44.6 ± 5.6	39.7 ± 1.5	12.5	3.9
Ankle range of dorsiflexion (°)	29.2 ± 2.7	35.7 ± 1.5	9.4	4.1	30.8 ± 2.3	30.8 ± 1.3	7.6	4.1
Ankle angle at TO (°)	156.4 ± 1.4	156.7 ± 1.7	0.9	1.1	148.4 ± 3.5	157.8 ± 1.9	2.3	1.2
Ankle range of plantarflexion (°)	59.9 ± 3.4	57.8 ± 3.2	5.6	5.5	54.2 ± 2.9	58.7 ± 2.6	5.3	4.4

Table A.7. Mean, standard deviation and coefficient of variation (CV) for left and right step MTP angle and angular velocity variables from eight redigitisations of a bend trial and a straight trial.

	Bend				Straight			
	Mean ± SD		CV (%)		Mean ± SD		CV (%)	
	Left	Right	Left	Right	Left	Right	Left	Right
MTP angle at TD (°)	143.9 ± 4.0	144.7 ± 5.7	2.8	3.9	147.9 ± 3.2	147.3 ± 3.5	2.2	2.4
Maximum MTP angle during absorption phase (°)	150.5 ± 2.4	150.3 ± 3.9	1.6	2.6	159.0 ± 2.6	151.8 ± 2.2	1.6	1.4
Time of maximum MTP angle during absorption phase of contact (% of contact)	13.5 ± 2.9	17.7 ± 10.4	21.8	58.7	17.4 ± 2.3	18.5 ± 7.3	13.4	39.3
MTP range of plantarflexion during absorption phase (°)	6.6 ± 3.2	5.6 ± 6.1	48.2	108.8	11.1 ± 2.3	4.5 ± 2.7	21.0	59.9
Minimum MTP angle during contact (°)	110.4 ± 4.9	114.0 ± 4.6	4.4	4.0	117.5 ± 2.9	114.3 ± 3.5	2.5	3.1
Time of minimum MTP angle (% of contact)	79.2 ± 2.2	80.7 ± 2.2	2.8	2.7	82.1 ± 4.3	83.2 ± 1.5	5.3	1.8
MTP range of dorsiflexion (°)	40.1 ± 4.6	36.4 ± 6.4	11.5	17.7	41.6 ± 4.2	37.5 ± 2.2	10.1	5.9
MTP angle at TO (°)	138.5 ± 5.1	137.2 ± 4.6	3.7	3.3	135.3 ± 6.1	136.4 ± 3.8	4.5	2.8
MTP range of plantarflexion during extension phase (°)	28.1 ± 8.7	23.2 ± 5.8	31.0	25.0	17.8 ± 5.2	22.2 ± 3.2	29.1	14.3
Peak MTP plantarflexion angular velocity ($°·s^{-1}$)	1540 ± 447	1317 ± 303	29.0	23.0	1172 ± 219	1429 ± 249	18.7	17.4

Table A.8. Mean, standard deviation and coefficient of variation (CV) for left and right step rearfoot angle variables from eight redigitisations of a bend trial and a straight trial.

	Bend				Straight			
	Mean ± SD		CV (%)		Mean ± SD		CV (%)	
	Left	Right	Left	Right	Left	Right	Left	Right
Rearfoot angle at TD (°)	33.6 ± 3.0	39.5 ± 1.4	8.9	3.4	30.6 ± 3.3	36.7 ± 2.1	11.0	5.6
Minimum rearfoot angle during contact (°)	31.8 ± 3.7	31.7 ± 2.9	11.7	9.0	27.6 ± 2.5	31.5 ± 1.3	9.2	4.1
Time of minimum rearfoot angle (% of contact phase)	12.0 ± 4.1	24.5 ± 3.5	34.5	14.2	17.9 ± 1.5	22.3 ± 1.5	8.6	6.9
Rearfoot drop (°)	1.9 ± 1.7	7.8 ± 1.9	90.1	24.6	3.0 ± 1.0	5.2 ± 1.4	35.4	26.5
Rearfoot angle at TO (°)	117.3 ± 0.9	112.6 ± 1.0	0.7	0.9	105.4 ± 3.7	112.1 ± 2.3	3.5	2.0
Rearfoot lift (°)	85.5 ± 3.1	80.9 ± 3.2	3.6	4.0	77.7 ± 1.8	80.6 ± 2.2	2.3	2.8

Table A.9. Mean, standard deviation and coefficient of variation (CV) for upper body variables from eight redigitisations of a bend trial and a straight trial.

	Bend				Straight			
	Mean ± SD		CV (%)		Mean ± SD		CV (%)	
	Left	Right	Left	Right	Left	Right	Left	Right
Maximum thorax rotation (°)	39.0 ± 4.8	50.5 ± 1.5	12.2	2.9	38.2 ± 3.2	34.2 ± 2.6	8.4	7.7
Shoulder flexion/extension ROM (°)	91.4 ± 3.9	95.4 ± 3.1	4.3	3.3	98.4 ± 2.8	74.1 ± 3.6	2.8	4.8
Shoulder abduction/ adduction ROM (°)	30.5 ± 3.0	34.2 ± 3.5	9.9	10.4	22.7 ± 2.6	25.1 ± 2.7	11.5	10.7
Elbow ROM (°)	89.0 ± 1.4	92.0 ± 3.1	1.6	3.4	72.2 ± 2.0	84.4 ± 5.5	2.8	6.5
Minimum wrist position [relative to CoM] in ML direction (m)	0.110 ± 0.007	0.040 ± 0.005	6.2	12.4	0.086 ± 0.006	0.113 ± 0.021	6.6	18.8
Maximum wrist position [relative to CoM] in ML direction (m)	0.332 ± 0.003	0.352 ± 0.003	1.0	0.8	0.316 ± 0.002	0.333 ± 0.003	0.7	1.0
Minimum wrist position [relative to CoM] in AP direction (m)	-0.304 ± 0.004	-0.228 ± 0.003	1.3	1.5	-0.234 ± 0.004	-0.229 ± 0.004	1.5	1.8
Maximum wrist position [relative to CoM] in AP direction (m)	0.320 ± 0.005	0.331 ±0.004	1.5	1.3	0.309 ± 0.006	0.362 ± 0.005	1.9	1.4
Minimum wrist position [relative to CoM] in vertical direction (m)	-0.074 ± 0.009	-0.137 ± 0.006	11.9	4.3	-0.055 ± 0.004	-0.143 ± 0.005	7.5	3.7
Maximum wrist position [relative to CoM] in vertical direction (m)	0.311 ± 0.006	0.294 ± 0.009	1.9	3.0	0.328 ± 0.006	0.309 ± 0.005	1.9	1.7