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Biomechanical analysis of performance and asymmetry during bend sprinting

Jonathan David White

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Director of studies: Dr Tim Exell

Supervisors:

Professor Gareth Irwin

Professor Cassie Wilson

Dr Joseph Moore

Declaration

Whilst registered as a candidate for the above degree, I have not been registered for any other research award. The results and conclusions embodied in this thesis are the work of the named candidate and have not been submitted for any other academic award.

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Abstract

This thesis aimed to understand the drivers of performance and inter-limb asymmetry during bend sprinting under conditions representative of competition. To inform methods of data collection and processing, a validation study was conducted which found differing methods as the most accurate detection of touchdown for the left (L-R) and right (R-L) steps.

The main body of work was split into two phases. Phase 1 investigated the effects of lane radius and lateral banking on step characteristics and lower extremity joint kinematics in conditions representative of indoor competition. Lateral banking increased step velocities primarily through enabling longer step lengths whilst tighter radii did not result in faster step velocities than less tight bend radii, suggesting the need for familiarisation with banked bends. Compared to flat bends, lateral banking decreased the magnitudes of body lateral lean, hip abduction/adduction and ankle eversion/inversion for the L-R and R-L steps. Despite these reductions in frontal and transverse plane joint angles, trends for increased inter-limb differences were observed on the banked bends.

Phase 2 investigated the drivers of performance during bend sprinting on radii representative of outdoor competition. Step length and peak inward force in the L-R step, and step frequency and duration of propulsive force generation for the R-L step were key determinants of step velocity. Novel insights were gained into the R-L step's role in generating inward and vertical forces during early stance, with minimised hip and knee flexion angles at touchdown aiding the generation of sufficient angular velocities throughout stance. For the L-R step, peak inward force and inward impulse related to step velocity and step length, respectively, reinforcing the L-R steps role in inward force generation. Therefore, in addition to optimising sagittal plane angles and angular velocities, to produce greater inward force athletes minimised hip adduction velocities at touchdown and peak knee adduction during stance whilst maximising ankle external rotation and inversion velocities. These findings highlight the need to stabilise in the frontal plane in addition to optimal sagittal plane angular velocities.

This thesis has provided new understanding of biomechanics of indoor bend sprinting, and the drivers of bend sprinting step velocities. While asymmetry in kinetics did not directly relate to performance, inter-limb differences were observed throughout the thesis. Plyometric drills, use of wearable resistance on the bend, and exercises inducing body lateral lean may have the potential to develop the kinetics and kinematics found to correlate with step velocity and or determinants of step velocity that are highlighted in this thesis.

Publications

White, J., Wilson, C., von Lieres Und Wilkau, H., Wyatt, H., Weir, G., Hamill, J., ... & Exell, (2023). Does lateral banking and radius affect well-trained sprinters and team-sports players during bend sprinting? *Journal of Sports Sciences*, *41*(6), 519-525.

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White, J., Irwin, G., Exell, T., Wilson, C., Hamill, J., Wyatt, H., ... & Weir, G. (2022). Joint Kinematics During Indoor Bend Sprinting. *Proceedings of the 40th International Conference of Biomechanics in Sports*, *40*(1), 751.

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Dedication

To my Grandad Ken and Grandpa Reg

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Nomenclature and definitions

SV - Step velocity

SF - Step frequency

SL - Step length

SD - Standard deviation

CI - Confidence interval

SA - Symmetry angle

PB - Personal best race time (PB)

L-R - Step initiated by left foot touchdown

R-L - Step initiated by right foot touchdown

ES - Effect size

TD - Touchdown

TO - Toe-off

FD = Flight distance

RQ - Research question

GCT - Ground contact time

FT - Flight time

TD_D - Touchdown distance

GRF - Ground reaction force

MTP - Metatarsophalangeal joint

CoM - Centre of mass

RoM - Range of motion

BW - bodyweight

ANOVA – Analysis of variance

SPM - Statistical parametric mapping

ICC - Intra-class correlation coefficient

CoP - Centre of pressure

GCS - Global co-ordinate system

FCA - Foot-contact algorithm

LoA – Limits of agreements

MT1H - First metatarsal head

MT5H - Fifth metatarsal head

L2B - Lane 2 banked

L4B - Lane 4 bank

L2F - Lane 2 flat

L4F - Lane 4 flat

LvR - Left versus Right

RTM - Rotation matrix

RMSE - Root-mean square error

IMU - Inertial measurement unit

Chapter 1: Introduction

1.1 Overview

The sprint events (100-400 m) are an exciting sub-group of athletics, where winning margins can be smaller than one-hundredth of a second. For example, the men's 100 m final at the 2024 Paris Olympic games was won by 0.005 seconds, therefore, marginal improvements in performance can have a substantial impact on an athlete's finishing position. In sprint events greater than 100 m, approximately 58% of total race distance is ran on the bend. Despite contributing more to the total race distance than the straight, the biomechanics of bend sprinting has, until recently, received little attention in the literature.

Achieving faster race times in the sprint events is the result of increased step velocity (SV); consequently, the development of SV is a critical factor to sprinting success (Mann & Herman, 1985). The two determinants of SV are step length (SL) and step frequency (SF) (Hunter et al., 2004). In sprinting, a step is defined as the interval between the initial touchdown (TD) of one foot and the subsequent TD of the opposite foot. When sprinting counter-clockwise on the bend, this definition results in the outside step being classified as right touchdown-to-left touchdown (R-L) and the inside step as left touchdown-to-right touchdown (L-R).

Step velocities during 60 m maximal bend sprints have been found to be between 2.3% - 4.7% lower than when compared to the 60 m maximal sprints along a straight path (Churchill et al., 2015, 2016). The bend portion of the race is, therefore, an area for potential performance improvements. For example, an elite sprinter with a 200 m personal best of 20.00 s could improve their horizontal velocity when sprinting on the bend (58% of the race) by as little as 0.5%, this would result in the improvement of up to 0.058 s; thus, improving race time to 19.95 s. The difference between achieving a bronze medal and fourth place in the women's 200 m at the 2024 Paris Olympic games was 0.02 s, therefore this level of improved velocity on the bend could have a profound effect on the athlete's finishing position.

A growing number of investigations have attempted to analyse the biomechanics of bend sprinting, highlighting several differences to the straight in relation to step characteristics, kinematics and kinetics (Alt et al., 2015; Chang & Kram, 2007; Churchill et al., 2015, 2016, 2018; Diaz et al., 2024; Ishimura & Sakurai, 2016; Judson, et al., et al., 2020a; Judson et al., 2019, Ohnuma et al., 2018). One of the major differences between bend and straight sprinting is the centripetal force required to follow the path of the bend (Ishimura & Sakurai, 2016). Generating centripetal force in addition to the propulsive forces necessary for sprinting requires additional time, thus increasing ground contact time, reducing step frequency and ultimately reducing SV (Churchill et al., 2015).

A number of researchers have indicated that the inside and outside legs appear to have functionally different roles when following the path of the bend (Alt et al., 2015; Churchill et al., 2015, 2016). On radii representative of outdoor competition inward forces have been found to be greater during the L-R stance than R-L (Churchill et al., 2016; Diaz et al., 2024). On radii representative of indoor competition there appears to be no difference between L-R and R-L step inward force (Diaz et al., 2024). Therefore, asymmetry in inward forces appears to be radius dependent. The inside and outside legs having different roles has the potential to result in inter-limb asymmetry that is developed through repeated bend sprinting, as sprint athletes typically train and compete solely in a counter-clockwise fashion around the track. Asymmetrical strength changes over the course of an indoor track season were reported in the hindfoot evertor and invertor muscles in a group of 25 intercollegiate track athletes (200 – 3000 m), where left invertors increased in strength significantly more than the right and the right evertors increased in strength significantly more than the left (Beukeboom et al., 2000). Furthermore, a high incidence of lower extremity injury (68%) was observed throughout the 12 week indoor athletics season (Beukeboom et al., 2000). Giakoumis et al. (2020) report significantly greater hamstring eccentric strength for the R-L limb compared to the L-R in long elite sprint athletes suggesting adaptations as a result of the differing roles for the L-R and R-L steps. Nevertheless, the effects of repetitive counter-clockwise sprinting are yet to be fully determined and the inter limb asymmetry is potentially one of the reasons for the large injury rates seen in athletes regularly training and competing on the bend (Ayres & Gottlieb, 2006; Beukeboom et al., 2000; Pollock et al., 2016).

A standard outdoor athletics track is made up two straights and two bend sections and consists of six to eight lanes. Mathematical models (Mureika, 1997; Usherwood & Wilson, 2006) and empirical evidence (Chang & Kram, 2007; Churchill et al., 2018) have demonstrated a disadvantage to athletes sprinting on tighter radii (inner lanes). For example, Churchill et al. (2018) found a reduction in race velocity from lane eight to lane five to be 0.20 m/s for the L-R step ($p = 0.01$, $d = 0.42$) and 0.19 m/s for the R-L step ($p = 0.029$, $d = 0.40$), no further reductions were seen between lane five and lane two. However, differences in technique were reported, including significantly shorter step length for the L-R step in lane 5 compared to lane 2 ($p = 0.005$, $d = 0.44$) and increased inward (more negative) body lateral lean at touchdown ($p < 0.05$).

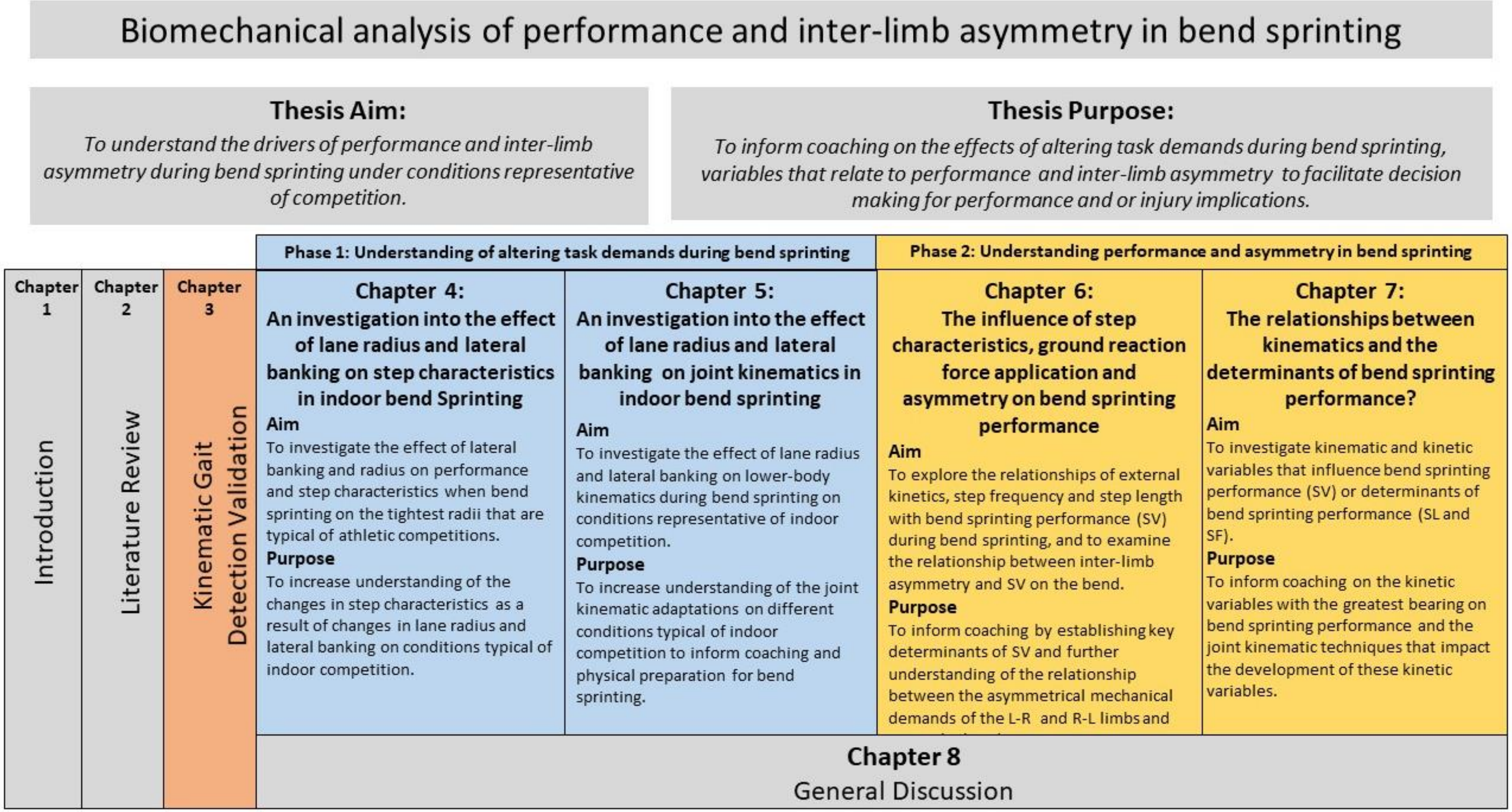
From a mathematical model viewpoint, Mureika (1997) suggested that 200 m race times should decrease from lane one to lane eight due to lower turning demands with each step. Despite this, it has been reported that sprinters prefer the middle lanes (four – six) (Green, et al., 2001). Preference of the middle lanes was suggested to be as a result of the sprinter having more awareness of their position amongst other sprinters, as well as this, the opportunity to 'chase' those in the outer lanes provides a psychological advantage (Green et al., 2001)., World Athletics (formerly IAAF) has updated the rules to further optimise lane assignments (World Athletics Technical Rules, 2023). In the 200 meters, lanes five, six, and seven are now considered the most favourable, with lane eight and lanes three and four assigned to the next ranked runners, and the lowest-ranked athletes placed in the two inside lanes. For the 400 meters, the top-ranked athletes are assigned to lanes four, five, six, and seven, the next-ranked to lanes three and eight, and the remaining athletes to lanes one and two. Despite the tighter lane radii typical of indoor athletics competition, research into indoor bend sprint radii is lacking. The only study to investigate a change in lane radius concluded that although the athlete may work at maximum effort on a tighter radius, they will be unable to maintain the flight distance component of stride length because of difficulties in generating enough impulse and consequently, stride length will decrease (Ryan & Harrison, 2003). Despite this insight into stride length changes, analysis of stride length does not provide information about the symmetry or asymmetry of the impact of tighter bend radii on the L-R and R-L steps.

Gait symmetry has been defined as the perfect agreement of the kinematics and external kinetics of the L-R and R-L legs, (Herzog et al., 1989), therefore, asymmetry can be defined as any divergence from symmetry (Exell, Irwin, et al., 2012). The assessment of asymmetry in athletes is particularly important due to the fact that asymmetry between limbs has been associated with an increased risk of new and recurring injuries (Croisier et al., 2002; Zifchock et al., 2006). Previous literature suggests that inter-limb asymmetry may be detrimental to jumping and kicking performance, but the effects of asymmetry on performance is less clear in sprinting, dynamic balance and sport-specific tasks (Bishop et al., 2018). Exell et al. (2017) reported that kinematic and kinetic inter-limb asymmetries had no significant relationships with linear sprint performance. However, after consideration of individual athlete asymmetry profiles, Exell et al. (2017) highlighted magnitudes and variables that showed significant asymmetry varied between athletes highlighting that interlimb asymmetry exists in a trained sprinting population when sprinting on the straight. No distinction was reported as to whether the athletes were short sprinters (60 - 100 m) or long sprinters, (200 - 400 m) thus, it cannot be confirmed if these asymmetries exist due to counter-clockwise sprinting when training and competing.

Since bend running is asymmetrical due to the centripetal force requirements to follow the path of the bend (Churchill et al., 2016), it is important to consider the notion of specificity of training from a biomechanical perspective (Brazil et al., 2020). For example, the inter-limb asymmetries that develop from bend sprinting in a counter-clockwise fashion may result in improved sprinting performance on the bend in this direction. However, with inter-limb asymmetry being associated with injury risk and potential to impact linear sprint velocities, these developed asymmetries may not necessarily be beneficial on overall race performance. As a result of this, research should investigate bend sprinting biomechanics and the interaction of inter-limb asymmetry and performance in bend sprint-trained athletes.

1.2 Statement of Aim and Purpose

Despite the greater turning demands and potential injury risks (Beukeboom et al., 2000), only five investigations have explored aspects of the biomechanics of bend sprinting on conditions representative of indoor competition (Bezodis & Gittoes, 2008; Ferro & Floria, 2013; Nevison et al., 2015; Pietraszewski et al., 2021; Ryan & Harrison, 2003). Additionally, the aforementioned research is yet to comprehensively understand the effects of altering the task demands during bend sprinting representative of indoor competition, such as the effect of lane radius and lateral banking. Furthermore, minimal research has investigated the optimal technique for bend sprinting (Churchill, 2012; Ohunuma et al., 2018) and the influence of inter-limb asymmetry on performance. Therefore, this research aims to understand the drivers of performance, and inter-limb asymmetry during bend sprinting under conditions representative of competition. The purpose of the research is to inform coaching on the effects of altered task demands during bend sprinting and variables that relate to performance and inter-limb asymmetry to facilitate decision making and training for performance and injury risk. The overview of thesis aims, purpose and breakdown of Chapters can be seen in Figure 1.1.



Biomechanical analysis of performance and inter-limb asymmetry in bend sprinting

Thesis Aim:

To understand the drivers of performance and inter-limb asymmetry during bend sprinting under conditions representative of competition.

Thesis Purpose:

To inform coaching on the effects of altering task demands during bend sprinting, variables that relate to performance and inter-limb asymmetry to facilitate decision making for performance and or injury implications.

Chapter 1
Introduction

Chapter 2
Literature Review

Chapter 3
Kinematic Gait Detection Validation

Phase 1: Understanding of altering task demands during bend sprinting

Chapter 4:
An investigation into the effect of lane radius and lateral banking on step characteristics in indoor bend Sprinting

Aim

To investigate the effect of lateral banking and radius on performance and step characteristics when bend sprinting on the tightest radii that are typical of athletic competitions.

Purpose

To increase understanding of the changes in step characteristics as a result of changes in lane radius and lateral banking on conditions typical of indoor competition.

Chapter 5:
An investigation into the effect of lane radius and lateral banking on joint kinematics in indoor bend sprinting

Aim

To investigate the effect of lane radius and lateral banking on lower-body kinematics during bend sprinting on conditions representative of indoor competition.

Purpose

To increase understanding of the joint kinematic adaptations on different conditions typical of indoor competition to inform coaching and physical preparation for bend sprinting.

Phase 2: Understanding performance and asymmetry in bend sprinting

Chapter 6:
The influence of step characteristics, ground reaction force application and asymmetry on bend sprinting performance

Aim

To explore the relationships of external kinetics, step frequency and step length with bend sprinting performance (SV) during bend sprinting, and to examine the relationship between inter-limb asymmetry and SV on the bend.

Purpose

To inform coaching by establishing key determinants of SV and further understanding of the relationship between the asymmetrical mechanical demands of the L-R and R-L limbs and

Chapter 7:
The relationships between kinematics and the determinants of bend sprinting performance?

Aim

To investigate kinematic and kinetic variables that influence bend sprinting performance (SV) or determinants of bend sprinting performance (SL and SF).

Purpose

To inform coaching on the kinetic variables with the greatest bearing on bend sprinting performance and the joint kinematic techniques that impact the development of these kinetic variables.

Chapter 8
General Discussion

Figure 1.1. Overview of thesis aim and breakdown of Chapters.

1.3 Organisation of thesis Chapters

1.3.1 Chapter 2

Chapter 2 contains a review of literature relating to the aims of this thesis. This chapter included the review of research on the kinematics, kinetics of sprinting on the bend along with studies that investigated inter-limb asymmetry in sprinting from both an injury and performance perspective. Finally, traditional and contemporary methodological approaches were considered, along with the benefits and weaknesses associated with each. The review of literature led to the development of research questions that guided the studies contained within Chapters 3 to 7 and raised in Section 1.4.

1.3.2 Chapter 3

The literature review in Chapter 3 highlighted that the key performance descriptors during sprinting require accurate detection of touchdown (TD) and toe-off (TO) events. The gold-standard method for detecting these events involves the use of force plates and utilising a threshold of vertical force to detect TD and TO events. Where force data is not available, the existing bend sprinting literature has utilised kinematic-based methods that lack validation during bend sprinting. Therefore, Chapter 3 investigated different kinematic event detection methods to establish their accuracy in determining gait events on the bend for the R-L and L-R steps.

Phase 1

The majority of bend sprinting research has been undertaken on radii too small (1-6 m) or on radii representative of outdoor competition (36-45 m) that limits generalisation of these findings to indoor competition. Substantial focus of training and competition is directed towards global indoor competition. For example, Olympic medal hopefuls for the 1500 m–-5000 m battled over 3000 m at the 2024 World Athletics Indoor Championship (https://www.theguardian.com/sport/2024/feb/19/josh-kerr-boosts-british-hopes-in-opting-to-run-at-world-indoor-championships, accessed 18/07/2024), highlighting that athletes are driven by success in both indoor and outdoor competition. Furthermore, due to the tighter bend radii and potential asymmetrical strength changes and injury risks observed during the indoor athletics season (Beukeboom et al., 2000), athletes who decide to compete indoors may increase asymmetries and risks of injury that compromise preparation for the outdoor season.

Unlike outdoor athletics tracks where dimensions must conform to international standards, indoor athletics tracks come in a variety of sizes with varied: lengths, bend radii, and banking of the bends (Beukeboom et al., 2000). The only consistent characteristic applicable to all indoor and outdoor tracks is the direction of running, which is counter-clockwise.

Phase 1 was split into Chapters 4 and 5. The aim of Phase 1 of the thesis, was to increase understanding of altering task demands during bend sprinting on conditions representative of indoor competition where the biomechanical demands are increased due to the tighter bend radii.

1.3.3 Chapter 4

Phase 1 of the thesis was initiated in Chapter 4. The aim of Chapter 4 was to investigate the effect of lateral banking on step characteristics when bend sprinting on radii typical of indoor competition. The purpose of Chapter 4 was to increase understanding of the changes in step characteristics as a result of changes in lane radius and lateral banking on conditions typical of indoor competition. The findings of Chapter 4 provided a foundation of knowledge to be used when evaluating the joint kinematic adaptations in Chapter 5.

1.3.4 Chapter 5

Chapter 5 progressed from the knowledge gained in Chapter 4 to understand the lower-limb joint kinematics on conditions representative of indoor competition. The aim of Chapter 5 was to investigate the effect of lateral banking on lower-limb kinematics when bend sprinting on radii typical of indoor competition. The purpose of this Chapter was to increase understanding of the joint kinematic adaptations to bend sprinting on different conditions typical of indoor competition to inform coaching and physical preparation for bend sprinting. The findings of Chapter 5 provided further explanation of the impact of lane radius and lateral banking on step characteristics and provided a basis of knowledge for further understanding bend sprinting performance in Phase 2.

Phase 2

Phase 1 increased understanding of altering task demands during bend sprinting representative of indoor competition and provided novel insights into how changing the lane radius and lateral banking could impact step characteristics and joint kinematics. The knowledge from Phase 1 can aid coaches and practitioners in the preparation of athletes for indoor athletics competitions, which gain global interest every year. Furthermore Phase 1 can inform future research into bend sprint performance and injury risk through a more detailed understanding of the biomechanics of bend sprinting on conditions representative of indoor competition.

Nevertheless, Phase 1 highlighted a need for greater understanding of the relationship between key variables and performance for both the L-R and the R-L steps, and to investigate the relationship between athlete asymmetry and bend sprinting performance. Phase 2 of the thesis aimed to increase understanding of performance and asymmetry in bend sprinting and was split into Chapters 6 and 7. Phase 2 built on from the understanding of step characteristics and joint kinematics on the tightest radii observed during athletic competition in indoor bend sprinting to further understand how successful performance is achieved on the bend on outdoor bends that are used for the major competitions that occur during the outdoor athletics season.

1.3.5 Chapter 6

Phase 2 began with Chapter 6 and addressed the following aims. Firstly, to explore the relationships of external kinetics, SF and SL with SV during bend sprinting, and to examine the relationship between inter-limb asymmetry and SV on the bend. The purpose of Chapter 6 was thus, to inform coaching by establishing key determinants of SV and further understanding of the relationship between the asymmetrical mechanical demands of the left and right limbs and SV on the bend. Chapter 6 progresses knowledge in the area by furthering understanding of how force is produced on the bend by the left and right steps, potential relationships between asymmetry and SV, and provides a foundation of key kinetic variables that were used to assess key kinematic techniques in Chapter 7.

1.3.6 Chapter 7

Chapter 7 progressed from the knowledge gained in Chapter 6 to further understanding of how successful bend sprinting is produced. The aim was to investigate kinematic and kinetic variables that influence bend sprinting SV or determinants of SV (SL and SF). Thus, the purpose was to inform coaching on the kinetic variables with the greatest bearing on bend sprinting performance and the techniques that impact the development of these kinetic variables. Utilising the knowledge gained from Phase 1 and Chapter 6, a selection of kinematic parameters were assessed for their relationship in respect to the key drivers of SV for the L-R and R-L steps. Results were interpreted to provide recommendations for developing bend sprinting performance through optimisation of technique.

1.3.7 Chapter 8

Chapter 8 collates the findings from Chapters 3-7 and discusses them in relation to the research questions raised in the following section (Section 1.4). The novel contributions to knowledge and practical implications of this research to sports biomechanics and bend sprinting training theory are discussed following an appraisal of key methodologies. Chapter 8 concludes with directions for future research study.

1.4 Development of Research Questions

Prior to achieving the main aims and purpose of the thesis it was important to determine an accurate method for detecting gait events during bend sprinting where the gold-standard use of vertical ground reaction force (GRF) data collected via force plates are not available, such as on banked bends representative of indoor competition. Vertical GRF data is not attainable on banked indoor athletics tracks and is difficult to capture multiple foot contacts with the use of force plates. Thus, the first experimental Chapter sought to answer Research Questions 3.1-3.2.

RQ3.1: How do different kinematic event detection methods compare in accuracy for detecting touchdown of the L-R and R-L steps?

RQ3.2: How do different kinematic event detection methods compare in accuracy for detecting toe-off of the L-R and R-L steps?

1.4.1 Phase 1

Phase 1 looked to further understanding of the biomechanics of bend sprinting on the most extreme bend radii that sprinters are exposed to. Furthermore, Phase 1 aimed to increase understanding of altering task demands during bend sprinting representative of indoor competition. There are eight RQs that were devised to guide this phase of work:

RQ4.1: How does lane radius affect within-limb step characteristics for the L-R and R-L steps?

Whilst it is commonly accepted that a tighter radius will lead to negative effects on bend sprinting performance (Chang & Kram, 2007; Churchill et al., 2018), research into the effect of lane radius on radii representative of indoor competition is lacking. Analysis of step characteristics for the L-R and R-L steps under two lanes were assessed when the bend was banked and flat. Answering this question provided novel insight into the impact of lane radius during indoor bend sprinting where bend radii are the most extreme that athletes will compete on and can either be banked or flat.

RQ4.2: How does lateral banking affect within-limb step characteristics for the L-R and R-L steps?

Lateral banking is often included on indoor athletics tracks due to their tighter radii but not outdoor tracks with larger radii. Research has suggested that lateral banking increases attainable velocities during bend sprinting (Barnes & Malcata, 2017; Greene, 1987; Neie, 1981), yet, the mechanism for this is not well understood. To further understanding of the effect of lateral banking on radii representative of indoor competition, analysis of step characteristics for the L-R and R-L steps when running in two lanes of different radii were assessed when the bend was banked and flat. Answering this question provided novel insight into the impact of lateral banking on performance during indoor bend sprinting.

RQ4.3: How does lane radius and lateral banking affect inter-limb differences of step characteristics?

Whilst the previous research questions looked to understand the effect of radius and lateral banking on the L-R and R-L steps separately, previous research has highlight the L-R and R-L steps to have functionally different roles during bend sprinting (Alt et al., 2015; Churchill et al., 2016). Thus, RQ 4.3 assessed the effect of changing the lane radius and inclusion of lateral banking on inter-limb differences of step characteristics.

RQ5.1: What are the within-limb effects of lateral banking on lower-limb joint kinematic variables when bend sprinting?

Whilst research has suggested that lateral banking increases attainable velocities during bend sprinting (Barnes & Malcata, 2017; Greene, 1987; Neie, 1981), understanding of the effect of lateral banking on radii representative of indoor competition has on joint kinematics for the L-R and R-L steps is lacking. Answering this question helped to explain some of the changes in step characteristics observed in Chapter 4 and provided novel insight into the impact of lateral banking on joint kinematics during indoor bend sprinting.

RQ5.2: What are the within-limb effects of lane radius on joint kinematic variables when bend sprinting?

To further understanding of the effect of lane radius on radii representative of indoor competition, lower-limb joint kinematics for the L-R and R-L steps under two lanes were assessed when the bend was banked and flat. Answering this question provided novel insight into the impact of lane radius on joint kinematics during indoor bend sprinting.

RQ5.3: What are the effects of lateral banking and lane radius on inter-limb differences in joint kinematic variables when bend sprinting?

The tighter radii of indoor competition likely change the demands of the L-R and R-L (Chang & Kram, 2007), whilst RQ 4.3 highlighted changes in the magnitudes of inter-limb differences across the lane conditions tested. Thus, RQs 5.3 looked to explain the effects of changing the lane radius and inclusion of lateral banking by investigating the inter-limb differences of joint kinematics.

1.4.2 Phase 2:

RQ6.1 What is the relationship between step length and frequency, and SV during bend sprinting?

Whilst research has investigated the determinants of SV on the bend, this has typically been done on differing radii (Churchill et al., 2016; Ishimura & Sakurai, 2016). Therefore, to form a basis for the reminder of the thesis relationships were determined between step length, step frequency and SV for the L-R and R-L steps.

RQ6.2 What external kinetic variables are related to bend sprinting performance SV?

Due to the three-dimensional nature of bend sprinting and the differences in the force generation requirements during the L-R and R-L steps (Chang & Kram, 2007; Churchill et al., 2016; Diaz et al., 2024; Judson et al., 2019), RQ6.2 sought to understand the kinetic variables that relate to successful bend sprinting performance. Therefore, relationships between external kinetics and SV were assessed to further understand the kinetics of how athletes achieve greater SVs.

RQ6.3 What are the inter-limb differences in force production of L-R and R-L limbs across the entire stance phase?

Previous research has reported discrete external kinetics at maximal velocity, whilst in the acceleration phase Judson et al. (2019) utilised statistical parametric mapping to highlighted asymmetry in force production across the stance phase that may not have been found presenting discrete values such as peak force. Therefore, force production between L-R and R-L steps were compared across the stance phase to provide novel understanding of force production at maximal velocities.

RQ6.4 What is the relationship between asymmetry of step length, step frequency, external kinetics and mean SV (L-R and R-L) during bend sprinting?

Previous research has highlighted that the L-R and R-L steps may have functionally different roles (Alt et al., 2015; Churchill et al., 2016). Furthermore, Ishimura & Sakurai, (2016) reported differences in the determinants of SV between steps, where SL and SF were significantly related to R-L SV but only SL for L-R. Thus, relationships between asymmetry of step characteristics and external kinetics were assessed for their effect on SV.

RQ6.5 What is the relationship between asymmetry of external kinetics and mean SV (L-R and R-L) during bend sprinting?

The L-R and R-L steps have been proposed to have different emphasis of force production, with the L-R providing greater inward forces (Churchill et al., 2016; Diaz et al., 2024), however research is yet to determine asymmetry of kinetics and the influence of asymmetry on bend sprinting performance. Hence, relationships between asymmetry of external kinetics and mean SV (L-R and R-L) were assessed.

RQ7.1 What are the key determinants and kinetic variables that relate to R-L SF?

In Chapter 6, it was identified that SF was the key determinant of R-L SV. Previous research has highlighted that changes in SF on the bend could come from changes in ground contact time or FT (Churchill et al., 2015; Usherwood & Wilson, 2006). Furthermore, whilst only duration of propulsive force was significantly related to R-L SV, there is often an interaction where increasing SF an associated decrease in SL is observed (Hunter et al., 2004). Therefore, the contribution from flight time and contact time and external kinetics of the R-L step that contribute to SF were explored.

RQ7.2 What kinematic variables relate to duration of propulsive force and kinetic variables that relate to R-L SF?

Chapter 6 highlighted that faster R-L SV were achieved by those athletes that were able to minimise propulsive durations. RQ 7.1 highlighted that vertical impulse was positively significantly related to SF. Thus, to better understand the technique that faster bend sprinters adopt to produce shorter durations of propulsive force and vertical impulse that produce faster SV and SF, respectively, kinematic variables were assessed for their relationship to duration of propulsive force and vertical impulse for the R-L step.

RQ7.3 What are the key determinants and kinetic variables relate to L-R SL?

Chapter 6 found that SL is the key determinant of L-R SV. Minimal previous research has reported stance and flight distances or, their relationship with SL (Ishimura & Sakurai, 2016). As with RQ7.1, whilst only peak inward force was significantly related to L-R SV, there is often an interaction where increasing SL an associated decrease in SF is observed (Hunter et al., 2004). Therefore, the contribution from flight and contact distance and external kinetics of the L-R step that contribute to SL should be explored.

RQ7.4 What kinematic variables relate to peak inward force and kinetic variables that relate to L-R SL?

Chapter 6 highlighted that faster L-R SV were related to larger peak inward forces, suggesting that those athletes that were to produce larger peak inward forces were able to achieve higher SV for the L-R step on the bend. Furthermore, RQ 7.3 highlighted that inward impulse was positively significantly related to L-R SL. Consequently, to understand the technique that faster bend sprinters adopt to produce large inward forces and kinetics that contribute to larger L-R SLs, kinematic variables were assessed for their relationship to L-R peak inward force and inward impulse.

Chapter 2: Review of Literature

2.1. Introduction

This literature review summarises the current knowledge and understanding of the biomechanics of bend sprinting. Sprinting is a maximal form of running, where the primary aim is to cover a given distance in the shortest time possible (Hay, 1993). Within the sport of athletics, the sprint events typically go from 60 – 400 m as well as the 400 m hurdles. A standard outdoor athletics track involves two bend sections of approximately 115 m for all lanes (International Association of Athletics Federations, 2008). In sprint events greater than 100 m, approximately 58% of the total race distance is ran around the bend (Meinel, 2008). Despite contributing more to the total race distance than the straight, the biomechanics of bend sprinting had until recently, received little attention in the literature. The biomechanics of bend sprinting from both an injury and a performance perspective will be reviewed. Finally, methods of data collection, processing, and analysis of bend sprinting are considered.

2.2. Biomechanics of Sprinting

2.2.1. Performance and Injury perspectives

The majority of biomechanical analyses on sprinting are focused either on performance factors, for example: (Funken et al., 2019; Tottori et al., 2016, 2018; Toyoshima & Sakurai, 2016) or on injury risk (Beukeboom et al., 2000; Nevison et al., 2015). Despite researchers investigating sporting techniques from performance or injury risk viewpoints, an injured athlete simply cannot perform at the highest level. Therefore, whilst the two areas are often researched in separation, injury prevention and performance enhancement are inherently linked (Brown et al., 2017). Nonetheless, both performance and injury investigations provide valuable information for coaches and their athletes. Reduced time spent out injured will ultimately result in greater opportunity for performance and or strength increases.

An emerging theme in the biomechanics literature is the assessment of inter-limb asymmetry and the subsequent effects on injury risk and on sporting performance (Bailey et al., 2015; Bishop, Blagrove, et al., 2018; Bishop, Turner, et al., 2018; Exell et al., 2017; Exell, Gittoes, et al., 2012b; García-Fresneda et al., 2024). Gait symmetry has been defined as the perfect agreement of the external kinetics and kinematics of the L-R and R-L legs (Herzog et al., 1989), therefore, asymmetry can be defined as any divergence from symmetry (Exell et al., 2012b). The assessment of asymmetry in athletes is particularly important since significant asymmetry between limbs has been shown to increase the risk of new and recurring injuries (Croisier et al., 2002; Zifchock et al., 2006). Inter-limb asymmetry has been investigated during sub maximal running (Carpes et al., 2010; Gilgen-Ammann et al., 2017) and sprinting (Exell et al., 2017; Exell, Gittoes, et al., 2012b; Haugen et al., 2018) but is yet to be fully understood when sprinting around the bend (Ishimura & Sakurai, 2016; Maćkała et al., 2010). Therefore, investigations into inter-limb asymmetry within bend sprinting are needed since bend sprinting is asymmetrical in nature (Beukeboom et al., 2000; Churchill et al., 2016) and has been shown to have associated injury risks (Ayres & Gottlieb, 2006; Beukeboom et al., 2000; Pollock et al., 2016). Therefore, more in-depth understanding of bend sprint technique will help coaches, clinicians and S&C coaches when looking to manage training load and monitor injury risk and when rehabbing injured athletes.

2.2.2. Breakdown of the Sprint events

Sprinting has been divided into several distinct phases, for example, Collier (2002) labelled three phases of sprinting: acceleration, transition, and full speed. Prior to this Mero et al. (1992) suggested there was in fact, four phases: the start, acceleration, maximum speed, and deceleration/maintenance. As many as six phases have been described by Seagrave (1996) however, this was proposed to be over-complicating the sprint race by elite sprint coaches (Jones et al., 2009). Yet, with some researchers and coaches considering the block start as a stand-alone phase (Brazil et al., 2016; Mero et al., 1992) and others further subdividing the acceleration phase into initial acceleration and the transition phase (Maćkała et al., 2015; von Lieres und Wilkau et al., 2020; Von Lieres Und Wilkau et al., 2020); a sprint race can be made “as complicated as you want” (Jones et al., 2009, p. 388). This complexity is only exacerbated when negotiating a bend, as seen in 200-400 m sprint events. Research in the acceleration phase has suggested an acceleration phase of 30 m (Judson, et al., 2020b) leaving 85 m for the rest of the bend in the maximum velocity phase. Furthermore, 400 m athletes negotiate two bends at high velocity, reaching the second bend already at high velocity. Additionally, athletes competing on 200 m indoor athletics tracks negotiate two (200 m) and four (400 m) bends of tighter radii at high velocities. Therefore, the majority of the literature review will focus on the biomechanics of the maximal velocity and velocity maintenance phases, as this has the most bearing for the long sprint events which include large proportions of bend sections.

Early biomechanics research focused on the determinants of performance Hay (1993), highlighting several key spatiotemporal characteristics that contribute to sprinting performance. Previous research has highlighted the impact of these on determining the different sprint acceleration phases (von Lieres und Wilkau et al., 2020) and the interaction between them (Hunter et al., 2004).

The following section will discuss the kinematics of bend sprinting. Ishimura & Sakurai, (2016) highlight that, due to centripetal force (medial-lateral/outward-inward) force requirements, bend sprinting becomes a lot more complex than following a straight path.

2.3 Biomechanics of bend sprinting

Several investigations have reported step characteristics for straight and bend portions of the track, with authors selecting different lane radius to measure. Table 2-1 shows the participants, radius, protocol used in these investigations, of the current bend sprinting literature, outdoor lanes 8, 5, 4, 2 and 1 have had data collected on. Whilst these investigations have provided understanding of the effects of the bend on step characteristics across outdoor bend radii, other than Churchill (2012), research is yet to associate step characteristics with kinetic and kinematic variables to inform how faster SV are produced on the bend. Furthermore, research on tighter bend radii found on indoor bend radii is limited, with the existing research discussed in section 2.5.

Table 2-1. Summary of publications investigating bend sprinting in the maximum velocity phase.

Authors	Participants	200 m PB (s)	Radius (m)	Protocol
Churchill et al. (2015)	7 males	22.15 ± 0.93 (21.18 - 23.90)	37.72 (lane 2)	2 separate sessions: 3 x 60 m straight and then 3 x 60 m bend
Alt et al. (2015)	6 males	22.6 ± 0.33	36.5 (lane 1)	90% max velocity ~ 50 m, 3 x straight and 3 x bend
Churchill et al. (2016)	7 males	22.04 ± 0.74 (20.89 - 22.90)	37.72 (lane 2)	Up to 6 x 60 m including bend and straight
Ishimura & Sakurai (2016)	10 males and 8 females	* 3.23 ± 0.13 and 3.62 ± 0.16	43.51 (lane 4)	3 x 60 m bend
Ohnuma et al. (2018)	12 males' sprinters and long jumpers	** 9.49 – 9.83 m/s	37.9 (lane 1)	8 ~50 m bend and straight sprints
Churchill et al. (2018)	9 males	21.1 - 22.6 ***47.36	45.1 (lane 8), 41.41 (lane 5), 37.72 (lane 2)	2 x 60 m in lanes 8, 5 and 2

* 30-m split time (s) ** Velocities captured during data collection *** 400 m PB

2.3.1 Bend versus Straight - Step Characteristics

Lower sprint velocities on the bend in comparison to the straight have been reported (Chang & Kram, 2007; Churchill et al., 2015, 2016; Judson et al., 2019). Table 2-2 provides comparison of the velocities, step length, step frequency, ground contact time and FT observed in the maximum velocity phase. On the other hand, Alt et al. (2015) found no significant differences between straight and bend (both L-R and R-L steps) or between L-R and R-L steps for step length and step frequency. This however is likely a consequence of the protocol involved controlling velocity at 90% ± 0.2 m/s of perceived maximum, rather than maximal velocity sprinting. Nonetheless, it was not reported whether trials were rejected if they fell above or below this threshold. One final study has reported step characteristics comparisons between the bend and straight. Ohnuma et al. (2018) grouped athletes into ‘poor’ and ‘good’ groups dependent on how large or small the difference between straight and bend step characteristics were. They found that speed was significantly lower on the bend in the poor group compared to the straight ($p = 0.03$) with the good sprint group maintaining similar velocities on bend and straight ($p > 0.05$) (Table 2-2). Nonetheless, Ohunuma et al. (2018) averaged velocity across steps so the effects on the L-R and R-L steps remain unclear. Similar trends observed in the acceleration phase, where (Judson, Churchill, Barnes, Stone, Brookes, et al., 2020b) found a 2% reduction in velocity for the L-R step (g = 0.52) but an increase in velocity for the R-L steps (g = 0.48) on the bend compared to the straight. Therefore, it appears to be consistent that velocity is reduced at maximum velocity on the bend but not during acceleration or at sub- maximal velocity.

Bezodis & Gittoes (2007) tested four male 400 m sprinters undertaking 95% efforts on straight, and banked lane one (radius = 15.0 m; banking = 12°) and four (radius = 18.0 m; banking = 12°). The authors found that velocity on the bend compared to the straight decreased in steps from the L-R leg (approximately 5%) whilst the R-L steps were only reduced by approximately 1% (Bezodis & Gittoes, 2008). This was proposed to be due to previously reported differences in force production between legs when sprinting on the bend. Therefore, the tighter radii may increase the effect of the bend disproportionately, with the L-R step more effected on bend radii representative of indoor competition.

Table 2-2. Commonly reported step characteristics across bend conditions.

Authors	Velocity (m/s)	Step length (m)	Step Frequency (Hz)	Ground Contact Time (s)	Flight time (s)
Churchill et al. (2015)	Bend L-R: 9.39 ± 0.45	Bend L-R: 2.14 ± 0.11	Bend L-R: 4.39 ± 0.26	Bend L-R: 0.116 ± 0.004	Bend L-R: 0.116 ± 0.009
	Bend R-L: 9.33 ± 0.44	Bend R-L: 2.10 ± 0.14	Bend R-L: 4.46 ± 0.31	Bend R-L: 0.109 ± 0.005	Bend R-L: 0.112 ± 0.014
	Straight L-R: 9.86 ± 0.55	Straight L-R: 2.20 ± 0.10	Straight L-R: 4.50 ± 0.19	Straight L-R: 0.105 ± 0.003	Straight L-R: 0.115 ± 0.004
	Bend R-L: 9.80 ± 0.59	Bend R-L: 2.20 ± 0.12	Bend R-L: 4.46 ± 0.29	Bend R-L: 0.105 ± 0.008	Bend R-L: 0.121 ± 0.012
Alt et al. (2015)	Bend L-R: 9.26 ± 0.45	Bend L-R: 2.24 ± 0.10	Bend L-R: 4.13 ± 0.21	Bend L-R: 0.108 ± 0.009	Bend L-R: 0.134 ± 0.009
	Bend R-L: 9.39 ± 0.25	Bend R-L: 2.24 ± 0.08	Bend R-L: 4.35 ± 0.23	Bend R-L: 0.957 ± 0.008	Bend R-L: 0.135 ± 0.001
	Straight L-R: 9.24 ± 0.40	Straight L-R: 2.18 ± 0.11	Straight L-R: 4.29 ± 0.25	Straight L-R: 0.105 ± 0.009	Straight L-R: 0.131 ± 0.0012
	Straight R-L: 9.25 ± 0.45	Straight R-L: 2.14 ± 0.12	Straight R-L: 4.31 ± 0.24	Straight R-L: 0.104 ± 0.008	Straight R-L: 0.127 ± 0.0015

Churchill et al. (2016)	Bend L-R: 9.34 ± 0.43	Bend L-R: 2.11 ± 0.05	Bend L-R: 4.44 ± 0.25	Bend L-R: 0.117 ± 0.006	Bend L-R: 0.118 ± 0.011
	Bend R-L: 9.29 ± 0.47	Bend R-L: 2.02 ± 0.07 m	Bend R-L: 4.59 ± 0.23 Hz	Bend R-L: 0.104 ± 0.005	Bend R-L: 0.108 ± 0.016
	Straight L-R: 9.56 ± 0.46	Straight L-R: 2.14 ± 0.05	Straight L-R: 4.46 ± 0.23	Straight L-R: 0.107 ± 0.008	Straight L-R: 0.116 ± 0.019
	Straight R-L: 9.51 ± 0.47	Straight R-L: 2.12 ± 0.08	Straight R-L: 4.49 ± 0.22	Straight R-L: 0.108 ± 0.008	Straight R-L: 0.120 ± 0.014
Ohnuma et al. (2018)	**Good group**	**Good group**	**Good group**	**Good group**	**Good group**
	Average SV Bend: 9.63 ± 0.14	Bend L-R: 2.09 ± 0.14	Bend L-R: 4.63 ± 0.27	Bend L-R: 0.120 ± 0.09	Bend L-R: 0.105± 0.011
	Average SV Straight: 9.60 ± 0.19	Bend R-L: 2.01 ± 0.20	Bend R-L: 4.84 ± 0.48	Bend R-L: 0.104 ± 0.036	Bend R-L: 0.105 ±0.022
		Straight L-R: 2.11 ± 0.12	Straight L-R: 4.59 ± 0.27	Straight L-R: 0.108 ± 0.08	Straight L-R: 0.111 ± 0.010
		Straight R-L: 1.99 ± 0.16	Straight R-L: 4.83 ± 0.44	Straight R-L: 0.105 ± 0.048	Straight R-L: 0.1033 ± 0.022

Poor group	**Poor group**	**Poor group**	**Poor group**	**Poor group**
Bend 9.83 ± 0.28	Bend L-R: 2.15 ± 0.11	Bend L-R: 4.39 ± 0.28	Bend L-R: 0.116 ± 0.061	Bend L-R: 0.113 ± 0.011
Straight 9.49 ± 0.27	Bend R-L: 2.03 ± 0.23	Bend R-L: 4.73 ± 0.55	Bend R-L: 0.100 ± 0.080	Bend R-L: 0.1146 ± 0.020
	Straight L-R: 2.13 ± 0.09	Straight L-R: 4.60 ± 0.31	Straight L-R: 0.106 ± 0.052	Straight L-R: 0.112 ± 0.012
	Straight R-L: 2.26 ± 0.09	Straight R-L: 4.32 ± 0.20	Straight R-L: 0.102 ± 0.082	Straight R-L: 0.130 ± 0.070

Whilst on tighter radii (9 m), Filter et al., (2020) found soccer players ‘good’ bend sprinting performance (defined as the faster sprint to either the clockwise or counter-clockwise direction) (2.45 ± 0.11 s) exceeded that of the straight sprint (2.47 ±0.13 s) on a 17 m bend sprint. Whilst this goes against traditional theory (Usherwood & Wilson, 2006), it is possible that due to the fact soccer players primarily run in a curved fashion (Calbeck, 2019), participants approached the bend sprints with more intent.

Reductions in SV for the L-R and R-L steps appear to be the result of different mechanisms when bend sprinting (Table 2.2). For example, for the R-L step lower bend SV occurs as the result of R-L step length being significantly lower on the bend compared to the straight (Ohnuma 2018; Churchill 2016; 2015). Reductions in R-L SL occurred as a result of reduced R-L flight distance (Ohnuma et al., 2018), with the authors highlighting potentially the reduced posterior GRF observed during R-L stance, minimised the resultant impulse and thus, potentially the flight distance achieved. For the L-R step, reduction in velocity were primarily caused by a reduced SF (Churchill et al., 2016; 2015). Similarly, Ohnuma et al. (2018b) reports L-R SF for the poor group to be SF was 0.21 Hz lower on the bend compared to the straight ($p > 0.05$).

Ishimura & Sakurai, (2016) reported that unlike linear sprinting, where athletes often exhibit an optimal ratio of step length to frequency (Salo et al., 2011), the bend appears to interfere with this interaction, suggesting that bend running imposes unique demands on sprinters' mechanics (Ishimura & Sakurai, 2016). For the significantly reduced SL for the R-L step: this was caused by reduced significant reductions in flight distance and non-significant reduced stance distance (Ohnuma et al., 2018). Ohunma et al. (2018) found: non-significant reductions in R-L FT on the bend in comparison to the straight (0.130 vs 0.114 s), resulting in non-significantly greater SF but likely contributing to the significant reduction in R-L flight distance and thus SL. Further, SF is made up by GCT and FT. For the R-L step, Churchill et al. (2015) reports significantly shorter FT on the bend along with non-significantly longer GCT, thus no change in SF observed for the R-L step. Despite controlling velocity to 90 % perceived maximum, Alt et al. (2015) found R-L GCT on the bend to be shorter than on the straight ($p < 0.05$). For the L-R step: Churchill et al. (2015, 2016) found significantly longer L-R GCT on bend than the straight whilst Ohnuma et al. (2018) reports non-significant, increases in GCT on the bend (0.0096 s) with very similar FT (0.0007 s) leading to reduced L-R SF on the bend (Table 2.2). Furthermore, Alt & colleagues (2015) observed greater L-R step ground contact time on the bend than on the straight ($p < 0.1$), therefore it appears that the L-R step is limited by its ability to minimise GCT on the bend.

Larger touchdown distance (TD_D) has been proposed to result in larger braking forces (Hunter et al., 2005; Mero et al., 1992). Furthermore, TD_D appears to have an impact on force production and ground contact time (Bezodis et al., 2015; Hunter et al., 2005; Mann & Herman, 1985; Mendiguchia et al., 2021; Mero et al., 1992) whilst greater braking forces not only interfere with attaining greater velocities but are associated with increased Achilles injury risk (Lorimer & Hume, 2014). Despite longer GCT occurring on the bend and being associated with larger TD_D (Hunter et al., 2005), few studies have reported this on the bend. Nonetheless, Churchill et al. (2015) report significantly greater L-R TD_D on the bend against the straight (L-R TD_D Straight = 0.30 ± 0.04 m; L-R TD_D Bend = 0.36 ± 0.04 m) whilst no differences were observed for R-L TD_D. In a thesis chapter, Churchill (2011) reports that change in touchdown distance was significantly negatively correlated with change in L-R step frequency ($r = -0.770$; $p < 0.043$) and R-L reduction in race velocity ($r = -0.822$; $p = 0.023$), this indicates that minimising the increased touchdown distance observed on the bend may be influential to producing faster bend SVs. Whilst focusing on the acceleration phase Judson et al. (2020a) found a condition*limb interaction for touchdown distance, ($F(1, 8) = 5.477$, $p = 0.04$) where L-R step TD_D was longer on the bend (0.30 ± 0.05 m) compared with the straight (0.25 ± 0.05 m).

2.3.2 Bend versus Straight - Kinematics

Stance Phase

Sagittal plane

Several research papers report joint angles at discrete time points including at touchdown and toe-off events, as well as peak values during swing and stance. Churchill et al. (2015) found larger sagittal lean angles (forward) during the L-R step on the bend compared to the straight, as well as reduced L-R hip extension angular velocity during stance on the bend compared with the straight. On the other hand, Ohnuma et al. (2018) found a smaller sagittal hip joint angle at TO for the R-L on the bend compared to the straight. This difference was only observed in the poor bend sprint group and thus, this reduction may have influenced the reduced FD and SL observed for the R-L step on the bend. Despite no differences in SV, SL or SF for the inside step (compared to the straight). Furthermore, Ohunuma et al. (2018) found the minimum value of knee and ankle joint angles to be significantly lower than on the straight path. Nonetheless, these angles could have been compensated for by the greater knee extension velocity shown on the bend compared to the straight, with the larger angle requiring greater angular velocity. At submaximal (90% max), Alt et al. (2015) found no changes in peak angles in the sagittal plane at the hip, knee, and ankle.

Whilst the acceleration phase during linear sprinting has not been reviewed, differences between bend and straight in this phase offer greater insight into the biomechanics of bend sprinting. Thus, where minimal comparisons of kinematics and kinetics between bend and straight are currently published, research in the acceleration phase have been included. For example, Judson et al. (2019) reports metatarsophalangeal (MTP) angular extension velocity between bend and straight during the acceleration phase. MTP angular velocity was reported since (Krell & Stefanyshyn, 2006) have shown a relationship between sprint performance and higher maximal rates of MTP extension. However, Judson et al. (2019) reported no significant condition x limb interaction for MTP angular velocity (F (1,8) = 1.672, P = 0.232). Despite observing no significant interaction, Judson et al. (2019) suggests there may be a decrease in MTP joint angular velocity during the L-R step on the bend compared to the straight (g = 0.50). Therefore, it is possible that decreased MTP joint angular velocity might contribute to the reduced L-R SVs found on the bend, however further research is required to strengthen this conclusion.

As suggested by Ohnuma et al. (2018), it is possible that one aspect to successful bend sprint technique is to maintain the same kinematics in the sagittal plane as a straight path. However, to minimise sagittal plane alterations as a result of the bend, it is possible that strength and or stability in the frontal and transverse planes are required to follow the path of the bend at high velocities.

Frontal and transverse plane

Research is in more agreement around the frontal plane kinematics. For example, during bend sprints on outdoor bend radii, athletes have been shown to lean into the bend at both touchdown (L-R Curve = -10.3 ± 2.3°; L-R straight = 3.5 ± 1.2°) and TO (L-R Curve = -8.3 ± 2.2°; L-R straight = 3.4 ± 1.2°) (negative value corresponding to lean to the L-R) with this resulting in more hip adduction (L-R step 10.6 ± 4.1. 4.1 ± 2.6°) and with more hip abduction (R-L step) on the bend compared to the straight (Churchill et al., 2015). Additionally, Alt et al. (2015) report significant differences in hip adduction between bend (13.8 ± 3.3°**)** and straight (7.7 ± 3.8°**)** L-R steps ($p < 0.05$). Further differences were reported for bend R-L (5.5 ± 4.4°) and straight R-L (9.8 ± 4.3°) ($p < 0.05$) (Alt et al., 2015). The combination of lateral lean and alteration of hip adduction and abduction appear to place the ankle joint in more extreme eversion. For example, Alt et al. (2015) found high peak ankle eversion for the L-R step (bend L-R: 12.7° ± 7.2°; straight L-R: 6.7 ± 2.3°; $p < 0.05$). Previous research has suggested ankle eversion of greater than 13° approaches physiological limits (Clarke,1984). Large eversion angles have also been highlighted in the acceleration phase of bend sprinting with and a large, but non-significant, increase in peak L-R step ankle eversion on the bend compared with the straight (g = 0.88) (Judson et al., 2019). Additionally, significantly greater L-R peak ankle internal rotation (g = 1.70) were observed (Judson et al., 2019). These findings support the theory from Alt et al. (2015) that the L-R limb is associated with a stabilising role achieved through the combination of greater hip adduction and ankle eversion. Nonetheless, with greater eversion angles the generation of joint extension moment and thus overall limb force may be compromised, with athletes pushing off the oblique axis of the metatarsophalangeal joint (MTP) joint rather than the transverse axis (Judson et al., 2019). Judson et al., (2019) found that mediolateral centre of pressure position to be more lateral in the stance phase of the L-R step during the acceleration phase on the bend, in comparison to that on the straight. Furthermore, Judson et al. (2019) reports multi-segment foot kinematics with a similar trend to ankle kinematics where greater peak midfoot eversion for the L-R step on the bend compared to the straight peak midfoot eversion (g = 0.79) whilst the R-L step showed an increase in R-L step peak midfoot inversion on the bend relative to the straight. Judson et al. (2019) goes on to suggest that the complex interaction of adaptations at the joints of the ankle and foot limit antero-posterior force production, particularly within the L-R step; thus, with this potentially one of the reasons for reduced SV when bend sprinting. Additionally, as the ankle joint deviates away from its neutral position in the frontal plane, the lateral compartment of the Achilles tendon can experience a large amount of stress during a quick plantarflexion (Wallenböck et al., 1995). This is potentially one of the reasons for the large number of plantaris tendon injuries in elite longer sprinters (200 – 400 m) (Pollock et al., 2016). This may have further bearing on tighter bend radii, such as indoor athletics tracks, where joint kinematics are yet to be comprehensively described.

Alt et al. (2015) report figures of kinematics for the entirety of stance, as well as several angle-angle plots, however, these are not analysed with inferential statistics. Nevertheless, the authors describe the difference in foot-plant patterns, reporting that the right foot displayed initial external rotation whilst the left foot was internally rotated, the peak values led to the right foot being significantly greater than the L-R (bend L-R: 2.4°; bend R-L: 7.3; P = 0.031; d = 1.31). Furthermore, the authors highlight the relation between different joint pairings, for example the L-R (inside) leg displayed external rotation with adduction and eversion, reinforcing these non-optimal positions for sagittal plane force production. On the other hand, the R-L leg displays modifications more in the transverse plane, described as a rotational mechanism. Thus, future research should look to describe joint kinematics across the entire stance phase in order to further understand joint kinematics during bend sprinting.

Swing phase

Whilst most of the spatiotemporal and kinematic descriptors have occurred during the stance phase. Significant differences in FT have been reported and thus, differences in kinematics may occur across the swing phase. Nonetheless, Churchill et al. (2015) reports peak and time to peak hip angular velocity during swing, with the only significant difference occurring between L-R and R-L on the straight. Nonetheless, high step frequency for the L-R step was associated with both greater peaks L-R hip flexion and faster hip flexion angular velocities, suggesting the ability to reposition the limb faster prior to the next touchdown enables shorter FTs and or shorter ground contact times. Previous research has highlighted that kinematic adaptations at touchdown can impact the touchdown distance which in turn may increase braking forces and ground contact times (Kunz & Kaufmann, 1981). Furthermore, altered joint angles in the frontal plane has been proposed to impact muscles also acting in the sagittal plane (Coqueiro et al., 2005), thus reducing the ability to achieve high angular velocities and reposition the limb prior to the next touchdown. Thus, the extent of kinematic alterations may be one of the reasons for lower SF on the bend. Furthermore, Ohnuma (2018) report no significant differences in lower limb movements during the flight phase between the paths (straight and bend) during the swing phase.

2.3.3 L-R versus R-L on the bend – Step characteristics

Whilst SV between L-R and R-L steps appear to be similar (Table 2.2), athletes have been shown to display asymmetrical step characteristics when running a bend. For example a trend exists where the L-R (inside) step produces greater SL but lower SF in comparison to the R-L (outside) step (Churchill et al., 2015, 2016; Ishimura & Sakurai, 2016; Ohnuma et al., 2018). Therefore, it is possible that due to the additional task constraints in bend compared with straight sprinting of having to follow the path and stay in the athletes' lanes, there is an optimal ratio of SL and SF during bend sprinting, and that there may be a different ratio for L-R and R-L steps (for example, a longer L-R step enables the repositioning of the R-L limb in preparation for R-L touchdown) or that R-L SL is reduced due to the greater TD_D of the L-R limb. Churchill et al. (2015) proposed that due to greater inward lean on the bend, the L-R leg has less space in relation to the centre of mass and thus contacts the ground earlier, inadvertently increasing TD_D and reducing R-L SL. Nonetheless, greater body lateral lean and frontal/transverse plane joint alterations are potentially required to enable the greater inward forces and contribute to greater turning of the centre of mass during the L-R stance phase (Churchill et al., 2016).

Ishimura & Sakurai (2016) report asymmetry of determinants of SV and associate step length, frequency and their determinants to SV, finding that step length was significantly correlated with SV for L-R (r = 0.81; $p < 0.01$) and R-L steps (r = 0.83; $p < 0.01$) whilst SF was only significantly correlated for the R-L step (r = 0.55; $p < 0.05$). Ishimura & Sakurai's results highlight the importance of SL but also potentially different optimal ratios of SL and SF for the L-R and R-L steps.

Previous literature has identified two trends that lead to changes in SF for the L-R and R-L steps. Trends for longer L-R GCT and shorter R-L FT has been observed (Alt et al., 2015; Churchill et al., 2015, 2016; Ishimura & Sakurai, 2016; Judson et al., 2019; Ohnuma et al., 2018). Ishimura & Sakurai, (2016) significant correlations for SL and SF to their respective determinants (stance and flight distance and times). For SF (presented as total step time), shorter GCT (r = 0.56; $p < 0.05$) and FT (r = 0.76; $p < 0.01$) were both significantly related to shorter step times for the L-R step. For the R-L step only shorter FT was significantly related to shorter step times (0.77; $p < 0.01$) (Ishimura & Sakurai, 2016). For SL both stance distance and flight distance were significantly positively correlated to stance distance and flight distance for the L-R and R-L steps (r = 0.68-0.89; $p < 0.01$) (Ishimura & Sakurai, 2016). These findings highlight that asymmetries exist in the determinants of bend sprint speed and highlight the potential differing roles of the inside and outside steps, as well as an interesting interaction of SL and SF.

Filter et al. (2020) showed that soccer athletes' Furthermore, both straight and 'good' bend sprint side were significantly faster ($p < 0.05$) than the 'poor' bend sprint side (2.56 ± 0.17 s). Interestingly, the inside leg (L-R during counter-clockwise sprints) had longer ground contact times for both bend sprint directions, the inside leg having greater contact time has been reported previously but only in a counter-clockwise direction. Nonetheless, soccer players are more accustomed to both bend directions, whereas sprint athletes solely compete in a counter-clockwise fashion. The authors conclude by suggesting both inside and outside leg play different roles during bend sprints, but that the inside leg is more affected by the change from straight to bend sprint. On a more similar lane radii to athletics competition, (17 m) Taboga et al. (2016) investigated the effect of bend sprint direction on step characteristics in L-R and R-L sided amputee and non-amputee athletes. They found that non-amputee athletes were 1.9% faster when counter-clockwise versus clockwise, whereas the amputee athletes were 3.9% slower where the effected limb was on the inside. This occurred due to longer GCT with only partial reductions in FT leading to reduced SF for the inside limb (Taboga et al., 2016). These findings suggest that the amputee athletes were limited in their ability to produce force sufficiently and rapidly to maintain short GCT with the effected limb on the inside, and were thus, not able effectively reposition the limb during swing. More recently Diaz et al. (2024) reports, SV in the counter-clockwise direction was 1.6% faster than the clockwise direction (B = 0.14 m/s; $p = 0.003$) however found no statistical difference was observed in GCT between the inside and outside leg or between running in the clockwise versus counter-clockwise direction. Nevertheless, there appears to be a direction effect where sprint athletes produce an optimal technique when sprinting counter-clockwise that produces faster SV. This may have bearing during athletic competition, where athletes solely compete in the counter-clockwise direction.

TD_D

Despite its association with shorter GCTs and technique, (Churchill et al., 2015, 2018) and Ishimura and Sakurai (2016) are the only researchers to report TD_D at maximal velocity on the bend. In agreement with the association between GCT and TD_D, L-R TD_D was significantly greater than R-L on the bend (Churchill et al., 2015; Ishimura & Sakurai, 2016), whilst the magnitude of difference appears to increase with tighter radii (Churchill et al., 2018). This trend of greater L-R TD_D than R-L is supported on the bend in the acceleration phase, where L-R TD_D was longer on the bend (0.30 ± 0.05 m) compared with the straight (0.25 ± 0.05 m) (Judson, et al., 2020a). Therefore, there appears to be a kinetic and or kinematic asymmetry that causes the L-R limb to have longer touchdown distances that are associated with greater braking force and GCTs.

Turn of CoM

Another key variable reported by Churchill et al. (2015;2018) is the amount of turning of the centre of mass achieved with each step. Churchill et al. (2015) finding that the turn of the CoM was greater during the L-R step (4.2 ± 0.9°) than the R-L (2.6 ± 0.7°) ($p < 0.05$). In another study, Ishimura and Sakurai (2016) report that the running direction was changed more by the R-L step. Nevertheless, Ishimura and Sakurai (2016) do not report their calculation method and data collection took place in lane 4 (radius 43.51 m), and so consideration of this should be taken when making comparisons between investigations. In the acceleration phase however, it appears that similar contributions occur through both L-R 2.48 ± 0.91° and R-L 2.61 ± 0.86° steps (Judson et al., 2020a). These differences suggest that as athletes approach the maximum velocity phase on the bend, the L-R limb contributes more to CoM turn than the R-L stances. Therefore, the amount of turn of the CoM appears to be a variable relevant to success during bend sprinting at maximal velocity, and thus warrants further study.

2.3.4 L-R versus R-L on the bend – Kinematics

Stance Phase

Sagittal

Churchill et al. (2015) reports several kinematics such as the greater L-R sagittal RoM and the L-R hip being more extended at TO and more flexed at peak flexion than the R-L hip on the bend ($p < 0.05$). Similarly, when investigating three lane radii, Churchill et al. (2018) observes significantly greater body sagittal lean RoM during L-R stance compared to R-L. Whilst not significantly lower than the R-L on the bend, L-R hip extension angular velocity during contact was reduced on the bend compared with the straight. The authors highlight that due to the three-dimensional nature of bend sprinting it is possible that the observed asymmetries in sagittal plane kinematics were a result of the asymmetrical nature of bend running in the frontal plane. Alt et al. (2015) reports peak hip, knee and ankle flexion/extension highlighting no significant differences between L-R and R-L steps across these variables. One potential explanation is the methodological differences (maximal vs submaximal and measurement methods) between Churchill et al. (2015;2018) and Alt et al. (2015) investigations.

Ishimura & Sakurai, (2016) report minimal kinematic variables for L-R and R-L steps, for example a significantly greater TO angle (calculated as the inverse-tan of the (vertical velocity takes off * horizontal velocity at TO)-1) was observed for the L-R step compared to the R-L. This is potentially the reason for the greater SL observed for the L-R step and occurred due to a greater vertical velocity and CoM height at TO for this step. The only explanation provided is that a smaller downward velocity at touchdown is reported. However this contradicts previous research that highlights a more active touchdown to minimise touchdown distance and braking forces and minimise ground contact time (Churchill et al., 2015), nevertheless it is possible that for the L-R step, lower downward velocity at touchdown is associated with the time to generate sufficient vertical and inward force required to produce turning of CoM and maintain SL.

Ohnuma et al. (2018) provides no inferential comparison between limbs, however, there appears to be some differences in inter-limb differences between poor and good group. For example, for minimum knee joint angle a large difference inside between outside in the poor group but not good group, a larger difference in minimum ankle joint in the poor group whilst a larger difference in knee joint angle at release for good group (Ohnuma et al., 2018). When considering angular velocities, these were generally larger for the poor group than good group, whilst there was also a trend for larger difference between L-R and R-L in poor group than good group (Ohnuma et al., 2018). This highlights that in addition to the complex interaction of asymmetrical step characteristics there is perhaps a relationship between inter-limb differences and performance.

Frontal and transverse

Hamill et al. (1987) investigated the kinetics and kinematics of the lower extremity as runners ran at a sub-maximal speed (6.31 m/s) around the bend of a 400 m track (radius 31.5 m). Findings indicated that runners lean into the bend, causing modifications in lower extremity mechanics such as large pronation angles for the L-R step (~ 22.26°*)* and an exaggerated supination position at touchdown for the R-L step (12.76°). Hamill and colleagues (1987) concluded that running on the bend introduces an environmentally produced stressor that appears to result in asymmetrical dysfunctions of the lower extremities. Since testing was carried out at sub-maximal speeds the authors could only suggest that the stress experienced would be greater at faster speeds, and on tighter radii. The finding that bend sprinting results in potential asymmetric adaptations was later confirmed by (Beukeboom et al., 2000) finding that invertor and evertor strength imbalances were developed over the course of an indoor athletics season.

Churchill et al. (2015) reports body lateral lean at touchdown and toe off (R-L > L-R), hip abduction/adduction at touchdown (R-L abduction L-R neutral (adduction)), peak adduction (L-R > R-L), similar abduction/adduction at toe-off. Similarly, Churchill et al. (2018) reports more inward lean for the R-L step in three lanes of an outdoor athletic track at touchdown and TO ($p < 0.05$). The greater inward lean highlights the differing demands during bend sprinting. Thus, different kinematic adaptations likely occur as a result. For example, whilst not reporting body lateral lean, Alt et al. (2015) report significantly greater hip adduction for the L-R (13.8 ± 3.3°) than the R-L (5.5 ± 4.4b°) whilst greater ankle eversion for the L-R (12.7 ± 7.2°) than R-L (2.6 ± 5.1°) was observed. These inter-limb differences suggest the L-R limb has less space available at TD (since knee and hip flexion were similar) and thus must change the inclination of the shank and ankle at touchdown and during stance. It is possible that an additional consequence of the body lateral lean is increased transversal plane adaptations. For example ankle external rotation (L-R: 2.4 ± 4.2°; R-L:7.3 ± 3.2°), knee internal rotation (L-R:8.8 ± 5.3° ;R-L: 12.8 ± 5.2°) and hip external rotation (L-R: 21.6 ± 6.7°; R-L:12.9 ± 4.1°) and internal rotation (L-R: −4.6 ± 4.3°; R-L: 2.1 ± 5.9°) suggests that changes in rotation is required in order to stabilise and produce inward forces.

In the acceleration phase, Judson et al. (2020a) reports, greater body lateral lean at touchdown for the R-L step, peak L-R hip adduction was greater on the bend (8°) compared with the R-L step on the bend (6°). Furthermore, L-R step peak ankle internal rotation was greater on the bend (12 ± 7°) compared with the R-L step on the bend (1 ± 7°). This highlights some similarities in the frontal and transverse plane requirements of the L-R and R-L steps between acceleration and maximal sprint phases. Nevertheless, Judson et al. (2020a) goes on to suggest that asymmetries may continue to develop as velocity increases and athletes progress around the bend.

Whilst this literature review has highlighted sagittal and frontal and transverse plane alterations separately, it is probable that differences in the frontal and transverse planes impact optimal sagittal plane kinematics. For example, increased adduction abduction may interfere with muscles that work across frontal and sagittal planes (Coqueiro et al., 2005), this in turn may limit athletes ability to generate greater angular velocities at both TD and TO and thus impact bend sprinting performance.

Swing phase

Whilst the majority of research has investigated the stance phase, Ishimura & Sakurai, (2018) investigated L-R versus R-L kinematics and kinetics in the swing phase during bend sprints. Ishimura & Sakurai, (2018) found the only differences occurred in the frontal plane of the knee joint, with greater adduction during the L-R swing phase with differences during 0-11% and 85-93% for the knee adduction/abduction angle, highlight that the kinematics at toe-off may influence the early swing in the frontal plane and in preparation for the subsequent touchdown.

Nonetheless, the authors conclude that in the swing phase, athletes may simply move the same as for straight sprinting (Ishimura & Sakurai, 2018).

2.4 Force on the bend

Bend sprinting requires additional force demands to follow the path of the bend, in addition to propulsive and vertical forces required to sprint linearly. Previous research has highlighted that greater vertical ground reaction forces and rate of force production is key to linear sprinting performance (Clark & Weyand, 2014; Weyand et al., 2000). Therefore the additional force demands to follow the path of the bend is potentially one of the reasons for reduced step velocities observed during maximal bend sprinting (Churchill et al., 2015, 2016; Ohnuma et al., 2018).

2.4.1 Conditions not representative of competition

Usherwood & Wilson, (2006) developed a model to determine whether performance of elite sprinters on banked bends with tight radii (indoor tracks) was consistent with the constant limb force hypothesis. Using results from the world indoor athletics championships 200 m as inputs to the model; the model suggested that indoor times are slower with the tighter bend radii, due to a greater increase in duty factor (the proportion of stride that the limb is in contact with the ground) that is required to preserve force, therefore leading to reductions in step frequency and ultimately velocity and race times. (Usherwood & Wilson, 2006) concluded that the very simple ‘constant limb force’ model appears effective in accounting for the observed indoor performance according to lane. Whilst this provided some mathematical insight into force generation when sprinting on bends of tighter radii it provides no experimental data to confirm the conclusions drawn.

One study that highlights the additional force demands when changing direction was during 90° turns. Glaister et al. (2008) found that turn initiation and termination steps included medial impulses across the entire stance phase, apex steps were characterized by a large lateral impulse. In the anterior–posterior direction, initiation steps had larger braking and smaller propulsive impulses compared to the straight, whilst apex steps had larger propulsive impulses than the straight (Glaister et al., 2008). Whilst this study is not representative of the conditions and velocities faced it highlights that there are likely differences between stages of the bend (start, initial acceleration, max velocity at the apex) as well as potential differences between limbs.

Chang & Kram, (2007) further tested the hypothesis that the maximum leg extension force during straight path sprinting was also generated on flat bends, with a secondary hypothesis that both legs act symmetrically when sprinting on flat bends. To test these hypothesis, five participants sprinted on a straight path and radii of 1 – 6 m radii over a force platform. Peak GRF were components were calculated for the inside and outside legs. Results showed that compared to the straight path peak vertical forces were smaller; additionally, the inside leg produced smaller peak lateral GRFs than the outside leg. The findings from (Chang & Kram, 2007), give experimental evidence that maximum force generation is not achieved when sprinting on tight bends, and that the inside and outside legs do not contribute equally to bend sprinting. Similarly Smith et al. (2006) investigated the contributions of the inside and outside leg to maintenance of curvilinear motion on a natural turf surface. Results showed that: vertical, propulsive and medio-lateral forces were lower for the L-R leg in comparison to the R-L step on the bend, with greater medial-lateral forces seen on the bend in comparison to the straight. These findings would suggest that the outside leg produces the forces in order to generate acceleration towards the inside of the bend. Nonetheless, despite providing experimental evidence to the kinetics of sprinting on bends, these investigations do not represent radii typical of athletics competition.

In order to test the hypothesis that bend sprinting performance is limited by restricted force generation of the inside leg: Luo & Stefanyshyn, (2012b) tested 13 males during 2.5 m radius bend sprints with and without added 12.6 kg mass. Results showed that significantly larger ground reaction forces were observed with the additional mass, (9.9% for centripetal and 12.3% for vertical, $p < 0.01$). Furthermore Luo & Stefanyshyn, (2012b) report similar peak ankle joint moment across conditions (p=0.2615) but a 15.2 % increase in extension moment at the knee joint. Previous research has suggested the primary force producers are the hip and the ankle with the knee allowing the transfer of energy (Bezodis et al., 2008). Therefore, additional mass of 12.6 kg demonstrating not only that greater force can be produced, but may also change the technique and not be optimal for generating force quickly. Luo & Stefanyshyn, (2012b) propose that the non-sagittal plane ankle or knee joint moments were not at their physiological limits suggesting that the joint stabilisers are able to endure external loading greater than that experience when bend sprinting without the mass (Luo & Stefanyshyn, 2012b). On the other hand, the finding that ankle plantarflexion moment remained unchanged with added mass suggests that during maximum- effort bend sprinting, the ability to generate ankle plantarflexion moment of the inside leg reaches its limit for the given operating states, the authors go on to suggest that plausible method to increase such moment generation may be by aligning the ankle joint towards a more optimal configuration for pushing off the ground (e.g. less everted/inverted). Nonetheless, despite the authors stating that in a pilot study with one subject, no changes in joint angle and angular velocity variables due to the additional mass were found, no joint kinematics are reported. Thus, it is not possible to determine that the sagittal and non-sagittal kinematics remained similar across the two conditions.

In order to test the hypothesis developed in the previous study Luo & Stefanyshyn, (2012a) investigated ankle plantarflexion moment generation during maximum bend sprinting (radius = 2.5 m) with and without experimental intervention of laterally wedged footwear. The aim of this was to assess the effect of aligning the ankle joint closer to its neutral position on planter flexion moment generation and bend sprinting speed. Luo & Stefanyshyn, (2012a) showed that the laterally wedged footwear reduced the inside leg ankle eversion by 4.21° and increased bend sprinting speed by 4.3%. The increased bend sprinting speed could be associated with the greater centripetal GRF was in the wedged footwear condition as vertical GRF remained unchanged. The findings from this study have potential bearing during indoor athletic sprint events, where the track length is typically 200 m (< 400 m) and the bends are often banked. The biomechanics of bend sprinting on banked bends will be discussed in the Section 2.5.1.

2.4.2 Bend versus Straight – Kinetics

Conditions representative of athletics competition

Churchill et al. (2016) investigated force production on the bend compared to the straight and highlighted that force production during the L-R step was significantly reduced. Peak vertical and resultant force were 0.37 bodyweights (BW) and 0.21 BW lower respectively, on the bend compared to the straight, whilst no significant differences in GRF were observed for the R-L stance between the bend and straight (Churchill et al., 2016). Therefore, it is possible that the reduced resultant and vertical force produced during the L-R stance is the limiting factor in bend sprinting. Resultant force decreased despite two-fold increases in mediolateral force (termed inward meaning directed in toward the bend) (Churchill et al., 2016). Interestingly, propulsive impulse was greater for the R-L step on the bend compared to the straight (Churchill et al., 2016), due to the centripetal accelerations required to follow the path of the bend it is possible the R-L step has greater propulsive requirements than during linear sprinting at maximal velocity. Greater propulsive demands for the R-L step is potentially one of the reasons for the greater incidences of plantaris and Achilles injuries and greater hamstring strength observed on the right leg in elite long sprint athletes (Pollock et al., 2016; Giakoumis et al., 2020). In agreement with Churchill et al. (2016) reduced SV coincided with decreased L-R mean vertical and A−P forces in the bend (Millot et al., 2024). Furthermore, increased L-R inward force observed without an increase in their resultant force (Millot et al., 2024). For the R-L stance, vertical force was similar to the straight whilst an increase in the mean inward force was paired with a decrease in the mean anterior-posterior force in comparison to the straight (Millot et al., 2024). Nonetheless, forces were averaged over stance and thus changes in the braking and propulsive phases cannot be determined. Despite this, the additional inward force demands appear to have a bearing on bend sprinting performance and the development of SV. Further differences between the mechanisms for reduced SV compared to the straight, with greater inward force produced by the L-R step and reduced vertical and anterior-posterior force highlighting the challenge of maintaining high SV on the bend. Previous linear maximal velocity sprinting research has highlighted that fast step velocities are achieved through sprinters' ability to generate appropriate vertical forces (Clark & Weyand, 2014) and the ability to generate a sufficiently large peak propulsive force (von Lieres Und Wilkau et al., 2020). Thus, factors that relate to linear SV should be further considered in future bend sprinting research.

Viellehner et al. (2016) report GRF whilst bend sprinting at 90% maximum finding that braking forces were significantly greater for the R-L step on the bend compared to the straight. No other significant differences were observed between bend and straight. Ohunma et al. (2018) significantly greater inward (medial) force production on the bend compared to straight in both groups (good and poor), with non-significantly less propulsive and vertical force and more braking on the bend compared to the straight. However, the only difference that occurred in the poor group and not the good group related to lower posterior (braking) force observed in the outside limb during bend sprints (Ohnuma et al., 2018). Therefore, as with step characteristics and joint kinematics, there appears to be inter-limb differences in kinetics during bend sprinting.

Analysis of key discrete force variables has demonstrated differences in force production when bend sprinting, however it is also important to understand how these differences present over the stance phase and how they relate to differences in the contribution of the L-R and R-L steps. Statistical parametric mapping (SPM) is a statistical approach to identify areas of significant differences between to waveforms (Pataky, 2010; Pataky et al., 2013). In the acceleration phase, SPM revealed a reduction in the ability to produce propulsive force during bend sprinting around the mid-stance (37-44%) whilst an increase in mediolateral force was observed for the majority of stance (3-96%) (Judson et al., 2019). Despite not reporting vertical force these alterations combined to result in a lower average ratio of force, highlighting that the bend leads to less effective force production in the acceleration phase (Judson et al., 2019).

2.4.3 L-R versus R-L - Kinetics

When comparing the kinetics of the L-R and R-L steps, Churchill et el., (2016) reports no significant differences between L-R and R-L steps on the bend for peak or mean vertical force or peak braking or propulsive force. This suggests that the assumption that the R-L step is less affected by the bend may not be fully appropriate as the non-significant reductions in R-L vertical and A-P force mean that the L-R and R-L force production were statistically similar. Nonetheless, braking impulse and duration of braking was greater during the L-R step suggesting greater braking demands during the L-R stance (Churchill et al., 2016). This finding was supported in the acceleration phase where braking impulse was increased on the bend but only for the L-R step (27%; g = 1.29) (Judson et al., 2019). In a more recent study, stance average vertical GRF were 0.10 BW lower (p=0.001) for the L-R leg compared to the R-L (Diaz et al., 2024), whilst A-P force is not reported, using the resultant force presented would suggest that A-P would be similar between steps. Whilst Millot et al. (2024) do not compare vertical and total force inferentially between limbs, both appear visually similar between L-R and R-L steps at 34-39 m. On the other hand, braking force appears visually greater during L-R (-0.4-0.5 N/kg) when compared to R-L (0-0.1 N/kg) (Millot et al., 2024). Therefore, the demands of the bend on the different limbs vertical and anterior-posterior force are not completely clear and thus further research is required. Similarly, Ohnuma et al. (2018) does not compare inside and outside limbs inferentially. Nevertheless, the vertical force inside limb in the poor group 2723.5 ± 532.0 N appears greater than vertical force of the inside limb in the good group 2384.1 ± 269.4 N with much greater asymmetry outside 2884.2 ± 886.0 N inside in good group (Ohnuma et al., 2018). For (propulsive) force a greater peak and smaller braking force in poor group compared to the good group and similar limb differences between groups (Ohnuma et al., 2018). As force is presented in N the effect of BW is unclear as this is not reported separately, however body mass of the whole participant group was 66.7 ± 4.6 kg suggesting there was a small spread across whole sample.

Research into inward force production appear to be more consistent. For example, Churchill et al. (2016) highlights that peak inward force (L-R =1.07 ± 0.22 BW vs R-L = 0.86 ± 0.25 BW) and net inward impulse (L-R =39.9 ± 6.5 N·s vs R-L = 24.7 ± 5.8 N·s) were significantly greater during L-R stance than the R-L. Similarly, greater centripetal (defined as the mediolateral axis rotated relative to the direction of travel) GRF for the L-R (0.68 BW) versus R-L leg (0.58 BW) ($p<0.001$) have been reported on a 36.5 m radius bend at maximal velocity (Diaz et al., 2024) and at 90% of maximal linear velocity (Viellehnerl et al., 2016.). Interestingly, on a 17.2 m radius bend, centripetal GRF was produced by the L-R (0.68 BW) and R-L legs (0.65 BW) were similar ($p = 0.089$, $\alpha = 0.0125$) (Diaz et al., 2024). Diaz et al's (2024) findings demonstrate that as radius decreases, the turning demands increase, for the right step. This is supported by the previous research on bends not representative that highlight on very tight radii (1-6 m), the right step (outside) generates more inward force (Chang & Kram, 2007; Smith et al., 2006).

Despite not comparing L-R vs R-L with inferential statistics: Millot et al. (2024) highlight that from 24 m, the L-R mean inward and inward impulse was visually greater than the R-L. Therefore, it is possible that as athletes approach the maximum velocity phase and apex of the bend, the L-R limb contributes more to CoM turn than the R-L stances. Likewise, Ohnuma et al. (2018) do not compare limbs inferentially, however visually, peak L-R inward force appears greater in good group (631.3 ± 347.7 N) than poor group (487.5 ± 47.9 N), whilst for the R-L step inward forces appear more similar between groups. In relation to interlimb differences: the poor group peak inward force and impulse were greater during R-L step than L-R step whereas this was reverse in the good group (L-R > R-L). Therefore, the ability to generate greater inward force with the L-R step is a potential limiting factor of bend sprinting performance. In addition to presenting force in N, the division between good and poor group was based off the percentage decrease in velocity on the bend compared to the straight, thus investigating relationships between force production is an area for future research.

In the acceleration phase, Judson et al. (2019) reports a significant main effect for limb, where differences between L-R and R-L were observed at 1-12 and 75-100% of stance. Interestingly, for the first period of difference, inward for produced by the R-L step was greater whilst for the end of stance the L-R step inward force was greater. The authors concluding that the reduced A-P and increased M-L force production, reducing the ratio of force and indicate a less effective force application on the bend, particular for the L-R step (Judson et al., 2019). Furthermore, the L-R step appears to be limited by the lateral centre of pressure position, suggesting the less effective oblique axis was used for push-off at the MTP joint, combined with increased midfoot eversion and ankle internal rotation (Judson et al., 2019).

In an alternative view of investigating inside vs outside limb during bend sprinting Hobara et al., (2015) indicates that bend sprint performance of athletes is not affected by amputation side on a standard 400-m track. Funken et al. (2017) investigated a single leg amputee during sprints in the counter-clockwise and clockwise directions, results showed that velocity was 5% slower for the counter-clockwise direction (prosthetic limb inside) whilst propulsive forces were lower when unaffected limb was inside (8.42 ± 0.57 N/kg vs 6.95 ± 1.05 N/kg; $p < 0.05$), with higher peak inward forces of the outside compared to the inside leg in both conditions also contrast the findings of studies investigating non-amputee athletes. Despite the limitations of a single case study design, the results contradict Hobara et al. (2015) and support the theory that the inside leg limits bend sprinting performance (Churchill et al., 2016; Luo & Stefanyshyn, 2012). It is possible that the ability of the left limb to evert and internally rotate and push off with the oblique axis of the MTP joint whilst less effective for anterior-posterior force production, enables the production of inward force required to follow the path of the bend.

Therefore, it appears that some level of asymmetry of external kinetics may have an influence on produces faster velocity on the bend. Ohnuma et al. (2018) highlights that the despite greater inward forces, anterior-posterior GRF and impulse on a bend path were lower than on a straight path during the outside limb. Consequently, whilst reduced braking force (posterior force) is commonly associated with improved sprinting velocities (Mero et al., 1992), the relationship between braking force and sprint velocity at maximum velocity is not completely clear (Hunter et al., 2005), and could differ between bend and straight sprinting. TD_D is commonly associated with greater braking forces but is not reported in that study, thus this could be one potential reason for a change in braking forces and has been associated with greater braking force and longer ground contact times during linear sprinting (Hunter et al., 2004, 2005), as well as a potential reason for the commonly reported longer GCT observed during the L-R step on the bend (Alt et al., 2015; Churchill et al., 2015, 2016). Nonetheless, details of the relationships between SL, SF, external kinetics and SV.

2.5 Competition factors

2.5.1 The effect of lane radius on step characteristics

A number of studies have attempted to quantify the difference between the individual lanes. For example, using standard dimensions of an outdoor track and world class male athlete times as inputs, Alexandrov & Lucht, (1981) proposed that the advantage of the greater outer lane radii of lane 8 over the smaller radii of lane 1 to be 0.12 s, equating to roughly 1.3 m. Another theoretical paper, showed that the effect on performance is inversely proportional to the square of the radius of the bend paths (Greene, 1985), predicting that 0.123 s would be the difference in race times between lanes 1-8 in a 200 m race. A third theoretical paper, Behncke, (1994) indicated that Greene's estimate to be slightly high, suggesting a value around 0.106 s. More recently, Munro, (2022) found that excluding outliers (such as athletes easing up before the finish line) of the women’s 200 m races at the world championships held between 2000 – 2019, lane 8 was estimated to be 0.1781 faster than lane 2. Munro’s (2022) support the effect of radius with the outside lanes producing faster race times. On the other hand, it is difficult to completely discount the effects of lane seeding, and so future is required to understand the effects of lane radius on performance, particularly on conditions representative of indoor competition.

Behncke (1994) went further to analyse indoor tracks, where the length of the bend is ~50 m and thus, the radius of curvature is substantially less (19 m compared with 38 m for lane one indoors and outdoors). The findings of this analysis demonstrated a much larger (by a factor in excess of 2.5) time advantage to the outermost lane in a 200 m indoor event. This is one of the main reasons for the IAAF (now World Athletics) removing the 200m from indoor athletics championships. Nonetheless, whilst the 200m does not take place at WA world indoor championships, it is still competed in domestically and at the national collegiate athletics association championships in the United States. Furthermore, the 400m and 4x400m relay events athletes negotiate two bends in lanes before completing the race in lanes 1 and 2 (if overtaking) at high velocities thus, research into indoor athletics conditions typical of competition is of interest. Moreover, athletes with access to facilities will likely train on indoor athletics tracks over the winter months, and thus understanding of the effects of lane radius on 200 m bend radii can inform coaches on the prescription of bend sprint training.

A model developed by Usherwood & Wilson (2006) used data from the 2004 Olympic Games and 2003 World Indoor Championships to explain the performance reduction on tighter bends and compare outdoor vs indoor 200m races. Their constant limb force model incorporated duty factor, mass-specific force, stance distance, and limb protraction velocity. Key assumptions included maximal limb force production on straights (Weyand et al., 2000), and similar kinematic parameters across sprinters of varying abilities. Usherwood & Wilson (2006) showed: accurate predictions for men's indoor finals times (less so for women), that indoor 200m times approximately 1 second slower than outdoor and an appropriate relationship between performance and lane number among finalists with performance decreases on tighter bends associated with increased duty factor for limb force preservation, necessitating speed reductions. No potential explanation is provided as to why the model appeared to underpredict the effect of lane radius for females, however it is possible the use of equal swing times (0.315 s) for male and female, and different stance distances (0.99 m for males and 0.90 m for females). Despite this, Usherwood & Wilson (2006) provide mechanical explanation for inside lane bias that supported the IAAF's decision to eliminate indoor 200m races.

Ryan & Harrison (2003) investigated the effect of bend radius on stride characteristics and performance on banked indoor lanes (r = 10.5m and 13.5m) and flat outdoor lanes (r = 36.5m and 45.04m). They observed significant bend-related performance reductions for all variables, including stride length, stride rate, contact time, and running speed ($p < 0.05$). The authors concluded that athletes struggle to maintain flight distance due to difficulties in generating sufficient impulse, leading to decreased stride length, with reduced stride rates through increased ground contact times. Despite these findings, the effect of banking on step characteristics remains unclear due to comparisons between flat and banked surfaces with different radii. Interestingly, Bezodis & Gittoes (2008) found contrasting results on a banked indoor track, with sprint velocity (SV) for the right-left step being 1.7% higher in lane 1 compared to lane 4, while the left-right step was 0.2% higher in lane 1. However, both studies had limitations, including averaged data across limbs, potential inaccuracies in gait event digitisation (due to sampling at 50 Hz) (Ryan & Harrison, 2003), and small sample size (Bezodis & Gittoes, 2008). Further research is needed to better understand the impact of lateral banking and lane radius during bend sprinting in indoor competition settings.

On very small radii (1-6 m), Chang & Kram (2007) investigated sprinting on flat bends and found that velocity decreased with bend radius. Lower velocity occurred primarily due to trends for decreasing SL. Furthermore, Chang & Kram (2007) report shorter L-R SL and faster SF than R-L across all lanes. The reduced SL for the L-R step was associated with reduced peak resultant ground reaction forces (Chang & Kram, 2007). Churchill et al. (2018) investigated the impact of bend radius on step characteristics in outdoor competition conditions finding that race velocity decreased as bend radius tightened, with significant reductions between lanes 8 and 5 for both L-R and R-L steps ($p < 0.05$). Furthermore, SL was shortest in lane 5, while step frequency showed a general decreasing trend as radius decreased. L-R step ground contact time increased significantly from lane 8 to 2 ($p = 0.004$), while R-L step ground contact time remained consistent across lanes. The study suggests a performance detriment of 0.170 s between lanes 8 and 5. Notably, inter-athlete variability increased in tighter bends, indicating differing abilities to negotiate smaller radii (Churchill et al., 2018). This has baring further for indoor sprint events where the tighter bend radii have a profound effect on performance (Usherwood & Wilson, 2006). Whilst these studies increased understanding of the effect of lane radius on step characteristics on radii representative of outdoor competition a comprehensive assessment is required to determine the effect of lanes radius on step characteristics for the L-R and R-L steps. Furthermore, understanding of the joint kinematics that may explain the step characteristic changes on indoor radii and conditions is an area for future research.

2.5.2 The effect of lane radius on kinematics

The only variables reported in Churchill et al. (2018) are body lateral lean and turning of the centre of mass. Results showed a trend for more inward (more negative) body lateral lean at touchdown as radius decreased for both the L-R and R-L steps. An inward lateral lean has been proposed to reduce space in relation to the CoM contributing to greater touchdown distances (Churchill et al., 2015). Additionally, greater lean may lead to further frontal plane adaptations in the lower extremity, for example greater abduction/adduction and ankle inversion/eversion values as highlighted by Alt et al. (2015). This is one of the reasons for indoor tracks to include lateral banking to minimise the degree of lean required and place less stress on the ankles (Greene, 1987).

Whilst describing the effect of lane radius on a banked track: Ryan & Harrison (2003) report greater knee flexion during the ground contact periods in the indoor lane 1 lane compared with outdoor lane 8, with a greater trend in the L-R knee compared with the R-L. However, Ryan & Harrison (2003) found no significant main effects for bend radius for knee, thigh or ankle joint amplitudes. Whilst only sagittal joint angles are presented perhaps the lateral banking minimises the effects of the tighter lane radii. Nonetheless, research yet to comprehensively describe lower extremity joint kinematics across the stance on conditions representative of indoor competition.

2.5.3 Banked Tracks

Unlike outdoor athletics tracks where dimensions must conform to international standards, indoor athletics tracks come in a variety of sizes with varied: length, bend radii, and banking of the bend (Beukeboom et al., 2000). The only consistent characteristic applicable to all indoor (and outdoor) tracks is the direction of running, which is counter clockwise. One feature that indoor athletics tracks often incorporate is, banked bends. Banking has been proposed to compensate for body lean, while it has also been suggested that banked bends place less stress on the ankles compared to running on a flat turn with no bank at the same speed (Greene, 1987). In addition, the angle of a banked bend can also affect peak running speed on the bend by10% (Greene, 1987). These factors combined not only improve performance but may also reduce the risk of lower limb injuries. More specifically, it is thought that a banked bend puts less torque on the ankles and that it is easier to reach maximum speed without increased risk of injury (Luo & Stefanyshyn, 2012a). Nonetheless, this is yet to be confirmed on radii and degree of banking typical of indoor competition within the biomechanics research.

Luo & Stefanyshyn, (2012a) investigated ankle plantarflexion moment generation during maximum bend sprinting (radius = 2.5 m) with and without experimental intervention of medial-/laterally wedged footwear. The aim of this being to assess the effect of aligning the ankle joint closer to its neutral position to see whether this resulted in increased planter flexion moment generation and bend sprinting speed. 17 male sportsmen (accustomed to sprinting in respective sports) completed counter-clockwise maximum effort sprints along a 2.5 m radius in a control and a wedged shoe. Bend sprinting speed increased by 4.3% ($p = 0.0001$) from the control to the wedged footwear condition. The wedged footwear intervention reduced the inside leg ankle eversion by 4.21° ($p < 0.0001$), with an 18.8% increase ($p < 0.0001$) in the peak ankle plantarflexion moment generation and greater centripetal GRF over stance observed. Nonetheless, the applicability of the findings from Luo & Stefanyshyn, (2012a) are reduced due to the small radii of 2.5 m not comparable to the radii typically seen in athletics competition.

Wannop et al. (2013) identified that many aspects of cutting movements and changes in direction can limit performance when performed on flat ground. As highlighted, peak resultant force on the bend has been shown to be similar to that on the straight (Chang & Kram, 2007) however, the direction of the resultant force changes due to centripetal force generation. This in turn reduces the vertical component and increases the horizontal component (Chang & Kram, 2007). Therefore, a smaller vertical force vector may require a greater GCT to maintain impulses, with this leading to a reduced SF. Because of the associated performance limitations Wannop et al. (2013) investigated the effect of lateral banking on the kinematics and kinetics during lateral cutting movements. They found ankle inversion to be significantly reduced during v-cut and side shuffle tasks, on a 10° bank ($p = 0.014$ and $p < 0.01$, respectively). In addition to this, the frontal plane angular impulse was significantly reduced on the 10° bank compared to the 0° for the v-cut by 19% for the v-cut and 33% for the side shuffle manoeuvre ($p = 0.038$, $p < 0.001$). The horizontal component of the ground reaction impulse was significantly increased in the 10° banked condition ($p < 0.05$) for the v-cut and side shuffle. Increases in horizontal impulse came with a reduction of vertical ground reaction impulse, reorienting the ground reaction vector to a much more advantageous position (Wannop et al., 2013). Although these movements were not directly similar to curvilinear running, the results show potential for decreased injury risk, by reducing inversion and frontal plane forces. The bank of indoor tracks is recommended to be between 10.00-15.00 ° for a radius of 15-19 m with 17.2 m referred to as the optimum (International Association of Athletics Federations, 2008). Therefore, a 10 degree bank potentially enables greater force production in the sagittal plane, with greater force production being associated with greater acceleration and producing a large vertical force during the maximal speed phase are essential for achieving greater acceleration and maintaining higher maximal speed, respectively sprint velocity (Nagahara et al., 2019; Weyand et al., 2000), it is therefore reasonable to predict that increased sagittal plane force generation will increase horizontal velocity.

2.6 Methods considerations

The validity of data collection assesses whether a test or apparatus measures its intended target. External validity determines if findings apply to the broader environment, while internal validity focuses on the accuracy and potential bias or error in the results. Both aspects are crucial for ensuring the overall validity of data collection methods and findings.

2.6.1 Kinematic Data collection

Whilst collecting data in competition is desirable to understand the determinants of an athlete's highest level of performance, this is often not achievable due to difficulty capturing uninterrupted video of athletes. Studies have investigated kinematics of linear sprinting using competition data successfully (Čoh et al., 2018; Salo et al., 2011), however this becomes increasingly challenging on the bend due to the three dimensional nature and potential for the view of athletes to be obstructed.

Previous research has utilised high speed cameras to capture bend sprinting kinematics in order to maintain greater ecological validity by the potential to use athletes normal training venues and avoiding the necessity of applying markers (Churchill et al., 2015, 2018). Nevertheless, as highlighted using these methods did not enable the calculation of 3D vector angles at the knee and the hip as a result of not having three anatomical locations on each segment of the lower limb. Therefore, where the 3D movement of these joints is of interest, data collection methods that enable this are a beneficial alternative to high-speed video.

The use of optoelectronic cameras has been established as the gold-standard motion capture system. These systems can be used outside the laboratory to permit data collection within the performance environment whilst allowing accurate collection of large samples of data with large sampling frequencies and reduced processing times, furthermore the removal of human digitisation further increases the reliability of these systems (Milner, 2008; Robertson & Caldwell, 2014). Nevertheless, one potential limitation is the application of the reflective markers, and the marker set utilised.

Whilst commonly used and validated marker sets have been introduced, for example the plug-in gait model, these were lacking in validation for use during bend sprinting, where variables such as midfoot eversion are of interest. Furthermore, it has been suggested that similar to linear sprinting, that the upper body does not influence bend sprinting performance (Churchill, 2012). Therefore, marker sets that require several upper body markers to calculate the centre of mass may introduce additional interference for the athlete as well as increase the time required for application. Judson et al. (2017) assessed the accuracy of simplification of a kinematic marker for the calculation of CoM during bend sprinting. The lower-limb and trunk model was deemed to provide good agreement with whole-body CoM, with a mean difference for mean SV of 0.0207 ± 0.0643 m/s for the R-L step and 0.0037 ± 0.0808 m/s for the L-R step. Therefore, a lower-limb and trunk marker set was suggested as a suitable substitute for use during bend sprinting. This study was followed up with an assessment of the marker sets reliability, finding that within-day reliability was greater than between-day reliability, suggesting that, where possible, data collection for a single athlete should take place on the same day (Judson et al., 2020b). However, results should be interpreted in line with the reported minimum detectable differences (MDD)'s in mind (ICC 3, 1: 0.228–0.999; MDD = 1–11°). Therefore, the lower-limb and trunk marker set enables the reliable calculation of joint angles and rotations relevant to bend sprinting.

2.6.2 Kinetic Data collection

Whilst the accuracy of the gold-standard force plates is regarded as sufficient, there are still several considerations for the accurate use of force plates to collect kinetic data. Firstly, the dimensions of a force plate are generally much shorter than the average step length at maximal velocity which could lead to missed or incomplete foot contacts with the force plate and result in rejected trials (Johnson & Buckley, 2001). Incomplete foot contacts with the plate could interfere with the number of trials needed to collect sufficient data and therefore fatigue could start to influence the data if trials are repeated. Even if ground contact occurred within the boundaries of the forces plate, errors in the calculation of the centre of pressure (CoP), which is a variable needed for the calculation of joint kinetics and or investigating the MTP push off axis, increases as contacts occur away from the centre of the force plate (Bobbert & Schamhardt, 1990).

Exell et al. (2012a) demonstrated superior trial success rates by using two force plates mounted end-to-end, increasing from 35% with a single plate to 87% with the dual-plate setup. Their analysis revealed that centre of pressure (CoP) calculation errors for foot contacts spanning both plates were minimal, at 0.003 ± 0.002 m compared to a control. The authors concluded that these errors were acceptably small. Whilst two-force plates can improve success rate, to overcome the effect of force plate targeting, previous studies placed a check mark where the sprinter begins their sprint (Mann, 1981; Bezodis et al., 2008). The occurrence of successful trials can therefore be increased by using two force plates in sequence and altering participants start distance from the force plates depending on the step required for investigation. This has greater bearing in the acceleration phase rather than maximal velocity phase and thus is a viable option for use when capturing maximal velocity steps.

When the researcher is interested in multiple steps from the same trial, for example in order to calculate step length for L-R and R-L steps a minimum of three foot contacts is required. Therefore, obtaining force plate data for each step becomes increasingly difficult, this has further bearing during bend sprinting, where the path of the athlete is curvilinear whereas force plates are commonly positioned along a linear path. Thus, it is often possible to gather up to two-foot contact events using force plates but challenging to capture beyond this point during bend sprinting.

Alternative methods of kinetic data collection include use of pressure mats and or pressure insoles. Nevertheless, since measure of the 3D force vector is not possible with pressure insoles or pressure mats these may not be suitable during bend sprinting where mediolateral/inward forces are of interest due to the larger magnitudes compared to linear sprints, as well as the comparison inward force during L-R and R-L steps (Churchill et al., 2016; Diaz et al., 2024; Judson et al., 2019; Smith et al., 2006).

Finally, recent publications have attempted to validate prediction models of forces during walking and running from marker based and or IMU kinematic data (Brownjohn et al., 2018; Callaghan et al., 2020; Carter et al., 2024; Hughes et al., 2019). However, these studies are typically focused on linear tasks and research highlights that accuracy of joint angle determination is reduced with increased gait velocity and task complexity (Mundt et al., 2017). Therefore, alternative methods for estimation of kinetic data may not be appropriate for the maximal velocity three-dimensional nature of bend sprinting analyses.

2.6.3 Rotation of forces

As a result of the continual change of direction with each step, the alignment of ground reaction forces is important to ensure the force plate axes match that of the progression of the athlete. One such method of this presented by Glaister et al. (2007) involved: aligning the horizontal forces in the force plate coordinate system (GCS) were with the direction of travel of the athlete. This is important since, Glaister et al. (2008) found that propulsive forces were large during a 90° walking turn, when GRFs were rotated to the direction of travel of the participant. Whilst the magnitudes of unrotated forces during bend sprinting are unknown, where rotation from the GCS has not been undertaken these results should be interpreted with caution. Furthermore, future bend sprinting research aligned the force plate coordinate system with the progression of the athlete when measuring ground reaction force variables (Churchill et al., 2016; Judson et al., 2020a).

2.6.4 Filtering

When collecting kinematic and kinetic data, it's crucial to address noise introduced from various sources such as electrical signals, light interference, and soft tissue movement. Noise effects are amplified with each differentiation, particularly when deriving velocity from displacement data (Wood, 1982). To draw meaningful conclusions, minimising noise in raw data is essential.

Several noise reduction methods exist, including polynomial approximations, spline functions, and digital filters. The Butterworth digital filter is commonly used in biomechanics, with low-pass, high-pass, and band-pass variants that selectively allow data of specific frequencies to pass while removing others. Given the low-frequency nature of human movement, a fourth-order low-pass Butterworth filter is frequently employed (Yu et al., 1999).

Determining the optimal cut-off frequency has been extensively researched. Winter's, (2009) residual analysis, involves visual inspection of a residual-frequency graph, is widely accepted but labour-intensive and subjective. The autocorrelation function proposed by Challis (1999) is another method for selecting cut off frequencies which calculates an autocorrelation function of the raw signal and identifies the first minimum in the autocorrelation function. The frequency corresponding to this minimum is used as the cut off frequency for filtering. The rationale is that true signal components will show stronger correlations over time compared to random noise. The first minimum in the autocorrelation function represents the point where the correlations transition from being dominated by the true signal to being dominated by noise. This data-driven method allows the cut off frequency to be tailored to the specific characteristics of each signal, rather than using a fixed cut off across all data, enabling an objective determination of the most appropriate cut-off frequency (Challis, 1999). This approach can be automated through computer scripts, allowing for efficient processing of multiple datasets while providing a more objective alternative to cut-off frequency selection.

2.6.5 Gait events

As highlighted in Section 2.5, when the researcher is interested in multiple steps from the same trial, obtaining force plate data for each step becomes increasingly difficult. The difficulty of collecting multiple steps has further bearing during bend sprinting, where the path of the athlete is curvilinear whereas force plates are commonly positioned along a linear path. Thus, it is often possible to gather up to two foot contact events using force plates but challenging to capture beyond this point during bend sprinting. To calculate SV, SL and SF for consecutive steps, a minimum of three-foot contact events is required. Additionally, indoor competition occurs primarily on banked bends, where it is not usually possible to embed force plates. Thus, where force data may not be available, kinematic methods to detect foot contact events are required. Therefore, alternative methods for accurately detecting TD and TO events using kinematic data are necessary.

Whilst research has validated a kinematic-based event detection method during linear accelerated sprinting (Nagahara & Zushi, 2013), this method lacks the ability to calculate multiple foot contact events due to being developed using a selection of 10 frames before touchdown and 10 frames after toe-off gathered from the force plate. Therefore, it is limited by the requirement of force data to generate this window. Furthermore, the growing body of bend sprinting literature highlights several kinematic differences, not only between accelerative and maximum velocity sprinting, but between linear and bend sprinting. These alterations include greater L-R leg adduction and eversion and greater R-L leg abduction, with authors proposing the L-R limb adopts an eversion/adduction strategy whilst the R-L adopts several adaptations in the transverse plane, suggesting a rotation strategy (Alt et al., 2015). Therefore, validated methods during linear sprinting may not be appropriate for use during bend sprinting.

Thus far, bend sprinting research has used several methods to calculate gait events using kinematic data, however none of these have been validated for use during bend sprinting. For example, in Alt et al's. (2015) study of lower extremity kinematics during bend sprinting, the events of touchdown and TO were identified using the foot contact algorithm (FCA) recommended by Maiwald et al. (2009). Nonetheless, this algorithm was produced using steady-state treadmill running at 3.5 m/s, not representative of the velocities or conditions experienced by bend sprinters. Furthermore, this method lacks the ability to calculate multiple foot contact events due to being developed from only a single gait cycle. More recently, Judson et al. (2020a) utilised methods described by Bezodis et al. (2007) where: the mean plus two standard deviations of the fifth metatarsal head vertical coordinates in the static trial were used as a threshold to detect touchdown and TO. Whilst this method could calculate multiple gait cycle events, it is lacking in validation during bend sprinting in the maximal velocity phase. Previous research using video capture rather than optoelectronic motion capture determined touchdown and toe-off by visual inspection of the video from the front view camera (Churchill et al., 2015). Thus, there appears to be no validated method for detecting multiple gait cycle touchdown events using kinematic data during maximal velocity bend sprinting.

2.7 Summary

The relevant literature relating to the biomechanics of bend sprinting was discussed in Sections 2.2-2.5. Furthermore, methods used to collect, process and analyse biomechanical data in the context of bend sprinting were discussed in Section 2.6. Several studies have highlighted changes in technique when comparing bend sprints to linear sprints, that may explain some of the reduced levels of performance on the bend, however research is yet to comprehensively explain the kinetics and kinematics of successful bend sprinting technique. Additionally, research has highlighted several inter-limb differences in kinetics and kinematics when bend sprinting, yet is still to explore whether the magnitude of inter-limb differences and or asymmetry has bearing on bend sprinting performance. Furthermore, minimal research has investigated bend sprinting on radii representative of indoor competition, with no empirical studies comparing flat and banked bends of equal radii. The tight bend radii observed during indoor competition has the potential effect performance however the technique changes are not well understood. Additionally, tighter bend radii may increase risks of injury through greater requirement of centripetal and inward force, yet research is yet to describe the joint kinematics of indoor bend sprinting. Finally, the existing investigations into bend sprinting have utilised different marker-based gait event detection methods, there is currently no validated method for accurate use during bend sprinting, where the kinematics are considerably different to that of the straight path and may reduce the accuracy of these methods.

Chapter 3: Development and recommendation of kinematic event detection methods for use during bend sprinting

3.1 Introduction

The key performance descriptors during sprinting require accurate detection of touchdown (TD) and toe-off (TO) events. For example, the primary performance determinants of SV, SF and SL require knowledge of the time of subsequent foot TD and TO events. The gold-standard method for detecting these events involves the use of force plates and utilising a threshold of vertical force to detect TD and TO events. Previous bend sprinting research has used the mean plus two standard deviations of the vertical ground reaction force (with zero load on the force plate) as a threshold (Churchill et al., 2016; Judson et al., 2019), as suggested by Bezodis et al. (2007). When the researcher is interested in multiple steps from the same trial, obtaining force plate data for each step becomes increasingly difficult. Furthermore, during bend sprinting, where the path of the athlete is curvilinear whereas force plates are commonly positioned along a linear path. Thus, it is often possible to gather up to two consecutive foot contact events using multiple force plates but challenging to capture beyond this point during bend sprinting. In order to calculate SV, SL and SF for consecutive steps, a minimum of three consecutive foot contact events is required. Additionally, indoor competition occurs primarily on banked bends, where it is not usually possible to embed force plates. Thus, where force data may not be available, kinematic methods to detect foot contact events are required. Therefore, alternative methods for accurately detecting TD and TO events using kinematic data are necessary.

Whilst research has validated a kinematic-based event detection method during linear accelerated sprinting (Nagahara & Zushi, 2013), this method lacks the ability to calculate multiple foot contact events due to being developed using a selection of 10 frames before TD and 10 frames after TO gathered from the force plate. Therefore, it is limited by the requirement of force data to generate this window. Furthermore, the growing body of bend sprinting literature highlights several kinematic differences, not only between accelerative and maximum velocity sprinting, but between linear and bend sprinting. For example, to generate the centripetal forces required to follow the path of the bend, large body lateral lean angles are observed when bend sprinting, leading to further alterations along the kinematic chain (Churchill et al., 2015). These alterations include greater L-R leg adduction and eversion and greater R-L leg abduction, with authors proposing the L-R limb adopts an eversion/adduction strategy (Alt et al., 2015). For the R-L step, several adaptations in the transverse plan occurred on the bend, suggesting a rotation strategy (Alt et al., 2015). Therefore, validated methods during linear sprinting may not be appropriate for use during bend sprinting.

Thus far, bend sprinting research has used several methods to calculate gait events using kinematic data, however none of these have been validated for use during bend sprinting. For example, in Alt et al's. (2015) study of lower extremity kinematics during bend sprinting, the events of TD and TO were identified using the foot contact algorithm (FCA) recommended by Maiwald et al. (2009). Nonetheless, this algorithm was produced using steady-state treadmill running at 3.5 m/s, not representative of the velocities or conditions experienced by bend sprinters. Furthermore, this method lacks the ability to calculate multiple foot contact events due to being developed from only a single gait cycle. Judson et al. (2020a) applied Bezodis et al.'s (2007) method to detect touchdown and toe-off events during sprinting. This approach uses the vertical coordinates of the fifth metatarsal head in a static trial, setting a threshold at two standard deviations above the mean. While this method can identify multiple gait cycle events, it has not been validated for maximal velocity bend sprinting. Previous research using video capture rather than optoelectronic motion capture determined TD and TO by visual inspection of the video from the front view camera (Churchill et al., 2015). Thus, there appears to be no validated method for automating the detection of multiple gait cycle TD and TO events using kinematic data during maximal velocity bend sprinting.

3.1.1 Aim & Research Questions

The aim of this Chapter was to determine the accuracy of different kinematic event detection methods to validate for use during maximal effort bend sprinting. The answering of Research Questions 3.1 and 3.2 will achieve the aim of the Chapter. The purpose of this Chapter was to validate kinematic event detection methods for use during bend sprinting that enable calculation of variables for multiple L-R and R-L steps to inform future research and increase understanding of the joint kinematic adaptations to bend sprinting on different conditions and their relationship to bend sprinting performance.

RQ3.1: How do different kinematic event detection methods compare in accuracy for detecting TD of the L-R and R-L steps?

RQ3.2: How do different kinematic event detection methods compare in accuracy for detecting TO of the L-R and R-L steps?

3.2 Methods:

3.2.1 Participants

Following institutional ethical approval (SHFEC 2021 – 096), eight competitive sprinters (one female and seven males) were recruited using convenience sampling for the study. All athletes specialised in the longer sprint events (200-400 m) and were, therefore, experienced at bend sprinting. Participants provided written informed consent prior to data collection. At the time of testing, participants were injury-free, including any injury preventing normal training and competitions in the previous 6 months**,** and completed maximal effort bend sprints on a weekly basis as part of their routine training. To standardise with previous research, a maximum 200 m personal best time of 23.5 s for males was set whilst 27.44 s was set for female participants. A 200 m PB of 27.44 s was chosen as it gave the equivalent IAAF points (731), thus representing equal abilities across genders (Spiriev, 2017).

Table 3-1. Mean ± Standard deviation Participant Characteristics for age, height, mass and 200 m personal best race time (PB).

Variable	Male n = 7	Female n = 1
Age (years)	22 ± 5	24
Height (cm)	178.28 ± 4.45	162.00
Mass (kg)	74.07 ± 4.62	62
200 m PB (s)	22.63 ± 0.82	24.89

3.2.2 Experimental setup

Data collection took place on the infield of an indoor track (Mondo, Warwickshire, UK) at the National Indoor Athletic Centre in Cardiff. A 60 m lane representing lane one of a standard 400 m athletics track (36.5 m radius) was measured out. At the 40 m mark, twelve optoelectronic cameras (Vantage V8, Vicon, Oxford Metrics, UK, 250 Hz) were mounted onto tripods creating a capture volume that enabled a minimum of one full stride (two complete steps) to be captured. Four force plates (Kistler 9281CA, Kistler Instruments AG, Switzerland) were placed within the testing area and sampled at 2000 Hz to collect two consecutive ground contacts (Figure 3.1). The reliability of an adapted Plug in Gait lower limb and trunk marker set with multi-segment foot has been established for bend sprinting (Judson et al., 2017). Therefore, this marker set was utilised with the addition of technical marker clusters (thigh and shank).

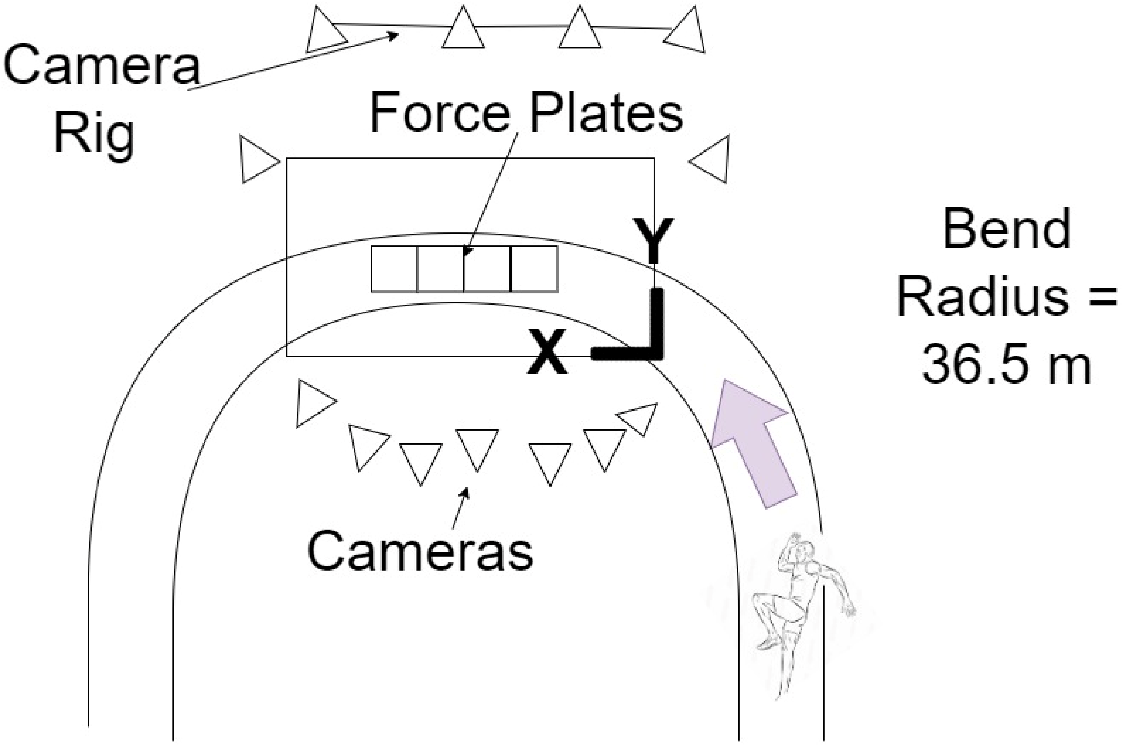


Figure 3.1. Experimental set up (not to scale). The box represents the capture volume at the apex of the curve created by the cameras at approximately the 40-50 m point whilst the four force plates are placed linearly along the direction of travel (X axis).

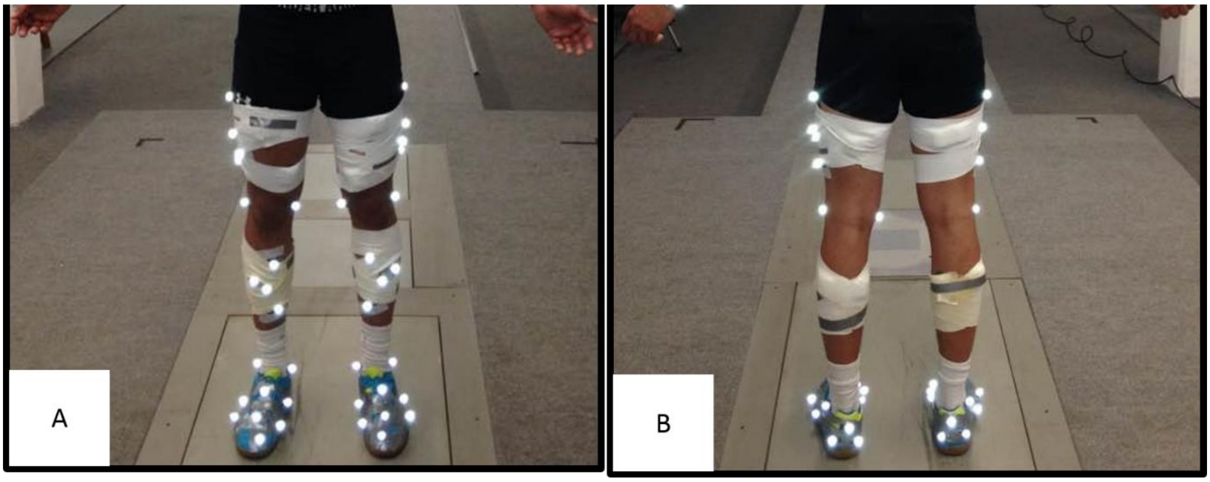


Figure 3.2. The custom marker set utilised for data collection. (A) anterior view, (B) posterior view.

3.2.3 Experimental Procedures

Before sprint data collection, height (Leicester Height Measure 220, Seca Ltd, UK), and mass (Seca 799, Seca Ltd, UK) were collected. Participants undertook nine 60 m counter-clockwise bend sprints around a 36.5 m radius. Sprints were undertaken at participants perceived maximum velocity. Recovery time was self-selected, but typically lasted five to ten minutes, similar to previous sprint research (Exell et al., 2017).

3.2.4 Data Processing

Kinematic marker trajectories were labelled using Vicon Nexus (v2.9.3) and gap filled when necessary, using both rigid body (for gaps in marker cluster trajectories) and pattern functions. Additionally, when no suitable trajectory was appropriate for pattern gap filling, the spline function was used. Spline interpolation has been shown to be suitable for short durations of less than 0.2 s (Howarth & Callaghan, 2010). Nonetheless, the spline function was only utilised for gaps < 10 frames (0.04 s), in line with previous bend sprinting research (Judson et al., 2018).

Ground reaction force data from the four force plates and marker trajectories for the toe and first and fifth metatarsal heads were exported to MATLAB (Mathworks, USA, 2021b). Force and marker data were filtered using a low-pass Butterworth filter, with cut-off frequencies for each trial determined using the autocorrelation method (Challis, 1999). TD and take-off events were identified using the mean plus two standard deviations of the last three seconds of vertical ground reaction force data (where there was zero load on the force plate) as a threshold (Bezodis et al., 2007). To eliminate occurrences of events due to noise and incomplete stance phases (TD or TO occurring before or after contact with the force plate), a further control was added where the vertical force must exceed the threshold for a minimum of 0.06 s (15 * 1/250) to be used as an event. This ensured that only trials where the force plate captured the entire stance phase were selected for use.

Four kinematic detection methods were selected based on use in recent sprinting research and will be described in full in the following paragraphs and highlighted in Figure 3.3. For all methods, the toe marker and the first and fifth metatarsal heads were used to calculate gait events.

Threshold method

The first method originally described by Bezodis et al. (2007) and utilised by Judson et al. (2020a), involved calculating the mean vertical position of the fifth metatarsal head marker during the static trial and adding two standard deviations. This value (mean static vertical position + 2* standard deviation vertical position) was calculated and used as a threshold for ground contact for each participant. This method is termed the threshold method. Using the threshold method, TD was considered as the first data point where the vertical coordinate of the marker dropped below the defined threshold and vice-versa for TO.

Peak Acceleration method

The second method is described by Nagahara & Zushi (2013) and identified TD using the peak vertical acceleration of the toe marker, hereafter termed the Nagahara Peak Acceleration method. The Nagahara Peak Acceleration method determined TO as one frame before the subsequent peak vertical toe acceleration (after TD). As highlighted in the introduction, one of the limitations of the Nagahara Peak Acceleration method was that the data were cropped to 10 frames before the TD event based off the force plate data, therefore additional controls were added and are discussed in Section 3.2.5.

Nagahara Position method

Within the same validation study as the peak acceleration method: Nagahara & Zushi (2013) found similar accuracy to the peak acceleration method was to detect TO using the first frame after the minimum vertical toe position. The difference between the two methods was 0.13 frames (0.00052 s), thus both methods were included in the present study and hereafter termed part of the Nagahara Peak acceleration method and the Nagahara position method.

Foot Contact Algorithm

Finally, the foot contact algorithm (FCA) used by Alt et al. (2015) but originally proposed by Maiwald et al. (2009). The FCA uses a characteristic maximum in the vertical acceleration curve of the target marker (the toe or the heel) to determine TD. The search for maximum vertical acceleration is within a given window around the minimum vertical position. For TO, the timing of a local maximum in the vertical acceleration of the target marker is detected and compared to the timing of the minimal vertical position of the target marker. A logical operation selects the event that occurs earlier in time, which is then used to estimate take off.

3.2.5 Additional controls added to the existing methods

To improve the functionality of the event detection methods and enable multiple gait events to be calculated, several controls were added to each method. For the threshold method: the TD or TO event had to be greater than 80 frames between consecutive events. The kinematic data was collected at 250 Hz, thus 80 frames is equal to 0.32 s. The value of 0.32 s represents the time for two complete steps (for example L-R TD to L-R TD) that would give a SF of 6.25 Hz, above that expected by world-class sprint athletes (4-5 Hz) (Čoh et al., 2018). Thus, this additional control ensures that incorrect TD and TO events are not picked up by this method.

For the Nagahara Peak Acceleration method and FCA methods, to remove peak accelerations that occur during the swing phase, a vertical position threshold of the target marker 0.10 m above the ground (determined by the global-coordinate system set on the force plates at 0,0,0) was added to remove additional peak accelerations that were observed. Furthermore, for the peak acceleration method: a minimum peak acceleration of 0.015 m/s/s was set in order to minimise likelihood of picking up small changes in acceleration. This threshold was determined by assessing the range of peak accelerations across the data set. Nonetheless, if less than four peak accelerations are detected above this threshold, the four highest peaks were used (representing two TDs and two-TOs), this can be modified to detect more foot contact events. A further control was added whereby if two peaks were separated by a single frame, the vertical position of the toe was checked and the greater of the two were selected. This was chosen since after visual inspection of data; the higher vertical position relates to TD or TO of the foot. Following this, the frames between subsequent events was calculated, if the frame difference was less than 50 frames (50 * 1/250 = 0.20 s), this would suggest that the first event was the TD and second was the TO. Therefore, the first event to occur was recorded as TD and the second as TO, otherwise the first event was recorded as TO, and the TD was discarded (these typically occurred where a ground contact occurred very close to the capture area and only the TO was picked up by the event detection methods).

For the FCA, the original algorithm sets a window based on the minimum vertical position, this is accomplished by constraining the search for peaks to a suitable time window for ground contact times observed during running at 3.5 m/s (-100 ms: + 400 ms). This was edited to 50 ms and 100 ms to reflect the faster running velocities observed during bend sprinting (7-11 m/s). Further, an additional control was added to factor in if an initial TD has been missed by calculating if the TD and TO events did not occur within 40 frames (0.16 s) that the TD event was in fact the TO event, this was confirmed by visually inspecting calculated trials.

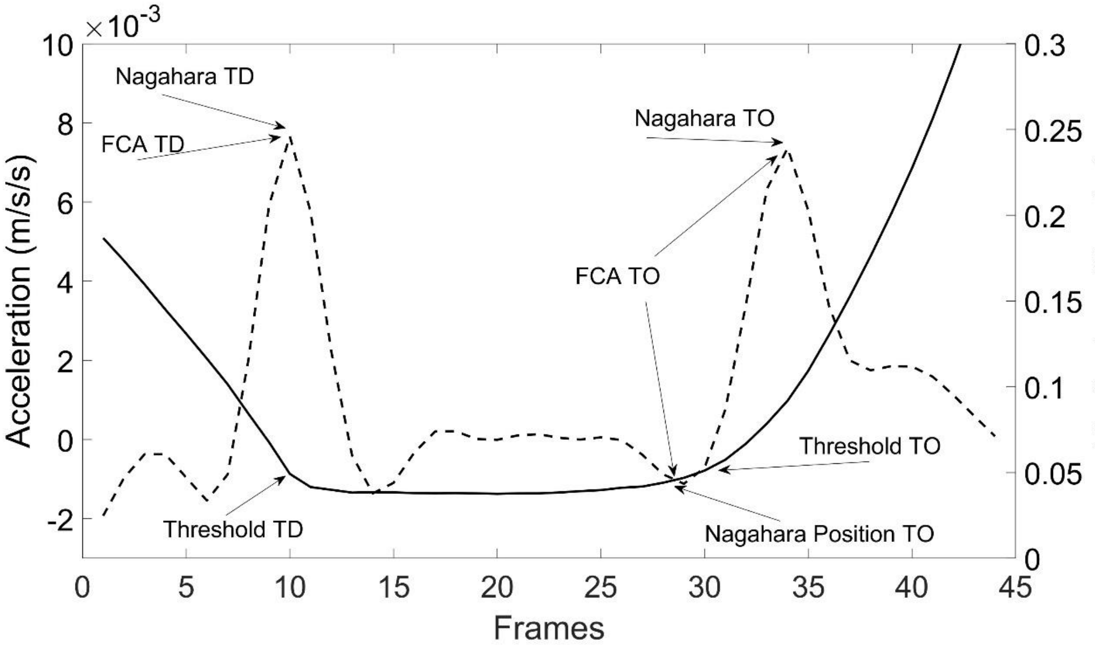


Figure 3.3. Example of event detection methods with peak vertical acceleration of toe marker (dashed line) and with vertical position of the MT5H marker (solid line).

Finally, the kinematic calculation methods would calculate all TD and TO events (including any made on the force plates), whereas the force plate would only have TD and TO events when contact was made with the plates. Therefore, a further MATLAB script was applied to find the trial number (a second row with trial number) and match this with the force plate and subtract each of the kinematic events from the force plate event, the minimum difference was then taken as the matching foot contact and this trial was utilised for further analyses. This was repeated for all methods and all subjects for all force plate events and the kinematic calculated equivalents providing 51 L-R and 44 right foot TD and TOs. Further TO events had to be removed due to participants partially contacting the force plate, thus, the TO calculated by the force-plate did not represent the actual TO of the foot at the end of ground contact, instead representing when the foot was no longer in contact with the force plate.

3.2.6 Statistical Analysis

In line with previous validation research: tests for significant differences between methods were not ran, as this requires the classification of a ‘general’ level of acceptable error (Maiwald et al., 2009). Furthermore, inferential statistics may not distinguish between methods. Therefore, to determine the accuracy of the adapted methods, several descriptive data have been provided. Firstly, Limits of Agreement (LoA) were used to calculate the systematic and random bias between the force plate and kinematic gait events, as per (Altman & Bland, 1983). Previous research has reported errors of 1-10 ms (Bezodis et al., 2007; Maiwald et al., 2009; Nagahara & Zushi, 2013), with the chosen methods achieving less than 5 ms of error. Thus, further accuracy criteria included a mean absolute error of within ± 5 ms (1.25 frames) for detecting TD and TO.

The mean absolute error was calculated to highlight the accuracy of methods in the context of key bend sprinting variables. Firstly, ground contact time was calculated as the time between TD and TO, ankle eversion at TD was defined using the distal segment relative to the proximal segment (foot relative to the shank) and eversion was defined as motion about the Y axis. Finally, touchdown distance (TD_D) was defined in line with Churchill et al. (2015) as the horizontal displacement between centre of mass and the MTP at TD relative to the direction of travel of the centre of mass at TD.

3.3 Results

3.3.1 Accuracy of touchdown detection

The additional controls enabled all methods to detect multiple gait cycles. LoA and mean absolute error for L-R TD can be seen in Table 3-2. For TD for the L-R step, the Nagahara Peak Acceleration and FCA methods (TOE and MT1H markers) performed similarly for detecting TD with mean errors < ±1.25 frame compared to the force plate method, as a result the Nagahara Peak Acceleration and FCA methods calculated key variables at TD almost identically, with the MT1H marker the most accurate (Table 36).

Table 3-2. Limits of Agreements (LoA) and Mean Absolute error (in frames) for all kinematic event detection methods compared to that of the force plate for the L-R touchdown.

Variable	LoA	Lower LoA	Upper LoA	Mean Error
Touchdown				
Nagahara Peak Acceleration LTOE	2.1	-1.7	2.5	0.42
Nagahara Peak Acceleration LMT1H	2.2	-1.8	2.5	0.36
Nagahara Peak Acceleration LMT5H	2.0	-0.7	3.2	1.30
Threshold LTOE	2.2	-1.0	3.4	1.20
Threshold LMT1H	3.8	-6.0	1.5	-2.24
Threshold LMT5H	2.2	-1	3.4	1.20
FCA LTOE	2.1	-1.7	2.5	0.41
FCA LMT1H	2.1	-1.7	2.6	0.43
FCA LMT5H	2.2	-1.0	3.5	1.30

Note: 1 frame = 4 milliseconds

For TD of the R-L step, all three methods produced at least one marker under the accuracy criteria (Table 3 3). The following detected TD with mean error < ±1.25 frame compared to the force plate method: the Nagahara peak acceleration using the RTOE, the threshold method with RTOE and RMT5H, and the FCA with the RTOE and MT1H markers. Comparison of key variables highlighted similar accuracy with the threshold RTOE produced the lowest values of error for variables calculated at TD (Table 3 7).

Table 3-3. Limits of Agreements (LoA) and Mean Absolute error (in frames) for all kinematic event detection methods compared to that of the force plate for R-L touchdown.

Marker	LoA	Lower LoA	Upper LoA	Mean Error
Touchdown				
Nagahara Peak Acceleration RTOE	1.4	-0.4	2.5	1.1
Nagahara Peak Acceleration RMT1H	1.6	-0.4	-2.9	1.2
Nagahara Peak Acceleration RMT5H	1.2	-0.2	2.7	1.5
Threshold RTOE	1.6	-0.6	2.6	1.0
Threshold RMT1H	4.7	-6.3	3.1	1.6
Threshold RMT5H	1.6	-0.6	2.6	1.0
FCA RTOE	1.4	-0.3	2.4	1.1
FCA RMT1H	1.7	-0.6	2.7	1.1
FCA RMT5H	1.0	0.5	2.5	1.5

3.3.2 Accuracy of toe-off detection

For the L-R TO, the Nagahara peak acceleration achieved the criteria when the TOE and MT1H markers were used (mean error < 0.86 frames) (Table 3-4), with the TOE producing the lowest mean error for GCT (0.0038 s) (Table 3 6). No other methods achieved less than 1.25 frame of error with any marker. High mean error values (mean error > 10 frames) were observed with the Nagahara position method (MT1H and MT5H), FCA (MT1H and MT5H) and Threshold method (MT5H) with this resulting in mean errors of greater than 0.01 s for calculating GCT (Table 3 7).

Table 3-4. Limits of Agreements and Mean Absolute error (in frames) for all kinematic event detection methods compared to that of the force plate for the L-R toe-Off.

Marker	LoA	Lower LoA	Upper LoA	Mean Error
TO				
Nagahara Peak Acceleration LTOE	2.3	-1.5	3.1	0.76
Nagahara Peak Acceleration LMT1H	2.0	-1.1	2.8	0.85
Nagahara Peak Acceleration LMT5H	3.7	-1.6	5.9	2.20
Threshold LTOE	5.6	-1.6	9.6	4.01
Threshold LMT1H	2.8	-0.81	4.8	2.06
Threshold LMT5H	17	-25	8.3	7.13
FCA LTOE	11	-4.9	16	5.62
FCA LMT1H	15	0.31	30	15.24
FCA LMT5H	17	-3.7	30	13.12
Nagahara Position LTOE	9.2	-4.6	14	4.52
Nagahara Position LMT1H	6.9	4.6	19	12.08
Nagahara Position LMT5H	13	0.84	27	14.21

For R-L TO the Nagahara peak acceleration method with the TOE achieved the < 1.25 frame criteria (Table 3 5), producing a mean error for GCT of 0.0035 s (Table 3 7). High degrees of error were observed for methods utilising vertical position, in particular the threshold method for marker MT5H and the FCA and Nagahara position methods (both MT1H and MT5H) (error > 6 frames).

Table 3-5. Limits of Agreements and Mean Absolute error (in frames) for all kinematic event detection methods compared to that of the force plate for R-L toe-off.

Marker	LoA	Lower LoA	Upper LoA	Mean Error
TO				
Nagahara Peak Acceleration RTOE	2.8	-1.8	3.8	1.01
Nagahara Peak Acceleration RMT1H	3.0	-2.6	3.5	0.43
	9.3	-7.4	11	1.94
Nagahara Peak Acceleration RMT5H	2.8	-0.59	5.1	2.22
Threshold RTOE	2.5	0.72	5.7	3.20
Threshold RMT1H	4.3	-2.2	6.4	2.12
Threshold RMT5H	18.1	-25.2	12.0	6.71
FCA RTOE	3.5	-1.3	5.7	2.28
FCA RMT1H	22.2	-5.2	38	17.34
FCA RMT5H	20.6	-4.3	35	15.46
Nagahara Position RTOE	3.8	-2.5	5.0	1.35
Nagahara Position RMT1H	8.5	-2.6	20	11.23
Nagahara Position RMT5H	12.1	-2.4	26.0	14.27

Table 3-6. Mean absolute error of kinematic methods compared to the force plate for key variables L-R step.

Marker	Eversion at Touchdown (°)	Touchdown Distance (m)	GCT (s)
Nagahara Peak Acceleration LTOE	1.45	0.0220	0.0038
Nagahara Peak Acceleration LMT1H	1.25	0.0202	0.0046
Nagahara Peak Acceleration LMT5H	2.40	0.0365	0.0063
Nagahara Position LTOE	N/A	N/A	0.0182
Nagahara Position LMT1H	N/A	N/A	0.0448
Nagahara Position LMT5H	N/A	N/A	0.0505
Threshold LTOE	2.71	0.0337	0.0119
Threshold LMT1H	4.91	0.0695	0.0177
Threshold LMT5H	2.72	0.0338	0.0105
FCA LTOE	1.45	0.0216	0.0189
FCA LMT1H	1.23	0.0192	0.0452
FCA LMT5H	2.41	0.0365	0.0063

Table 3-7. Mean absolute error of kinematic methods compared to the force plate for key variables for the R-L step.

Marker	Eversion at Touchdown (°)	Touchdown Distance (m)	GCT (s)
Nagahara Peak Acceleration RTOE	1.40	0.0250	0.0035
Nagahara Peak Acceleration RMT1H	1.44	0.026	0.0057
Nagahara Peak Acceleration RMT5H	1.74	0.0354	0.0052
Nagahara Position RTOE	N/A	N/A	0.0059
Nagahara Position RMT1H	N/A	N/A	0.0448
Nagahara Position RMT5H	N/A	N/A	0.0545
Threshold RTOE	1.29	0.221	0.0090
Threshold RMT1H	2.94	0.0524	0.0171
Threshold RMT5H	1.80	0.036	0.0095
FCA RTOE	1.48	0.0255	0.0064
FCA RMT1H	1.33	0.0166	0.0275
FCA RMT5H	1.89	0.0359	0.029

3.4 Discussion

The aim of this study was to determine the accuracy of adapted previously utilised kinematic event detection methods to validate for use during maximal bend sprinting.

3.4.1 RQ3.1: How do different kinematic event detection methods compare in accuracy for detecting touchdown of the L-R and R-L steps?

For detecting TD, several markers across methods fell below the criteria of ± 1.25 frame, thus, were deemed acceptable for detecting TD during maximal velocity bend sprinting (Table 3-2 & Table 3-3). However, the lowest mean errors were found in the threshold method using the TOE (R-L step = 1.02 frame), Nagahara peak acceleration toe (R-L step = 1.10 frame) and MT1H (L-R step = 0.36 frame). Previous research has reported mean errors of 1.24 ms for detecting TD using the Peak acceleration method during linear accelerative sprinting (Nagahara & Zushi, 2013), whilst Bezodis et al. (2007) found root mean square errors of 3 ms when using the threshold method. The present study sampled at 250 Hz, with 1.25 frames equating to 5 ms, thus, the most accurate methods achieved mean errors of 1.4 ms for the L-R step and 4.1 ms for the R-L step, showing similar accuracy to previous validated methods during linear sprinting. Furthermore, the other accepted methods within the current study found mean errors of less than 5 ms highlighting similar accuracy across the tested methods during linear accelerative and maximal bend sprinting.

In the context of key variables at TD, L-R step mean eversion was 13.31° whilst TD_D was 0.37 m. Thus, using the Nagahara peak acceleration method with the MT1H had errors expressed as a percentage of the average calculated from the force plate data of 9.37% and 6.03%. Similarly, for the R-L step mean eversion was 13.13° and TD_D was 0.25 m, thus, this equates to errors of 9.81% and 10.40%. Whilst a mean error of equal or less than 4.1 ms is observed, variables calculated using kinematic methods should be considered with a potential error of ~10% in key variables calculated at this timepoint. Furthermore, other methods/markers achieved the accuracy desired and thus are acceptable for use during bend sprinting if, for example marker set, computational demands, or lacking in a static trial dictate use of these methods.

Previous research has suggested that the L-R and R-L steps possess differing roles during bend sprinting. For example, Alt et al. (2015) proposing the L-R limb adopts an eversion/adduction strategy whilst the R-L adopts several adaptations in the transverse plane, suggesting a rotation strategy. This is potentially one of the reasons for the different methods and markers achieving the best level of accuracy for the L-R and R-L steps.

3.4.2 RQ3.2: How do different kinematic event detection methods compare in accuracy for detecting toe-off of the L-R and R-L steps?

For TO the Nagahara peak acceleration method with the toe marker performed the most accurately for both the L-R and R-L steps. For the L-R TO Nagahara peak acceleration TOE had a mean error of (0.76) whilst the MT1H (0.85), for R-L TO Nagahara peak acceleration achieved RTOE (1.00). Whilst the R-L step approached the accuracy threshold of ± 1.25 frame, this is similar to previous research where values of 1.88 - 4 ms have been reported (Bezodis & Gittoes, 2008; Maiwald et al., 2009; Nagahara & Zushi, 2013). Thus, a mean error of 0.76 frames for the L-R step is equal to 3 ms and the R-L step is equal to 4.1 ms, and thus is comparable to previous research.

The methods solely incorporating use of vertical position to determine TO, in particular for the MT5H (Nagahara Position, Threshold and FCA) were found to be less effective for detecting TO (mean error > 6 frames). The mean ± SD for ankle eversion at TD was 13.31 and 13.13° for the L-R and R-L steps respectively. However, eversion appears to increase from TD through to the mid-stance phase (Alt et al., 2015). Thus, it is possible the high error in TO determinants occurs from large ankle and foot eversion during the stance phase on the bend causing the target marker to exceed the vertical position threshold and or reach minimum marker position during early-mid-stance (Figure 3.4). Large eversion angles have been reported during bend sprinting analyses, ~ 12°(Alt et al., 2015); 22° pronation (medial roll of the ankle) (Hamill et al., 1987). Therefore, this method may have picked up frames during the mid-stance and not the TO, often being greater than 6 frames off the force plate TO, thus should not be recommended for use during bend sprinting analyses.

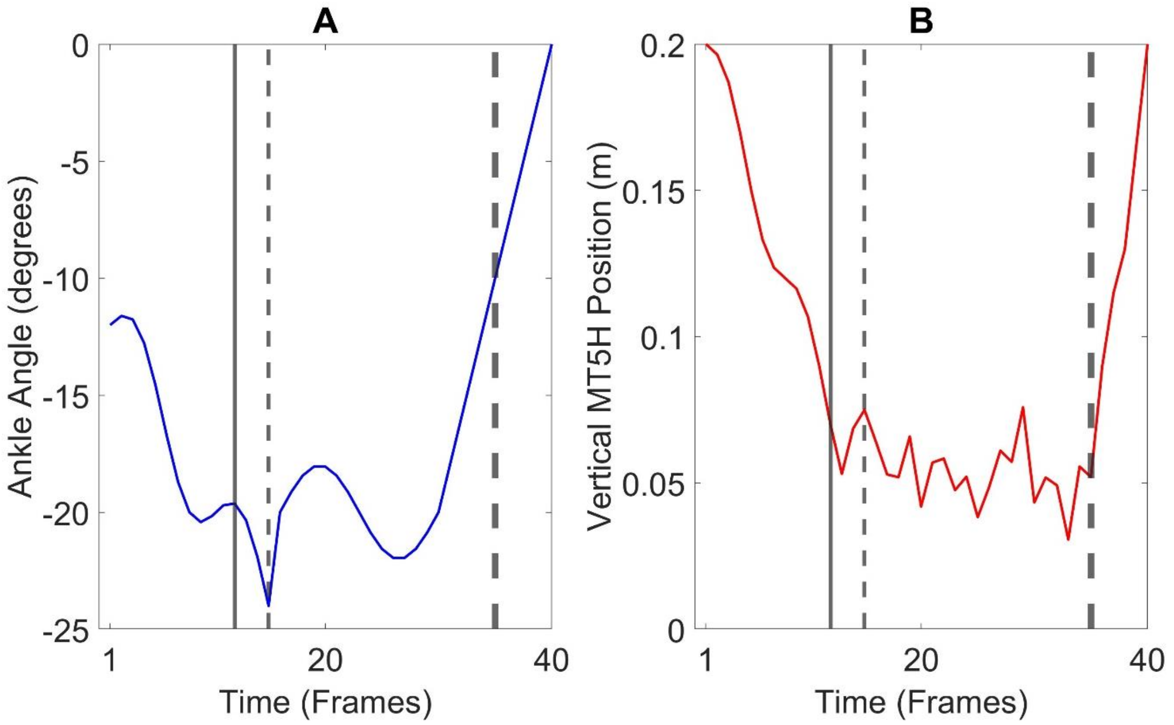


Figure 3.4. A: Example Frontal plane ankle angle during the L-R step (Negative = Eversion; + = Inversion) and B) – Example Vertical position of the left fifth metatarsal head. *Black solid line represents the force plate touchdown, thin grey dashed line represents the toe-off determined by the position method, the thick black dashed line represents the force plate toe-off.

The mean GCT for the present study was 0.118 s (L-R) and 0.1072 s (R-L). Using the accepted methods (L-R TD Nagahara peak acceleration MT1H, L-R TO Peak acceleration method) (R-L TD Threshold method RTOE, R-L TO Nagahara peak acceleration RTOE) gives an error of 3.2% (L-R) and 7.56% (R-L) for this data set of well-trained sprinters. World-class sprinters produce GCTs as short as 0.086 (Čoh et al., 2018), thus the magnitude of error against these marks using the combined mean errors from the accepted methods are 5.22% and 9.42% for L-R and R-L respectively. Therefore, care should be taken when considering TD and TOs using the proposed kinematic event detection methods. It is likely that increased sampling frequencies will improve the accuracy of these kinematic event detection methods, thus bend sprinting studies could look to utilise sampling frequencies greater than 250 Hz. Nonetheless, where force plate data is not available, the accepted methods enable calculation of TD and TO events during maximal bend sprinting.

Despite acceptable accuracy for TD and TO, several additional controls were required to improve the ability of the methods to accurately detect TD and TO events. For example, Nagahara & Zushi, (2013) peak acceleration method selects only ten frames prior to and ten frames after TD and TO based off the force plate data, when no force plate is present this is not possible. Thus, two controls were added: Firstly, that peak accelerations greater than a threshold and that the timing of this coincided with a vertical position of the toe marker was above a vertical position threshold (where 0 represents the track surface). This control ensured no peaks were taken from the swing phase where typically one peak vertical acceleration occurs. Similarly, the FCA utilises a time frame of the minimum toe position to create a sufficiently narrow time interval of: time frame – 50 ms: + 100 ms to detect events. Nonetheless, using the minimum toe position will only result in calculation of one stance phase, further measures such as a searching for minimum toe positions at least 100 frames (0.4 s; SF of 6 Hz) apart may enable additional stance phases to be detected. Finally, whilst the threshold method enabled calculation of multiple stance phases, there is no guarantee that these do not pick up multiple times when the marker drops below the threshold (as highlighted in Figure 3.4), thus the possibility exists that incorrect stance phases are produced. Therefore, a minimum of 80 frames (0.32 s) between ipsilateral foot contacts was added to remove likelihood of this occurring. Furthermore, controls were added to automate the methods ability to detect whether events were TD or TO, for example, early in capture volume where only a TO is picked up by the kinematic events calculations.

3.6 Conclusion:

For TD, differing methods and markers produced the best level of accuracy for the L-R and R-L steps, this is potentially the result of differing roles of the L-R and R-L steps (Alt et al., 2015). For the L-R step the Nagahara peak acceleration method produced the lowest mean absolute error when the MT1H was used. For R-L TD the threshold method with the TOE marker achieved the best accuracy compared to the force plate. For TO detection, the Nagahara peak acceleration method using the TOE marker was the most accurate for the L-R and R-L steps. Further methods were considered acceptable, with mean absolute error values below 1.25frames (5 ms). In summary, this Chapter contributes to the validation and improvement of kinematic-based event detection methods for maximal bend sprinting. These methods, when carefully applied with the proposed additional controls, offer an accurate alternative to force-plate detection methods for use during biomechanical analyses of bend sprinting.

Since future research should investigate indoor athletics radii, the proposed methods enable the detection of gait events where force plates cannot be laid flush with the ground (for example on banked bends). Therefore, for the remainder of the thesis, where kinetic data are not available: the Nagahara peak acceleration method (MT1H) will be used to determine the L-R TDs, the threshold method with the TOE marker for R-L TD. For TO detection, the Nagahara peak acceleration method using the TOE marker was the most accurate for the L-R and R-L steps and thus will be used to determine TO events.

Chapter 4: An investigation into the effect of lane radius and lateral banking on step characteristics in indoor bend sprinting

The work from this Chapter formed the basis of the following peer-reviewed conference abstract

White, J., von Lieres und Wilkau, H., Exell, T., Irwin, G., Wilson, C., Wyatt, H., ... & Hamill, J. (2021). An investigation into the Effect of Lane Radius on Step Characteristics in Indoor Bend Sprinting. Proceedings of the 39th International Conference of Biomechanics in Sports, 39(1), 188.

4.1 Introduction

The review of literature in Chapter 2 highlighted that velocity is reduced when running the bend in comparison to the straight during sprinting (Alt et al., 2015; Churchill et al., 2015). In previous studies, reduced velocities on the bend have been brought about by lower step frequency values for the L-R step on the bend as a result of longer ground contact times (Alt et al., 2015; Churchill et al., 2015). For the R-L step however, reduced performance occurred primarily as the result of shorter SL on the bend in comparison to the straight, with SF remaining similar (Churchill et al., 2015).

SV is further affected when running on tighter radii (Bezodis & Gittoes, 2008; Chang & Kram, 2007; Churchill et al., 2018; Ryan & Harrison, 2003). Churchill et al. (2018) reports increased variability in performance between participants when comparing an innermost lane (lane 2; radii = 37.72 m) and the outermost lane (lane 8; radius = 45.10 m). Greater between participant variability in performance suggests that individual athletes display different capabilities for maintaining high velocities on the innermost lanes on the bend (Churchill et al., 2018). For example, whilst mean SV was reduced, the standard deviation grew in the inner lane ((lane 2: R-L: SD = ±0.63 m/s, L-R: SD = ±0.61 m/s) compared to the outer lane (lane 8: R-L: SD = ± 0.41 m/s, L-R: SD = ±0.43 m/s). Due to the greater turning demands, there may be larger discrepancies in SV when running on tighter bends representative of indoor competition (Usherwood & Wilson, 2006).

The indoor athletics season occurs over the winter months with world and continental championships occurring biennially, with further national championships occurring annually. Indoor tracks can be classed as one of the four categories: flat (200 m), banked (200 m), oversized (> 200 m) or undersized (< 200 m) (Barnes & Malcata, 2017), with radius typically 13 – 21 m for a standard 200 m track. World athletics highlight that indoor tracks should look to be 200 m in length with radius of 15-19 m and 10-15 ° of banking. Therefore, the environmental conditions are considerably different to that of outdoor tracks, with these being 400 m in length with lanes having a radius from 36.5 – 45.1 m, and no lateral banking. Whilst it is commonly accepted that sprinting on tighter bend radii results in lower SVs or performance times (Chang & Kram, 2007; Churchill et al., 2018; Greene, 1985), this has yet to be determined comprehensively for L-R and R-L steps under banked conditions representative of competition. For example, in contrast to previous research, on a banked indoor track Bezodis & Gittoes, (2008) found SV for the R-L step to be 1.7% lower in Lane 4 compared to Lane 1 whilst L-R step was 0.2% higher in lane 1 than in lane 4. Meanwhile under similar conditions, Ryan & Harrison (2003) found running speed to be 8.14 ± 0.83 m/s in lane 1 and 8.44 ± 0.87 m/s in lane 4. Nonetheless, step characteristics data were averaged across L-R and R-L steps (Ryan & Harrison, 2003), and on a limited sample of four athletes (Bezodis & Gittoes, 2008), or on radii not representative of indoor competition (Chang & Kram, 2007; Churchill et al., 2018; Greene, 1985). Thus, since indoor athletics facilities could be flat or banked, further research to understand the effect of lateral banking and lane radius during bend sprinting representative of indoor competition is required.

Chapter 2 emphasised the potential impact that lateral banking has on performance and step characteristics when sprinting on banked bends. Authors have reported both benefits to performance and reduced injury risks as a result of utilising banked bends in comparison to flat bends (Barnes & Malcata, 2017; Greene, 1987; Luo & Stefanyshyn, 2012b). For example, shorter ground contact times (GCT) were observed for the inside step (L-R) that contributed to increase sprinting velocity when on a banked surface around a tight radius (2.5 m) (Luo & Stefanyshyn, 2012b). In theory, lateral banking minimises the amount of lateral lean (inward toward the bend) the athletes are required to undertake in order to follow the path of the bend (Neie, 1981). Body lateral lean refers to the angle between the foot and the centre of mass (CoM) in the frontal plane, with a more negative angle showing greater lean in towards the bend, and is required to create centripetal forces (Churchill et al., 2015). Nonetheless, greater lean angles have been proposed to compromise vertical force generation (Luo & Stefanyshyn, 2012b). Consequently, lateral banking may reduce the amount of lateral lean required, which could align the ankle joint in a more neutral position than on a flat bend of equal radii, with this enabling more effective ground reaction force generation in relation to direction (contributing to greater turning) and magnitude (greater vertical and propulsive force to maintain SV) (Luo & Stefanyshyn, 2012b). Nonetheless, despite international and national competition occurring on banked indoor tracks every year, the effect of lateral banking on step characteristics is yet to be determined during bend sprinting on radii typical of indoor competition.

Furthermore, Chapter 2 highlighted that the demands of bend running have been previously shown to be asymmetrical, resulting in different alterations in step characteristics for the L-R and R-L steps. For example, on outdoor radii, Churchill et al. (2016) found lower L-R SF than R-L SF, as a consequence of longer GCT during the L-R step. Contrastingly, L-R SL were longer than the R-L SL, resulting in similar SVs (L-R = 9.34 ± 0.43 m/s; R-L = 9.29 ± 0.47 m/s). When comparing the less tight and more tight radii of an outdoor track, Churchill et al. (2018) found significantly greater L-R SV in lanes 8 and 5, but L-R and R-L steps were similar in lane 2. Interestingly, L-R GCT was significantly longer than R-L GCT across all lanes. On very small radii (1-6 m), Chang & Kram (2007) investigated sprinting on flat bends (radius < 6.0 m) and found that velocity decreased with bend radius. Reduced velocity occurred due to trends for decreasing SL, with shorter L-R SL than R-L SL across all lanes (Chang & Kram, 2007). The reduced SL for the L-R step was associated with reduced peak resultant ground reaction forces (Chang & Kram, 2007). Lower overall force production has also been observed for the L-R step during outdoor bend sprinting, despite greater inward forces and greater turning demands during L-R stance (Churchill et al., 2016). Bezodis & Gittoes, (2008) found the L-R step to be more impacted by the bend on conditions representative of indoor competition. For example, L-R SV was 4.9% lower in lane 1 than compared to the straight, whilst SV for the R-L step remained similar (0.1% greater than on the straight). Nonetheless, a 0.5 m/s difference between L-R (~8.5 m/s) and R-L (~9.00 m/s) steps was observed on the straight and only a small sample of 4 well-trained long sprinters were included, thus results should be interpreted with caution. Therefore, the impact of the bend on inter-limb differences of step characteristics is not fully understood and thus further research is required.

4.1.1 Aim and Research Questions

Chapter 4 seeks to address some of the identified gaps exposed in Chapter 2 and quantify the responses to running on banked and flat bends representative of the tightest radii during competition. Furthermore, Chapter 4 seeks to provide a basis of knowledge when moving through the following Chapters. Thus, the aim of this Chapter was to investigate the effect of lateral banking and radius on performance and step characteristics when bend sprinting on the tightest radii that are typical of athletic competitions. To meet this aim, the following three research questions were addressed:

RQ4.1: How does lane radius affect within-limb step characteristics for the L-R and R-L steps?

RQ4.2: How does lateral banking affect within-limb step characteristics for the L-R and R-L steps?

RQ4.3: How does lane radius and lateral banking affect inter-limb differences of step characteristics?

Based on previous literature investigating lane radius on outdoor (Churchill et al., 2018) and small radii (Chang & Kram, 2007; Luo & Stefanyshyn, 2012b) the following hypotheses were made:

4.1.2 Hypotheses

H1: SV would be reduced in lane 2 in comparison to lane 4 under flat and banked conditions.
H2: Reductions in SV due to lane radius would be caused by an interaction of SL and SF.

H3: SV would be reduced in flat conditions in comparison to banked conditions.

H4: Reductions in SV due to lane banking would be caused by an interaction of SL and SF.

H5: L-R step characteristics would be reduced in comparison to the R-L across all conditions

The answering of Research Questions 4.1-4.3 will achieve the aim of the Chapter; with the purpose being to increase understanding of the biomechanics of banked and flat bend sprinting on radii typical of indoor competition.

4.2 Methods

4.2.1 Participants

Following institutional ethical approval, eight competitive sprinters (two females and six males) were recruited using convenience sampling for the study. All athletes specialised in the longer sprint events (200-400 m) and were, therefore, experienced at bend sprinting. As in Chapter 3, to standardise with previous research, a maximum 200 m personal best time of 23.5 s for males was set whilst 27.44 s was set for female participants, giving equivalent IAAF points (731) (Spiriev, 2017). Additionally, all participants had trained and competed on a banked 200 m indoor track within the previous 6 months prior to undertaking this study. All participants provided written informed consent prior to data collection. At the time of testing, participants were injury-free, including any injury preventing normal training and competitions in the previous 6 months, and were completing maximal effort sprints on a weekly basis as part of their routine training.

Table 4-1. Mean ± Standard deviation Participant Characteristics for age, height, mass and 200 m personal best race time (PB).

Variable	Male n = 6	Female n = 2
Age (years)	20.14 ± 0.86	18 ± 1.41
Height (cm)	179.42 ± 5.13	165.00 ± 3.40
Mass (kg)	69.86 ± 11.63	61.85 ± 4.59
200 m PB (s)	23.05 ± 0.86	25.49 ± 0.91

4.2.2 Experimental setup

Data collection took place on a 200 m indoor track (Mondo, Warwickshire, UK) at the National Indoor Athletic Centre in Cardiff, UK. Twelve optoelectronic cameras (Vantage V8, Vicon, Oxford Metrics, UK, 250 Hz) were mounted onto tripods or attached to a rig that ran adjacent to the track creating a capture volume that enabled one full stride to be measured across all four conditions (Figure 4.1). The calibration volume on the bend (10.5 m long, 6.5 m wide and 3.0 m high) was located tangentially to the apex of the bend to record data through the 45.0 - 55.5 m section of the 80 m sprints. The origin of the capture volume was set with a right-handed orthogonal global coordinate system of X (medio-lateral pointing to the right), Y (anterior-posterior, pointing forwards) and Z (superior, pointing upwards). Three markers were attached to the track surface on the bend, to enable transformation of the global-coordinate system between banked and flat conditions.

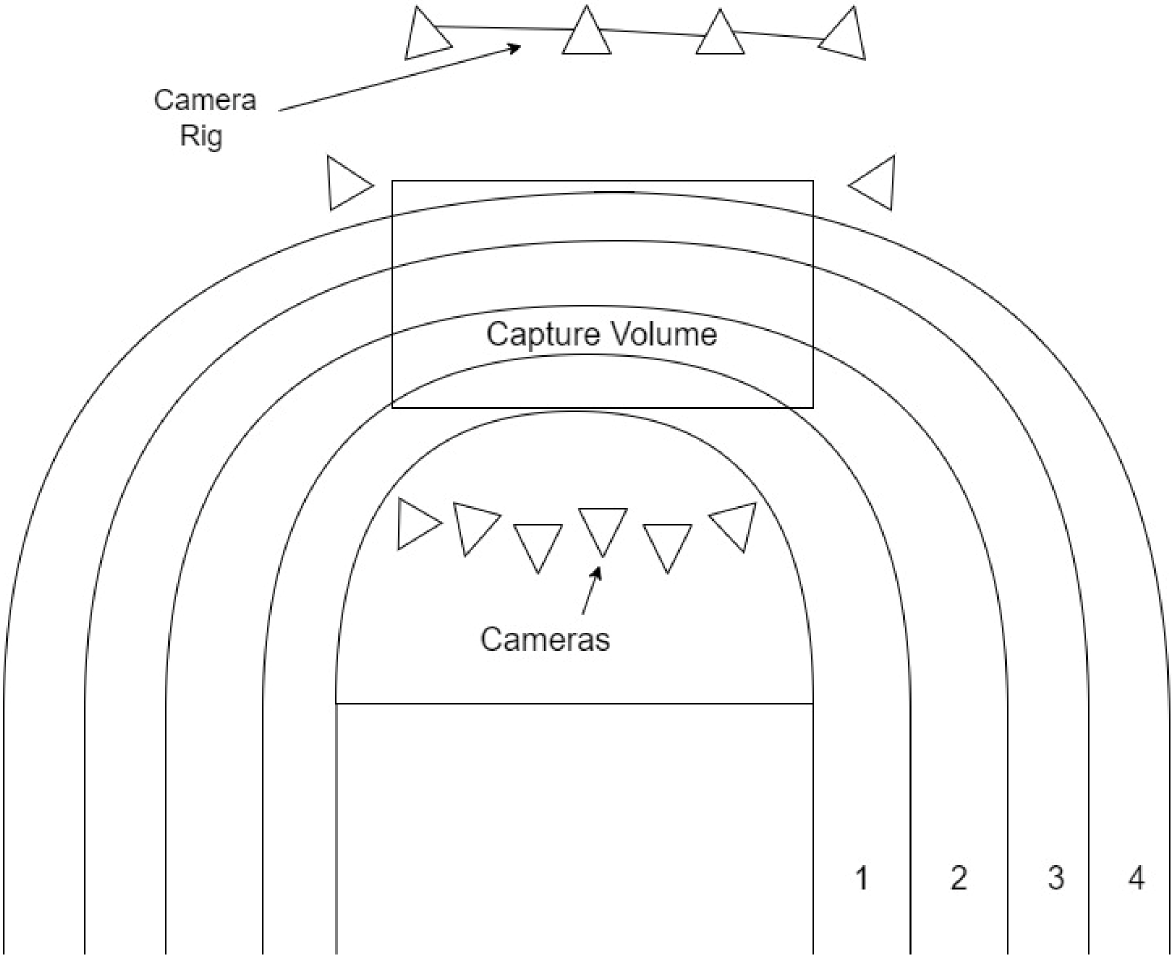


Figure 4.1. Plan view of the experimental set up (not to scale). The bends could be raised to incorporate a banking of 10 degrees and flattened to 0 degrees. ◁ *= Vicon Camera*

The reliability of an adapted Plug in Gait lower limb and trunk marker set with multi-segment foot has been established for bend sprinting (Judson et al., 2018). Therefore, this marker set was utilised with the addition of technical marker clusters and the placement of upper body markers (Figure 4.2). Additional markers were attached bilaterally on the styloid processes of Radius and Ulna, the lateral and medial condyles of the Humerus, and the greater and lesser Tubercles of the Humerus. Three-marker semi-rigid technical clusters were attached to the distal end of thigh and shank segments and to the acromion. A four-marker headband was also worn. Finally, foot markers were placed on the corresponding anatomical positions on the surface of the sprint spikes on the: posterior calcaneus, medial calcaneus, lateral calcaneus, 1st and 5th metatarsal base, 1st, 2nd and 5th metatarsal head and head of the 2nd toe (Judson et al., 2018).

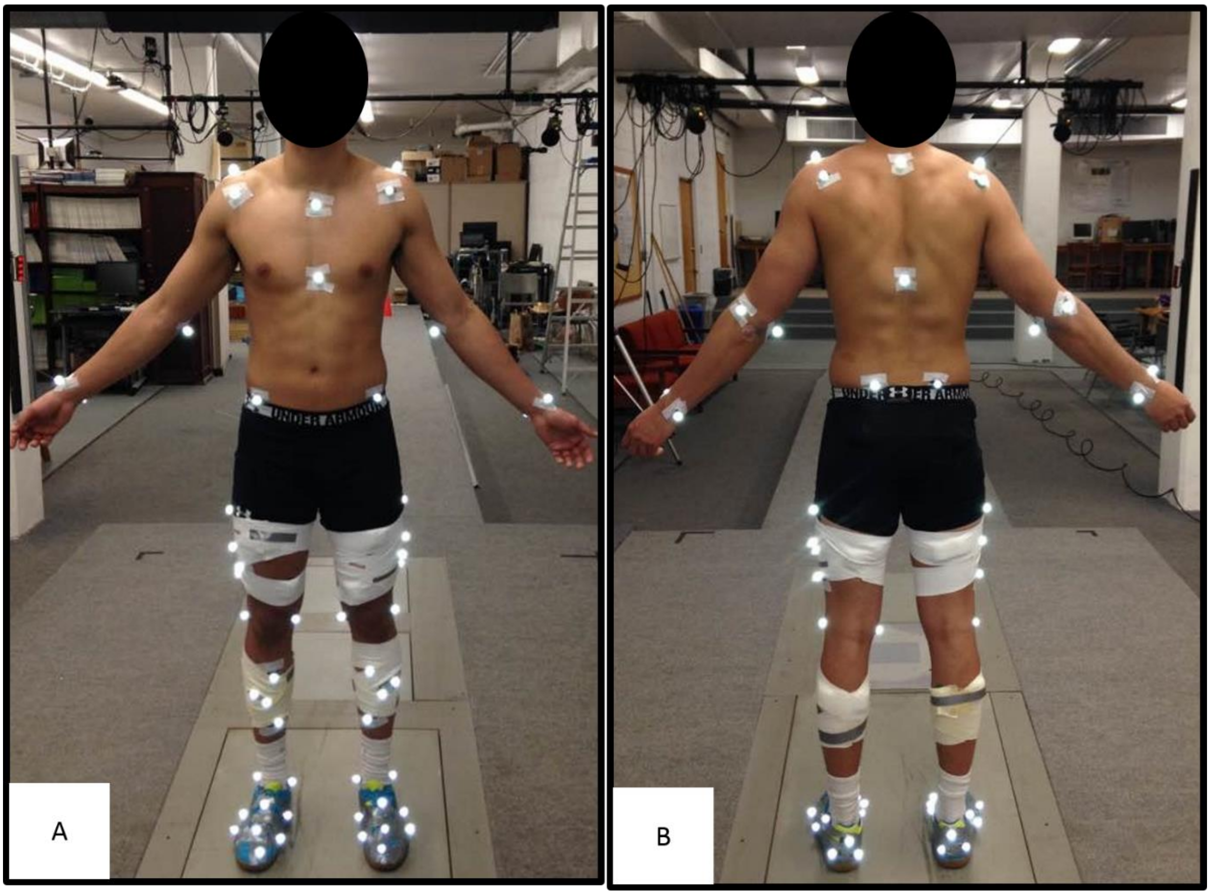


Figure 4.2. The custom marker set utilised for data collection. (A) anterior view, (B) posterior view.

To eliminate the influence of motion artefact as much as possible, markers and marker clusters were fixated to the skin with double sided tape and wrapped with neoprene wrap (Figure 4.2).

4.2.3 Experimental Procedures

Before sprint data collection, height (Leicester Height Measure 220, Seca Ltd, UK), and mass (Seca 799, Seca Ltd, UK) were collected. A banked indoor 200 m track with 10° of banking and radius of 13.98 m for Lane two and 15.94 m for Lane four was used for testing**.** The track contained motorized bends enabling the track to be flattened to give the four experimental conditions (Lane 2 Bank, Lane 4 Bank, Lane 2 Flat and Lane 4 Flat. Participants then undertook a self-prescribed warm up. Participants were asked to undertake two 80 m sprints in each of the four conditions in a randomised order of conditions (athletes ran both 80 m sprints in each condition prior to the next randomised condition). Sprints were undertaken at 85% of their perceived maximum velocity**,** described to participants as a constant submaximal sprinting velocity that should be attained after an approach run of 40 m. Sub-maximal velocities were selected due to the high injury risk associated with maximum velocity on flat bends of small radii (Ryan & Harrison, 2003). Furthermore, previous bend sprinting research has highlighted differences in step characteristics and joint kinematics with high sub-maximal sprint velocities (Alt et al., 2015). Recovery time was self-selected, but typically lasted five to ten minutes, similar to previous sprint research (Churchill et al., 2016; Douglas et al., 2020; Exell et al., 2017).

4.2.4 Data Processing

Kinematic marker trajectories were labelled using Vicon Nexus (Vicon, Oxford UK, v2.9.3) and gap filled when necessary, using both rigid body (for gaps in marker cluster trajectories) and pattern functions. Additionally, when no suitable trajectory was appropriate for pattern gap filling, the spline function was used. Spline interpolation has been shown to be suitable for short durations of less than 0.2 s (Howarth & Callaghan, 2010). Nonetheless, the spline function was only utilised for gaps < 10 frames (0.04 s), in line with previous bend sprinting research (Judson et al., 2018). After labelling marker trajectories, data were exported for further data processing using Visual 3D software (C-Motion Inc, Germantown, USA). Raw marker trajectories were filtered using an 8-12 Hz low-pass fourth-order Butterworth filter. Cut-off frequencies were determined using the autocorrelation method described by Challis (1999).

To identify TD and TO events, custom code written in MATLAB (MathWorks, USA, 2018a) were used. As highlighted in Chapter 3, the Nagahara peak acceleration method (MT1H) was used to determine the L-R TDs, the threshold method with the TOE marker for R-L TD. For TO detection, the Nagahara peak acceleration method using the TOE marker was the most accurate for the L-R and R-L steps and thus was used to determine TO events. Step characteristics were defined in line with Churchill et al. (2015) where: ground contact time (GCT) was defined as the time between the instant of TD and the instant of TO, FT, the time from TO to the subsequent TD of the contralateral foot, SF was calculated by dividing one by the total step time (GCT+FT). SL was calculated as the product of the angle between the MTP at two consecutive ground contacts and the radius of the race line (lane radius + 0.2 m). Touchdown distance (TD_D) was calculated in line with (Churchill et al., 2015; Judson, 2019) and was defined as the horizontal displacement between the CoM and the MTP at TD relative to the direction of travel of the CoM of the athlete at TD.

Due to segment drop out at the end of the capture areas, displacement of the pelvis segment was used to calculate SV of participants for the L-R and R-L steps. A Bland Altman comparison was run for four participants' data, where centre of mass data was available for the full two step period (Figure 3). An r value of 0.99 and root-mean-square-error of 0.05 m/s were calculated showing excellent agreement for the calculation of SV using pelvis displacement. Therefore, pelvis position was used to calculate SV.

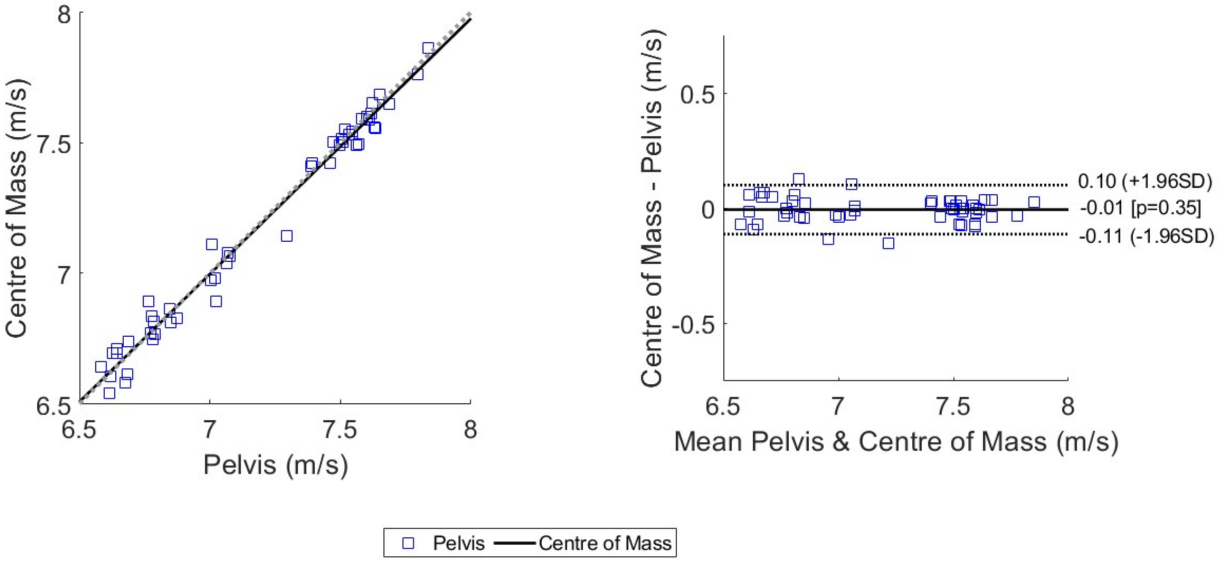


Figure 4.3.Left: Scatter diagram showing Velocity calculated using Centre of Mass and Pelvis displacement. Right: Bland-Altman plot showing the systematic bias in the calculation of Velocity using the Pelvis, 95% confidence interval of the bias (thin black line), the 95% limits of agreement.

The amount of turning per step (turn of the centre of mass) was calculated in line with Judson (2019). Due to marker drop out at the end of the calibration volume, an inadequate number of foot contacts where the centre of mass could be quantified meant that not enough trials produced a value for turn of the centre of mass, therefore this variable is not reported.

4.2.5 Statistical Analysis

Group descriptive data (mean ± SD) were calculated for all variables and checked for normal distribution using the Shapiro–Wilk statistic. To determine the difference between the four lane conditions and between limbs within each lane: a two-way ANOVA with two within-subjects' factors was conducted to analyse each variable, considering different lane conditions (Lane 2 and Lane 4 - flat and banked) and between limbs (L-R and R-L within each lane condition). Partial-eta squared η^2 was used to determine omnibus effect size and was interpreted with the suggested norms: small = 0.01; medium = 0.06; large = 0.14 (Field, 2005). Post-hoc paired-t tests were run to identify where differences between conditions (within limb) existed. To assess between limb differences, paired-t tests were run in each of the four conditions. A Bonferroni correction was applied to account for multiple tests. Effect sizes were calculated using

Hedges G to account for small sample size and were interpreted with the suggested norms: trivial = < 0.20; small = 0.20 ≥ 0.50; moderate = 0.50 ≥ 0.80; large = ≥ 0.80 (Cohen, 2013).

4.3 Results

Table 4-2 shows mean ± SD for all step characteristics in all lane conditions across L-R and R-L steps. Table 4-3 and 4-4 show effect size and the percentage change for the L-R and R-L step variables respectively, whilst Table 4-5 shows effect size and percentage change for the between limb comparison for each variable in each condition.

4.3.1 Step velocity

For SV there was no limb*condition interaction (F (3) = 1.150; $p = 0.36$; $\eta^2 = 0.16$) however, main effects were observed for both limb (R-L > L-R; F (1) = 14.173; $p = 0.009$; $\eta^2 = 0.703$) and condition F (3) = 9.81, $p < 0.001$. $\eta^2 = 0.62$). Post-hoc comparisons revealed significant differences between L-R and R-L SV in Lane 2 Flat (Lane 2 Flat) ($p = 0.011$; ES = 0.69). L-R SV in each condition can be seen in

For the L-R step, Lane 2 Bank was significantly greater than Lane 2 Flat ($p = 0.026$; ES = 1.25) and approached significance with large ES in Lane 4 Flat ($p = 0.057$; ES = 0.91), and Lane 4 Bank with Lane 2 Flat ($p = 0.060$; ES = 0.88). R-L SV in each condition can be seen in Figure 4.4. No significant differences were observed between conditions for the R-L step.

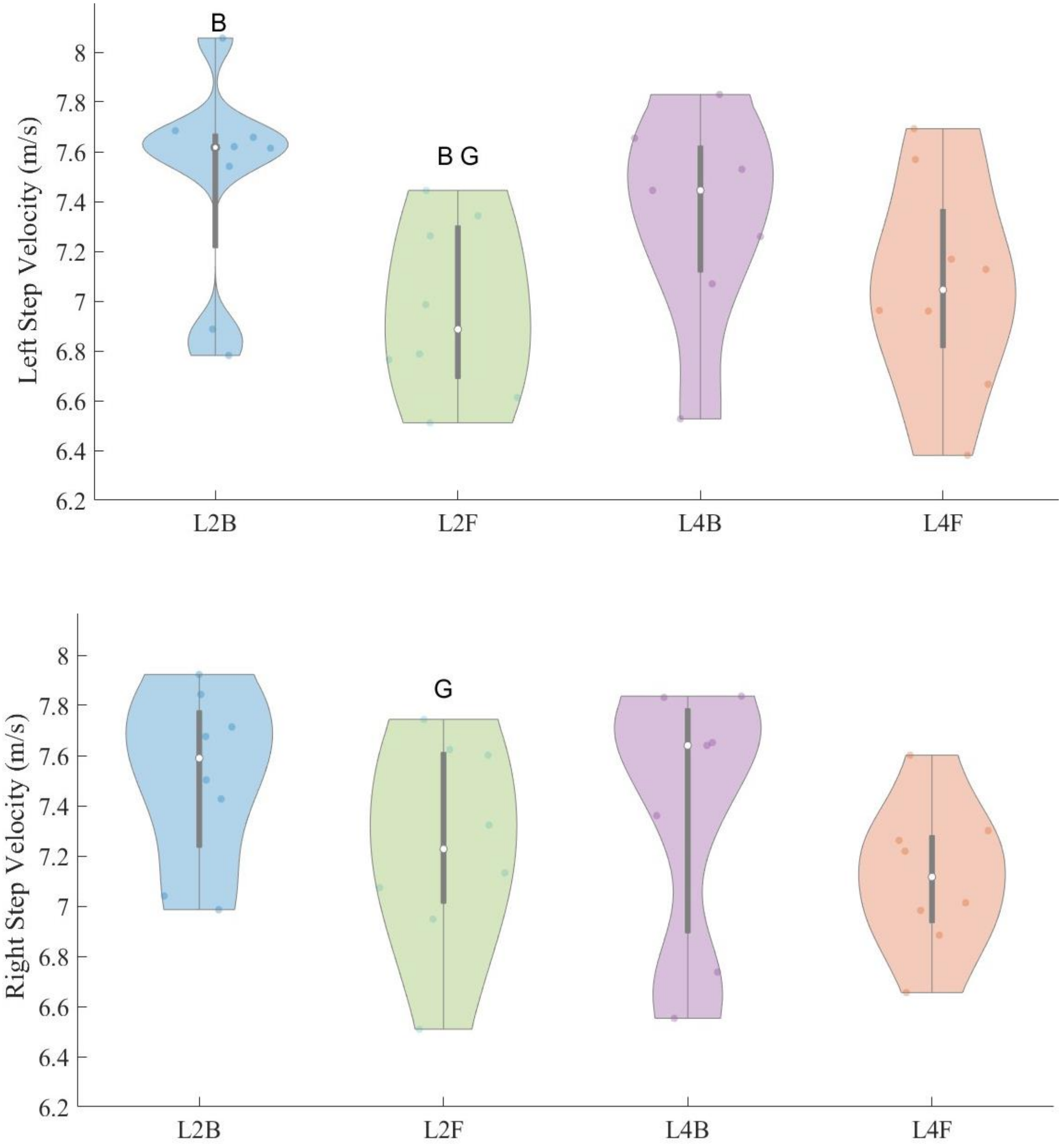


Figure 4.4. Violin plots to show the distribution of L-R (Top) and R-L (Bottom) Step Velocity across all four conditions. The width of each violin indicates the frequency of data points at that value. The white dot in each violin represents the median. Interquartile range: The thick black bar in the centre of each violin spans from the first quartile (25th percentile) to the third quartile (75th percentile). Data range: the thin black lines extend to show the rest of the distribution, except for points that are considered outliers.

*key ^{A} = difference between Lane 2 Bank versus Lane 4 Bank, ^{B} = difference between Lane 2 Bank versus Lane 2 Flat, ^{C} = difference between Lane 2 Bank versus Lane 4 Flat, ^{D} = difference between Lane 4 Bank versus Lane 2 Flat, ^{E} = difference between Lane 4 Bank versus Lane 4 Flat, ^{F} = difference between Lane 2 Flat versus Lane 4 Flat, ^{G} = difference between LVR within condition.

4.3.2 Step characteristics

For SF, there was no limb*condition interaction (F (3) = 1.94; p = 0.154; η^2= 0.53), however main effects for both limb (R-L > L-R; F (1) = 13.65; p = 0.010; η^2 =0.25) and condition (F (3) = 6.93; p = 0.003; η^2 = 0.70) reached statistical significance. Post-hoc comparisons revealed that L-R SFs were significantly lower than R-L in Lane 2 Bank (p = 0.0071; ES = 0.72), Lane 4 Bank (p = 0.003; ES = 0.79) and Lane 2 Flat (p = 0.004; ES = 0.96). For the effect of condition, L-R SFs were greater in Lane 2 Bank than Lane 4 Bank (p = 0.012; ES = 0.41) whilst no significant differences were observed between conditions for the R-L step.

For SL, no significant limb*condition interaction was observed (F (3) = 3.70); p = 0.031; η^2 = 0.38). A significant main effect for condition (F (3) = 12.113; p = 0.0001; η^2 = 0.67) but not limb was observed (F (1) = 0.091; p = 0.773; η^2 =0.0150). Post-hoc pairwise comparisons revealed SLs were shorter in Lane 2 Flat in comparison to both Lane 2 Bank (p = 0.049; ES = 0.65) and Lane 4 Bank (p = 0.018; ES = 0.78). For the R-L step Lane 2 Bank SLs were significantly greater than Lane 2 Flat (p = 0.039; ES = 0.66), whilst Lane 4 Bank approached being significantly greater than Lane 2 Flat (p = 0.063; ES = 0.59) and Lane 2 Flat significantly lower than Lane 4 Flat (p = 0.031; ES = 0.45). No differences between L-R and R-L SLs were observed across any condition**.**

For GCT no significant limb*condition interaction (F (3) = 1.97; p = 0.155; $\eta^{2\,=}$ 0.25), no main effect was observed for limb (L-R > R-L; F (1) = 0.83; p = 0.398; $\eta^{2\,=}$ 0.12), however was significant for condition (F (3) = 3.45; p = 0.039; η^2 = 0.37). Post-hoc pairwise comparisons revealed L-R GCTs were significantly lower in Lane 2 Bank than Lane 4 Bank (p = 0.002; ES = 0.27). No significant differences were observed between conditions for the R-L step, however Lane 4 Bank approached significance compared to Lane 4 Flat (p = 0.055; ES = 1.04). No differences between L-R and R- L were observed for GCT across any condition.

For FT, no significant limb*condition interaction (F (3) = 2.95); p = 0.061; η^2 = 0.33) was observed, a significant main effect for limb was observed (L-R > R-L; F (1) = 12.88; p = 0.012; η^2 = 0.68) but not for condition (F (3) = 1.06; p = 0.39; η^2 = 0.15). Post-hoc pairwise comparisons revealed no differences between conditions for L-R or R-L FTs across all conditions. For between limb: L-R FT was significantly longer than R-L in Lane 4 Bank (p = 0.018; ES = 0.85) and Lane 2 Flat (p = 0.002; ES = 1.14).

Table 4-2. Mean ± Standard Deviation for all Step characteristics for the L-R and R-L steps across Banked and Flat conditions

Variable	Lane 2 Bank		Lane 4 Bank		Lane 2 Flat		Lane 4 Flat	
	L-R	R-L	L-R	R-L	L-R	R-L	L-R	R-L
Step Frequency (Hz)	3.90 ± 0.260 $^{A\,G}$	4.11± 0.300 ^{G}	3.78 ± 0.280 $^{A\,G}$	4.03 ± 0.320 ^{G}	3.81 ± 0.290 ^{G}	4.15 ± 0.370 ^{G}	3.74 ± 0.210	3.96 ± 0.350
Step length (m)	1.92 ± 0.100 ^{A}	1.92 ± 0.110 ^{B}	1.93 ± 0.100 $^{A\,E}$	1.92 ± 0.130	1.84 ± 0.120 ^{E}	1.83 ± 0.150 $^{B\,F}$	1.86 ± 0.110	1.90 ± 0.130 ^{F}
Ground contact time (s)	0.119 ± 0.013 ^{A}	0.117 ± 0.016	0.122 ± 0.014 ^{A}	0.117 ± 0.008	0.122 ± 0.014	0.122 ± 0.009	0.123 ± 0.010	0.127 ± 0.011
Flight Time (s)	0.139 ± 0.008	0.128 ± 0.011	0.144 ± 0.009 ^{G}	0.133 ± 0.014 ^{G}	0.142 ± 0.016 ^{G}	0.121 ± 0.019 ^{G}	0.145 ± 0.014	0.127 ± 0.018

*key ^{A} = difference between Lane 2 Bank V Lane 4 Bank, ^{B} = difference between Lane 2 Bank V Lane 2 Flat, ^{C} = difference between Lane 2 Bank V Lane 4 Flat, ^{D} = difference between Lane 4 Bank V Lane 2 Flat, ^{E} = difference between Lane 4 Bank V Lane 4 Flat, ^{F} = difference between Lane 2 Flat V Lane 4 Flat, ^{G} = difference between LVR within condition.

Figure 4.5 shows mean ± SD touchdown distance (TD_D) for L-R step and R-L step within each condition No significant limb*condition interaction was observed (F (3) = 1.01; $p = 0.41$ $\eta^2 = 0.13$), whilst a significant main effect for limb (L-R > R-L; F (1) = 45.93; $p < 0.001$; $\eta^2 = 0.86$) but not for condition (F (3) = 1.12; $p = 0.37$; $\eta^2 = 0.14$) were observed for TD_D. Post-hoc comparison revealed no differences between conditions for L-R or R-L TD_Ds across any conditions. L-R TD_D was significantly larger than R-L across all conditions (Lane 2 Bank: $p = 0.010$; ES =1.80, Lane 4 Bank $p < 0.001$; ES = 1.20, Lane 2 Flat $p = 0.013$; ES =1.47, Lane 4 Flat $p = 0.010$; ES = 1.47).

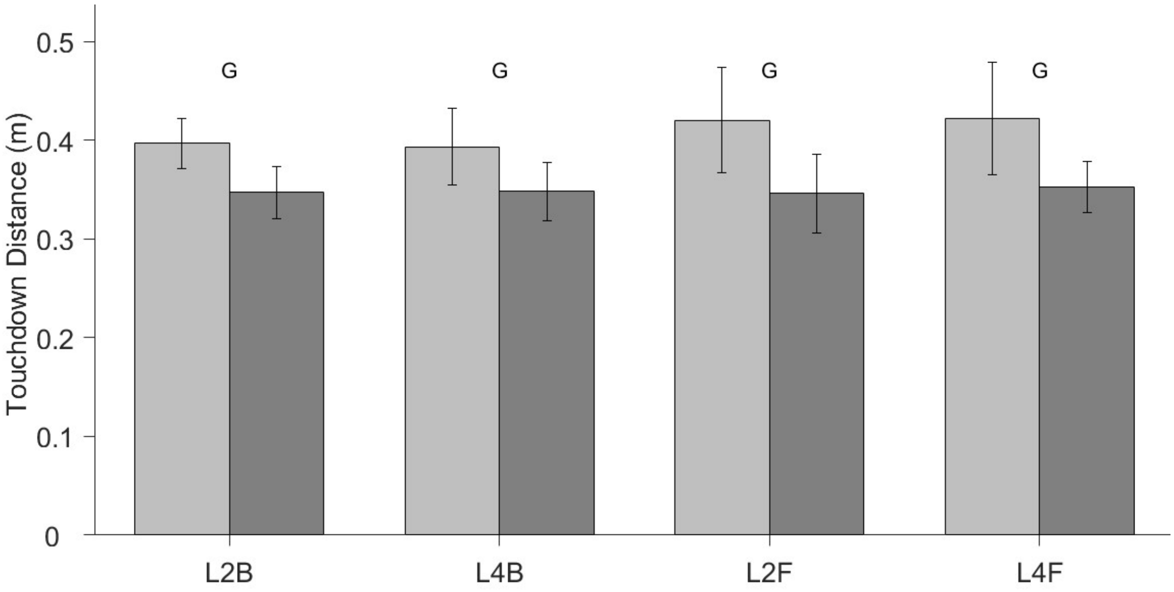


Figure 4.5. Mean ± SD for touchdown distance for the L-R step (light grey) versus the R-L step (dark grey) within each condition: Lane 2 Bank, Lane 4 Bank, Lane 2 Flat and Lane 4 Flat. * G highlights a significant difference between the L-R step and R-L within a lane condition ($p < 0.05$).

Table 4-3. Effect size (% change) for all within lane comparisons for the L-R step for all variables.

Variable	Lane 2 Bank V Lane 4 Bank	Lane 2 Bank V Lane 2 Flat	Lane 2 Bank V Lane 4 Flat	Lane 4 Bank V Lane 2 Flat	Lane 4 Bank V Lane 4 Flat	Lane 2 Flat V Lane 4 Flat
Step Velocity	🟧 0.33 (2.01)	🟩 1.25 (6.95)	🟩 0.91 (5.48)	🟩 0.88 (5.05)	🟨 0.58 (3.55)	🟧 0.24 (1.56)
Step Frequency	🟧 0.41(3.08)	🟧 0.30 (2.31)	🟨 0.63 (4.10)	0.10 (0.79)	0.16 (1.06)	🟧 0.27 (1.84)
Step Length	0.17 (0.52)	🟨 0.65 (4.17)	🟧 0.48 (3.12)	🟨 0.78 (4.66)	🟨 0.62 (3.63)	0.18 (1.08)
Ground Contact Time	🟧 0.27 (2.46)	🟧 0.25 (2.46)	🟧 0.39 (3.25)	0.02 (0)	0.08 (0.81)	0.10 (0.81)
Flight Time	🟨 0.50 (3.47)	🟧 0.21 (2.11)	🟨 0.51 (4.14)	0.12 (1.39)	0.12 (0.69)	🟧 0.21 (2.07)
Touchdown Distance	0.10 (0.76)	🟨 0.52 (5.48)	🟨 0.54 (5.92)	🟨 0.50 (6.19)	🟨 0.51 (6.64)	0.04 (0.47)

*Cell shading indicates effect size: White = trivial, Orange = small, Yellow = moderate, Green = Large

Table 4-4. Effect size (% change) for all within lane comparisons for the R-L step for all variables.

Variable	Lane 2 Bank v Lane 4 Bank	Lane 2 Bank v Lane 2 Flat	Lane 2 Bank v Lane 4 Flat	Lane 4 Bank v Lane 2 Flat	Lane 4 Bank v Lane 4 Flat	Lane 2 Flat v Lane 4 Flat
Step Velocity	🟧 0.30 (1.86)	🟨 0.67 (3.60)	🟩 1.17 (5.33)	🟧 0.26 (1.76)	🟨 0.59 (3.53)	🟧 0.34 (1.80)
Step Frequency	🟧 0.23 (1.95)	0.11 (0.964)	🟧 0.43 (3.65)	🟧 0.43 (3.65)	🟧 0.20 (1.74)	🟧 0.49 (4.58)
Step Length	0.03 (0)	🟨 0.66 (4.69)	🟧 0.20 (1.04)	🟨 0.59 (4.69)	0.16 (1.04)	🟧 0.45 (3.68)
Ground Contact Time	0.01 (0)	🟨 0.51 (4.10)	🟩 0.92 (7.87)	🟨 0.59 (4.10)	🟩 1.04 (7.87)	🟨 0.52 (3.94)
Flight Time	🟧 0.33 (3.76)	🟧 0.45 (5.47)	0.08 (0.781)	🟨 0.67 (9.02)	🟧 0.34 (4.51)	🟧 0.31 (4.72)
Touchdown Distance	0.04 (0.29)	0.03 (0.29)	0.19 (1.70)	0.06 (0.58)	0.15 (1.42)	0.18 (1.98)

*Cell shading indicates effect size: White = trivial, Orange = small, Yellow = moderate, Green = Large

Table 4-5. Effect Size (% change) for the comparison of L-R and R-L steps for variables and lane conditions.

Variable	Lane 2 Bank	Lane 4 Bank	Lane 2 Flat	Lane 4 Flat
Step Velocity	0.08 (0.39)	0.08 (0.54)	0.69 (3.87)	0.13 (0.56)
Step Frequency	0.72 (5.11)	0.79 (6.20)	0.96 (8.19)	0.72 (5.56)
Step Length	0.05 (0)	0.14 (0.52)	0.11 (0.54)	0.24 (2.11)
Ground Contact Time	0.16 (1.68)	0.48 (4.10)	0.00 (0)	0.39 (3.15)
Flight Time	1.08 (7.91)	0.85 (7.64)	1.14 (14.80)	1.10 (12.40)
Touchdown Distance	1.80 (12.60)	1.20 (11.68)	1.47 (17.62)	1.47 (16.35)

*Cell shading indicates effect size: White = trivial, Orange = small, Yellow = moderate, Green = Large

4.4 Discussion

There is still a lack of understanding of the technical changes associated with a change in lane radius and inclusion of lateral banking during bend sprinting. Therefore, Phase 1 set out to investigate the effects of altering task demands during bend sprinting. This will provide a new understanding of the changes in performance and technique on radii representative of indoor competition, which will add valuable novel information to the body of knowledge of bend sprinting. To address the aim of Phase 1 an analysis of step characteristics was undertaken within a group of sprinters. The aim of this Chapter was to investigate the effect of lateral banking and radius on step characteristics when bend sprinting on radii that are typical of indoor competition.

4.4.1 RQ4.1: How does lane radius effect step characteristics for the L-R and R-L steps?

The effect of lane radius on within-limb SV

It was hypothesized (H1) that step characteristics would be reduced in tighter lanes in comparison to outer lanes. Results showed main effects of condition for: SV, SF, FT and SL but not for GCT or TD_D. The change in radius showed no significant differences between lanes for the L-R step; however, SV was 2.01% greater in Lane 2 Bank than in Lane 4 Bank whilst on the flat, SV was 1.56% greater for Lane 4 Flat than Lane 2 Flat. For the R-L step, SV in Lane 2 Bank and Lane 2 Flat were non-significantly greater than lane 4 banked (Lane 2 Bank > Lane 4 Bank; 1.86%) and (Lane 2 Flat > Lane 4 Flat; 1.80%).Whilst no differences in

SV as a result of lane radius were observed, all with a small ES, differences of ~2% have been highlighted to be meaningful in terms of performance (Churchill et al., 2018). In contrast to previous research, SV in Lane 2 Bank were non-significantly greater than in Lane 4 Bank (~ 2%) (for the L-R step), whereas R-L SV were greater in Lane 2 Flat compared to Lane 4 Flat. Therefore, for SV, H1 is partially rejected except for L-R step in the flat condition. Typically a decrease in performance is observed on tighter radii (Chang & Kram, 2007; Churchill et al., 2018; Ryan & Harrison, 2003; Usherwood & Wilson, 2006). Comparing results is challenging due to the different methodologies adopted and bend radii tested. Nonetheless, the findings from this study support anecdotal evidence from Bezodis & Gittoes (2008), who found in a small sample of 4 well-trained sprinters that SV in Lane 4 of an indoor athletics track was 1.7% and 0.2% slower for the R-L and L-R steps, respectively, in comparison to Lane 1.

In this study participants were all well-trained sprinters regularly training and competing on the bend; however, in the participant information, it was only specified that participants were required to have competed on a banked indoor bend within the past six months. Therefore, athletes may not have undertaken training on a banked bend and thus have been unfamiliar with the degree of banking. This unfamiliarity potentially minimised the expected benefits of sprinting on a banked bend, evidenced by an increase in radius resulting in marginally lower SV in Lane 4 Bank compared to Lane 2 Bank for the L-R step. Consequently, it may be beneficial for athletes to ensure bend sprint training is undertaken on banked bends of varying radii in preparation for indoor competition to familiarise themselves with the different conditions.

The effect of Lane radius on within-limb interaction of SF and SL

It was hypothesised (H2**)** that reductions in SV due to lane radius would be caused by an interaction of SL and SF. On the banked conditions, changes in L-R and R-L SV were brought about by greater SF in Lane 2 Bank than Lane 4 Bank, whilst SLs similar. Interestingly, greater SF were achieved through shorter GCT in Lane 2 Bank. In the flat conditions a contrasting pattern occurred where for the R-L step: SF in Lane 2 Flat were non-significantly greater than Lane 4 Flat with significantly lower SL than Lane 4 Flat (3.68%; ES = 0.45). Therefore, H2 can be partially accepted for the flat conditions due to the fact changes in SV were brought about by alterations in both SL and SF.

Previous research on outdoor radii bends has suggested that reductions in performance with tightening radii occur due to a trend for reduced SF on the inner lanes (Churchill et al., 2018; Ryan & Harrison, 2003). For instance, Churchill et al. (2018) reported reduced velocity between Lane 8 and Lane 2 of an outdoor athletics track to be the result of a general trend for reduced SF in lane 2 (L-R = 4.35 ± 0.25 Hz; R-L = 4.36 ± 0.22 Hz) compared to lane 8 (L-R = 4.48 ± 0.19 Hz; R-L = 4.48 ± 0.18 Hz), with this a result of significantly longer GCT in Lane 2 versus Lane 8 for the L-R step (p = 0.004; d = 0.69). On very tight radii (1-6 m) however, Chang & Kram (2008) found that reductions in SV occurred largely through smaller SL on the tighter radii. SL reduced from 1.53 ± 0.1 m (L-R) and 1.70 ± 0.10 m (R-L) on a 6 m radius to 0.77 ± 0.02 m (L-R) and 0.80 ± 0.04 m (R-L) on 1 m radius (all $p < .05$) whilst SF remained similar ($p > .05$) across all conditions for both L-R and R-L steps (Chang & Kram, 2007). Therefore, on larger radii representative of outdoor competition, reductions in SV may occur as the result of reduced SF, whilst on very tight radii (1-6 m) this may occur due to reducing SL. In agreement with the present findings, previous research under similar conditions suggest that alterations in SV occur as a result of interactions between SL and SF (Bezodis & Gittoes, 2008; Ryan & Harrison, 2003). For example, Bezodis & Gittoes (2008) reported that steps from the L-R leg decreased in SV by approximately 0.2% from Lane 1 to Lane 4, with a greater contribution coming from SF (Lane 1 = - 2.4% to Lane 4 = - 3.7%) rather than decreases in SL (-1.4 to -1.7%). For the R-L step, Bezodis & Gittoes (2008) found small increases in SF (+1.2% in Lane 1 and +0.7% in Lane 4) in comparison to the straight condition whilst SL were reduced by 2.3% (Lane 1) and 1.6% (Lane 4). These findings in combination with those from the present study suggest that alterations in SV due to change in radii on banked and flat bends are brought about by changes in both SL and SF.

4.4.2 RQ4.2: How does lateral banking effect step characteristics for the L-R and R-L steps?

It was hypothesised that: SV would be reduced in flat conditions in comparison to banked conditions (H3), and that reductions in SV due to lane banking would be caused by an interaction of SL and SF (H4). For the effect of lateral banking: L-R SV was reduced by 6.95% with a large effect size in Lane 2 Flat in comparison to Lane 2 Bank. The lower SV observed in the flat conditions were brought about through non-significant reductions in SL and SF. For the R-L step, SV was non-significantly greater in Lane 2 Bank than Lane 2 Flat (3.60%), due to a significantly longer, SL in Lane 2 Bank (4.69%) whilst SF were similar. A similar pattern was observed between Lane 4 Bank and Lane 4 Flat where a reduction in SV was brought about by small alterations in both SL and SF (all $p > .05$; ES= 0.183-0.487). Therefore, both H3 and H4 are accepted.

The present findings support previous research (in-silico and in-vivo) that demonstrate faster velocities on banked bends compared to flat bends. For instance, Greene (1987), found lateral banking to improve running speeds by approximately 10%. A recent conversion equation based on National Collegiate Athletic Association results has suggested the difference in 200-400m performance between flat and banked tracks to be closer to 2% (Barnes & Malcata, 2017). From the findings of this investigation, it may be that these reductions in SV are a result of a combination of reduced SL and SF in flat conditions compared to banked conditions of equal radii, nonetheless, the contribution may be larger due to SLs (larger ES and significant difference for R-L SL). Conversely, for the L-R step: a general trend was observed for longer GCT in the flat conditions compared to the banked, with these accompanied by a similar trend for larger TD_Ds. Previous research has associated large TD_Ds with larger braking forces and longer GCTs (Hunter et al., 2004, 2005)**.** Thus, a potential area for improved performance is by increasing SF through reducing TD_D for the L-R step.

The only study to compare bend sprinting performance on flat and banked conditions was carried out on smaller radii of 2.5 m using a laterally raised shoe to align the ankle in a more neutral position and replicate a banked sprinting condition. Luo & Stefanyshyn (2012b) found that the laterally raised shoe produced a 4.3% (P = 0.0001) increase in sprinting speed in comparison to a flat shoe, occurring partially due to reduced GCTs (0.231 vs 0.236 s; $p = 0.0074$). Nonetheless, velocity was calculated as pelvis speed over stance, thus no insight can be gathered on the impact of the wedged footwear on SL, FT and thus, SF. Furthermore, the large difference in experimental protocols (radii used and wedged footwear vs banked track) reduces the generalization of results. Despite this, the present findings are in agreement with the general consensus that bend sprinting performance is reduced on flat bends in comparison to banked bends of equal radii (Barnes & Malcata, 2017; Greene, 1987; Luo & Stefanyshyn, 2012b).

4.4.3 RQ4.3: How does lane radius and lateral banking affect inter-limb differences of step characteristics?

The hypothesis (H5) that L-R step characteristics would be reduced compared to R-L across all conditions was partially supported. Results indicated a trend for greater R-L SV than L-R, with this trend significant in Lane 2 Flat (3.87%). Greater R-L SV was brought about by greater

R-L SF and similar SLs. Despite this, L-R FTs were significantly greater than R-L across all conditions ($p < .001 – .04$; ES = 0.85 – 1.14), except for Lane 4 Flat ($p = 0.052$; ES = 0.51). The longer L-R FTs observed in this study suggests that it took participants longer to reposition in preparation for touchdown. Longer L-R FTs are potentially a consequence of more altered L-R step kinematics during bend sprinting (Alt et al., 2015; Churchill et al., 2015; Judson et al., 2020). These findings are in agreement with Judson et al. (2020) who found L-R FT to be 9% greater than the R-L (ES = 0.53) during the acceleration phase in lane 1 of an outdoor track.

Interestingly, despite greater R-L SF, GCTs were similar across all lane conditions. Previous research has also reported lower L-R SF in comparison to R-L SF on outdoor bend radii (Churchill et al., 2018). At maximal velocity, Churchill et al. (2018) reports that reduced L-R SF were brought about by increases in both L-R step GCT and FT as bend radius decreased (Churchill et al., 2018). For the R-L step, Churchill et al. (2018) found GCT to be similar across lanes. In other studies, longer GCTs have been observed for the L-R step, with FT remaining similar (Alt et al., 2015; Churchill et al., 2015) whilst in the acceleration phase both L-R step FT and GCT were found to be longer than R-L (Judson, et al., 2020a). In the present study, larger L-R TD_Ds were observed for the L-R step across all lane conditions, in agreement with previous bend sprinting research (Churchill et al., 2018; Ishimura & Sakurai, 2016). Interestingly, the increased L-R TD_D only resulted in non-significantly longer L-R GCT in the banked conditions. However, the aforementioned studies were undertaken on a range of outdoor radii so are not directly comparable to the results from this study. Therefore, L-R SV appears to be reduced as a result of longer FTs the potential consequence of greater TD_Ds. Longer L-R FT could occur because of the frontal and transverse plane kinematic adaptations required to produce centripetal force and follow the path of the bend. Thus, kinematics of bend sprinting on conditions representative of indoor competition is an area for future research.

4.5 Conclusion

The relationship between SV and radius may not follow the traditional pattern of reduced SV with decreasing radii when on a laterally banked track. Due to the differing effects of radii and banking, it is suggested that athletes should ensure sufficient bend sprint training undertaken across radii and banked bends in preparation for competition. Lateral banking increased L-R SV through a combination of SF and SL whilst for the R-L step no significant differences were observed in SV or SF. Both lateral banking and increased radius brought about significant increases in R-L SL.

There was a trend for reduced L-R SV because of slower L-R SF, brought about primarily by longer L-R FTs. The L-R step appears to be more affected than the R-L step when sprinting on radii typical of indoor competition, this should be considered when implementing training and competition strategies in preparation for indoor competition. Coaches and athletes should ensure bend sprint training is undertaken on banked bends of varying radii to ensure athletes are familiarised with sprinting on a banked bend to maximise competition performance. Future research should explore more detailed kinematics during bend sprinting on conditions representative of indoor competition. Following the conclusions drawn from this study, the next study (contained within Chapter 5) investigated body lateral lean and lower-body kinematics across the stance phase during bend sprinting on radii representative of indoor competition.

4.6 Coaching and Practical Recommendations for Training on Banked Tracks and tight radii

Where possible, coaches should include training on banked bends with varying radii to ensure familiarity with the unique demands of sprinting on laterally banked tracks. This will help athletes adapt to the changes in step length and step frequency that occur as a result of lateral banking. It is acknowledged that not all athletes have regular access to banked indoor athletics facilities, however pre-meet strides or key sessions carried out on conditions representative of target competitions may ensure athletes are sufficiently familiarised.

The Left-Right (L-R) step appears to be more affected by lateral banking, with significant decreases in step frequency due to longer flight times in the flat conditions. Further, a general trend was observed for longer left ground contact times in the flat conditions compared to the banked, was accompanied by a similar trend for larger touchdown distances. To counteract this, coaches should focus on drills that emphasise reducing the left touchdown distance, which can help increase step frequency and improve overall performance on banked tracks.

Chapter 5: An investigation into the effect of lane radius and lateral banking on lower limb joint kinematics in indoor bend sprinting

THE WORK FROM THIS CHAPTER FORMED THE BASIS OF THE FOLLOWING PEER-REVIEWED CONFERENCE ABSTRACT

White, J., Irwin, G., Exell, T., Wilson, C., Hamill, J., Wyatt, H., ... & Weir, G. (2022). Joint Kinematics during Indoor Bend Sprinting. Proceedings of the 40th International Conference of Biomechanics in Sports, 40(1), 751.

5.1 Introduction

The literature review in Chapter 2 highlighted that both lateral banking and lane radius had the potential to impact step characteristics and ultimately SV. Chapter 4 identified that the relationship between SV and radius may not follow the traditional pattern of reduced SV on a less tight bend radii when sprints were undertaken on a laterally banked track. When compared to the flat, lateral banking increased L-R SV through a combination of increased SF and SL, whilst for the R-L step, no significant differences were observed in SV or SF. Both lateral banking and increased radius brought about significant increases in R-L SL. Additionally, there was a trend for reduced L-R SV in comparison to R-L SV across all conditions because of lower L-R SF, brought about primarily by longer L-R FTs. Thus, the L-R step appears to be more affected than the R-L step when sprinting on radii typical of indoor competition, this should be considered when implementing training and competition strategies in preparation for indoor competition.

Previous bend sprinting research has identified altered discrete joint kinematics when comparing the bend to the straight (Alt et al., 2015; Churchill et al., 2015; Ohnuma et al., 2018), and across the stance phase during acceleration on the bend (Judson et al., 2020). Churchill et al. (2015) found larger sagittal lean angles during the L-R step on the bend compared to the straight. On the other hand, Ohnumma et al. (2018) found a smaller sagittal hip joint angle at TO for the R-L step on the bend compared to the straight. This difference was only observed in the poor bend sprint group and thus, this reduction may have influenced the reduced FD and SL observed in this group for the R-L step on the bend. Furthermore, Ohunuma et al. (2018) found the minimum value of knee and ankle joint angles to be significantly lower than on the straight path. At submaximal (90% maximum velocity), Alt et al. (2015) found no changes in the sagittal plane in the hip, knee, and ankle. Thus, it is possible that one aspect to successful bend sprint technique is to maintain the same kinematics in the sagittal plane as a straight path (Ohnuma et al., 2018).

In the frontal and transverse planes, athletes have been shown to lean into the bend at both touchdown and TO, with this resulting in larger peak hip adduction (L-R step bend = 10.6 ±4.1°; L-R step straight = 4.1± 2.6°) and with a trend for more R-L step hip abduction at TD and peak during stance on the bend compared to the straight (Churchill et al., 2015). Additionally, Alt et al. (2015) report several peak stance angles finding: significantly increased ($p < 0.05$) hip adduction between bend (13.8 ± 3.3°) and straight (7.7 ± 3.8°) during the L-R step and reduced adduction for bend R-L (5.5 ± 4.4°) compared to straight R-L (9.8 ± 4.3°; $p < 0.05$). The combination of lateral lean and alteration of hip adduction during the L-R step contributes to more extreme ankle eversion on the bend (bend L-R: 12.7° ± 7.2°; straight L-R: 6.7 ± 2.3°; $p < 0.05$), whilst peak eversion during R-L stance was significantly reduced compared to the straight (Alt et al., 2015).

Research has further highlighted some kinematic differences between limbs on the bend. Alt et al. (2015) found that maximum values of L-R ankle eversion, hip adduction and hip external rotation were significantly higher than the R-L. Large ankle eversion and lateral centre of pressure position has been observed during the L-R stance during the acceleration phase on outdoor radii (Judson et al., 2019). Large frontal plane ankle angles reported during bend running have approached or exceeded the proposed physiological limits of 13° (Clarke, 1984) whereby injury risks increase if exceeded regularly (Beukeboom et al., 2000). For example: Hamill et al. (1987) reported group mean peak pronation values of L-R: 22.3° and R-L: 12.5°, Smith et al. (2006) reported frontal plane ankle angles of 34.0° (L-R) and 6.7° (R-L), whilst Luo & Stefanyshyn (2012b) reported peak eversion angles of 35° (L-R).

Research into the effect of differing lane conditions has been carried out on bends with radii of typical outdoor athletics tracks (Churchill et al., 2018). The effect of lane radius on joint kinematics has received minimal attention in the literature. Only limited variables are reported by Churchill et al. (2018) who calculated body sagittal and lateral lean and turning of the centre of mass (CoM) in lane 8, 5 and 2 of outdoor athletics tracks (radius = 37.72 – 45.10 m). Results showed a tendency for more inward (more negative) body lateral lean at touchdown as bend radius decreased, in both the L-R and R-L steps. Additionally, more body lateral lean for the R-L step at touchdown compared to L-R touchdown was observed within each lane. It has been hypothesised that to maintain velocity on tighter radii, greater centripetal force is required, with this requiring more inward body lateral lean (Neie, 1981). Moreover, Churchill et al. (2018) observed that the turn of the centre of mass during the R-L step was increased as lane radius decreased (tighter) whilst the L-R turn of the centre of mass remained the same. However, across all lanes, the CoM turned significantly more during the L-R step than the R-L step (Churchill et al., 2018). Greater turn of the CoM suggests that the L-R step contributes more than the R-L step to following the path of the bend, however the contribution of the R-L step appears to increase as radius decreases. The greater turning demands is one of the reasons for indoor tracks including lateral banking, with the aim of minimising the degree of lateral lean required, and placing less stress on the ankles (Greene, 1987).

Whilst Churchill et al. (2018) provided fundamental insights of the effects of lane radius on radii representative of outdoor competition, these are typically over double that of indoor tracks (14-21 m vs 36.5-45 m). Additionally, the bias between lanes has been suggested to be greater during indoor bend sprinting (Usherwood & Wilson, 2006). Despite the greater turning demands and three-dimensional nature of indoor bend sprinting, only sagittal plane variables have been reported on conditions representative of indoor competition (Ryan & Harrison, 2003). Ryan & Harrison (2003) report greater knee flexion during the ground contact periods in the ‘Indoor 1’ lane compared with ‘Outdoor 8’. Further, this trend of more knee flexion in the inner lane was more apparent in the L-R knee compared to the R-L. However, the authors reported no significant main effects for bend radius for knee, thigh or ankle joint amplitudes. Ryan & Harrison’s (2003) study highlighted potential inter-limb asymmetry in knee joint kinematics that was present primarily on the banked indoor bends, which may indicate that asymmetry increases because of the tighter bend radii and or lateral banking.

Previous research has highlighted that lateral banking improves performances measures (Barnes & Malcata, 2017; Greene, 1987). However, few studies describe changes in technique as a result of lateral banking that may contribute to improvements in performance, nor have they associated these with increased or decreased risk of injury. One study that is somewhat representative of a flat versus banked bend sprint comparison is, Luo & Stefanyshyns (2012b) investigation into the effect of laterally raised footwear. Luo & Stefanyshyn, (2012b) changed the angle at the calcaneus by 7.3° (to align the ankle closer to its neutral position in the frontal plane during counter-clockwise bend sprinting). The laterally raised footwear reduced peak L-R step eversion by 4.2 ° ($p < 0.0001$) in comparison to a flat shoe when performing maximal sprints on a 2.5 m radius. Furthermore, GRF was applied more effectively, with greater peak plantar-flexion moments (18.8%) and significantly greater centripetal force produced contributing to a 4.3% increase in bend sprint speed. Whilst providing good information, these methods are not representative of indoor competition and provide no information on the outside limb (R-L step when sprinting counter-clockwise). Willwacher et al. (2013) investigated the effects of 6° of lateral elevation during linear running, finding that the point of force application drifted 1–1.5 cm laterally. Further, Willwacher et al. (2013) found external eversion moments at the ankle were significantly increased by 35% when on the 6 ° surface, suggesting that lateral elevation increased the frontal plane demands at the ankle. Contrastingly, during banked cutting manoeuvres, Wannop et al. (2014) found increased eversion but reduced frontal plane joint loading in comparison to a flat condition. Furthermore, the authors highlighted an orientation of the ground reaction force vector during a 10° banked cutting manoeuvre to point in a more favourable direction, coupled with greater loading in the sagittal plane at the ankle and the knee, suggesting that the laterally banked surface provided some evidence for potential increases in performance as well as reduced injury risks. Whilst not representative of lateral banking and bend sprinting observed in athletics, these studies highlight how a laterally raised surface can impact kinematics and kinetics during bend sprinting (Luo & Stefanyshyn, 2012b), linear running (Willwacher et al., 2013) and cutting manoeuvres (Wannop et al., 2014).

Therefore, investigations into lower-limb kinematics during indoor bend sprinting can aid coaches and practitioners understanding of the movement patterns associated with negotiating tight radii at high-velocities and the technique adaptations during bend sprinting on flat and banked lane radii representative of indoor competition.

5.1.1 Aim & Research Questions

The aim of this Chapter was to investigate the effect of lane radius and lateral banking on body lateral lean and lower-body kinematics during bend sprinting on conditions representative of indoor competition. The answering of Research Questions 5.1-5.4 will achieve the aim of the Chapter. The purpose of this Chapter was to increase understanding of the joint kinematic adaptations on different conditions typical of indoor competition. Greater understanding of the changes in technique that contribute to the changes in step characteristics observed in Chapter 4 will help to inform coaching and physical preparation for bend sprinting.

RQ5.1: What are the within-limb effects of lateral banking on joint kinematic variables when bend sprinting?

RQ5.2: What are the within-limb effects of lane radius on joint kinematic variables when bend sprinting?

RQ5.3: What are the effects of lane radius and lateral banking on inter-limb differences in joint kinematic variables when bend sprinting?

5.1.2 Hypotheses

Based on the previous literature investigating lane radius on outdoor (Churchill et al., 2018) and small radii (Chang & Kram, 2007; Luo & Stefanyshyn, 2012b) the following hypotheses were made:

H5.1: Joint kinematics would undergo greater adaptations in the frontal and transverse planes in flat conditions compared to banked conditions.

H5.2: Joint kinematics would be similar in tighter radii in comparison to less tighter radii.

H5.3: Inter-limb differences would increase on flat compared with banked running and on tighter radii versus greater radii.

5.2 Methods

5.2.1 Participants

Following institutional ethical approval, six male and two female participants provided informed consent (Mean ± SD: Age = 19.8 ± 2.1 years, Mass = 69.8 ± 10.2 kg, Height = 175.8 ± 8.1 cm). Participants were well-trained long sprinters (200 – 400 m) with 200 m personal best race times of 23.05 ± 0.86 s and 25.49 ± 0.91 s for males and females respectively. Full participant details can be found in section 4.2.1.

5.2.2 Experimental Set up

The experimental set-up is provided with full details of the adapted Vicon Plug-in Gait marker (Judson et al., 2018) in section 4.2.2.

5.2.3 Protocol

Full experimental protocol can be found in section 4.2.3.

5.2.4 Data Processing

The same data processing procedures for gap filling, and filtering as reported in 4.2.4 were used. For kinematic analysis, additional data processing procedures are described within this section.

Functional hip and knee joint centres were determined using the method described by Begon et al. (2007), using a hip range of motion trial where participants underwent repeated flexion-extension, abduction-adduction, and circumduction. For the knee joint, functional dynamic squat trials were undertaken.

Joint angles were defined using the distal segment relative to the proximal segment. Joint rotations were determined using Cardan sequencing, where motion about the X axis was defined as flexion/extension at the hip and knee and plantar flexion/dorsiflexion at the ankle. Motion about the Y axis was defined as abduction/adduction at the hip and knee and inversion/eversion at the ankle. Motion about the Z axis was defined as internal/external rotation. Stance phases were normalised to 101 data points via linear interpolation.

Body lateral lean was calculated as described by Judson (2019) using custom MATLAB code, (MathWorks 2020b) where two progression matrices were created. Firstly, a centre of mass (CoM) progression coordinate system was defined using the horizontal progression vector divided by its norm, giving i, representing forward progression. Vertical progression, represented by j was defined as [0 1 0] and the cross-product of forward (i) and vertical (j) to give unit vector k (mediolateral progression), as shown in [4.1].

$$PROG = \begin{bmatrix} ix\ iy\ iz \\ jx\ jy\ jz \\ kx\ ky\ kz \end{bmatrix} \qquad [4.1]$$

Secondly a body coordinate system was created [4.2], i from the CoM progression coordinate system represented i in the body coordinate system. A temporary unit vector j (vertical) was created by subtracting the second metatarsal head position from the CoM position and divided by its norm. Vector k (mediolateral) was then created using the cross-product of i and j. Next, j was then recalculated as the cross product of k and i.

$$BODY = \begin{bmatrix} ix\ iy\ iz \\ jx\ jy\ jz \\ kx\ ky\ kz \end{bmatrix} \qquad [4.2]$$

The rotation matrix (RTM) used to calculate body lateral lean was defined as:

$$RTM = [BODY] * ([PROG]') \qquad [4.3]$$

It was then possible to solve for body lateral lean:

Body lateral lean = $\sin^{-1}$(RTM (2,3)) [4.4]

Body lateral lean was calculated at touchdown (TD) and toe-off (TO) in order to enable comparison with previous research (Churchill et al., 2015, 2018; Judson, et al., 2020b).

Since the aim of this study of this Chapter was to investigate the effect of lane radius and lateral banking on body lateral lean and lower-body kinematics during bend sprinting. Figures 5.1-5.4 demonstrate how body lateral lean is interpreted on flat and banked conditions. During linear running, athletes exhibit minimal body lateral lean, thus, Figure 5.1 shows an athlete sprinting along the straight. The angle formed between the vectors that connect the whole-body CoM and the second metatarsal head (point of foot contact) and the vertical, (the vertical represents perpendicular to the global horizontal plane, in this example the unbanked track surface) in this example is a zero-degree lean.

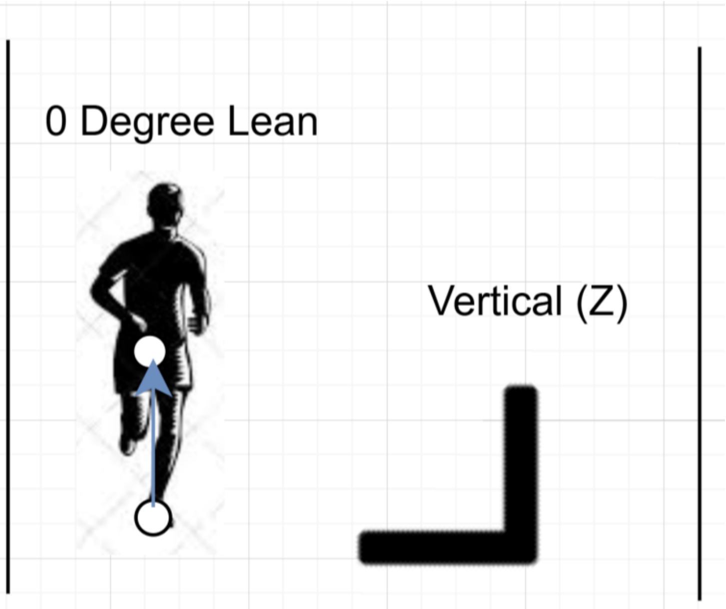


Figure 5.1. An athlete sprinting along the straight at the point of right foot touchdown. The white markers represent the second metatarsal head position (distal marker) and the CoM position (proximal marker), with the blue line representing the connecting vector. The axis represents the global coordinate system.

Figure 5.2 shows the athlete running on a flat bend, the angle formed between the vectors connecting the whole-body CoM and the second metatarsal head, and the vertical, (the vertical being perpendicular to the global horizontal plane and the unbanked track surface) in this example is 20 °.

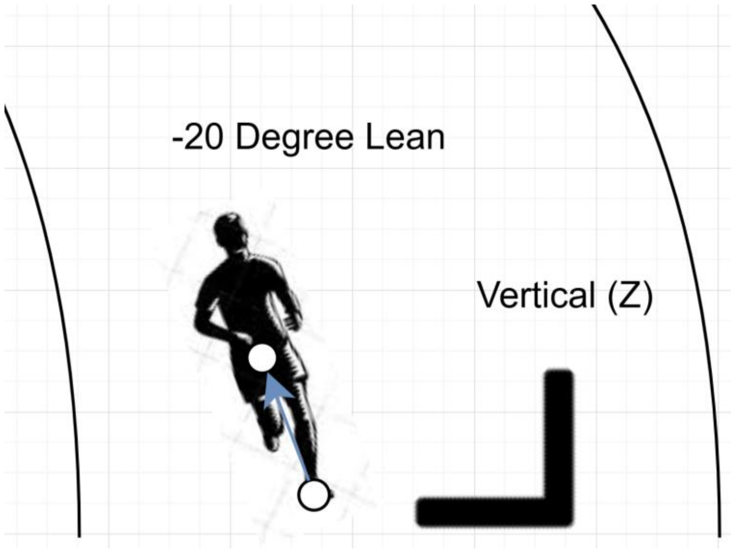


Figure 5.2. A flat (unbanked) bend with athlete following the path of the bend, at the point of right foot touchdown. The white markers represent the second metatarsal head position (distal marker) and the CoM position (proximal marker), with the blue line representing the connecting vector. The axis represents the global coordinate system.

Figure 5.3 shows the angle formed between the vectors connecting the whole-body CoM and the second metatarsal head position, and the vector running perpendicular to the banked track surface (representing the 'vertical' vector) in this example is 10 °.

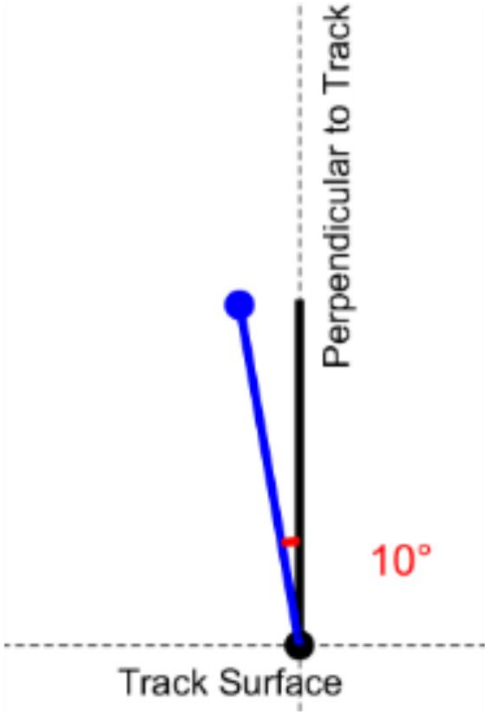


Figure 5.3. A -10° angle between the vector perpendicular to the track surface (black line) and the vector connecting the second metatarsal head (black marker) and CoM (blue marker) forming a -10° angle for body lateral lean (blue line and red curved line). The horizontal dashed line represents the track surface, while the vertical dashed line is perpendicular to the track surface in both banked and flat conditions.

Figure 5.4 shows a banked bend with athlete following the path of the bend, at the point of right foot touchdown. Due to the track banking being 10 °, the angle formed between the vectors connecting the whole-body CoM and the second metatarsal head (point of foot contact) and the vector that is perpendicular to the global horizontal plane (representing the vertical vector) is 20 °. The example in Figure 5.4 gives the same overall global lean angle as Figure 5.2. Since the body lateral lean angle is formed between the vectors connecting the centre of mass, and the vector running perpendicular to the track surface (which is banked 10 °), this represents the magnitude of body lateral lean undertaken by the athlete. Thus, the data presented in section 5.3 refers to the body lateral lean angle, rather than the total global lean angle (which includes the banking angle).

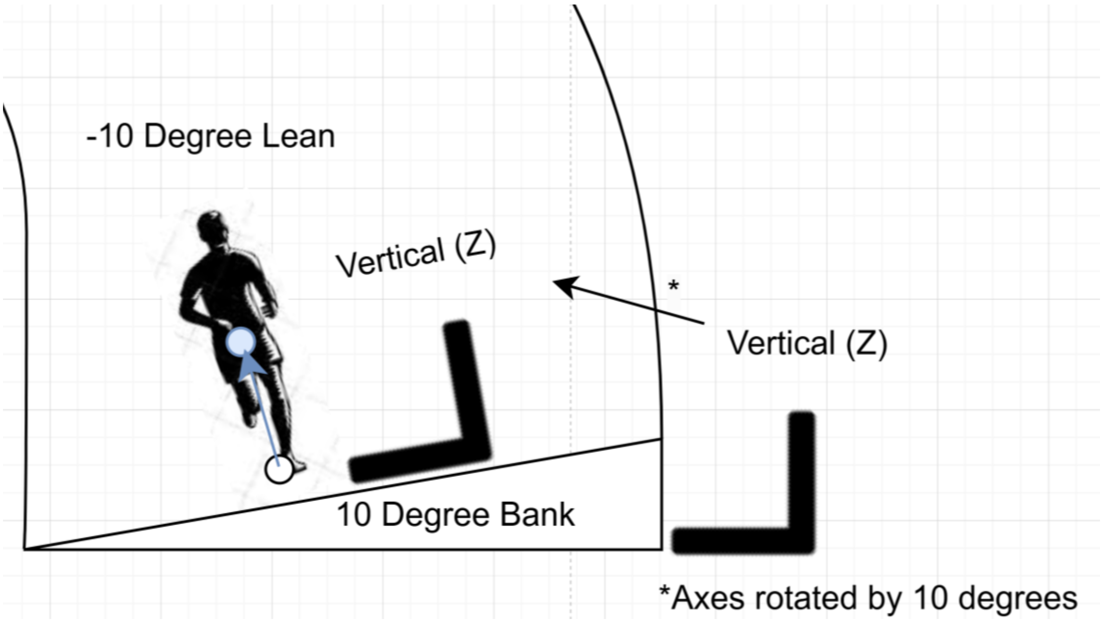


Figure 5.4 A banked bend with athlete following the path of the bend, at the point of right foot touchdown. The white markers represent the second metatarsal head position (distal marker) and the CoM position (proximal marker), with the blue line representing the connecting vector. The axis represents the global coordinate system.

5.2.5 Statistical analysis

Discrete variables

Group descriptive data (mean ± SD) were calculated for all variables and checked for normal distribution using the Shapiro–Wilk statistic. To determine the difference between the four lane conditions and between limbs within each lane: a two-way ANOVA with two within-subjects' factors was conducted to analyse each variable, considering different lane conditions (Lane 2 and Lane 4 - flat and banked) and between limbs (L-R and R-L within each lane condition). This was repeated for body lateral lean at touchdown and toe-off. Partial-eta squared η^2 was used to determine omnibus effect size and was interpreted with the suggested norms: small = 0.01; medium = 0.06; large = 0.14 (Field, 2005). Post-hoc paired-t tests were run to identify where differences between conditions (within limb) existed. Further paired-t tests were run to assess between limb differences in each condition. A Bonferroni correction was applied to account for multiple tests. Effect sizes were calculated using Hedges G to account for small sample size and were interpreted with the suggested norms: trivial = < 0.20; small = 0.20 ≥ 0.50; moderate = 0.50 ≥ 0.80; large = ≥ 0.80 (Cohen, 2013).

Continuous Variables

To determine the interaction between lane conditions (banked Lane 2 and Lane 4 and flat Lane 2 and Lane 4), and limb (L-R and R-L), two-way repeated measures ANOVA were run using one-dimensional Statistical Parametric Mapping (Pataky et al., 2013). This was repeated for sagittal, frontal and transverse axes for the hip, knee and ankle joints. To identify any differences between conditions post-hoc paired t-tests were run with Bonferroni correction applied to account for multiple tests (Pataky et al., 2013). To test between limbs within a condition, further paired-t tests were run. A criterion alpha of 0.05 was set a priori for all statistical tests whilst a minimum of five subsequent clusters (five continuous percent of the stance phase) was set as a threshold above which clusters were deemed to be meaningful (Colyer et al., 2018).

5.3 Results

5.3.1 Body Lateral Lean

The mean ± SD for body lateral lean at TD and TO across all conditions are presented in Table 5-3. For body lateral lean at TD a significant limb*condition interaction was observed (F (3) = 5.31; $p = 0.007$; η2 = 0.43), whilst significant main effects were observed for limb (L-R > R-L; F (1) =; 32.38; $p = 0.001$; $\eta^2 = 0.82$) and for condition (F (3) = 27.88; $p < 0.001$; $\eta^2 = 0.80$). Significant post-hoc comparisons for within-limb between lanes can be seen in

. For the effect of limb within each condition: body lateral lean at L-R TD was significantly greater (more inward toward the bend) than at R-L TD in Lane 2 Bank (p = 0.002; ES = 1.66), Lane 4 Bank ($p = 0.001$; ES = 1.44) and Lane 4 Flat ($p = 0.012$; ES = 0.64), but not in Lane 2 Flat ($p > 0.05$; ES = 0.16).

Table 5-1. Statistically significant comparisons of body lateral lean at touchdown (TD) across conditions, for the left to right (L-R) and right to left (L-R) steps.

Limb	**Lane Comparison**	**P value**	**ES**	**Direction**
L-R	Lane 2 Flat vs Lane 2 Bank	0.009	1.79	Lane 2 Flat > Lane 2 Bank
L-R	Lane 4 Flat vs Lane 2 Bank	0.012	1.50	Lane 4 Flat > Lane 2 Bank
L-R	Lane 2 Flat vs Lane 4 Bank	0.006	1.99	Lane 2 Flat > Lane 4 Bank
L-R	Lane 4 Flat vs Lane 4 Bank	0.019	1.78	Lane 4 Flat > Lane 4 Bank
R-L	Lane 2 Flat vs Lane 2 Bank	0.001	2.61	Lane 2 Flat > Lane 2 Bank
R-L	Lane 4 Flat vs Lane 2 Bank	0.005	2.10	Lane 4 Flat > Lane 2 Bank
R-L	Lane 2 Flat vs Lane 4 Bank	0.002	2.66	Lane 2 Flat > Lane 4 Bank
R-L	Lane 4 Flat vs Lane 4 Bank	0.007	2.29	Lane 4 Flat > Lane 4 Bank
R-L	Lane 2 Flat vs Lane 4 Flat	0.006	0.81	Lane 2 Flat > Lane 4 Flat

For body lateral lean at TO, no significant limb*condition interaction was observed (F (3) = 1.16; p = 0.35 η2 = 0.15). Significant main effects for limb (L-R > R-L; F (1) =28.28; $p < 0.001$; $\eta^2 = 0.80$) and condition (F (3) = 31.90; $p < 0.0001$; $\eta^2 = 0.82$) were observed. Significant post-hoc comparisons for within-limb between lanes can be seen in Table 5-2. For the effect of limb within each condition: L-R body lateral lean at TO was significantly greater than R-L in all conditions (all $p < 0.05$; ES = 0.35-1.87).

Table 5-2. Statistically significant comparisons of body lateral lean at touchdown (TD) across conditions, for the left to right (L-R) and right to left (L-R) steps. The table presents the p values, effect sizes (ES), and direction of differences for each comparison.

Limb	**Lane Comparison**	**P value**	**ES**	**Direction**
L-R	Lane 2 Flat vs Lane 2 Bank	0.010	1.78	Lane 2 Flat > Lane 2 Bank
L-R	Lane 4 Flat vs Lane 2 Bank	0.015	1.61	Lane 4 Flat > Lane 2 Bank
L-R	Lane 2 Flat vs Lane 4 Bank	0.003	2.31	Lane 2 Flat > Lane 4 Bank
L-R	Lane 4 Flat vs Lane 4 Bank	0.003	2.32	Lane 4 Flat > Lane 4 Bank
L-R	Lane 2 Flat vs Lane 4 Flat	0.002	0.44	Lane 2 Flat > Lane 4 Flat
R-L	Lane 2 Flat vs Lane 2 Bank	<0.001	2.59	Lane 2 Flat > Lane 2 Bank
R-L	Lane 4 Flat vs Lane 2 Bank	0.005	2.03	Lane 4 Flat > Lane 2 Bank
R-L	Lane 2 Flat vs Lane 4 Bank	<0.01	2.72	Lane 2 Flat > Lane 4 Bank
R-L	Lane 4 Flat vs Lane 4 Bank	<0.01	2.26	Lane 4 Flat > Lane 4 Bank
R-L	Lane 2 Flat vs Lane 4 Flat	0.004	0.71	Lane 2 Flat > Lane 4 Flat

Table 5-3. Mean ± SD for all body lateral lean at touchdown (TD) and toe-off (TO) for the L-R and R-L steps across Banked and Flat conditions.

Variable	Lane 2 Bank		Lane 4 Bank		Lane 2 Flat		Lane 4 Flat	
	L-R	R-L	L-R	R-L	L-R	R-L	L-R	R-L
Lean at TD	-11.13 ± 2.43 $^{B\,C\,G}$	-7.71 ± 1.29 $^{B\,C\,G}$	-9.69 ± 2.39 $^{D\,E\,G}$	-5.91 ± 2.44 $^{D\,E\,G}$	-18.80 ± 5.33$^{B\,D}$	-17.89 ± 5.22 $^{B\,D\,F}$	-16.80 ± 4.46 $^{C\,E\,G}$	-14.02 ± 3.81 $^{C\,E\,F\,G}$
Lean at TO	-10.64 ± 2.40 $^{B\,C\,G}$	-6.86 ± 1.27 $^{B\,C\,G}$	-8.28 ± 2.10 $^{D\,E\,G}$	-5.33 ± 2.20 $^{D\,E\,G}$	-18.27 ± 5.33 $^{B\,D\,G}$	-16.36 ± 4.90 $^{B\,D\,F\,G}$	-16.14 ± 3.87 $^{C\,E\,F\,G}$	-13.07 ± 3.89 $^{C\,E\,F\,G}$

* key ^{A} = difference between Lane 2 Bank V Lane 4 Bank, ^{B} = difference between Lane 2 Bank V Lane 2 Flat, ^{C} = difference between Lane 2 Bank V Lane 4 Flat, ^{D} = difference between Lane 4 Bank V Lane 2 Flat, ^{E} = difference between Lane 4 Bank V Lane 4 Flat, ^{F} = difference between Lane 2 Flat V Lane 4 Flat, ^{G} = difference between LVR within condition.

5.3.2 Hip kinematics

L-R versus R-L hip joint kinematics within each lane are displayed in Figure 5.. Two-way repeated measures using SPM revealed no significant limb*condition interaction or main effects in sagittal hip kinematics.

For frontal plane hip kinematics, a significant limb*condition interaction was observed for the entirety of the stance phase (F = 9.01 ;0-100%; $p < 0.001$), with a significant main effect for limb occurring from 28 – 84% (F = 10.58; $p < 0.001$). For the effect of condition, no main effect was observed (F = 4.56; $p > 0.05$). Post-hoc testing for the effect of limb, showed significantly greater adduction for the L-R hip compared to the R-L hip in Lane 2 Flat (F = 4.91; 14 – 91%; $p < 0.001$) and Lane 4 Flat (F = 4.90; 33 – 93%; $p < 0.001$).

For transverse hip kinematics, no significant interaction or main effect for condition was observed whilst a significant main effect for limb was observed (F = 9.93; 70 – 100; $p < 0.001$). Pairwise differences were observed with greater external rotation during R-L stance than L-R in Lane 2 Flat (F = 4.83; 64 – 100; $p < 0.001$) and Lane 2 Bank (F = 4.94; 81-94%; $p < 0.001$).

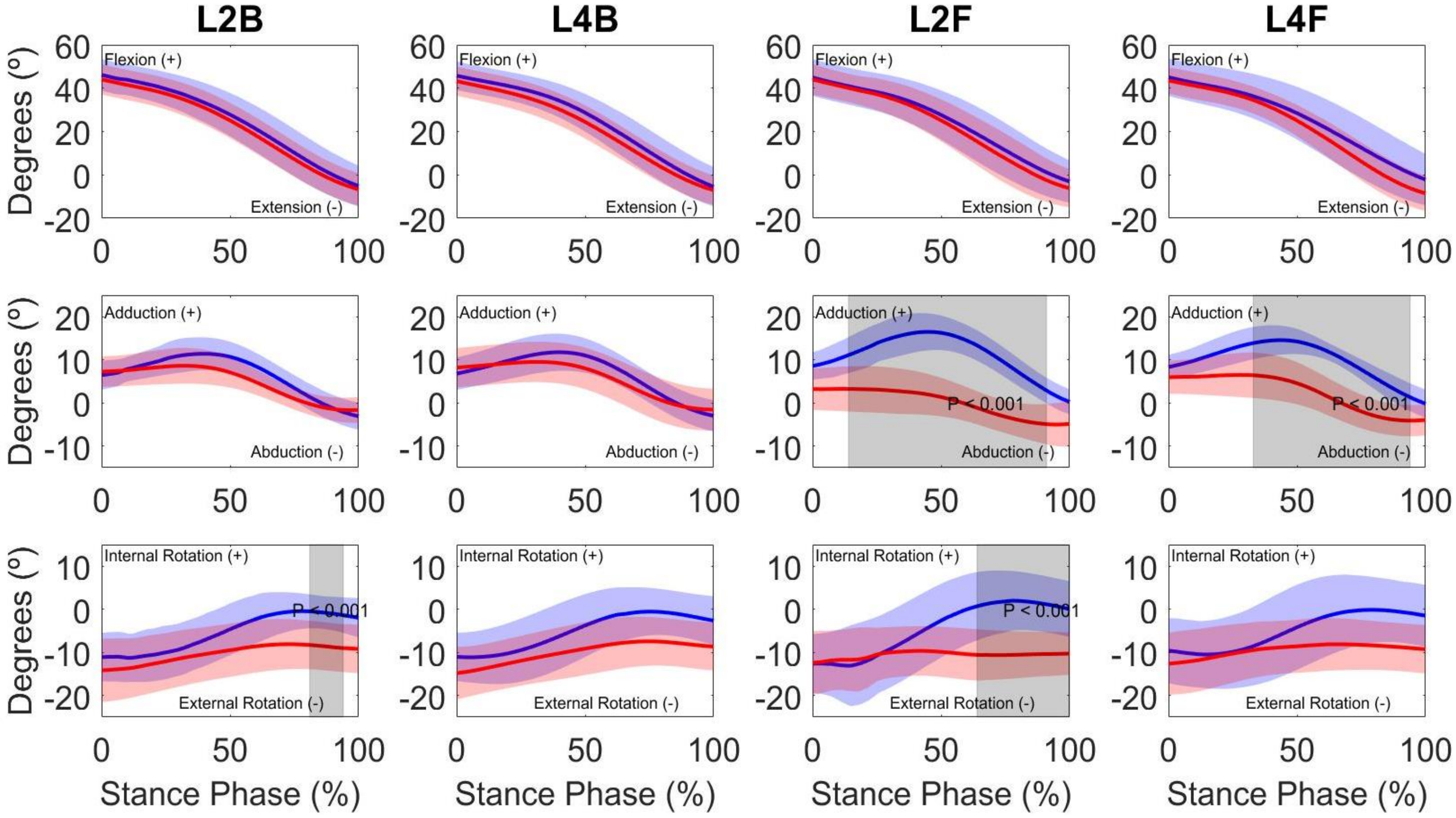


Figure 5.5. R-L (Red) and L-R (Blue) mean (solid line) ± standard deviation (shaded area) for Sagittal (top row), frontal (middle row) and transverse (bottom row) hip joint kinematics during the stance phase. Grey shaded area represents supra-threshold clusters determined using SPM indicating a significant difference between R-L and L-R.

5.3.3 Knee kinematics

L-R versus R-L knee joint kinematics within each lane are displayed in Figure 5.. SPM revealed a significant limb*condition interaction in sagittal knee kinematics where the critical threshold of F = 4.67 was exceeded between 8-47% (F =4.70; p = 0.00089) and 82-100% (F = 4.70; p < 0.001), whilst no pairwise differences were observed.

For frontal knee kinematics, no significant limb*condition interaction was observed, however, a main effect for limb was observed from early to mid-stance (L-R > R-L; F = 12.00; 20-70%; p = 0.00089). Post hoc tests revealed more adduction for the L-R knee in Lane 2 Flat than R-L across two supra-threshold clusters (F =5.21; 2-79% p = < 0.001), however the second of these (F = 5.24; 88- 92%; p < 0.001) did not exceed the 5 threshold cluster deemed to be meaningful (Colyer et al., 2018). Additionally, greater adduction was observed in L-R stance than during R-L stance in Lane 2 Bank (F = 5.17; 2-70%; p < 0.001) and in Lane 4 Bank (F = 5.08; 20-54%; p < 0.001).

For transverse knee kinematics, no significant limb*condition interaction or main effects were observed.

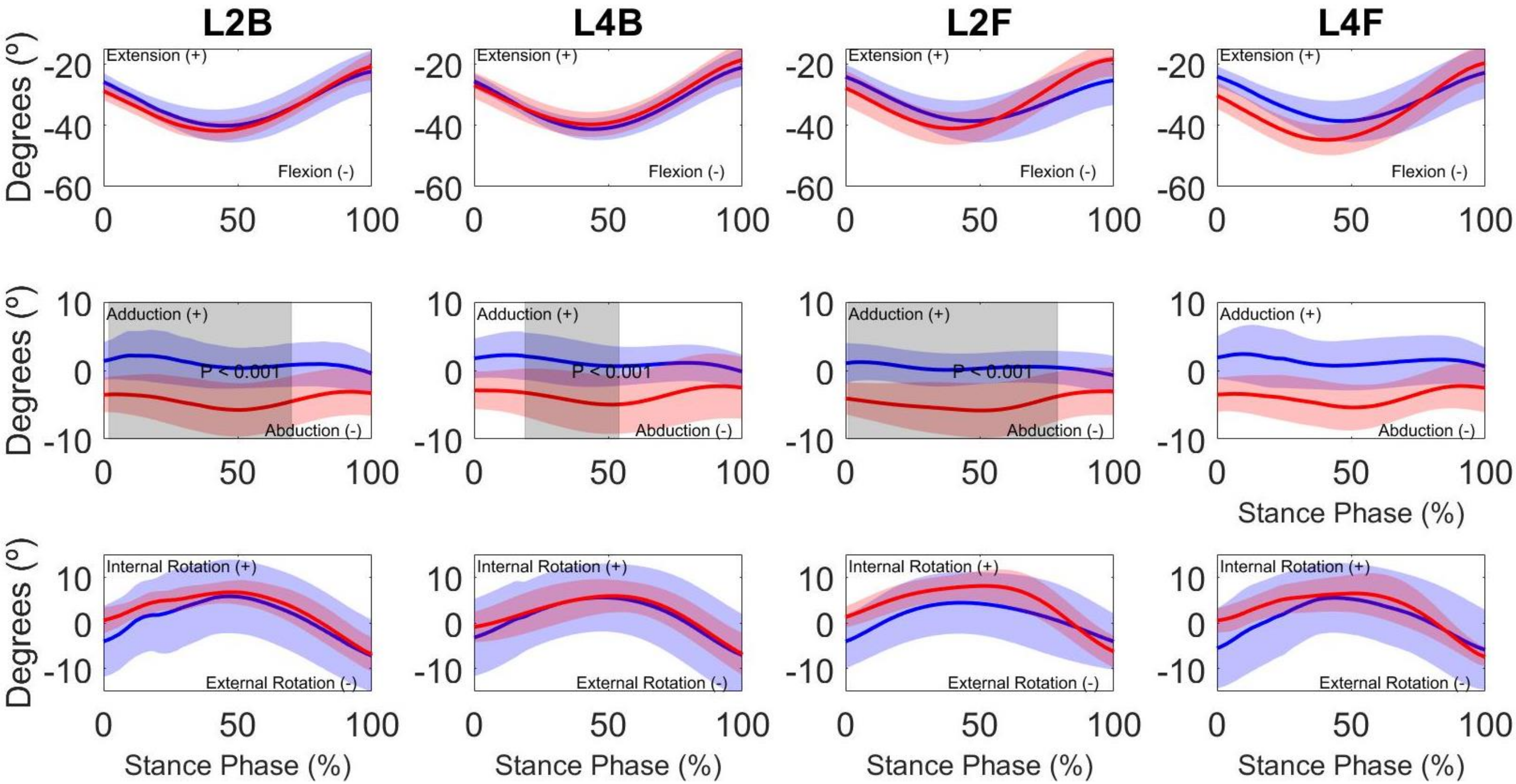


Figure 5.6. R-L (Red) and L-R (Blue) mean (solid line) ± standard deviation (shaded area) for Sagittal (top row), frontal (middle row) and transverse (bottom row) knee joint kinematics during the stance phase. Grey shaded area represents supra-threshold clusters determined using SPM indicating a significant difference between R-L and L-R.

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5.3.4 Ankle kinematics

L-R versus R-L ankle joint kinematics within each lane are displayed in Figure 5.7. SPM revealed a significant limb*condition interaction in sagittal ankle kinematics where the critical threshold of F = 4.84 was exceeded between 21-60% ($p < 0.001$), no main effects were observed for limb or condition ($p > 0.05$). Post-hoc testing showed for L-R v R-L: one supra-threshold cluster was observed during late stance in Lane 2 Flat (F = 5.24; 96-100%; $p < 0.001$) where more plantar-flexion was observed for the R-L step, however this cluster fell below the minimum duration of five percent of significant difference threshold deemed to be meaningful (Colyer et al., 2018).

For frontal plane ankle kinematics, a significant limb*condition interaction was observed (F = 39.6; 0 – 100%; $p < 0.001$) along with significant main effects of limb (F = 183; 0 – 100%; $p < 0.001$) and condition (F = 4.00; 0-12% & 62-94%; $p < 0.001$). Post hoc comparisons for within limb between lane comparisons can be seen in Table 5-4. For the effect of between limb within conditions can be seen on Figure 3: significantly greater eversion during L-R stance compared to the R-L in Lane 2 Bank (F = 12.54; 0-100%; $p < 0.001$), Lane 4 Bank (F = 9.11; 0-100%; $p < 0.001$), Lane 2 Flat (F = 18.10; 0- 100%; $p < 0.001$) and, Lane 4 Flat (F = 12.18; 0-100%; $p < 0.001$).

Table 5-4. Statistically significant comparisons of ankle inversion/eversion across conditions, for the left to right (L-R) and right to left (L-R) steps.

Limb	Lane Comparison	Percentage of Stance Significant	P value	Direction
L-R	Lane 2 Flat vs Lane 2 Bank	0-100%	<0.001	Lane 2 Flat > Lane 2 Bank (more eversion)
L-R	Lane 4 Flat vs Lane 2 Bank	5-88%	<0.001	Lane 4 Flat > Lane 2 Bank (more eversion)
L-R	Lane 2 Flat vs Lane 4 Bank	0-100%	<0.001	Lane 2 Flat > Lane 4 Bank (more eversion)
L-R	Lane 4 Flat vs Lane 4 Bank	0-98%	<0.001	Lane 4 Flat > Lane 4 Bank (more eversion)
R-L	Lane 2 Flat vs Lane 2 Bank	5-100%	<0.001	Lane 2 Flat > Lane 2 Bank (more inversion)
R-L	Lane 4 Flat vs Lane 2 Bank	17-83%	<0.001	Lane 4 Flat > Lane 2 Bank (more inversion)

R-L	Lane 2 Flat vs Lane 4 Bank	0-100%	<0.001	Lane 2 Flat > Lane 4 Bank (more inversion)
R-L	Lane 4 Flat vs Lane 4 Bank	0-100%	<0.001	Lane 4 Flat > Lane 4 Bank (more inversion)

For transverse plane ankle kinematics, a significant limb*condition interaction was observed (F = 4.86; 42-94%; $p < 0.001$). Post-hoc tests showed more external rotation occurred during L-R stance than R-L in Lane 2 Flat between 74 -94% of stance (F = 5.41 $p < 0.001$).

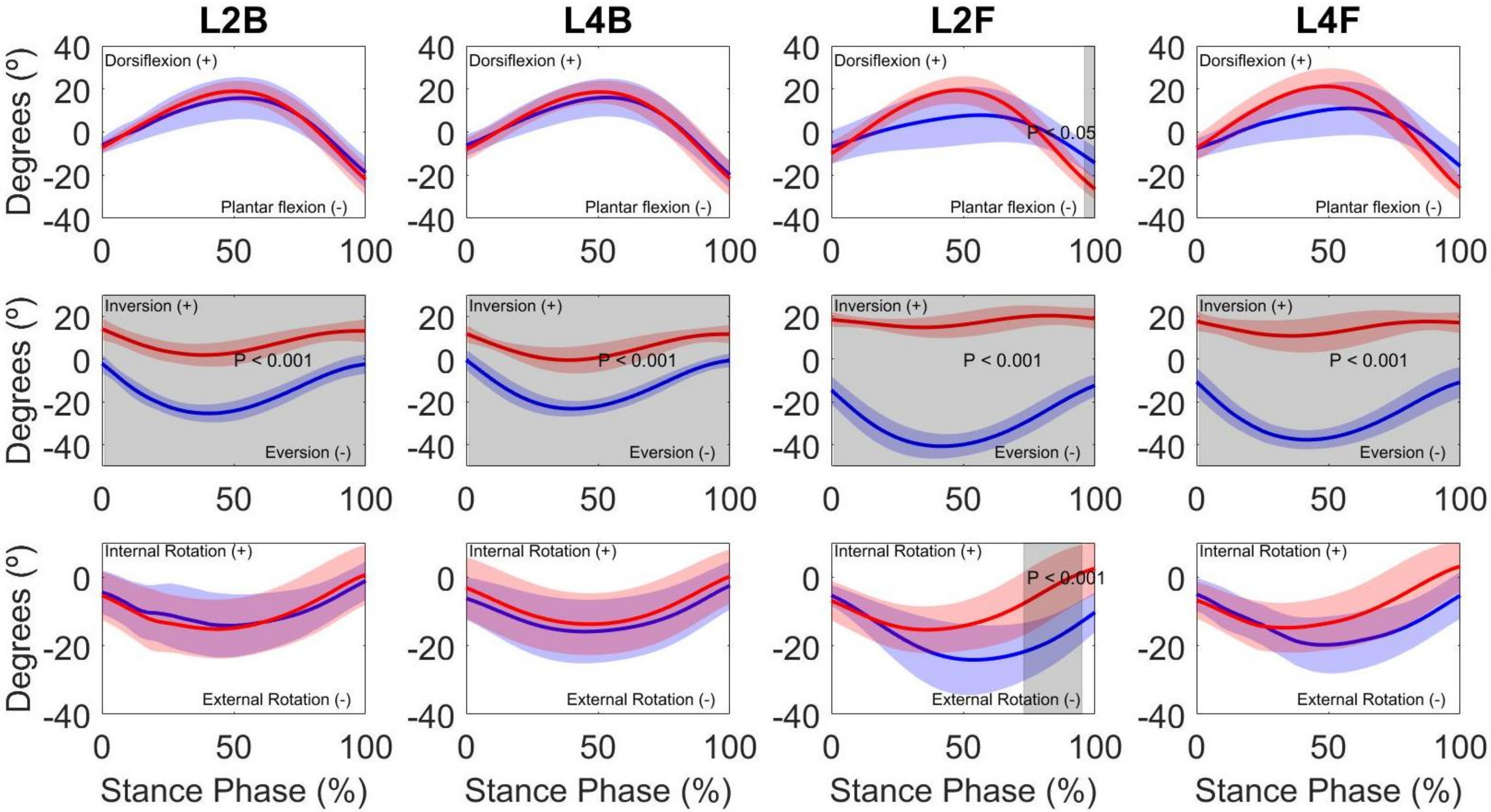

Figure 5.7. R-L (Red) and L-R (Blue) mean (solid line) ± standard deviation (colored shaded areas) for Sagittal (top row), frontal (middle row) and transverse (bottom row) plane ankle joint kinematics during the stance phase. Grey shaded area represents supra-threshold clusters determined using SPM indicating a significant difference between R-L and L-R.

5.4 Discussion

Chapter 4 identified that the relationship between SV and radius may not follow the traditional pattern of reduced SV on a less tight bend radii when sprints were undertaken on a laterally banked track, furthermore SV were non-significantly increased by sprinting on the banked bend in comparison to the flat. To complete Phase 1 by explaining the changes in step characteristics as a result of changing the banking and radius: the aim of this Chapter was to investigate the effect of lane radius and lateral banking on body lateral lean and lower-body kinematics during the stance phase. Thus, the purpose was to increase understanding of the joint kinematic adaptations that contribute to the changes in performance during bend sprinting on conditions typical of indoor competition to inform coaching on the prescription of bend sprint training.

5.4.1 RQ5.1: What are the effects of banking on within-limb joint kinematic variables when bend sprinting?

Previous research has highlighted that peak velocities and performance times are greater in banked conditions compared to the flat (Barnes & Malcata, 2017; Greene, 1987). This was supported in Chapter 4, with faster SV in the banked condition than flat (significant for the L-R in Lane 2 Bank). Nonetheless, research has yet to highlight the kinematic adaptations that may explain some of the differences in performance between flat and banked bends representative of indoor competition. For both the L-R and R-L steps, body lateral lean at TD and TO were significantly greater (more inward) in Lane 2 Flat and Lane 4 Flat compared to Lane 2 Bank and Lane 4 Bank. Therefore, when sprinting on a flat track, athletes must produce significantly more body lateral lean relative to the track surface than on the banked track. The greater body lateral lean coincided with greater adaptations in the frontal plane, for example, greater L-R hip adduction was observed between 38-70% in Lane 2 Flat compared to Lane 2 Bank and between 61 – 70% in Lane 4 Flat compared to Lane 4 Bank. Greater L-R hip adduction was coupled with greater L-R eversion in flat compared to banked for almost entire stance (Figure 5.7). Additionally, more inversion was observed for almost the entire R-L stance in Lane 2 Flat than Lane 2 Bank (5- 100%). Consequently, H5.1 can be accepted. Previous research has highlighted that there may be an association between the three-dimensional nature of bend sprinting that impact muscles acting in the sagittal plane, and injuries to the plantaris and or Achilles tendon (Pollock et al., 2016). Thus, the large inversion angles observed during R-L stance in Lane 2 Flat may be a risk factor for injury.

Previous research has suggested that lateral banking minimises the body lateral lean required to maintain high velocities and reduce ankle eversion (Luo & Stefanyshyn, 2012b; Neie, 1981;

Willwacher et al., 2013). For instance, in agreement with the present study, Luo & Stefanyshyn, (2012b) found a laterally wedged footwear to significantly reduce L-R maximum eversion by 4.2°, and, improve sprinting speed by 4.3% in comparison to a flat shoe whilst sprinting maximally around a 2.5 m radius bend. A neutral ankle position likely reduced hip adduction and body lean, enabling greater force production and performance (Luo & Stefanyshyn, 2012b). Therefore, lateral banking appears to improve athletes' ability to reach high velocities by minimising body lateral lean, which in turn reduces further kinematic alterations in the frontal plane. One potential reason for this is greater body lean, adduction and inversion/eversion may induce pushing off the less effective oblique axis of the MTP joint as previously observed during the acceleration phase on the bend (Judson et al., 2019). A small cluster of less plantar-flexion for the L-R limb was observed during TO (96 – 100%) in Lane 2 Flat, suggesting that the L-R limb was in a less favourable position to produce propulsive forces and fully extend through TO. Despite occurring at an important period of the stance phase, this finding should be interpreted with caution as it has previously been suggested that in SPM analysis, clusters less than five nodes are unlikely to be meaningful (Colyer et al., 2018).

Greater frontal plane alterations on flat bends may impair muscles working in the sagittal plane (Coqueiro et al., 2005), and thus potentially reducing sprint velocities. Additionally, Churchill et al. (2016) proposed that increased body lateral lean may limit the amount of space in relation to the CoM, with less space to extend fully during the flight phase leading to earlier contact and larger braking forces. Furthermore, Ohnuma et al. (2018) suggests more effective bend sprinters (defined as: less discrepancy in bend sprinting velocity in relation to linear sprinting velocity) are able to maintain similar sagittal kinematics on the bend to that on the straight. Nonetheless, in the present study, no main effects for condition or pairwise differences between flat and banked were observed for sagittal plane kinematics. However, the present study only considered stance phase kinematics. Whilst previous research has highlighted minimal difference between swing phase kinematics between bend and straight (Ishimura & Sakurai, 2018), differences in swing phase kinematics may provide some explanation for the differences in SV between flat and banked bends representative of indoor competition, where turning demands are greater.

Peak L-R (inside) ankle eversion angles of 23-25° were observed in Lane 2 Bank and Lane 4 Bank respectively, whilst peak values in Lane 2 Flat and Lane 4 Flat were 37-40° for the L-R step, therefore, the use of banked bends has potential for altering injury risks during bend sprinting by reducing peak eversion angles during stance. Previous research has highlighted that excessive eversion and or pronation angles (~ 13°) may lead to injuries (Beukeboom et al., 2000; Clarke et al., 1984). Furthermore, research has associated greater eversion angles and duration of time spent in eversion whilst treadmill running with greater risk of Achilles injury (Becker et al., 2017). Additionally, values in this study exceed those previously reported in the literature, for example: Hamill et al. (1987) reported group mean peak pronation values of L-R: 22.3° and R-L: 12.5°, Smith et al. (2006) reported L-R: 34.0° and R-L: 6.7°, whilst Luo & Stefanyshyn (2012b) reported L-R: 35°. Despite methodological differences, the eversion values reached whilst sprinting on flat radii represent concern for injury. Similar to Luo & Stefanyshyn (2012b), the lateral banking appears to align the ankle joint more favourably by minimising the excessive eversion of the L-R (inside) stance. Consequently, the reduction in eversion angles of ~15° has the potential to minimise frontal and transverse plane stress on joint soft tissues that may increase the likelihood of injury (Stefanyshyn et al., 2006).

5.4.2 RQ5.2: What are the effects of lane radius on within-limb joint kinematic variables when bend sprinting?

For the effect of lane radius, body lateral lean at TD and TO for the R-L step were significantly greater in Lane 2 Flat than Lane 4 Flat. A large effect size was observed at TD (0.81) highlighting that because of greater centripetal force requirements, when changing between Lane 4 Flat and Lane 2 Flat, a greater degree of body lateral lean is required. Furthermore, a trend for non-significantly greater lean at TD and TO for R-L and L-R steps in lane 2 compared to lane 4 banked and flat was observed. Thus, H5.2 is partially accepted for body lateral lean but rejected for lower-extremity joint kinematics, as no differences were found in hip, knee, and ankle kinematics between lanes. Chapter 4 highlighted that minimal changes occurred for the L-R and R-L steps because of the change in radius, with only significantly higher L-R SF in Lane 2 Bank compared to Lane 4 Bank and smaller R-L SL in Lane 2 Flat compared to Lane 4 Flat. Previous research on small (1-6 m) and large (37.72-45.1 m) radii has reported trends for reduced SV and step characteristics as a result of a change in radius (Chang & Kram, 2007; Churchill et al., 2018). Furthermore, in agreement with the present study, Churchill et al. (2018) reports a tendency for more inward lateral lean on tighter radii at TD for both L-R and R-L steps. In order to maintain velocity on tighter radii, greater centripetal force is required with this requiring greater body lateral lean (Neie, 1981). Therefore, it is possible that greater inward lean will minimise the amount of space down the kinetic chain and lead to greater adaptations outside the sagittal plane. However, the change in radius of 2 m between lane 2 and lane 4 may not be enough to alter within limb-between lane differences, or that differences may only be exposed at maximal sprinting velocities. Nevertheless, Beukeboom et al. (2000) proposed that tighter radii would induce greater torsional rolling of the sub-talar joint, in addition to an inward lean, this may result in kinematic adaptations along the kinetic chain. Hamill et al. (1987) found during bend runs that the left foot rotates further to counter body-lateral lean resulting in large pronation values (pronation was defined as where the foot rolls medially to a pronated position). Whilst Lane 2 Flat showed greater body lateral lean requirements in comparison to Lane 4 Flat, no differences in stance phase kinematics were observed between the lane conditions. As suggested by Churchill et al. (2016), greater lean may impact the ability to reset the limb during the swing phase, thus this is an area for future research. Furthermore, greater turning demands during each step have been shown when comparing the outer lanes to inner lanes on an outdoor track, thus, it may be reasonable to predict that when comparing larger changes in radii, that greater frontal and transverse plane joint adaptations are required (Diaz et al., 2024). Moreover, greater turning forces will lead to larger lean angles and with this, greater mediolateral GRF requirements (Chang & Kram, 2007; Diaz et al., 2024; Neie, 1981). This is potentially one of the reasons for the large injury rates seen in athletes regularly training and competing on the bend (Ayres & Gottlieb, 2006; Beukeboom et al., 2000; Pollock et al., 2016).

5.4.3 RQ5.3: What are the effects of lane radius and lateral banking on inter-limb differences in joint kinematic variables when bend sprinting?

There were several differences between L-R and R-L steps across conditions. For example, the flat conditions were typified with greater hip L-R adduction and greater L-R eversion, whilst specific to Lane 2 Flat were greater R-L hip external rotation, greater R-L plantar-flexion (96-100%) and more external rotation of the L-R ankle (74-94%). Interestingly, in the banked conditions, L-R stance displayed greater knee adduction and greater ankle eversion compared to the R-L. In Lane 2 Bank, greater R-L hip external rotation was observed, whilst in Lane 4 Bank, more L-R hip flexion was observed. These results suggest that greater L-R eversion was present in both banked and flat conditions, whilst kinematic asymmetry shifts from the hip on banked conditions to the knee under flat conditions of equal radii. Thus, it is possible that whilst radius may affect within-limb differences minimally, greater inter-limb differences are observed due to tighter radii, therefore, H5.3 for the effect of radius can be accepted. For example, in Lane 2 Flat, the L-R ankle displayed greater external rotation than the R-L but no differences were observed in Lane 4 Flat or the banked conditions. Greater external rotation of the R-L hip occurred in Lane 2 Flat; thus, the external rotation of the L-R limb occurs at the ankle during L-R stance and the hip during R-L stance. This has bearing for force generation, where alteration of joint positions outside the sagittal plane can impact muscle activity in muscles acting within the sagittal plane (Coqueiro et al., 2005). In contrast, Alt et al. (2015) found that the L-R limb appeared to adopt a stabilizing role through hip adduction and eversion whilst the R-L underwent a greater rotational strategy through greater hip and ankle external rotation. Despite this, several studies have reported acute inter-limb asymmetries during bend sprinting, highlighting that the L-R and R-L steps may have functionally different roles (Alt et al., 2015; Churchill et al., 2016; Nevison et al., 2015). However, this study is the first to provide continuous kinematic data across the stance phase on radii representative of indoor competition.

Previous research has suggested that during L-R stance, more turn of the CoM is achieved than R-L across all lanes ($p < 0.01$) during outdoor bend sprinting but that greater body lateral lean for the R-L step was observed across lanes ($p < 0.01$) (Churchill et al., 2018). In the present study however, greater body lateral lean was observed during L-R stance at both TD and TO in Lane 2 Bank, Lane 4 Bank, Lane 4 Flat. Nonetheless, this difference is likely due to the large difference in radius between indoor and outdoor competition, with the tighter indoor radii requiring greater lean during L-R stance to direct ground reaction force centripetally and follow the path of the bend. For the effect of lateral banking on inter-limb differences of body lateral lean, larger ES were observed in the banked conditions (1.29 – 1.87) than the flat conditions (0.16 – 0.75). Therefore, it is possible that lateral banking aids in reducing the overall lateral lean required but increases the differences in body lateral lean between L-R and right foot strikes. Thus, H5.3 for lateral banking on inter-limb differences of body lateral lean, can be rejected.

Previous research has highlighted that the effect of the bend may accumulate as the athlete progresses, with greater kinematic modifications during the maximal speed phase and thus a greater reduction in speed (Judson et al., 2019). Therefore, it was possible that the increase in asymmetry occurred because of difference in progression of the athlete at the point of the capture volume. Despite efforts to standardise starting positions between lanes, the number of the first measured contact for each step are reported in

Table 5-5. In Lane 2 Bank the majority of trials were recorded as L-R to R-L step whilst in Lane 4 Bank trials were primarily R-L to L-R. On the athletics track participants sprinted on the lateral banking at the apex of the bend was 10°. Thus, with SLs of ~2 m, the banking angle will increase from 0 to 10° within 30-35 metres (distance to the apex of the bend), leading to a potential increase in banking of 0.66° per step. This value does not approach the magnitude of difference in body lateral lean between lanes on the banked conditions. Therefore, it is unlikely to have contributed to the increase in inter-limb differences in lane 2 compared to lane 4.

Table 5-5. Number of first foot contact trials by lane condition.

Condition	Left to Right	Right to Left
Lane 2 Bank	12	4
Lane 4 Bank	5	11
Lane 2 Flat	6	9
Lane 4 Flat	6	8

In terms of inter-limb differences and injury risks in well-trained bend sprint athletes, research is beginning to highlight longitudinal asymmetries in relation to strength and injury rates. For example, Pollock et al. (2016) show greater incidence of R-L sided plantaris injuries in an elite cohort of bend sprint athletes, suggesting that due to the rotational demands of the L-R (inside step), the R-L leg is required to generate more propulsive force. This has previously been demonstrated during maximal bend sprints on outdoor radii (Churchill et al., 2016), where the bend did not disrupt vertical or horizontal force production for the R-L step. Recently Diaz et al. (2024) compared 17.2 and 36.5 m radii finding that resultant and vertical GRF were similar for the R-L step despite significantly greater inward force on 17.2 m radius, this differed for the L-R step where resultant and vertical force were reduced on the tighter radii. Therefore, increasing the inward force demands likely restricts propulsive force capabilities. Giakoumis et al. (2020) report significantly greater hamstring eccentric strength for the R-L limb compared to the L-R in long elite sprint athletes, providing some potential evidence of greater propulsive requirements during the R-L step. On the other hand, in a epistemological study of elite sprint athletes, Ayres & Gottlieb, (2006) report that L-R sided hamstring injuries were reported three times per R-L-sided hamstring injury. This increased injury risk may align with the greater frontal plane alterations (hip adduction and ankle eversion) observed during the L-R stance on the flat radii, impacting hamstring muscle activity and force generation during L-R stance (Coqueiro et al., 2005). Beukeboom et al. (2000) reported asymmetrical increases in L-R invertor strength and R-L evertor strength over a 12-week indoor athletics season, with 68% of athletes sustaining lower extremity injuries. Beukeboom et al. (2000) go on to suggest strategies like bidirectional sprinting and using outer lanes to limit asymmetry development.

Despite the reported asymmetries and injuries associated with counter-clockwise bend running, it is not clear how this relates to performance. Ohunuma et al. (2018) suggest that better bend sprinters are those who can maintain sagittal plane kinematics similar to that during linear sprinting. However, the authors do not report frontal or transverse plane kinematics, thus it may be that successful maintaining velocity on the bend is the result of better control of the frontal and transverse plane demands of bend sprinting. Therefore, improved control in these planes may minimise alterations in the sagittal plane and enable more effective force production that contributes to higher velocities on the bend.

Similar to suggestions for minimising injury risk by cautiously reflecting on the rate at which sprint training volume increases (Orendurff et al., 2009), it may be reasonable to suggest that athletes follow a progressive overload approach (Ball & Herrington, 1998) to bend sprint training. A progressive approach could involve avoidance of tight radii during early pre-competition training phases and slowly integrating tighter radii at faster velocities. This has the potential to maintain specificity of training (replication of the motor-skill) and develop bend sprinting capacity but avoid introducing too much asymmetry during the early phases of training. This cycle could be repeated if athletes are competing in both indoor and outdoor athletics seasons (typically January-March and then May-September). Furthermore, as mentioned, the replication of joint positions similar to that achieved during bend sprinting during strength training and or plyometric training may enable athletes to improve bend sprinting performance (Churchill et al., 2016).

5.5 Conclusion

The effect of condition was split into two parts: the effect of lateral banking, where several within-limb differences were observed between flat and banked conditions across the frontal plane and the effect of lane radius, where minimal differences were observed between lane 2 and lane 4: banked or flat. However, the change in radius introduced greater levels of inter-limb differences in the frontal and transverse planes which may contribute to the reduced step velocities observed on tighter radii, and impact injury risks for both left and right limbs.

Except for undersized (< 200 m) indoor tracks, a flat radius of 14.94 m is likely to be close to the tightest radii that athletes will compete on. Therefore, this study provides insight into the acute adaptations across the frontal and transverse planes and the increase in inter-limb differences as complexity of the bend condition increased (tight and flat bend).

Whilst this study provides insight into the asymmetrical acute kinematic adaptations during bend sprinting, future research should seek to further understand the relationship between key variables and performance for both the L-R and the R-L steps, and to investigate the relationship between athlete asymmetry and bend sprinting performance.

5.6 Coaching and Practical Recommendations for Sprinting on Banked Tracks and Tight Radii

This chapter highlights technique differences between flat and banked conditions, lateral banking reduced the body lateral lean required whilst minimising magnitudes of hip adduction and ankle eversion that may interfere with vertical force production and explain the reduction in step length and step frequency on flat bends (Chapter 4). Furthermore, greater frontal plane joint angles have been linked with greater risk of selected injuries. Despite this, body lateral lean is required to generate centripetal forces necessary to follow the path of the bend, thus flat bends may develop the ability to lean toward the bend whilst maintaining sprinting velocity. Coaches should reflect on exercises that incorporate these joint positions, ensuring that athletes are physically prepared for the frontal plane movements when transitioning between flat and banked conditions. This will help prevent inefficiencies and potential injury risks, particularly in the left to right step.

As lane radii decrease, significant inter-limb differences emerged in both the frontal and transverse planes. Training should target the balanced development of both the Left-Right (L-R) and Right-Left (R-L) steps. This could involve progressing the tightness of the radii and or degree of banking as well as the sprinting velocity on such radii to gradually improve athlete’s ability to run at high velocities on tight radii whilst potentially minimising injury risks.

Chapter 6: The influence of step characteristics, ground reaction force application and asymmetry on bend sprinting performance.

THE WORK FROM THIS CHAPTER FORMED THE BASIS OF THE FOLLOWING PEER REVIEWED CONFERENCE ABSTRACT

White, J., Moore, J., von Lieres und Wilkau, H., Irwin, G., Wilson, C., & Exell, T. (2024). The Impact of Ground Reaction Force Variables on Bend Sprint Running Performance. *Proceedings of the 42nd International Conference of Biomechanics in Sports*, *42*(1), 1014.

6.1 Introduction

Chapters 4 and 5 identified differences in step characteristics and kinematics between different bend conditions representing indoor athletics competition. Chapters 4 and 5 provided novel information into the performance related effects of lateral banking and the large frontal plane alterations that potentially explain the reduced performance on flat bends, suggesting that minimising alterations in the frontal plane may be important for maximising bend SVs. Furthermore, the change in radius introduced greater levels of inter-limb differences in the frontal and transverse planes which may contribute to the reduced SVs observed on tighter radii on the flat, and impact injury risks for both L-R and R-L limbs. SV did not follow the traditional pattern of reducing with decreasing radii when on a laterally banked track, suggesting that greater familiarisation is required for athletes competing on a banked track.

While Chapters 4 and 5 examined the tightest radii that athletes will compete on, athletes typically prioritise outdoor competitions like the Olympics. Therefore, understanding biomechanics on outdoor radii (36.5 – 45.1 m) may be more relevant for training programs, as these are more commonly encountered in major competitions.

Churchill et al. (2016) investigated force production on the bend compared to the straight and highlighted that force production during the L-R step was significantly reduced on the bend (0.37 BW for vertical and 0.21 BW for resultant force). For the R-L step, no significant differences in ground reaction force were observed between the bend and straight (Churchill et al., 2016). Therefore, it is possible that the reduced resultant and vertical force produced during the L-R stance is the limiting factor in bend sprinting. Resultant force decreased despite two-fold increases in mediolateral force directed inwards toward the bend (Churchill et al., 2016). Similarly, Millot et al. (2024) found reduced sprint performance on the bend due to lower L-R resultant force owed to decreased vertical and anterior-posterior forces in the bend.

On the other hand, Ohnuma et al. (2018) reports lower posterior GRF and impulse on the bend compared to the straight for the R-L limb. Typically reduced posterior force (braking force) is commonly associated with improved sprinting velocities (Mero et al., 1992), the relationship between braking force and sprint velocity at maximum velocity is not completely clear (Hunter et al., 2005) and could differ between bend and straight sprinting. Additionally, in agreement with Churchill et al. (2016) there was an increased L-R inward force observed without an increase in their resultant force (Millot et al., 2024). For the R-L stance, vertical force was similar to the straight whilst an increase in the mean inward force was paired with a decrease in the mean anterior-posterior force in comparison to the straight (Millot et al., 2024). Nonetheless, forces were averaged over stance and thus changes in the braking and propulsive phases cannot be determined. Despite this, the additional force demands appear to have a bearing on bend sprinting performance and the development of SV, with differences existing between the mechanisms for this in relation to force production between limbs, particularly for the L-R step, where vertical and anterior-posterior force are impacted. Thus, relationships between external kinetics and SV should be considered in future research.

As highlighted in Chapter 2 and previous experimental Chapters (see Sections 4.4 and 5.4), inter-limb differences have been reported for step characteristics, joint kinematics and external kinetics during bend sprinting. In one study, no significant differences were observed between L-R and R-L steps on the bend for peak vertical or anteroposterior propulsive force (Churchill et al., 2016). However, in a similar study, stance average vertical GRF were 0.10 BW lower ($p=0.001$) for the L-R leg compared to the R-L (Diaz et al., 2024). Whilst Diaz et al. (2024) does not report anteroposterior force, Churchill et al. (2016) reports greater braking impulse during the L-R step suggesting greater braking demands during the L-R stance. For inward force this appears to be significantly greater during the L-R step (Churchill et al., 2016; Diaz et al., 2024). Despite not comparing L-R vs R-L with inferential statistics: Millot et al. (2024) highlight that from 24 m the L-R mean inward and inward impulse was visually greater than the R-L, suggesting that as athletes approach the maximum velocity phase on the bend, the L-R limb contributes more to CoM turn than the R-L stances.

Analysis of key discrete force variables has demonstrated differences in the contribution of the L-R and R-L limbs to bend sprinting, however it is also important to understand how these differences present over the stance phase and how they relate to differences in the contribution of the L-R and R-L steps. Utilising SPM to compare force production on the bend to the straight during the acceleration phase, Judson et al. (2019) found one cluster of significant difference

(37%-44%) where propulsive force was lower on the bend compared with the straight in both the L-R and R-L steps. For inward force: Judson et al. (2019), found an increase in inward force production across most of the stance phase (3%-96%) compared to straight-line sprinting. Furthermore, Judson et al. (2019) reports that the R-L limb produced greater inward force than the L-R limb during the early stance phase (1%-12%), and that the L-R limb produced greater inward force than the R-L limb during the late stance phase (75%-100%). The authors highlighted this finding as further evidence for the left foot fulfilling a different role to the right foot during bend sprinting. Moreover, it is possible that the effects of the bend, and the asymmetries that come with this may develop as athletes approach max velocity further toward the apex of the bend (Judson et al., 2019). Furthermore, these reported inter-limb differences demonstrate the benefit of exploring the full waveform of the stance phase which has provided insight that may have been lost with the analysis of discrete values (Judson et al., 2019).

It is commonly accepted that an interaction is often observed between SL and SF whereby increases in one occur to the detriment of the other (Hunter et al., 2004). Furthermore, athletes may have their own optimal ratio of SL and SF to produce their best performance (during linear sprinting) (Salo et al., 2011). When running a bend, athletes have been shown to display asymmetrical step characteristics, with trends for greater L-R step SL and lower SF in comparison to the R-L step (Churchill et al., 2015, 2016; Ishimura & Sakurai, 2016; Ohnuma et al., 2018). Therefore, it is possible that due to the additional task constraints of following the path of the bend whilst staying in lane, there is an optimal ratio of SL and SF during bend sprinting, and that there may be a relationship between L-R and R-L steps.

Ishimura et al. (2016) report asymmetry of determinants of SV and relationships with determinants of SV to SV, finding that SL was significantly correlated with SV for L-R ($r = 0.81$; $p < 0.01$) and R-L limbs ($r = 0.83$; $p < 0.01$) whilst SF was only significantly correlated for the R-L limb ($r = 0.55$; $p < 0.05$). Nonetheless, whilst the authors investigated inter-limb differences of selected variables, force production was not directly measured. Furthermore, asymmetry of variables was not calculated and thus, the potential relationship between asymmetry and SV is unknown. Ohunma et al. (2018). investigated how some athletes maintain similar velocities when sprinting on the bend in comparison to their linear velocity. Several differences are reported between bend and straight, however, the only difference that occurred only in the poor group and not the good group related to lower posterior (braking) force observed in the R-L limb during bend sprints (Ohunma et al., 2018). Closer examination of the results highlights that some asymmetries (L-R versus R-L was not statistically tested) are present in the good group but possibly not the poor group, for example inward impulse (Good group: L-R = 28.7 ± 6.7 Ns; R-L = 12.2 ± 6.8 Ns; Poor group: L-R = 27.9 ± 11.4 Ns; R-L = 17.0 ± 12.7 Ns) and peak vertical force (Good group: L-R = 2384.1 ± 269.4 N; R-L = 2884.2 ± 886.0 N; Poor group: L-R = 2723.5 ± 532.0 N; R-L = 2664.3 ± 432.0 N). Therefore, it is possible that some level of asymmetry of external kinetics may have an influence on producing faster velocities on the bend.

Since several variables have been reported to be significantly different between limbs during bend sprinting, calculating values of inter-limb asymmetry of step characteristics and external kinetics may inform coaches and practitioners on the relationship between asymmetry and bend sprinting performance. Using the previously validated symmetry angle method (Zifchock et al., 2008) can enable comparison of asymmetry during maximal bend sprinting compared to previously reported data during straight sprinting (Exell et al., 2017). Asymmetry of step characteristics during linear sprinting was low (maximum of 1.68%) whilst kinetic variables were greater (peak of 90%) (Exell et al., 2017). Therefore, due to the asymmetrical demands of bend sprinting, it is likely that different relationships between SV, step characteristics and external kinetics exist than during straight sprinting.

6.1.1 Aim and Research Questions

Therefore, this Chapter addressed the following aims, to explore the relationships of external kinetics, step frequency and step length with SV during bend sprinting, and to examine the relationship between inter-limb asymmetry and SV on the bend. The purpose of this Chapter was to inform coaching by establishing key determinants of SV and further understanding of the relationship between the asymmetrical mechanical demands of the L-R and R-L limbs and SV on the bend. To address the aims of this Chapter, the following research questions were posed:

RQ6.1 What is the relationship between step length, step frequency, and step velocity during bend sprinting?

RQ6.2 What external kinetic variables are related to step velocity during bend sprinting?

RQ6.3 What are the inter-limb differences in force production of L-R and R-L limbs during the stance phase?

RQ6.4 What is the relationship between asymmetry of step length and step frequency, and mean SV (L-R and R-L) during bend sprinting?

RQ6.5 What is the relationship between kinetic asymmetry and mean SV (L-R and R-L) during bend sprinting?

6.1.3 Hypotheses

To address the research questions the following null hypotheses were tested.

H6.1 - Step length will not be significantly correlated to SV for the L-R and R-L steps.

H6.2 - Step frequency will not be significantly correlated to SV for the L-R and R-L steps.

H6.3 - There will be no significant correlations between SV and discrete external kinetic variables for the L-R and R-L steps.

H6.4 - There will be no differences in force production between limbs across the entire stance phase for vertical, anterior-posterior or inward-outward force.

H6.5 – Inter-limb asymmetry of SL and SF would have no significant relationship with SV.

H6.6 - Inter-limb asymmetry of discrete external kinetics would have no significant relationship with SV

6.2 Methods

6.2.1 Participants

The participants, experimental procedures, experimental set up were the same as in Chapter 3 and can be seen in section 3.2.

6.2.2 Experimental Set up

The experimental set-up is provided with full details of camera set up and force plate positioning in section 3.2.

The reliability of an adapted Plug in Gait lower limb and trunk marker set with multi-segment foot has been established for bend sprinting (Judson et al., 2018). Therefore, this marker set was utilised with the addition of technical marker clusters and the placement of upper body markers (Figure 6.1). Additional markers were attached bilaterally on the styloid processes of Radius and Ulna, the lateral and medial condyles of the Humerus, and the greater and lesser Tubercles of the Humerus. Three-marker semi-rigid technical clusters were attached to the distal end of thigh and shank segments and to the acromion. A four-marker headband was also worn. Finally, foot markers were placed on the corresponding anatomical positions on the surface of the sprint spikes on the: posterior calcaneus, medial calcaneus, lateral calcaneus, 1st and 5th metatarsal base, 1st, 2nd and 5th metatarsal head and head of the 2nd toe (Judson et al., 2018).

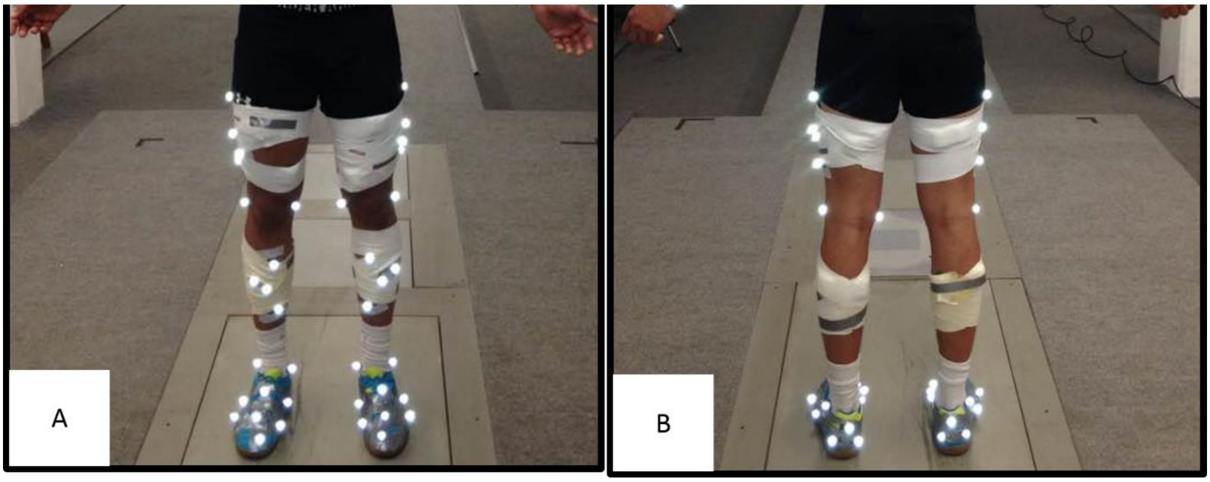

Figure 6.1. The custom marker set utilised for data collection. (A) anterior view, (B) posterior view.

To eliminate the influence of motion artefact as much as possible, markers and marker clusters were fixated to the skin with double sided tape and wrapped with neoprene wrap (Figure 6.1).

6.2.3 Data Processing

Ground reaction force data from the four force plates and marker trajectories for the toe, first and fifth metatarsal heads were exported to MATLAB (Mathworks inc, USA, 2021b). Force and marker data were filtered using a low-pass Butterworth filter, with cut-off frequencies for each trial determined using the autocorrelation method (Challis, 1999). TD and TO events were identified using the mean plus two standard deviations of the last three seconds of vertical ground reaction force data (where there was zero load on the force plate) as a threshold (Bezodis et al., 2007). This was chosen as there was not a consistent time pre-foot contact. To eliminate occurrences of events due to noise and incomplete stance phases (TD or TO occurring before or after contact with the force plate). To ensure that only trials where the force plate captured the entire stance phase were selected for use, a further control was added where the threshold had to be achieved for a minimum of 0.06 s (15 * 1/250) to be used as an event. Once TD and TO events were determined, the foot that initiated the step was aligned with the global coordinate system (Glaister et al., 2007). For calculation of SV, SL and SF of L-R and R-L steps within the same trial, TD events were determined using the peak acceleration method with the MT1H marker for the L-R step and the threshold method using the TOE marker for the R-L step. These methods of TD detection were used as they were the most accurate in Chapter 3 (see section 3.2 for full details of these methods). This enabled comparisons between limbs where at least one TD event took place off the force plate.

All variables were calculated separately for the L-R and R-L step, with steps defined by the foot that initiated the step (L-R step and R-L step). SL and SF were calculated based of the definitions of Churchill et al. (2015), described in full in Chapter four (Section 4.2.5). For the L-R and R-L steps, the fastest SV trial with a successful force plate contact was selected for analysis. Peak and mean force were calculated in all three directions as the peak and mean values observed across the stance phase. Impulse calculated in line with Churchill et al. (2016) as the absolute values using numerical integration of the force data and expressed relative to body mass, representing change of direction. Anteroposterior force is defined as braking (negative) and propulsive (positive). Duration of braking and propulsion were determined by negative or positive anteroposterior force duration. Mediolateral force was defined as inward and outward in line with previous bend sprinting research (Churchill et al., 2016; Judson et al., 2019). Finally, for each variable the symmetry angle (θSYM) was calculated with the following equations, proposed by Zifchock, et al. (2008):

$$\theta SYM = \frac{(45\,° - \arctan\left(\frac{XLeft}{XRight}\right))}{90°} * 100 \qquad [6.1]$$

θSYM = symmetry angle value (ranging from -100% to 100%, with 0% indicating perfect symmetry)

XL-R = L-R side value for variable being quantified

XR-L = R-L side value for variable being quantified.

if: (45° - arctan (XL-R/XR-L)) >90° then [Equation 6.2] was utilised:

$$\theta SYM = \frac{(45\,° - \arctan\left(\frac{XLeft}{XRight}\right) - 180\,)}{90°} * 100 \qquad [6.2]$$

Since the fastest R-L step wasn’t necessarily the same trial as the fastest L-R step, symmetry angle was calculated for all trials with a successful force plate contact for the L-R and R-L stance phases. If multiple trials with L-R and R-L contacts were observed, the contact with the fastest mean velocity was taken for further analysis. For one participant, no trial contained a successful L-R and right foot contact, thus for the asymmetry angle calculations this participant was omitted.

For continuous analyses, vertical, anterior-posterior and mediolateral force produced during L-R and R-L stance phases were normalised to BW and interpolated to 101 data points, representing 0-100% of stance. Interpolation was performed using a spline function in MATLAB.

6.2.4 Statistical analysis

To achieve answer RQs 6.1-6.5, the following statistical methods were employed:

RQ6.1 – Bivariate Pearson correlation coefficients to assess the relationships between SV and step length and step frequency.

RQ6.2 – Bivariate Pearson correlation coefficients to assess the relationships between SV and external kinetic variables.

RQ6.3 Paired t-tests were run using statistical parametric mapping for vertical, inward and anteroposterior GRF to compare the L-R and R-L stance phases (Pataky et al., 2013).

RQ6.4 Bivariate Pearson correlation coefficients to assess the relationships between asymmetry of step length, step frequency and mean SV (L-R and R-L).

RQ6.4 Bivariate Pearson correlation coefficients to assess the relationships between asymmetry of external kinetics and mean SV (L-R and R-L).

Thresholds for the magnitudes of all correlation coefficients were defined according to (Hopkins, 2003) as trivial (0.0), small (0.1), moderate (0.3), large (0.5), very large (0.7), nearly perfect (0.9) and perfect (1.0). These thresholds have been used in similar sprinting research to determine the relationships between selected kinematic characteristics and initial acceleration performance (King et al., 2022). Furthermore, in line with previous maximal velocity linear sprint research (von Lieres Und Wilkau et al., 2020): a threshold of 0.10 was set for the smallest worthwhile effect, and 90% confidence intervals were used to make inferences about the magnitude of the correlation (range from very likely harmful to almost certainly beneficial) (Batterham & Hopkins, 2006). The term harmful was substituted for detrimental to emphasise the performance, rather than injury implications of the relationship between tested variables and SV.

6.3 Results

6.3.1 RQ6.1

Table 6-1 shows mean ± SDs for the L-R and R-L steps and the relationships between SL, SF and SV. L-R SL was significantly correlated (almost certainly beneficial) to L-R SV. R-L SF was significantly correlated (almost certainly beneficial) to R-L SV.

Table 6-1. Mean (± SD) step velocity, step length, and step frequency for left-to-right (L-R) and right-to-left (R-L) steps, with correlations (r) and significance levels (p) for relationships between step velocity and step parameters.

Variable	L-R		R-L	
	Mean ± SD	*r (p)*	Mean ± SD	*r (p)*
Step Velocity (m/s)	8.54 ± 0.88	N/A	9.13 ± 1.00	N/A
Step Length (m)	1.98 ± 0.16	0.80 (0.03)	2.01 ± 0.12	0.31 (0.51)
Step Frequency (Hz)	4.31 ± 0.27	0.65 (0.11)	4.54 ± 0.49	0.86 (0.012)

6.3.2 RQ6.2

Mean ± SD for all external kinetic variables for the L-R and R-L steps can be seen in Table 6-2. For the L-R step, peak inward force was significantly positively correlated (almost certainly beneficial) with SV ($r = 0.88$; $p = 0.01$). No other significant correlations were observed between external kinetics and L-R SV (Figure 6.2).

Table 6-2. Mean ± SD for all external kinetic variables for the L-R and R-L steps

Variable	L-R	R-L
Vertical impulse (m/s)	2.15 ± 0.23	2.30 ± 0.36
Peak braking force (BW)	1.25 ± 0.20	1.27 ± 0.23
Peak propulsive force (BW)	0.64 ± 0.10	0.75 ± 0.09
Peak vertical force (BW)	3.27 ± 0.27	4.03 ± 0.92
Mean vertical force (BW)	1.86 ± 0.13	2.06 ± 0.21
Peak resultant force (BW)	3.39 ± 0.31	4.08 ± 0.93
Peak inward force (BW)	0.86 ± 0.14	0.70 ± 0.14
Peak outward force (BW)	0.09 ± 0.11	0.07 ± 0.10
Inward impulse (m/s)	0.67 ± 0.64	0.58 ± 0.41
Outward impulse (m/s)	0.85 ± 1.31	0.15 ± 0.22

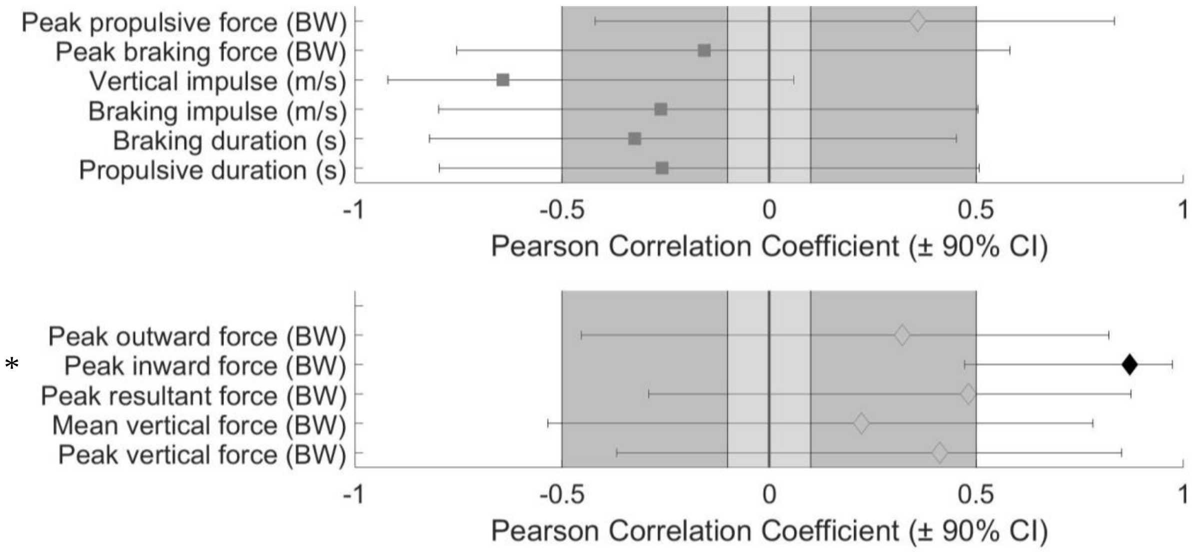

Figure 6.2. Pearson correlation coefficients (± 90% CI) between SV and kinetic variables for the L-R step. Marker type (beneficial = diamond, trivial = square, detrimental = circle) and colour indicates unclear (grey outline), likely (grey fill), very likely (black outline), and almost certain (black fill) relationships. The central area (r = −0.1 to 0.1) indicates a trivial relationship. Dark grey region (r = −0.1 to −0.5 & 0.1 to 0.5) indicates small to moderate relationships. * Denotes a significant relationship (p < 0.05).

Figure 6.3 shows correlation and confidence intervals between external kinetic variables and SV for the R-L step. Duration of propulsive force (0.038 ± 0.0087 s) was significantly negatively (almost certainly detrimental) correlated with SV (r = -0.78; p = 0.04). No other significant correlations were observed between external kinetics and SV, with non-significant correlations ranging from very likely negative (braking duration, braking and vertical impulse), to almost certainly beneficial (peak propulsive force).

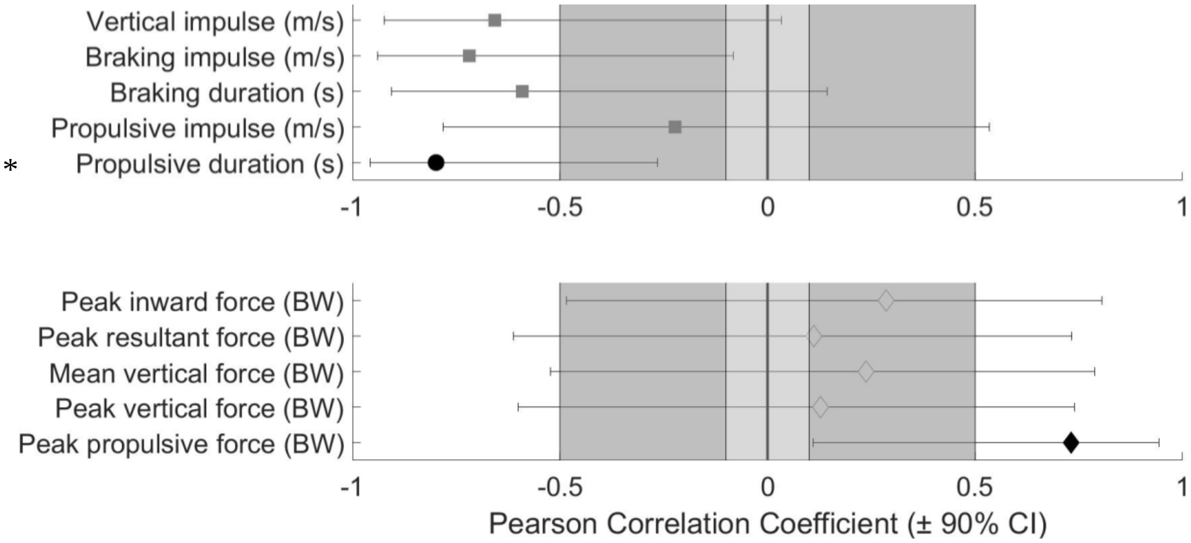

Figure 6.3. Pearson correlation coefficients (± 90% CI) between SV and kinetic variables for the R-L step. Marker type (beneficial = diamond, trivial = square, detrimental = circle) and colour indicates unclear (grey outline), likely (grey fill), very likely (black outline), and almost certain (black fill) relationships. The central area (r = −0.1 to 0.1) indicates a trivial relationship. Dark grey region (r = −0.1 to −0.5 & 0.1 to 0.5) indicates small to moderate relationships. * Denotes a significant relationship (*p* < 0.05).

6.3.3 RQ6.3

Figure 6.4 shows L-R and R-L anterior-posterior force across the stance phase. No supra-threshold clusters exceeded the critical value of 4.76 (*p* > 0.05).

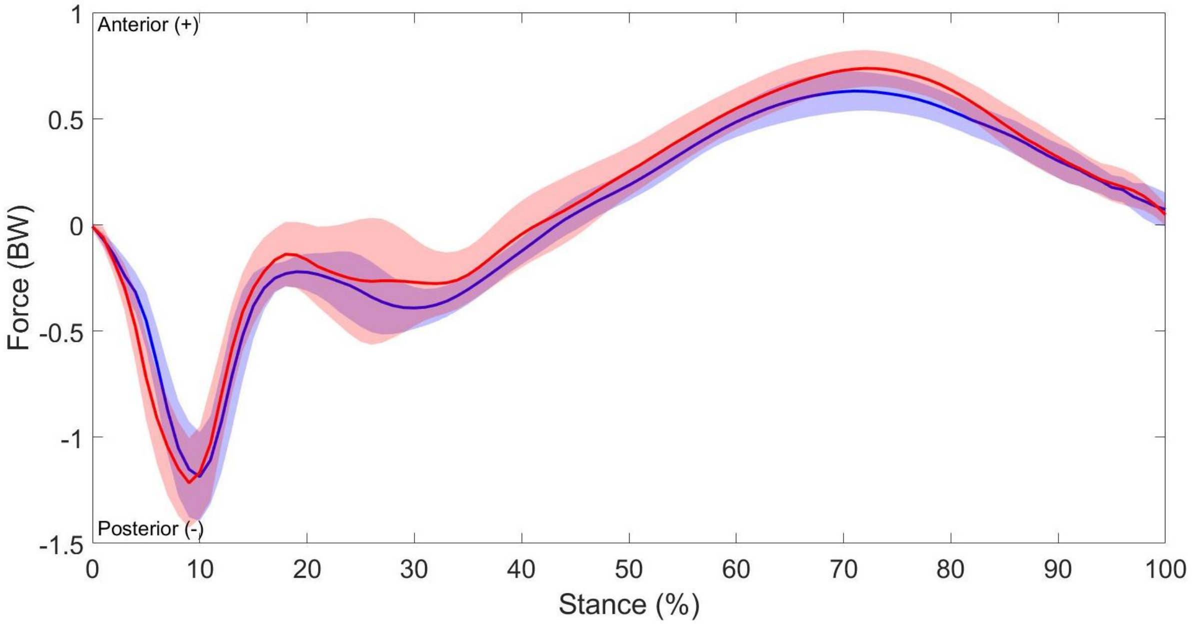

Figure 6.4. R-L (red) and L-R (blue) mean (solid line) ± SD (shaded area) for anteroposterior force.

Figure 6.5 shows L-R and R-L vertical force across the stance phase. A trend was observed for greater R-L vertical force throughout stance, with this was significantly greater during early R-L stance (1-5%; h = -4.70; p = 0.0059).

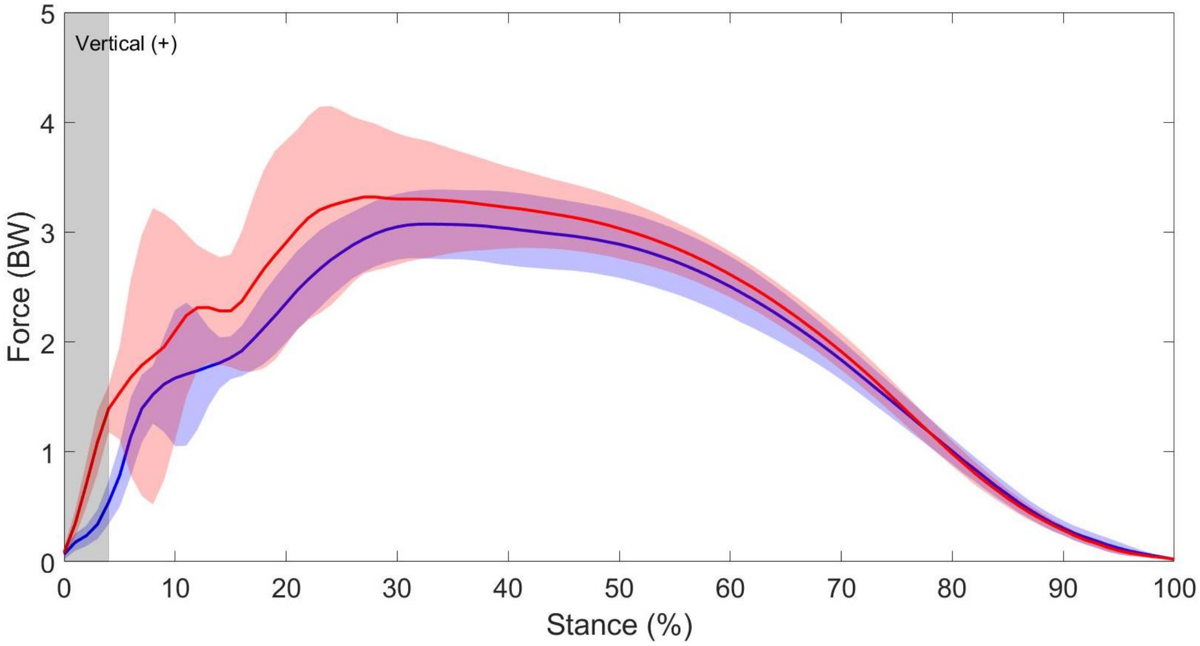

Figure 6.5. R-L (red) and L-R (blue) mean (solid line) ± SD (shaded area) for vertical force. Grey shaded regions indicate regions of significant difference between L-R and R-L ($p < 0.01$).

Figure 6.6 shows L-R and R-L inward-outward force across the stance phase. Significantly greater inward force produced during early R-L stance compared to L-R (6-11%; h = 4.69; $p = 0.0018$), this trend is reversed toward mid-stance (27-41%; h = -4.69; $p < 0.001$) and prior to TO (68-98%; h = -4.69; $p < 0.001$).

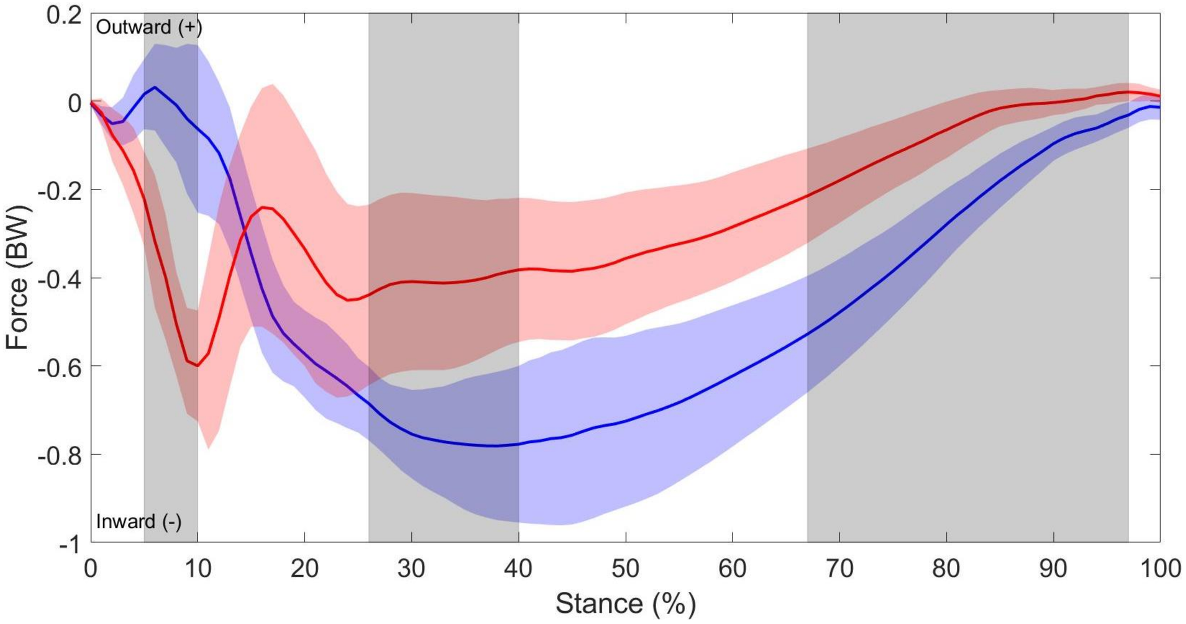

Figure 6.6. R-L (red) and L-R (blue) mean (solid line) ± SD (shaded area) for inward and outward force. Grey shaded regions indicate regions of significant difference between L-R and R-L ($p < 0.01$).

6.3.4 RQ6.4

Figure 6.7 shows the non-significant relationships for asymmetry of SF to mean SV (r = 0.41; $p = 0.41$) and for asymmetry of SL to mean SV (r = -0.24; $p = 0.65$) (Figure 6.8).

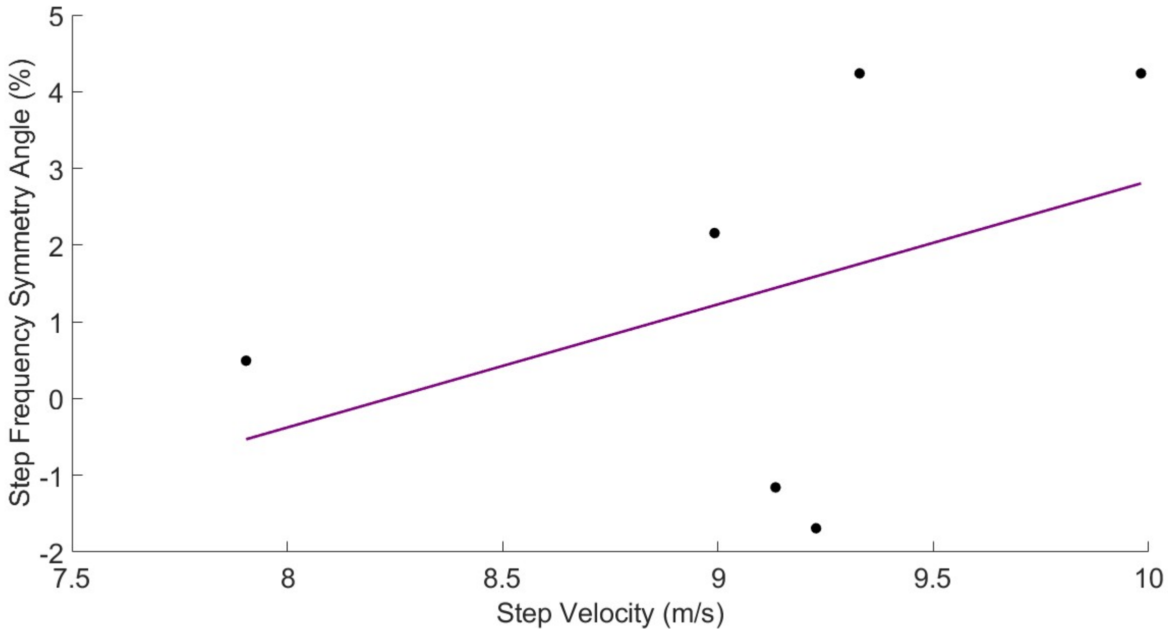

Figure 6.7. Mean Step Velocity (L-R and R-L steps) and the step frequency symmetry angle. Positive SA represents greater R-L step frequency than L-R. Each dot represents participants fastest trial with successful left and right force plate contacts.

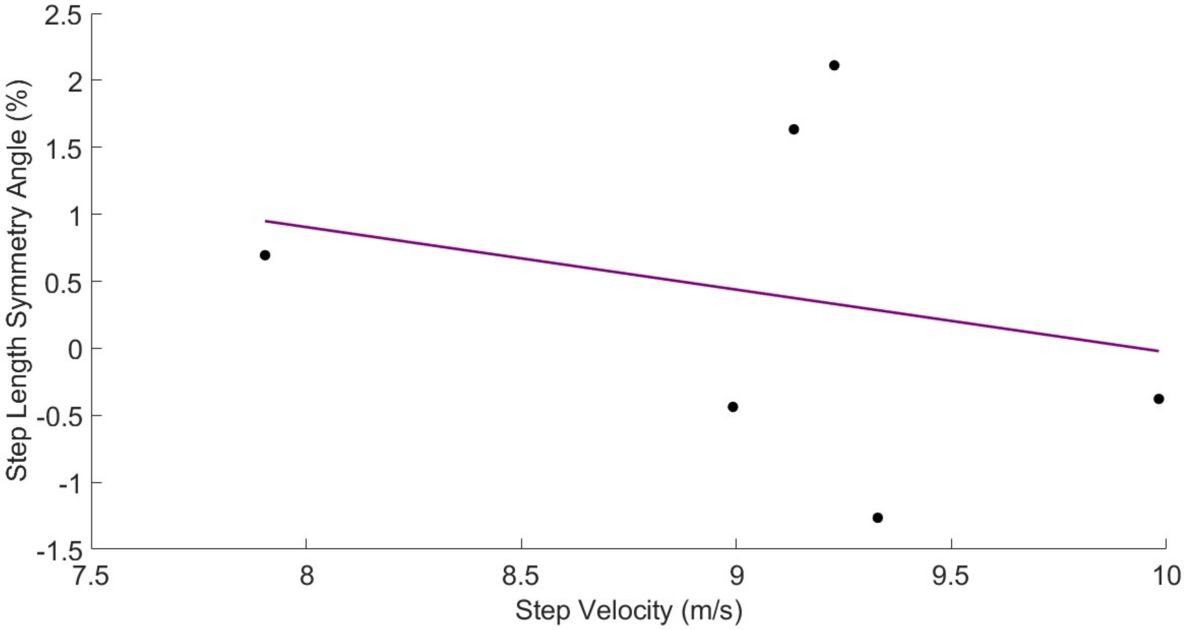

Figure 6.8. Mean Step Velocity (L-R and R-L steps) and the step length symmetry angle. Negative SA represents greater L-R step length than R-L. Each dot represents participants fastest trial with successful left and right force plate contacts.

6.3.5 RQ6.5

For kinetic variables, mean ± SD symmetry angle values can be seen in Table 6-3. A positive symmetry angle (SA) represents a greater R-L value than L-R, whilst a negative SA represents a greater L-R value than R-L. No significant relationships were observed between asymmetry and mean SV (all r = -0.66 – 0.31; p all > 0.05) (Figure 6.9).

Table 6-3. Mean ± SD for all symmetry angle (SA) of external kinetic variables. Positive SA represents greater R-L than L-R whilst a negative SA represents greater L-R than R-L.

Variable	Symmetry Angle
Vertical impulse (m/s)	-6.08 ± 19.81
Peak braking force (BW)	-19.63 ± 18.12
Peak propulsive force (BW)	-18.31 ± 36.88
Peak vertical force (BW)	-18.01 ± 37.19
Mean vertical force (BW)	-4.59 ± 4.26
Peak resultant force (BW)	-10.21 ± 9.04
Peak inward force (BW)	-2.73 ± 5.75
Peak outward force (BW)	0.80 ± 6.65
Inward impulse (m/s)	-2.32 ± 3.90
Lateral impulse (m/s)	0.16 ± 6.92

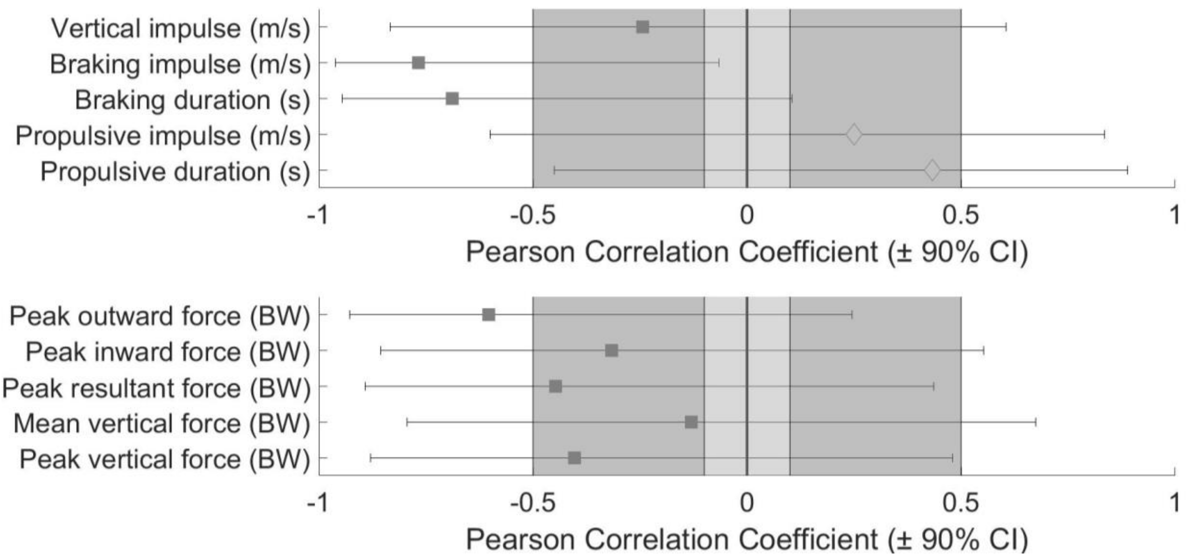

Figure 6.9. Pearson correlation coefficients (± 90% CI) between mean SV and asymmetry of kinetic variables. Marker type (beneficial = diamond, trivial = square, detrimental = circle) and colour indicates unclear (grey outline), likely (grey fill), very likely (black outline), and almost certain (black fill) relationships. The central area (r = −0.1 to 0.1) indicates a trivial relationship. Dark grey region (r = −0.1 to −0.5 & 0.1 to 0.5) indicates small to moderate relationships.

6.4 Discussion

Following on from the findings of Phase 1 where variations in performance were observed as a result of changing the lane radius and lateral banking, as well as large alterations in joint kinematics in the frontal and transverse plane. Phase 2 looks to further understanding of bend sprinting performance and asymmetry. Thus, this chapter looked to explore the relationships of external kinetics, step frequency and step length with SV during bend sprinting, and to examine the relationship between inter-limb asymmetry and SV on the bend.

6.4.1 RQ6.1: What is the relationship between step length, step frequency, and step velocity during bend sprinting?

For the L-R step, SL was significantly positively correlated to SV whilst a large but non-significant correlation existed between SF and SV. This finding is consistent with previous research, where SL was significantly correlated with SV for the L-R step (r = 0.81; $p < 0.01$) and SF was not significantly correlated with SV (r = 0.42; $p > 0.05$) (Ishimura & Sakurai, 2016). Thus, for the L-R step H6.1 can be rejected for L-R SL and accepted for L-R SF. It is generally accepted that the L-R step contributes to more turning by producing inward force, which has been proposed to take additional time to produce (Churchill et al., 2016), thus it is possible that the better bend sprinters are able to maintain L-R SL in addition to generating the inward forces necessary, thus SFs are likely to be reduced as a result of the extended contact and FTs. Ohnuma et al. (2018) highlight that some athletes can maintain SV on the bend (in comparison to their straight velocity) by maintaining the same kinematics and kinetics in the sagittal plane as on a straight path. Whilst this conclusion is logical, it ignores the frontal and transverse adaptations that occur during bend sprinting. Therefore, it may be that the successful athletes are strong enough to maintain sagittal kinetics and kinematics that contribute to SL despite the necessary frontal plane adaptations. Sašek et al. (2024) found 59% of variance in bend sprint deficit (deficit of bend to linear 30 m sprint times) was explained by hip abduction and knee flexor strength. Nonetheless, despite the bend sprints being undertaken around a 9 m radius, where turning demands will be greater within each step, hip abduction strength appears to be an important factor for bend sprinting and highlights the importance of hip stabilisation in the frontal plane in addition to propulsive force generation (Chang & Kram, 2007). Previous research has highlighted altered quadricep muscle activity when hip angles have been changed in the frontal plane (Coqueiro et al., 2005). Nonetheless, research is yet to understand if this altered muscle activity because of altered frontal plane kinematics can be improved through improved muscle strength in these positions. For example, Judson et al. (2020) suggested it may be beneficial for bend sprint athletes to increase plantar flexion strength in internally rotated positions representative of bend sprinting. Further research is required to determine if longer L-R SLs during bend sprinting is related to technique (kinematics) or muscle strength.

For the R-L step, SF was significantly positively correlated to SV whilst a moderate non-significant correlation existed between SL and SV. Thus, for the R-L step H6.1 can be partially rejected for R-L SF and accepted for R-L SL. Unlike the present findings, previous research reports that both SF ($r = 0.55$; $p < 0.05$), and SL ($r = 0.83$; $p < 0.01$) were significantly correlated with R-L SV (Ishimura & Sakurai, 2016). One potential explanation for the current findings is an interaction between steps exists. For example, Churchill et al. (2016) reports that R-L SV was reduced on the bend due to shorter SL, and that this possibly occurred as a result of repositioning the L-R leg for the next TD. Furthermore, TD_Ds are often greater for the L-R step, highlighting that the kinematics in preparation for the L-R TD are not optimal for maintaining R-L SV. Therefore, it is possible that the faster bend sprinters produce short GCT to compensate for the reduced SL (and thus FT) to prepare for L-R TD and as a result, produce faster R-L SF. However, future investigations are required to determine the mechanism for faster R-L SV on the bend. When comparing the results from the present study to, Ishimura &

Sakurais's, (2016) study, athletes ran on a radius of 43.51 m compared to the 36.5 m radius in this study. Previous research has found differences in step characteristics when comparing lane 5 and lane 2 (3.69 m difference in radius) (Churchill et al., 2018). Thus, differing lane radius is a possible reason for discrepancies compared to the present findings. Furthermore, it could be that tighter radii inhibit the outside limb's ability to maintain larger SLs due to the amount of turning required with each step, thus producing faster R-L SF increases the number of foot contacts over the course of the bend that could minimise the turning and inward force required with each step. Interestingly, Churchill et al. (2018) found SLs to increase and SF to decrease when comparing lane 5 and lane 2 thus, SV remained similar. Nonetheless, Churchill et al. (2018) went on to suggest, similar to Ohnuma et al. (2018) that some athletes are better able to maintain SV in addition to the inward force required to follow the path of the bend. Therefore, research should seek to further understanding of the kinematic techniques that contribute to the external kinetics that relate to faster SVs on the bend.

6.4.2 RQ6.2: What external kinetic variables are related to step velocity during bend sprinting?

A negative correlation between propulsive duration and R-L SV. Due to the aim of minimising propulsive durations, a smaller duration being related to faster SV is indicative of more successful performance. For the L-R step: a positive correlation between peak inward force and SV, thus H6.2 is partially accepted with the exception for these findings. Churchill et al. (2016) found that the duration of propulsion was significantly longer for the L-R step on the bend compared to the straight, whilst this is the other limb it may indicate a relationship between better bend sprinters being able to minimise contact time, particularly the duration of propulsive force generation. Additionally, propulsive force has been shown to be significantly positively correlated with absolute speed on the bend (Churchill, 2012). Furthermore, previous linear sprint research reported a non-significant (likely detrimental) relationship between propulsive time and SV during the maximal velocity phase (defined as step 19) (von Lieres Und Wilkau et al., 2020). These findings suggest that being able to minimise propulsive force generation durations is a contributing factor to more successful bend sprinting. Previous bend sprint research has highlighted shorter GCT for the R-L step (compared to the L-R) on the bend (Alt et al., 2015; Churchill et al., 2016). Thus, it is possible that requiring longer propulsive time extends ground contact time enough to reduce SF and thus result in a negative relationship with SV. Therefore, athletes that can minimise the time on the ground during this phase are likely to produce faster SF and thus contribute to SV.

Peak inward force was significantly correlated to SV for the L-R step. Despite requirement of inward force to follow the path of the bend, this is in contrast with previous bend sprinting research where Churchill, (2012) did not observe a significant correlation between inward force and SV for L-R or R-L steps. Previous research has highlighted that peak inward force is two-fold greater on the bend (for L-R and R-L steps) compared to medial-lateral forces on the straight, (Churchill et al., 2016). It has been highlighted that inward force is significantly greater during L-R stance compared to R-L and thus aids generation of turning achieved during stance (Churchill et al., 2016). Therefore, since greater inward forces are produced on the bend compared to the straight, and this is larger during L-R than R-L stance phases, how athletes produce large inward forces during L-R stance should be investigated in future studies. Since SL was also significantly positively correlated with L-R SV, and increased SV on the bend will increase centripetal force (Equation 6.1), increases in SV or SL will require increases in inward force to ensure athletes stay in lane.

$$Centripetal\ Force = \frac{m*v^2}{r} \qquad [6.5]$$

Where:

m is the mass of the athlete

v is the velocity of the athlete

r is the radius of the bend

It has been hypothesised that the greater inward force demands require greater time to produce (Churchill et al., 2016; Usherwood & Wilson, 2006), thus it is possible that a negative relationship exists between inward force and SF that impacts the relationship to SV. Conversely, the L-R step contributes to more turning of the CoM required to follow the path of the bend, thus large inward force is required to achieve this and to maintain the change of direction in addition to anterior-posterior displacement aspect of SL. Therefore, investigating how external kinetic variables relate to the primary determinants of SV is an area of interest.

Average vertical and resultant force were not significantly positively correlated with SV for L-R or R-L steps. Previous research has highlighted vertical force to be significantly correlated with SL, but not SF for the L-R step (Churchill, 2012). Therefore, it is possible that no relationship, or negative relationship to SF means that vertical force does not significantly correlate with SV. In linear sprinting, vertical force contributed to the majority of total variance (59%) of a regression model for SV (von Lieres Und Wilkau et al., 2020). Further research has shown that greater mean vertical force is associated with faster top running velocities (6.2 -11.1 m/s) (Weyand et al., 2000), and within a homogenous group of well-trained sprinters (Nagahara et al., 2018). The lack of relationships could partially be explained by von Lieres Und Wilkau et al's. (2020) finding that most of the variance contributed by vertical force was shared with contact time and peak propulsive force. This highlights that an interaction may exist between optimal vertical and horizontal forces to maintain short GCT. Since bend sprinting requires additional horizontal force in the inward direction it may be that these additional demands change the requirements to maintain sufficient bend sprinting velocity and reduced the contribution of vertical force to maintaining SV on the bend.

6.4.3 RQ6.3: What are the inter-limb differences in force production of L-R and R-L limbs during the stance phase?

No significant differences were observed in anteroposterior force across the stance phase between L-R and R-L limbs; thus, hypothesis H6.3 can be accepted for this comparison. The results of this study therefore appear to show that the braking demands of the L-R and R-L limb are comparable across the stance phase during bend sprinting on an outdoor competition radius bend. This finding is in support of Judson et al. (2019), who found no significant difference in anteroposterior force across the stance phase in the acceleration phase between L-R and R-L steps. Churchill et al. (2016) reported greater braking impulse and duration of braking during the L-R stance than the R-L stance on the bend. Although not compared statistically in the present study, these values appear similar between L-R and R-L steps (L-R step: 0.202 ± 0.059 m/s, 0.051 ± 0.010 s; R-L step: 0.185 ± 0.096 m/s, 0.048 ± 0.013 s). Additionally, despite being in the acceleration phase Judson et al. (2019) also found no differences in anteroposterior force between L-R and R-L stance phases. The only other study on comparable radii and phase of sprinting does not report anterior-posterior forces (athletes tested on 36.5 m and 17.2 m radius) (Diaz et al., 2024), suggesting that results were not significant and thus not presented. On small radii (1-6 m), Chang & Kram, (2007) found propulsive and braking forces to decrease with smaller radii. Furthermore, Chang & Kram, (2007) found the outside limb produced both greater propulsive and greater braking forces than the inside limb. Despite this, the large difference in radii tested, and the velocities achieved (< 6 m/s) limit the generalisation of these findings. Therefore, the present results provide novel information that the magnitude of braking and propulsive forces during L-R and R-L stance are comparable across the stance phase in the maximum velocity phase on conditions representative of outdoor competition (lane 1 – 36.5 m radius).

The present study's findings that the pattern of greater inward force production switched suggests that the R-L step produces greater inward forces during early stance whilst the L-R step stabilises laterally before producing greater inward forces prior to TO. Therefore, the hypothesis (H6.3) is rejected as asymmetry of inward force production was observed between L-R and R-L steps whilst this differed in direction between early and late stance. Peak inward force during L-R stance was 0.86 ± 0.14 BW in comparison to 0.70 ± 0.14 BW during R-L stance, whilst not compared statistically, these results support the findings of Churchill et al. (2016) and Millot et al. (2024) in that peak inward force is greater during L-R stance. Interestingly, the greater inward force trend reversing was also observed during the acceleration phase on the bend (Judson et al., 2019). The duration of greater L-R inward force in the present study is much greater than reported by Judson et al. (2019). One potential reason for this discrepancy is that it is possible that the effect of the bend, and the asymmetries that come with this may develop as athletes approach max velocity further toward the apex of the bend (Judson et al., 2019)**.** Therefore, it may be that the inward force requirements of the L-R and R-L stance phases change as athletes progress on the bend towards maximum velocity, where asymmetry has been shown to increase at higher velocities on a 6 m radius (Mesquita et al., 2024). Recently, Millot et al. (2024) highlighted that: from 24 m, the L-R mean inward force and L-R inward impulse were visually greater than the R-L, whilst the lack of inferential statistics limits the generalisation of these findings, they support of Churchill et al. (2016) as athletes approach the maximum velocity phase, the L-R stances contribute more to CoM turn more than the R-L stances. Furthermore, whilst a typical participant's data is presented in Churchill et al. (2016) (figure 2a and 2b), the L-R and R-L steps on the bend follow the same trend where R-L inward force is greater during early stance before L-R inward force is greater for the remainder of stance. Thus, this finding highlights novel information on the initial peak in R-L inward force production and reinforces previous research in that greater inward force is produced but provides new information on the magnitude and durations of this greater inward force production. Therefore, whilst peak inward force is greater during L-R stance, the R-L limb still plays a role in producing inward force and thus generating inward forces in addition to propulsive and vertical forces should be an area for training focus. These findings support previous research highlighting that sufficient high-speed training be undertaken on the bend and focusing strength and conditioning on replicating positions commonly observed during bend sprinting, such as body lateral lean and internal rotation at the hip and or ankle (Churchill et al., 2016; Judson et al., 2020c) .

Vertical force was greater during early R-L stance (1-5%) compared to L-R stance, thus, H6.3 is rejected for vertical force. Since previous research reports only discrete variables, this novel finding highlights the intricacies of vertical force production during maximal velocity bend sprinting. Churchill et al. (2016) reported no differences in peak and mean vertical force or vertical impulse between L-R and R-L stance. Since R-L GCTs have been shown to be shorter (Alt et al., 2015; Churchill et al., 2016), normalising stance phases to 101 data points may have resulted in some of this temporal information being lost. Nonetheless, both vertical impulses (2.15 ± 0.23 m/s L-R; 2.30 ± 0.36 m/s R-L) and the peak vertical forces were non-significantly higher in the R-L (4.03 ± 0.91 BW) than L-R (3.27 ± 0.27 BW). Similar to previous research, these mean values were influenced by one participant who produced substantially more vertical force with the R-L step (5.52 BW versus 3.17 BW), suggesting an individualised technique. Despite this, a 1.29 % difference in SV (R-L: 9.28 m/s versus L-R: 9.16 m/s) suggests that the greater vertical force did not produce substantially faster SV. These findings of similar peak vertical force between limbs supports the conclusion of Churchill et al. (2016) that peak vertical force is consistent between limbs on the bend, whilst the finding that R-L vertical force is greater during early stance is potentially one of the reasons for shorter R-L GCT and faster R-L SF. Previous research highlights that the rate of force production is how sprinters accelerate beyond plateau of team sport players (Clark & Weyand, 2014). Thus, the findings that greater R-L step vertical force during early stance may contribute to shorter ground contact times that aided the higher R-L SF. One other interpretation is that Figure 6.5 highlights a clearer impact peak for the R-L limb, which is likely to have increased vertical force during early stance. Churchill et al. (2015) highlights that the R-L limb is potentially better placed to extend quickly which may enable greater force generation during early stance and contribute to faster R-L SV. Therefore, it is pertinent to explore the relationships between the kinematics of the L-R and R-L steps with SV that may explain the differences in external kinetics and in performance. Whilst Churchill et al. (2016) presented a typical force trace from one participant (figure 2a, 2b), the R-L step on the bend appears to show a similar trace to the present study. Nonetheless, this is the first research to highlight asymmetry of force production across the stance phase and can be used to further highlight variables that may be associated with SV on the bend.

6.4.4 RQ6.4: What is the relationship between asymmetry of step length and step frequency, and mean step velocity (L-R and R-L) during bend sprinting?

Finally, this Chapter aimed to further understanding of the relationship between the asymmetrical mechanical demands of the L-R and R-L limbs and SV on the bend. The answering of RQ6.1 highlighted that SL and SF appear to be of more importance for the L-R and R-L limbs, respectively. Thus, the additional demands when running around a bend may constrain the SF and SL for the outside and inside steps differently. Furthermore, the answering of RQ6.3 highlighted asymmetries in force production. The greater R-L vertical force during early stance may contribute to short R-L GCT and thus the faster R-L SFs observed that produced fast R-L SV. Interestingly, there was no difference between L-R (1.98 ± 0.16 m) and R-L (2.01 ± 0.12) SLs, thus it may be that the ability to maintain L-R SL is what sets faster athletes apart and vice versa with fast R-L SF.

RQ6.4 highlighted there were no significant relationships between asymmetry of SL or SF to mean SV, suggesting that there is no consistent ratio of SL or SF between L-R and R-L steps that contributes to faster overall SVs, thus H6.5 can be accepted. These findings are similar to Exell et al. (2017) study of asymmetry during linear sprinting, where no group consistent trend for asymmetry was observed in step characteristics or the relationship with SV (Exell et al., 2017). In the present study, asymmetry angles for SF ranged from -1.69 - 4.24% and SL from -1.26 – 2.11%, Similarly Exell et al. (2017) highlighted step characteristics all contained small amounts of asymmetry (<1.70%). Therefore, like linear sprinting (Salo et al., 2011) it may be that athletes produce their individual ratio of SL and SF to produce their best bend sprinting step velocities. Nonetheless, the findings from RQ6.1 and that asymmetry of SF (1.38 ± 2.59%) suggest that some level of asymmetry may be related to performance. As highlighted one potential explanation for the current findings is an interaction between steps exists. For example, Churchill et al. (2016) reports that R-L SV was reduced on the bend as a result of shorter SL, and that this possibly occurred as a result of repositioning the L-R leg for the next TD, where TD_Ds are often greater. Therefore, it is possible that the faster bend sprinters emphasise short R-L GCT to compensate for the reduced SL (and thus FT) and or are more able to effectively reposition and avoid an early and less active L-R TD and as a result, produce longer R-L SL. However, research is yet to comprehensively determine the relationships between joint kinematics and bend sprinting performance.

6.4.5 RQ6.5: What is the relationship between kinetic asymmetry and mean step velocity (L-R and R-L) during bend sprinting?

For asymmetry of kinetic variables, no significant relationships were observed with mean SV, thus H6.6 can be accepted. For the trials included in this analysis (fastest trial with two successful contacts with the force plates), nine out of ten variables produced a negative SA, highlighting that the left value was greater than the right. Nevertheless, the large standard deviations and trend for non-significant negative correlations with mean SV suggest that greater asymmetry was not beneficial for performance. The present findings are consistent with Judson, (2019) who found no interaction between symmetry angle on performance during the acceleration phase on the bend. Despite Judson, (2019) studying a different portion of the race and capturing only one force contact per trial (thus, values for the L-R and R-L were taken from different trials), the findings are consistent that asymmetry of force production was not related to bend sprinting performance (mean SV). Since both L-R and R-L limbs have the role of reducing braking forces, maintaining vertical force in addition to producing inward force required to follow the path of the bend and maintain maximal velocities, asymmetry of these variables would perhaps be detrimental to bend sprinting velocity. On a linear path, despite some large asymmetry of kinetic variables, kinetic asymmetry showed no significant relationships with sprinting performance (Exell et al., 2017). Nonetheless, where the current study and previous research have highlighted significantly greater inward force during L-R stance (Churchill et al., 2016; Diaz et al., 2024), it is potentially surprising that asymmetry of peak inward force production was not correlated to SV. One potential reason for this is that with the discrete measures utilised, it is not possible to indicate precisely at which point in the stance phase these differences occur. RQ6.3 highlighted that L-R inward force was significantly greater than R-L between 27-41% and 68-98% of stance. The peak inward force occurred at 38% (0.81 BW), whilst R-L peak inward force occurred at 10% (0.70 BW), at the equivalent point of stance the inward force was 0.42 BW, thus the difference between these points, or a measure of the total inward force may be a better measure of inward force production and have a clearer relationship to mean SV. Similar methods have been adopted to distinguish between performance levels of mean velocity across stroke cycles in swimming (Morais et al., 2023), where no differences were observed between discrete measures but differences reported when assessing the entire waveform. Therefore, future research should seek to understand inter-limb asymmetry across the entire gait cycle and the relationship to bend sprinting performance.

6.5 Conclusion

This Chapter highlights that SL in the L-R step and SF for the R-L step are the key determinants of SV during bend sprinting. Thus, it is possible that faster bend sprinters are the ones best able to produce faster R-L SF whilst maintaining L-R SL. Furthermore, duration of propulsive force generation was significantly negatively correlated with R-L SV, highlighting the importance of short contact durations that reinforces the relationship between SF and SV for the R-L step. For the L-R step, peak inward force was significantly positively correlated with SV, this is associated to the increased centripetal force requirements observed with increased SV on the bend. It was also identified that peak propulsive force, average vertical and resultant forces were not associated with SV and suggest that the mechanical determinants of bend sprinting performance are not equivalent to linear sprinting. It is theorised that the additional inward force demands of bend sprinting may alter the contribution of other force variables which have previously been suggested to be related to sprint performance. These identified differences reinforce the need to consider bend sprinting as a separate entity to linear sprinting.

No significant differences in braking force were found between limbs, however, greater inward force production switched between limbs throughout stance. Initially, the R-L step produced greater inward force whilst in mid-late stance, the L-R step produced greater inward force. Greater early stance vertical force was observed in the R-L step and combined with the greater inward force early in stance may enable shorter ground contact times leading to the observed higher SF and velocities in the R-L step. The novel findings of greater R-L step inward and vertical force during early stance may contribute to the faster SVs reported for the R-L step.

Asymmetry of SL and SF were not correlated to SV, therefore, like linear sprinting it may be that athletes produce their individual ratio of SL and SF to produce their best bend sprinting step velocities. Furthermore, asymmetry of external kinetics was not correlated to SV, in agreement with research in the acceleration phase of bend sprinting.

6.6 Coaching and Practical Recommendations for Bend Sprinting Based on Key Findings

Step frequency for the right-left step was identified as a key determinant of step velocity. Further, shorter time during the propulsive (push off) phase was related to faster step velocity. This emphasises the importance of reducing ground contact time for the right-left step on the bend. Additionally, the right-left step showed greater inward and vertical force during early stance, which may contribute to higher SF and faster step velocity. Coaches should incorporate drills that focus on the ability to apply force quickly, and contribute to powerful toe-offs by enhancing force application during the propulsive phase to shorten ground contact times on the bend. This could be achieved through use of plyometric drills or use of wearable resistance applied on the bend.

For the left to right step, maintaining step length was important to optimising step velocity. Exercises that strengthen the propulsive phase and improve hip extension in bend specific positions such as with body lateral lean may help athletes generate the necessary step length without compromising step frequency. More inward force was related with faster left step velocity, which highlights the increased centripetal force required when sprinting on a bend. Coaches could look to incorporate strength and conditioning exercises targeting body lateral lean and the hip abductors and adductors, as well as exercises that may enhance stability in the frontal plane. Furthermore, bend-specific drills that incorporate, inward force application in addition to vertical and propulsive forces may enhance bend step velocities.

Chapter 7: The relationships between kinematics and the determinants of bend sprinting performance?

7.1 Introduction

Chapter 6 investigated the relationships of external kinetics, SF and SL with the performance outcome, SV on the bend to establish key determinants of SV. Additionally, Chapter 6 furthered understanding of the relationship between the asymmetrical mechanical demands of the L-R and R-L limbs and SV. For the R-L step, SF was the key determinant of SV. For kinetic variables, propulsive duration was significantly negatively correlated to SV, thus it is suggested from the results of Chapter 6 that those who produce short propulsive durations maintain short GCTs and thus achieve high SFs that contribute to fast R-L SV. When considering force production across stance, the R-L step produced significantly more inward and vertical force than the L-R during early stance, which potentially contributes to the higher SF of the R-L step.

As discussed in Chapter 2, previous research has highlighted several kinematic characteristics that relate to faster linear sprinting velocities, such as rapid angular velocities during stance and swing, more optimal peak angles and angles at TD and TO for the MTP, ankle, knee and hip joints. Previous research has highlighted strong relationships between kinematics and performance indicators at maximum velocity (Kunz & Kaufmann, 1981), and in the acceleration phase (Hunter et al., 2005; King et al., 2023b). These approaches have emphasised variables that are indicative of successful linear sprinting. Chapter 2 further highlighted several kinematic adaptations that occur between bend and straight for the L-R and R-L steps as well as differences between the L-R and R-L steps on the bend. Churchill's (2011) thesis chapter appears to be the only previous investigation to relate kinematic characteristics to bend sprinting velocities, as well as to SL and SF.

For the R-L step, Churchill (2011) reported several kinematic variables that appear to be strongly related to SL and SF on the bend. For example, a greater knee flexion angle at TD, greater hip angular velocity at TD and later time of full hip extension (% of step time) were related to greater SF. Furthermore, greater knee flexion at TD was significantly negatively correlated with foot horizontal velocity and thigh separation at R-L TD (Churchill, 2012), suggesting that the flexion angle of the knee at TD is linked foot horizontal velocity, which is associated with a more active TD (Kunz & Kaufmann, 1981; Mann, 1985). Greater knee flexion therefore may allow athletes to adopt a more optimal position to make an active TD, which itself leads toward a stiffer limb, faster application of GRF and thus has the potential to contribute to shorter GCT. Contrary to the findings for SF, for R-L SL a less flexed (more extended) knee angle at TD, an earlier time of full hip flexion (% of contralateral limb step time), lower knee angular velocity at TD and greater knee range of motion were related to greater SLs (Churchill, 2012). This suggests that whilst more knee flexion at TD may be beneficial to producing larger SF, athletes that arrive at TD in a more extended position are better able to potentiate and create a stiffer limb by not actively flexing (i.e. minimising flexion angular velocity) which contributes to a longer SL. Furthermore, larger knee range of motion was also found to be related to larger SLs suggests that the ability to utilise knee extension-flexion-extension during stance (due to more extended knee at TD and larger knee RoM) is a key driver in producing longer R-L SLs on the bend. During linear sprinting, Bezodis et al. (2008) highlights the action of the knee joint during stance to act more of a facilitator for the transfer of power from the hip through the ankle, however, during curved sprints with added mass, Luo & Stefanyshyn, (2012a) found that the contribution from the knee increased while hip and ankle remained similar. Therefore, on the bend the knee may have a larger role in generating torque than on the straight and some athletes may be more able to utilise this to increase SL. Churchill (2011) related the variables that related to SL and or SF to other mechanically relevant variables, finding that various sagittal and frontal plane kinematics help contribute to high SF and long SLs. The previous studies focussed mainly on sagittal plane joint kinematics, therefore there may be useful out of plane movements that influence bend running performance and which have not been previously reported. Furthermore, whilst kinematics that relate to SF and SL may be useful, further associating kinematics with the external kinetics that produce large SL and or fast SF would aid understanding of bend sprinting performance.

Chapter 6 highlighted that for the L-R step, SL was the significant determinant of SV with peak inward force also significantly positively correlated with SV. Whilst the relationship between inward force is associated with the centripetal force requirements with increased SV on the bend and the necessity of staying in lane, future research should explore how faster athletes are able to produce greater inward force. When comparing L-R and R-L force production, significantly greater inward force production was observed during L-R stance compared to R-L for the majority of stance, therefore inward force may contribute to the maintenance of SL that leads to greater SV for the L-R step.

Churchill (2011) found that select kinematics were related to L-R SF and SL during bend sprinting on outdoor bend radii. A larger body sagittal lean RoM, greater hip angle at full flexion, larger thigh separation and a lower peak MTP plantarflexion angular velocity were all significantly related to greater L-R SF. These highlight that kinematic alterations in the frontal and sagittal plane across multiple joints have bearing on key bend sprinting velocity determinants. For SL: a more extended knee at TD was related to longer SLs while an earlier time of peak hip adduction (% of stance) was related to longer SL. Furthermore, inverse relationships were highlighted for thigh separation at TD (greater separation related to lower SL but greater SF) and Peak MTP plantar flexion angular velocity (greater MTP velocity related to greater SL and lower SF). These results highlight the complexity of increasing bend sprinting speed due to the three-dimensional nature, as well as the traditional challenge of increasing SL or SF without an associated decrease in the other.

Ohnuma et al. (2018) investigated differences in kinematics between ‘good’ and ‘poor’ bend sprint athletes. Ohnuma et al. (2018) found that the only variable that was significantly different between bend and straight in the poor group but not the good group was sagittal hip joint angle at TO for the R-L step on the bend. Since a less extended hip joint angle at TO on the bend was only observed in the poor group (Straight: 196.7 ± 6.4°; bend: 191.0 ± 7.9°), this reduction may have influenced the reduced FD and SL observed for the R-L step on the bend for this group. Therefore, comparing sagittal plane kinematics is not sufficient to explain differences in bend sprinting performance between more successful and less successful bend sprint athletes. Furthermore, whilst Ohnuma et al. (2018) created an ad hoc division based on the percentage reduction in sprint velocity on the bend compared to the straight, Churchill, (2012) reported that there was no relationship between how fast an athlete was on the straight and whether they could maintain their speed to be a greater or lesser extent.

Thus, further comprehensive quantification of 3D joint kinematics and the relationship between these and the drivers of L-R and R-L SV may help inform understanding of the mechanics of bend sprinting. Therefore, the aim of this Chapter was split into two to further understanding of the drivers of bend sprinting performance for the L-R and R-L steps.

7.1.1 Aims and Research Questions

The aim of this Chapter was to investigate kinematic and kinetic variables that influence bend sprinting performance (SV) or determinants of bend sprinting performance (SL and SF). Thus, the purpose was to inform coaching on the kinetic variables with the greatest bearing on bend sprinting performance and the techniques that impact the development of these kinetic variables.

The following research questions were raised based on the findings of Chapter 6 where: for the R-L step SF and shorter duration of propulsive force were found to be the key determinants of R-L SV and, for the L-R step, SL and peak inward force were the key determinants of SV. The outlined RQs will achieve the aims of this Chapter:

RQ7.1 For the R-L step, what are the key determinants of SF and kinetic variables that relate to SF?

RQ7.2 What kinematic variables relate to duration of propulsive force and any kinetic variables that relate to R-L SF?

RQ7.3 For the L-R step, what are the key determinants of SL and kinetic variables that relate to SL?

RQ7.4 What kinematic variables relate to peak inward force and any kinetic variables that relate to L-R SL?

7.1.2 Hypotheses

To address the research questions the following null hypotheses will be tested.

RQ7.1

H7.1 - SF will not be significantly correlated to GCT or FT for the R-L step.

H7.2 - SF will not be significantly correlated to any external kinetic variables for the R-L step.

RQ7.2

H7.3 - There will be no significant correlations between R-L duration of propulsive force and selected mechanically relevant kinematic variables for R-L step.

H7.4 - There will be no significant correlations between kinetic variables related to R-L SF and selected mechanically relevant kinematic variables for R-L step.

RQ7.3

H7.5 - SL will not be significantly correlated to stance distance or flight distance for the L-R step.

H7.6 - SL will not be significantly correlated to any external kinetic variables for the L-R step.

RQ7.4

H7.7 - There will be no significant correlations between L-R peak inward force and selected mechanically relevant kinematic variables for R-L step.

H7.8 - There will be no significant correlations between kinetic variables related to L-R SL and selected mechanically relevant kinematic variables for L-R step.

7.2 Methods

7.2.1 Participants

The participants, experimental procedures, experimental set up were the same as in Chapter 3 and can be seen in section 3.2.

7.2.2 Experimental Set up

The experimental set-up is provided with full details of camera set up and force plate positioning in section 3.2.

For calculation of kinematic variables, joint segments were defined as in Section 5.2. The following section describes the definition of the multi-segment foot. The multi-segment foot was defined in line with Judson (2019), where the rearfoot was defined as the posterior calcaneus, medial calcaneus, lateral calcaneus and virtual intermedius calcaneus marker, the forefoot defined as the 1st and 5th metatarsal bases and 1st and 5th metatarsal heads. Finally, the toe box was defined as the 1st and 5th metatarsal heads and head of 2nd toe. This enabled the calculation of midfoot inversion and eversion (forefoot relative to the rearfoot) and metatarsophalangeal (MTP) joint plantar and dorsiflexion (toe box relative to the forefoot).

7.2.3 Data Processing

Force and marker data were filtered using a low-pass Butterworth filter, with cut-off frequencies for each trial determined using the autocorrelation method (Challis, 1999). The methods for detecting TD and toe-off (TO) events using kinematic data can be seen in section 6.2. Similarly, the same methods for calculating discrete external kinetics and step characteristics were implemented (see section 6.2 for full details).

7.2.4 Variable Selection

Due to the three-dimensional whole-body nature of bend sprinting, variables were included based on the criteria presented in Table 7.1. Previous research has highlighted that athletes appear to swing their legs in the same way as on a linear path (Ishimura & Sakurai, 2018), therefore this Chapter focuses on the stance phase.

Table 7-1. Justification of selected variables included in the analysis.

Variables	Justification	References
Step characteristics (SL, SF)	Mechanical links to sprint performance	Hunter et al., (2005); Kunz & Kaufmann, (1981)
Sagittal plane variables (TD_D, angular velocities and angles at peak, TD, and TO for hip, knee, ankle, and MTP joints)	Mechanical links to SL, SF, and SV; Athletes may attempt to replicate sagittal plane kinematics on the bend	Hunter et al., (2005); Kunz & Kaufmann, (1981); Ohnuma et al., (2018)
Frontal and transverse plane joint kinematics (minimum, peak, angles at TD and toe-off, range of motion, angular velocities for hip, knee, ankle and midfoot joints)	Bend-specific techniques may contribute to performance; Large alterations observed on the bend in comparison to the straight that may be important for producing faster bend sprinting velocities; Differences between limbs on the bend.	Churchill, (2012); Churchill et al. (2015); Ohnuma et al., (2018); Alt et al. (2015), Judson et al. (2020a)

7.2.3 Statistical Analysis

To answer RQs 7.1:7.4, the following statistical methods were employed:

RQ7.1 – Bivariate Pearson correlation coefficients to assess the relationships between SF and GCT and FT, and external kinetic variables for the R-L step.

RQ7.2 – Bivariate Pearson correlation coefficients to assess the relationships between R-L duration of propulsive force and selected mechanically relevant kinematic variables. Furthermore, correlation coefficients will be calculated between external kinetic variables deemed to have significant relationships with R-L SF and kinematic variables.

RQ7.3 – Bivariate Pearson correlation coefficients to assess the relationships between SL and stance distance and flight distance, and external kinetic variables for the L-R step.

RQ7.4 – Bivariate Pearson correlation coefficients to assess the relationships between L-R peak inward force and selected mechanically relevant kinematic variables. Furthermore, correlation coefficients will be calculated between external kinetic variables deemed to have significant relationships with SL, and kinematic variables.

Thresholds for the magnitudes of all correlation coefficients were defined according to (Hopkins, 2003) as trivial (0.0), small (0.1), moderate (0.3), large (0.5), very large (0.7), nearly perfect (0.9) and perfect (1.0). These thresholds have been used in similar sprinting research to determine the relationships between selected kinematic characteristics and initial acceleration performance (King et al., 2023). Furthermore, in line with previous maximal velocity linear sprint research (von Lieres Und Wilkau et al., 2020): a threshold of 0.10 was set for the smallest worthwhile effect, and 90% confidence intervals were used to make inferences about the magnitude of the correlation (range from very likely detrimental to almost certainly beneficial) (Batterham & Hopkins, 2006).

7.3 Results

7.3.1 RQ7.1

For the R-L step, SF was significantly negatively correlated to GCT (0.107 ± 0.017 s; r = -0.83; $p < 0.05$) but not FT (0.115 ± 0.013 s; r = -0.73; $p > 0.05$). R-L SF was significantly positively correlated (almost certainly beneficial) with only vertical impulse (r = 0.79; $p = 0.020$).

7.3.2 RQ7.2

For kinematics, significant relationships with R-L duration of propulsive force (0.039 ± 0.009 s) can be seen in Table 7-2. Since shorter duration of propulsive force is related to faster SV, significant negative correlations with kinematic variables have been highlighted in blue to show likely beneficial to producing shorter duration of propulsive force times. The peak hip flexion angle during the stance phase coincided with the moment of TD. As a result, the values for peak hip flexion angle and hip flexion angle at TD were identical. Therefore, to avoid redundancy, only the hip flexion angle at TD is presented and discussed in the results.

Table 7-2. Kinematic variables that were significantly correlated to R-L Propulsive Duration. Significant positive correlations with kinematic variables have been highlighted in brown to show likely detrimental effect resulting in longer duration of propulsive force and significant negative correlations have been highlighted in blue to show likely beneficial effect resulting in shorter duration of propulsive force.

Variable	R-L	
	Mean ± SD	r (p)
Hip flexion angle at TD (°)	52.00 ± 8.54	0.93 (0.01)
Peak knee extension velocity during Stance (°/s)	557.40 ± 179.30	-0.90 (0.02)
Peak knee flexion angle during stance (°)	43.34 ± 7.66	0.81 (0.049)
Knee flexion angle at TD (°)	34.64 ± 6.68	0.97 (0.00)
Knee extension velocity at TO (°/s)	488.84 ± 231.21	-0.83 (0.043)
Knee flexion-extension RoM during Stance (°)	22.78 ± 7.70	-0.86 (0.03)
Time of peak knee extension angle (°)	99± 3.06	-0.99 (<0.001)
Time of peak knee extension velocity (% stance)	79 ± 2.94	-0.88 (0.023)
MTP plantarflexion velocity at TD (°/s)	-1243.27 ± 390.97	-0.86(0.029)
MTP plantarflexion velocity at TO (°/s)	-1448.78 ± 480.15	-0.95 (0.004)

*full knee extension is equal to 0 °.

Table 7-3 shows significant relationships between kinematic variables with R-L vertical impulse (2.19± 0.32 BW/s). Greater vertical impulse is related to higher SF, thus, significant positive correlations with kinematic variables have been highlighted in blue to show likely beneficial to producing greater vertical impulse. significant negative correlations with kinematic variables have been highlighted in brown to show likely detrimental effect resulting in smaller vertical impulse.

Table 7-3. Kinematic variables that were significantly correlated to R-L Vertical Impulse. Significant correlations with kinematic variables have been highlighted in brown to show likely detrimental effect resulting in smaller vertical impulse and significant correlations have been highlighted in blue to show likely beneficial effect resulting in greater vertical impulse.

Variable	R-L	
	Mean ± SD	r (p)
Hip extension angle at TO (°)	13.16 ± 10.06	0.83 (0.020)
Peak hip extension velocity (°/s)	732.90 ± 124.80	0.78 (0.039)
Peak knee extension angle (°) *	22.01 ± 6.511	-0.89 (0.007)
Peak knee extension velocity (°)/s	557.39 ± 179.30	0.75 (0.048)
Knee flexion angle at TO (°)	23.77 ± 9.95	-0.93 (0.002)
Knee abduction angle at TO (°)	1.59 ± 4.99	-0.81 (0.029)
Knee adduction-abduction angle RoM (°)	5.29 ± 3.44	0.88 (0.009)
Peak ankle dorsi-flexion angle (°)	8.21 ± 6.21	0.95 (0.001)
Peak ankle inversion angle (°)	7.36 ± 4.46	-0.84 (0.019)
Ankle plantar flexion angle at TD (°)	19.73 ± 8.60	0.95 (0.001)
Ankle plantar flexion angle at TO (°)	37.73 ± 6.66	0.95 (0.001)
Time of peak ankle dorsi-flexion angle (% stance)	49.43 ± 3.70	0.82(0.044)

*full knee extension is equal to 0 °.

7.3.3 RQ7.3

For the L-R step, SL was not significantly correlated to stance distance (1.01 ± 0.13 m; r = 0.29; $p > 0.05$) or flight distance (1.02 ± 0.19 m; r = 0.74; $p > 0.05$). L-R SL was significantly positively correlated (very likely beneficial) with inward impulse ($p < 0.05$) (Figure 7.1).

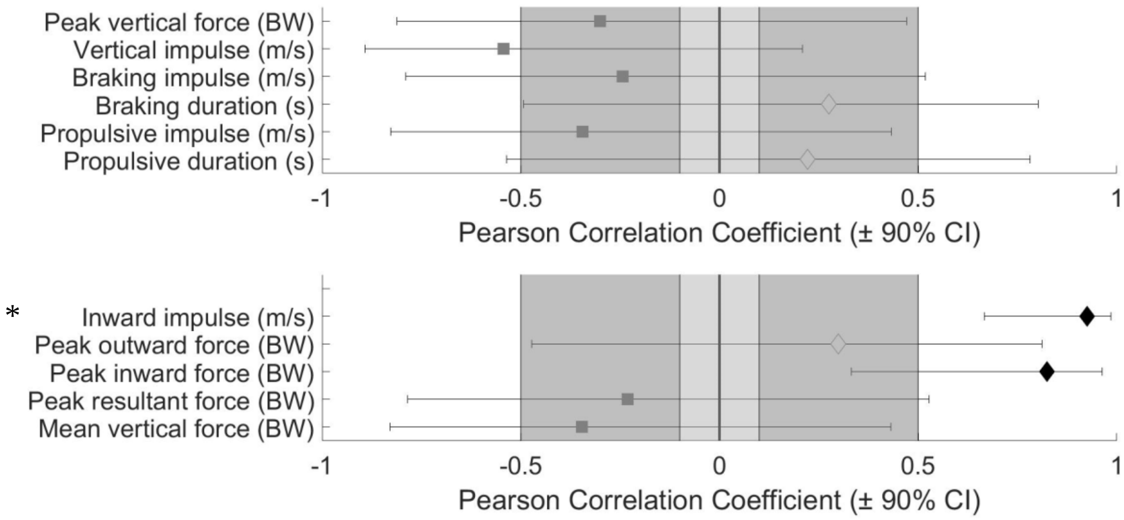

Figure 7.1. Pearson correlation coefficients (± 90% CI) between SL and kinetic variables for the L-R step. Marker type (beneficial = diamond, trivial = square, detrimental = circle) and colour indicates unclear (grey outline), likely (grey outline), very likely (black outline), and almost certain (black fill) relationships. The central area (r = −0.1 to 0.1) indicates a trivial relationship. Dark grey region (r = −0.1 to −0.5 & 0.1 to 0.5) indicates small to moderate relationships. * Denotes a significant relationship ($p < 0.05$).

7.3.4 RQ7.4

For kinematics, significant relationships with L-R peak inward force (0.80 ± 0.19 BW) and inward impulse (0.46 ± 0.09 BW/s) can be seen in tables Table 7-4 and Table 7-5 shows significant relationships between kinematic variables with L-R peak inward force and inward impulse. Greater peak inward force and inward impulse were related to faster SV and longer SL respectively. Significant positive correlations with kinematic variables have been highlighted in blue to show likely beneficial to producing greater inward force and impulse. Significant negative correlations with kinematic variables have been highlighted in brown to show likely detrimental effect resulting in smaller inward peak force and impulse.

Table 7-4. Kinematic variables that were significantly correlated to L-R Peak inward force. Significant correlations with kinematic variables have been highlighted in brown to show likely detrimental effect resulting in lower peak inward force and significant correlations have been highlighted in blue to show likely beneficial effect resulting in greater peak inward force.

Variable	L-R	
	Mean ± SD	*p* (r)
Hip abduction-adduction velocity at TD (°/s)	91.60 ± 54.70	-0.85 (0.030)
Ankle peak eversion-inversion velocity (°/s)	461.36 ± 103.76	0.84 (0.035)
Ankle external rotation angle at TD (°)	-7.62 ± 8.69	-0.89 (0.018)
Ankle external - internal rotation velocity at TO (°/s)	-106.13 ± 200.99	-0.81 (0.049)

Table 7-5. Kinematic variables that were significantly correlated to L-R Inward impulse. Significant correlations with kinematic variables have been highlighted in brown to show likely detrimental effect resulting in smaller inward impulse and significant correlations have been highlighted in blue to show likely beneficial effect resulting in greater inward impulse.

Variable	L-R	
	Mean ± SD	*p* (r)
Hip Extension velocity at TO (°/s)	-303.92 ± 174.61	-0.87 (0.029)
Peak knee adduction angle (°)	3.94 ± 4.29	-0.81 (0.0494)
Knee extension velocity at TO (°/s)	-286.90 ± 153.68	-0.88 (0.022)
Body lateral lean angle at TD (°) *	-5.28 ± 1.78	-0.89 (0.020)
Time of peak hip extension Velocity (% stance)	52.57 ± 42.61	-0.92 (0.010)
Time of peak knee extension angle (% stance)	59 ± 48.53	0.89 (0.018)
Time of peak knee velocity extension (% stance)	81.29 ± 8.71	0.89 (0.018)

* negative indicates lean in toward the bend.

7.4 Discussion

Following on from the findings of Chapter 6 where: for the R-L step SF and shorter duration of propulsive force were found to be the key determinants of R-L SV and, for the L-R step, SL and peak inward force were the key determinants of SV. The aim of this Chapter was to investigate kinematic and kinetic variables that influence bend sprinting performance (SV) or determinants of bend sprinting performance (SL and SF).

7.4.1 RQ7.1: What are the key determinants and kinetic variables that relate to R-L SF?

SF was significantly correlated with GCT but not FT, reinforcing the findings of the previous Chapter where shorter duration of propulsive force were related to faster R-L SVs. Furthermore, the previous Chapter highlighted significantly more vertical and inward force was produced by the R-L step during early stance. Previous research has highlighted that the ability to apply large forces quickly during early stance is one of the reasons elite athletes accelerate beyond the velocities achieved by team sports players (Clark & Weyand, 2014). Therefore, the greater ability of the R-L limb to apply force quickly during early stance is perhaps one of the reasons for the shorter duration of propulsive times that also contribute to short GCT and increased SF. Furthermore, the present study found that vertical impulse was significantly positively correlated to R-L SF. Due to the significant relationships between duration of propulsive force and SV, and vertical impulse and GCT with SF suggests that the ability to produce vertical force quickly and minimise GCT relates to R-L SF and is one of the key drivers in producing faster R-L SVs. RQ6.3 in Chapter 6 highlighted that the R-L step produced greater vertical force during early stance, therefore as in linear sprinting perhaps for the R-L step, the ability to apply vertical force quickly is related to faster SVs (Clark & Weyand, 2014). FT was not significantly correlated with SF; this is perhaps less surprising since longer FT are generally associated with larger SLs. Therefore, whilst the ability to minimise GCT is more apparent, there is likely an optimal ratio of short FT for faster SF and longer FT durations because of longer SLs. In contrast to the present findings, Ishimura & Sakurai, (2016) found that FT was significantly related to step time ($r = 0.77$ $p < 0.01$) (inverse of SF) whereas GCT was not significantly related to step time ($r = 0.47$; $p > 0.05$).

Faster SF because of shorter GCT has been associated with greater abilities to apply vertical force and greater leg stiffness (Clark et al., 2020; Nagahara & Zushi, 2017) whilst shorter FT may be associated with reduced TO velocity and thus reduced vertical displacement and earlier subsequent TD (Ishimura & Sakurai, 2016). The kinematics of the L-R limb can impact the FT of the R-L step, for example, because of body lateral lean, the hip and ankle adduct and evert as there is less space in relation to the CoM to bring the right limb through to prepare for TD. Reduced space in relation to the CoM thus potentially results in lower extension angular velocities and larger TD_D (Churchill et al., 2015). Nevertheless, TD_D wasn't significantly correlated with R-L SF or duration of propulsive force.

As a performance measure, ensuring athletes are able to produce short GCT with the outside limb appears to be a key driver in bend sprinting performance. In linear sprinting, this can be achieved through developing vertical leg stiffness, highlighted by Nagahara & Zushi, (2017) who found athletes significantly increased maximal SV through achieving greater SLs following 6 months of training. Significantly larger vertical stiffness and ankle stiffness contributed to the larger SL whilst training incorporated plyometric training, weight (strength training), circuit training, sprint speed, sprint endurance and individualised event sessions (participants included sprinters, jumpers and pole-vaulters). Therefore, whilst the method for improving ankle stiffness cannot be solely attributed to one particular training intervention, Nagahara & Zushi, (2017) highlight that the ability to increase sprinting speed in well trained sprinters was associated increases in ankle stiffness. Additionally, the increased SV were achieved through increased SL during linear sprints (Nagahara & Zushi, 2017), this may not be as beneficial on the bend whereby increased SL will increase the turning demands. Whilst not specific to sprinting, an applied plyometric program has been shown to be effective in reducing ground contact time and therefore likely increasing leg stiffness in rhythmic gymnasts (Dallas et al., 2020). Nonetheless, as bend sprinting requires additional inward forces, which require transverse and frontal kinematic adaptations compared to linear sprints (Alt et al., 2015; Churchill et al., 2015), it is important that training exercises mimic the demands of the bend. One popular drill utilised by 60% of surveyed coaches (Whelan et al., 2016) that could be adapted for use on the bend is the use of bounds. Bounds can be performed with the emphasis on greater height or greater distance. In a recent study: Washif & Kok, (2020) found that a 10-step speed bound using the reactive bound coefficient (time taken, distance covered normalised to leg length) could distinguish between faster and slower sprinters on a linear path in a well-trained population (100 m pb =10.77 ± 0.32 s). Additionally, previous research has highlighted potential efficacy of small loads of wearable resistance attached to the shank and or thigh to overload selected step characteristics and prevent detraining magnitudes (Feser, Bayne, et al., 2021a; Feser et al., 2023). Therefore, undertaking speed bounds on the bend and or the use of wearable resistance may enable the overload of early stance phase forces and developing shorter duration of propulsive force that may improve R-L SF.

7.4.2 RQ7.2: What kinematic variables relate to duration of propulsive force and kinetic variables that relate to R-L SF?

RQ6.2 identified duration of propulsive force to be a significant factor in producing fast R-L SVs. Therefore, kinematic factors that contribute to short duration of propulsion were investigated. Several variables at the hip, knee and MTP joints were significantly related to duration of propulsive forces. Firstly, the positive correlation for hip flexion at TD (peak hip flexion) suggests that having greater hip flexion related to longer durations of propulsion. It is possible that greater hip flexion at TD is less indicative of an active TD technique that has been related to better positioning at TD (Thompson et al., 2009). Furthermore, less hip flexion at TD has been associated with shortened GCT during linear sprinting (Kunz & Kaufmann, 1981). Previous research during linear sprinting has highlighted the important contributions of the hip during early stance (Bezodis et al., 2008), thus optimal hip flexion at TD potentially enables the hip joint to generate greater torque during early stance and if transferred through the knee and ankle joints, contribute to shorter duration of propulsion. On the bend, Ohnuma et al. (2018) reports the R-L hip flexion at TD on the bend to be non-significantly greater for the poor group (137.6 ± 4.3°) compared to the good group (134.5 ± 6.0°). Whilst this finding is non-significant, a 2.25% reduction may indicate that the hip flexion angle at TD has bearing on bend sprint performance. Additionally, Ohnuma et al. (2018) reported that significant differences between bend and straight occurred in hip extension at TO in the poor group, where anterior-posterior GRF and impulse were reduced. Reduced anterior-posterior force could suggest that the increased hip flexion at TD and the decrease in the hip joint extension movement during the stance phase were related to the reduced bend sprint velocities. Ishimura & Sakurai, (2016) build upon Hay's, (1993) deterministic model to highlight that vertical and horizontal (anterior-posterior and outward-inward) impulse are related to GCT, thus it is possible that less hip flexion is a pre-requisite for a better opportunity to produce greater impulse and thus minimise duration of propulsive force and contact time.

Similar to the hip, the peak knee flexion and flexion at TD were positively correlated to propulsive duration, highlighting that a more flexed knee is potentially related to a less stiff limb during contact and slower production of forces required to maintain short contact times. This finding supports previous research that found less knee flexion at TD to be significantly related to greater R-L SF (Churchill, 2012). Therefore, it is possible that minimising knee flexion at TD enables greater force production during stance and thus minimises contact time for the R-L step and contributes to faster R-L SF. Nevertheless, knee range of motion during stance was negatively correlated with propulsive duration highlighting that perhaps whilst minimising knee flexion is beneficial, maximising knee extension is beneficial to short propulsive duration.

Both peak knee extension velocity and velocity at TO were negatively correlated with propulsive duration. During linear sprinting, Bezodis et al. (2008) highlights the action of the knee joint during stance to act more of a facilitator for the transfer of power from the hip through the ankle, the larger values of knee extension velocity are potentially the consequence of effective hip and ankle force generation. Interestingly, the large SD for knee extension velocity at TO suggest that some athletes were less able to coordinate knee extension velocity at TO. Whilst not significant or not tested inferentially, Ohnuma et al. (2018) reported peak knee extension velocity that appears to be lower in the poor sprint group on the bend (383.9 ± 84.5°/s) than both the straight (441.2 ± 90.7°/s), and the good group on the bend (447.0 ± 66.8°/s) respectively. Furthermore, in the present study the negative correlations for the time of peak knee extension and knee extension velocity highlight that those best able to reach peak knee extension velocity and angle later during stance were those that produced short propulsive durations.

A negative correlation between duration of propulsion and MTP joint plantar flexion at TO, in combination with greater peak knee extension velocity at TO highlights that short propulsive durations were associated with good proximal to distal sequencing of knee extension and MTP plantar flexion in order to achieve high angular velocity at TO. A lack of proximal-distal sequencing has been proposed to contribute to explaining lower magnitudes of positive power in the rear block of the sprint start (Brazil et al., 2016), Therefore, greater proximal-distal sequencing of joint extension is likely to result in more energy at the knee joint to aid more forceful ankle plantarflexion (Jacobs et al., 1996). Similarly, MTP plantarflexion velocity at TD was significantly negatively correlated with shorter duration of propulsion, indicating that an active MTP plantar flexion at TD contributed to the opportunity to produce short propulsive durations. This is supported by Thompson et al.'s, (2009) investigation into elite sprint coaches perception of technical constructs, where coaches looked for athletes to pull the foot under the body, thus generating powerful forward drive at the beginning of stance. Therefore, initiating a more active TD to minimise braking forces and enable greater anterior forces early in stance to enable shorter duration of propulsion is potentially achieved by minimising hip and knee flexion whilst maximising MTP plantar flexion at TD.

Vertical Impulse

Faster knee extension was related with both short duration of propulsive force and greater vertical impulse. For kinematic variables associated with greater impulse included: greater hip extension angle at TO, peak hip extension velocity, greater knee extension and greater ankle plantar flexion at TO. Therefore, similar to sprinting on a straight path, it is possible that greater hip extension velocity is associated with greater vertical impulse (Clark et al., 2020), potentially through a greater ability to apply higher vertical force quickly (Clark & Weyand, 2014). Additionally, greater hip extension velocity likely contributes to a more extended hip and plantar flexed ankle at TO. Ohnuma et al.'s (2018) finding of significant differences between bend and straight in hip extension at TO in the poor group along with reduced anterior-posterior GRF and impulse, supports the current finding that greater hip extension at TO is associated with greater vertical impulse. Therefore, the ability to maximise hip extension velocity and extend the hip and knee to a greater extent, in addition to the frontal and transverse plane alterations is an area for coaching and research attention as an area for improvement in bend sprinting performance.

At the ankle, those athletes that initiated stance with greater plantar flexion, achieved greater dorsiflexion and reached peak dorsiflexion later in stance produced greater vertical impulse. Furthermore, as highlighted, plantar flexion at TO was positively correlated with vertical impulse. Whilst greater dorsiflexion is not suggestive of a stiffer ankle joint, perhaps generating greater dorsiflexion enables greater use of stretch shortening capability of the Achilles tendon and contributes to achieve greater plantar flexion at TO. This appears not to be the case during the acceleration phase, where reducing dorsiflexion, appears to be beneficial for improving early acceleration performance (Bezodis et al., 2015). Nevertheless, Bezodis et al. (2015) found that reducing dorsiflexion required increases in the peak ankle plantar flexor moment, thus at maximum velocity perhaps greater plantar flexor moment generation abilities enable athletes to make greater use of the dorsiflexion stretch-shortening cycle and generate greater vertical impulse. Nonetheless, the small standard deviation (8.21 ± 6.21 °) perhaps limits the generalisation of this finding due to potential challenges in making technical changes in technique to achieve small margins of greater dorsiflexion during stance. It is possible that performance benefits may occur through development of planter-flexor moment generation abilities and associated ankle stiffness (Nagahara & Zushi, 2017), as long as this increase is observable in bend sprinting specific joint positions, such as additional internal rotation (Judson et al., 2020c**).** Ohnuma et al. (2018) reports non-significantly reduced plantar flexion on the bend in the poor group (104.3 ± 9.2°) compared to their respective straight sprint (109.4 ± 6.8°). For the good group, mean and standard deviation values were closer and smaller respectively, suggesting less effected by the effect of the bend and maintained similar plantar flexion. Furthermore, for plantar flexion at TO the good group were able to non-significantly increase their plantarflexion from the straight (118.5 ± 9.4°) to the bend (123.0 ± 5.2°) whereas a non-significant decrease was observed in the poor group from straight (122.6 ± 5.7°) to bend (120.5 ± 8.6°) (Ohnuma et al., 2018). Therefore, as highlighted by the present results, there is a potential relationship between increased ankle plantarflexion, ankle RoM and greater vertical impulse. This is supported by Bezodis et al.'s, (2008) finding that the ankle plantar flexors are the key drivers during the late stance during maximal linear sprinting.

In the frontal plane, it appears that those athletes who utilised a greater knee abduction-adduction movement produced greater vertical impulse. The previous Chapter highlighted that the R-L step produced greater vertical and inward force than the L-R during early stance. Whilst an abduction-adduction is unlikely the key contributor to greater vertical impulse, it is possible this strategy is used to produce inward force early in stance or stabilise in the frontal plane. Previous research has highlighted that the hip is the primary generator of inward force (Judson et al., 2020c; Nevison et al., 2015; Viellehner et al., 2016). Nevertheless, despite the small magnitudes of knee abduction-adduction, there appears to be large standard deviations across the stance phase for knee abduction adduction moment for the R-L step on the bend during the acceleration phase (figure 3 – Judson et al., 2020) and an adduction-abduction moment toward late stance at maximum velocity (Viellehner et al., 2016). Therefore, perhaps the faster athletes were able to utilise knee abduction-adduction throughout the stance phase to produce inward and vertical force. Furthermore, as a result of the previously highlight kinematic adaptations in the frontal plane observed during bend sprinting, such as greater body lateral lean and hip abduction, knee adduction would suggest that the knee is involved with generating inward forces during early stance. The knee having a role in inward force generation is supported by the fact that, athletes that minimised the knee abduction at TO produced greater vertical impulse, suggesting that a knee abduction-adduction movement occurred throughout stance. Similarly, during sidestepping and crossover cutting the varus/valgus and internal/external rotation moments applied to the knee were found to be larger than during linear running (Besier et al., 2001), as well as greater activation of medial/lateral and internal/external rotation muscles to stabilise the knee joint under planned cuts compared to unplanned (Besier et al., 2003). Chang & Kram (2007) hypothesised that on small bend radii, the reduced resultant force leads to a proportional increase in both sagittal plane leg extensor forces and frontal plane joint stabilization forces as sprint speed increases or bend radius tightens. This increase continues until a physiological limit is reached in one or more muscle groups. Therefore, it is possible that those sprinters able to generate inward force in addition to anterior and vertical can achieve greater velocities on the bend, and that the knee is potentially a strategy for controlling force produced at the hip. Furthermore, whilst it appears that the inversion velocity of the L-R ankle plays a role in maximising inward forces, reducing peak inversion during R-L stance was related to producing greater vertical impulse required to maximise SF. The previous Chapter highlighted that inward force during the R-L stance was produced earlier than on the L-R step, thus the ability to lean toward the bend, minimise ankle inversion and generate inward force through abduction adduction of the knee is potentially the effective strategy of applying inward force of the R-L step. This suggests a pushing outwards strategy for the R-L step as suggested by Hirono & Fujii, (2024) as a strategy for generating inward forces.

7.4.3 RQ7.3: What are the key determinants of SL and kinetic variables that relate to L-R SL?

For the L-R step, SL was not significantly correlated to stance distance or flight distance, since both values were similar perhaps athletes have differing techniques for achieving greater SLs. This finding contrasts with Ishimura and Sakurai (2016) who found stance (r = 0.73) and flight distance (r = 0.86) to significantly correlate with L-R SL. However, in Ishimura and Sakurai’s (2016) investigation, bend sprints were undertaken in lane 4 (43.51 m) compared to lane 1 (36.5 m) in the present study. Tighter radii may reduce the emphasis on greater flight distance as a result of the requirement to turn the centre of mass more with each step. Whilst stance and flight distance are not reported, Churchill et al. (2018) reports significant increases in GCT and non-significant increases in FT for the L-R step when comparing lane 8 (45.10 m) and lane 2 (37.72 m) suggesting that the change in radius has an impact on the contributions from stance and flight phases to bend sprinting performance.

In agreement with the previous chapter on the importance of inward force for the L-R step, L-R SL was significantly positively correlated (very likely beneficial) with inward impulse. This builds upon the previous Chapter by highlighting that as well as the peak magnitude of inward force, the duration of application is important to producing large SL that contribute to L-R SVs. Whilst vertical impulse was not significantly related to L-R SL, the relationship with inward impulse suggests that the ability to not only generate inward force but to do this quickly is a factor that sets faster athletes apart on the bend. During linear sprinting, previous research has highlighted that the ability to apply vertical force quickly during early stance is what enables sprint athletes to achieve greater velocities than team-sports players (Clark & Weyand, 2014). Therefore, training exercises that can develop inward force generation magnitudes and rate of application may be an area for potential improvements in bend sprinting velocities and warrants future research. As highlighted for the R-L step, this could involve application of wearable resistance, use of plyometric drills on the bend and adapting existing training exercises to replicate the demands of the bend, for example the modified lateral split squat (Maddy, 2020).

7.4.4 RQ7.4: What kinematic variables relate to peak inward force and kinetic variables that relate to L-R SL?

Peak inward force

Addressing RQ7.4 highlights that the external rotation angle at TD and velocity of L-R Ankle at TO were positively correlated with peak inward force. This suggests that the L-R ankle generates turning forces via external rotation of the ankle and thus, greater velocity at TO indicates more turning of the centre of mass prior to the subsequent TD. Previous research has highlighted that the L-R step underwent more of a stabilising role in the frontal plane whilst the R-L step adopted a more rotational strategy (Alt et al., 2015). Nevertheless, Alt et al. (2015) reports large external rotation at the hip during L-R stance, therefore it is possible that faster external rotation of the hip and or ankle at TO enables athletes to more effectively transfer inward force. Additionally, greater peak inversion velocity was significantly beneficial to inward force production. Previous research highlights high peak eversion angles during L-R stance, whilst Chapter 5 and Alt et al. (2015) show that the L-R step followed an inversion-eversion-inversion movement throughout L-R stance (Figure 5.7 & Figure 1 - (Alt et al., 2015). Therefore, the ability to produce high inversion velocity to counteract the large eversion angles is necessary to produce the large inward forces that help contribute to SL on the bend.

A negative relationship with for hip adduction velocity at TD with peak inward suggests that smaller adduction velocity at TD is beneficial to larger inward forces and thus contributes to longer SLs. RQ6.3 highlighted that the L-R step stabilises laterally before producing greater inward forces prior to TO. Therefore, it is possible that the athletes that were able to minimise adduction velocity at TD minimised lateral force during early stance and produced inward force earlier that contributed to greater inward forces and ultimately SL. Previous research has highlighted that peak adduction during L-R stance is greater on the bend than straight and the R-L step on the bend, suggesting its importance to the L-R step and potential inward force generation. Churchill (2011) found that athletes with a smaller thigh separation at TD produced longer L-R SLs. This suggests that the ability to bring through the swing leg to a better position at TD contributes a longer L-R step. In support of this, studies have highlighted that altered frontal plane hip kinematics can impact muscle activity to drive sagittal plane movement, suggesting that minimising hip adduction/abduction at TD enables these muscles to work more effectively (Coqueiro et al., 2005). Whilst the adduction angle at TD was not significantly correlated with peak inward force in the present investigation ($r = 0.18$; $p > 0.05$; 3.28 ± 3.97°) it could be that minimising the adduction velocity at TD results in less requirement to stabilise in the frontal plane during stance. Chang & Kram (2007) highlight stabilising in the frontal plane as a potential limiting factor during tight radii bend sprinting. Thus, it is possible that minimising hip adduction velocity at TD reduces the stabilisation demands during the L-R stance and enables athletes to produce greater inward forces that contribute to larger L-R SL.

Inward impulse

In support of previous theories, body lateral lean was significantly negatively correlated with inward impulse, highlighting that to produce inward force, or centripetal force that enable faster SV, athletes lean in toward the bend (Neie, 1981). Inward impulse was significantly positively correlated with hip and knee extension velocities at TO, this suggests that those athletes that were able to produce rapid extension at TO were able to effectively balance the generation of inward force and maintain short force application time whilst producing the vertical/horizontal force required to maintain bend sprint velocity. Churchill (2011) found that longer L-R SLs were related with more extended L-R knee at TD, highlighting that this may result in better positioning of the extensor muscles to exert force (Mero & Komi, 1985) and contribute to produce longer SLs. In the present study however, the drivers of inward impulse (which in turn was significantly correlated with SL) were the extension velocities of the knee and hip at TO. Fast thigh angular velocities have been associated with faster running speeds (Clark et al., 2020; Kunz & Kaufmann, 1981), thus, it is possible that the knee and hip extension velocities are the consequence of optimal positions at TD that enable rapid force application during early stance (Bezodis et al., 2008). Nonetheless, since hip adduction/rotation can impact the ability to move in the sagittal plane, these velocities are perhaps dependent on optimal positioning of the knee and hip at TD.

Previous research has highlighted that the ability to generate and maintain high angular velocities is important for sprinting velocities (Clark et al., 2020). Therefore, as high extension velocities are likely not aiding inward force generation, as evidenced by no significant relationship to peak inward force, it may enhance the athlete's ability to produce force quickly and produce shorter contact times that increase impulse. Furthermore, the rapid extension velocities potentially help to maintain the inward force generated and enable the athlete to turn the CoM in the flight phase. This supports Ohnuma et al. (2018) who highlight that perhaps the best bend sprinters closely replicate their sagittal plane kinematics as on a linear path, thus maximising athletes' ability to rapidly extend the hip and knee during stance in altered frontal and transverse plane kinematics is an area for potential improved performance. In addition, significant correlations were found for the timing of minimum (time of slowest hip extension velocity) and peak hip and knee extension velocities and knee extension angle. For hip extension velocity, those athletes that produced their slowest hip extension velocity earlier in stance produced greater inward-impulse, this suggests that those athletes with the ability to initiate hip extension earlier in stance produce greater inward impulse, and thus SL. This finding supports the notion that greater hip and knee extension velocity at TO were related to greater inward-impulse.

For knee extension angle and velocity, the positive correlation suggests that those that produced peak knee extension later in stance produced greater inward impulse suggesting a more effective proximal - distal sequencing of peak knee extension angle and velocity closer to TO. It is noted the large standard deviation of the time of peak knee extension, some athletes' peak extension occurring at TD, which means it is possible that these athletes produced greater larger TD_D which have been proposed to result in larger braking forces (Hunter et al., 2005; Mero et al., 1992) and force production and ground contact time (Bezodis et al., 2015; Hunter et al., 2005; Mann & Herman, 1985; Mendiguchia et al., 2021; Mero et al., 1992). Churchill et al. (2015) refers to the ability to execute a more active TD with the L-R step as a potential beneficial technique during bend sprinting, whilst the present findings finding build on this by highlighting the ability to produce greater magnitudes at the correct times will help to produce greater inward impulse and contribute to longer SLs and SVs for the L-R step.

Peak knee adduction during stance was negatively correlated with inward impulse. Whilst frontal and transverse plane adaptations are generally thought to be required to produce inward force, perhaps for the L-R step it is more important that inward force is produced from the body lateral lean and actions of the hip and ankle joints rather than the knee. Thus, the athletes with greater frontal plane stability can minimise knee valgus and thus enable the smoother transfer of force and rapid extension of hip and knee prior to and at TO. In support for this, Chang & Kram (2007) suggested that the ability to stabilise in the frontal plane is a potential limiting factor to bend sprinting performance. Previous cutting manoeuvre research has highlighted soccer players are able to selectively co-contract thigh musculature such as vastus medialis obliques and tensor fascia late to minimise knee valgus during planned but not unplanned cuts (Besier et al., 2003). Therefore, it is possible the ability to stabilise in the frontal plane differs between athletes and impacts their ability to generate greater inward impulse. Furthermore, previous research has highlighted the ability to reduce peak knee valgus during cutting manoeuvres through training interventions (Schwameder & Seeber, 2020). Moreover, since greater body lateral lean at TD was correlated with greater inward-impulse, this suggests that athletes who can lean into the bend whilst minimising knee adduction/valgus are better able to generate inward impulse. The relationship between body lateral lean and peak inward force was not significant ($r = 0.2115$; $p > 0.05$), suggesting that greater lean does not necessarily contribute as much toward the magnitude of inward force, but the rate of inward force and minimises the contact time.

7.5 Conclusion

This is the first study to describe the relationship between mechanically relevant kinematics and drivers of R-L and L-R SV during bend sprinting. This study highlights the importance of GCT and vertical force application in determining R-L SF during bend sprinting. Shorter GCTs were significantly correlated with faster R-L SF, while FT showed no significant correlation. Vertical impulse was significantly correlated with R-L SF, reinforcing the relationship between GCT and SF. These findings suggest that developing vertical leg stiffness is crucial for improving bend sprinting performance. Nevertheless, the need for additional inward forces requires training interventions that address both vertical and horizontal force application.

For shorter propulsive durations, minimising hip and knee flexion at TD while maximising MTP plantar flexion appears beneficial. Effective proximal-to-distal sequencing, particularly in knee extension and MTP plantar flexion towards TO, is associated with shorter propulsive times. Greater vertical impulse is related to higher knee extension velocity, increased hip extension at TO, and greater ankle range of motion during stance. The ability to generate inward forces through knee abduction-adduction movements, while maintaining stability, may also contribute to greater vertical impulse and thus potentially bend sprinting performance.

For the L-R step SL was not significantly correlated to stance distance or flight distance, since both values were similar perhaps different athletes have differing techniques for achieving greater SLs. Ankle external rotation angle at TD and velocity of the external rotation at TO were positively correlated with peak inward force. This finding suggests that greater external rotation and velocity at TO enhance the turning of the centre of mass before the next TD. High inversion velocity was beneficial to greater inward force in addition to potentially counteracting large eversion angles. Smaller hip adduction velocity at TD is linked to larger inward forces and longer SLs, indicating that minimising adduction velocity reduces stabilisation demands and enhances force production.

For inward impulse: greater body lateral lean at TD was associated with greater inward impulse, highlighting the role of body lean in generating inward impulse while minimising knee adduction/valgus. Hip and knee extension velocities at TO were significantly correlated with inward impulse, suggesting that rapid extension helps balance inward force generation and maintain sprint velocity. Athletes who initiated hip extension earlier in stance produced greater inward impulse, indicating the importance of proximal-distal sequencing of knee extension for effective force application.

Therefore, coaches and practitioners should seek to make training specific to the bend, to ensure athletes are able to generate sufficient angular velocities in the sagittal, frontal and transverse planes with the appropriate angular positions at TD and TO as well as peak values. This could involve the use of plyometric drills on the bend, wearable resistance during normal training or adapting existing strength training exercises to replicate bend specific positions.

7.6 Coaching and Practical Recommendations for Bend Sprinting Based on Key Findings

For the right-left step, shorter ground contact times and greater vertical force were related to higher step frequency. Coaches could focus on drills that improve the ability to apply greater vertical force quickly, such as plyometrics, bounding or sprint drills undertaken on the bend to develop vertical leg stiffness and rapid joint extension that enable shorter contact times.

For the left step, coaches could look to adapt strength and conditioning exercises that include body lateral lean and target the hip abductors and adductors and ankle eversion, inversion and rotation muscles. For example, a modified split squat using the landmine and front-loaded position that enables body lateral lean and a more lateral force application. Additionally, exercises that improve develop external rotation and inversion velocities such as use of resistance bands or cables, may help increase inward force abilities that contribute to maintaining step length on the bend.

Furthermore, similar to the right step, undertaking more bend-specific drills that incorporate changes in direction, and optimising inward forces may enhance bend step velocities in particular for the left-right step.

Chapter 8: General Discussion

8.1 Introduction

The literature review highlighted a lack of research on indoor competition despite global significance and a lack of understanding of the kinetic and kinematic drivers of bend sprinting performance compared to straight sprinting. In order to achieve the thesis aim and purpose, the experimental Chapters were split into two main phases, Phase 1 sought to increase understanding of altering task demands during bend sprinting representative of indoor competition whilst phase 2 explored the relationships between key variables and performance for both the L-R and the R-L steps, and investigated the relationship between athlete asymmetry and bend sprinting performance However, prior to the commencement of Phase 1, to improve the accuracy of gait event detection where force plates are not available, kinematic gait event detection methods were assessed for their accuracy to inform use throughout the thesis. This Chapter will sequentially consider the RQs addressed throughout this thesis to synthesise the new and original contributions to knowledge, make recommendations on coaching practice, discuss limitations of methods and identify key areas for future research.

Chapter 3

The literature review emphasised that whilst gait events were important to understanding bend sprinting performance no consensus on accurate methods using kinematic data had been established for use during bend sprinting. The aim of this Chapter was to determine the accuracy of adapted previously utilised kinematic event detection methods to validate for use during maximal bend sprinting. The purpose of this Chapter was to validate kinematic event detection methods that enable calculation of variables for multiple L-R and R-L steps where force plate data is not available. Validated methods informed use throughout the thesis to increase understanding of the joint kinematic adaptations to bend sprinting on different conditions and their relationship to bend sprinting performance.
RQ3.1: *How do different kinematic event detection methods compare in accuracy for detecting TD of the L-R and R-L steps?*

For TD detection during maximal velocity bend sprinting, several methods achieved acceptable accuracy of less than ±1.25 frames (250 Hz; 5 ms). The most accurate methods were the threshold method for the R-L step using the TOE marker (mean error = 1.02 frames) and Nagahara peak acceleration for the L-R step using the MT1H (mean error = 0.36 frames). Previous research has suggested that the L-R and R-L steps possess differing roles during bend sprinting. This is potentially one of the reasons for the different methods and markers achieving the best level of accuracy for the L-R and R-L steps. Nevertheless, these errors translate to approximately 4.1 ms and 1.4 ms, respectively, comparable to previously validated methods for linear sprinting (Bezodis et al., 2007; Nagahara & Zushi, 2013).

RQ3.2: *How do different kinematic event detection methods compare in accuracy for detecting TO of the L-R and R-L steps?*

TO detection was most accurate using the Nagahara peak acceleration method with the toe marker for both L-R (mean error = 0.76 frames) and R-L (mean error = 1.00 frames) steps. This equates to errors of 3 ms and 4.1 ms respectively, aligning with previous research findings. Methods solely relying on vertical position, particularly for the MT5H marker, were less effective for TO detection, likely due to high ankle eversion angles during bend sprinting.

Using the most accurate methods for each event, the overall error in detecting gait events was 3.2% for the L-R step and 7.56% for the R-L step. While care should be taken when using these kinematic event detection methods, using the peak vertical acceleration of the TOE and MT1H markers, and vertical position of the TOE marker provide a viable alternative for detecting TD and TO events when force plate data are unavailable during maximal velocity bend sprinting.

8.2 Phase 1

Phase 1 sought to increase understanding of altering task demands during bend sprinting representative of indoor competition providing novel insights into how changing the lane radius and effect of lateral banking could impact step characteristics and joint kinematics. The knowledge from Phase 1 will aid coaches and practitioners in the preparation of athletes for the indoor athletics competition.

Chapter 4

Following Chapter 3, it was possible to calculate gait events for the R-L and L-R steps with known accuracy where force data were not available, such as on a banked athletics track. Chapter 4 sought to address some of the identified gaps exposed in Chapter 2 and to provide a basis of knowledge when moving through the following chapters. Thus, the aim of this Chapter was to investigate the effect of lateral banking and radius on performance and step characteristics when bend sprinting on the tightest radii that are typical of athletic competitions.

Eight well-trained sprinters undertook sub-maximal sprints in lane 2 and lane 4 of an indoor athletics track, whilst flat and laterally banked. A full body marker set was used to capture the 3D kinematics including calculation of the centre of mass and enable calculation of step characteristics to compare between bend conditions using the validated methods from Chapter 3. To meet the aim of the chapter, RQs 4.1-4.4 addressed:

RQ4.1: How does lane radius affect within-limb step characteristics for the L-R and R-L steps?

Chapter 4 revealed a novel finding that sprinters may achieve higher SF on tighter radii (Lane 2) compared to wider radii (Lane 4) during indoor bend sprinting. These findings contradict previous research on outdoor tracks, where SF typically decreases on tighter radii. On the flat bends, SL appears to increase in lane 4 compared to lane 2 to non-significantly increase SV. The results suggest that the relationship between SL, SF, and SV may vary depending on the radius range and degree of banking, with previous research finding that SL was more influential on flat very tight radii (1-6 m) (Chang & Kram, 2007), and primarily SF on outdoor radii (36-45 m) (Churchill et al., 2018).

RQ4.2: How does lateral banking affect within-limb step characteristics for the L-R and R-L steps?

Banked tracks appear to enhance sprint velocity compared to flat tracks of the same radius, supporting previous research (Greene, 1987). Moreover, the novel contributions from RQ4.2 highlight that greater SV on banked bends occurs primarily through increased SL and a reduction in TD_D, particularly for the L-R step. These results suggest that performance on flat tracks might be improved by reducing TD_D, which in addition to increasing SL could minimise braking forces and thus lead to shorter GCT and higher SF (Hunter et al., 2004, 2005).

RQ4.3: How does lane radius and lateral banking affect inter-limb differences of step characteristics.

This study reveals novel insights into indoor bend sprinting mechanics, showing a trend for greater R-L SV compared to L-R, with this significant in Lane 2 flat conditions. The R-L step exhibited higher SFs with similar SLs, while L-R steps consistently showed longer FTs across most conditions. Interestingly, despite differences in SF, GCTs remained similar across all lane conditions. The findings suggest that reduced L-R SV is primarily due to longer FTs and potentially larger TD_D, which may result from the differing kinematic adaptations required of the L-R and R-L steps during bend sprinting.

Chapter 5

The aim of this Chapter was to investigate the effect of lane radius and lateral banking on body lateral lean and lower-body kinematics during bend sprinting on conditions representative of indoor competition. Building on from the methods and results of Chapter 4, body lateral lean and joint angles were calculated across the stance phase at the hip and knee and ankle. The purpose of this Chapter was to increase understanding of the joint kinematic adaptations to bend sprinting on different conditions typical of indoor competition to inform coaching and physical preparation for bend sprinting.

RQ5.1: What are the within-limb effects of lateral banking on joint kinematic variables when bend sprinting?

The main finding from this study was that for both the L-R and R-L steps, body lateral lean at TD and TO were significantly greater (more inward) in Lane 2 Flat and Lane 4 Flat compared to Lane 2 Bank and Lane 4 Bank. The greater body lateral lean coincided with greater adaptations in the frontal plane including greater L-R hip adduction during midstance in Lane 2 Flat compared to Lane 2 Bank and in Lane 4 Flat compared to Lane 4 Bank. Greater L-R hip adduction was coupled with greater L-R eversion in flat compared to banked bends. Additionally, more inversion was observed for almost the entire R-L stance in Lane 2 Flat than Lane 2 Bank (5- 100%), which is potentially a risk factor associated with plantaris and or Achilles injuries (Pollock et al., 2016). These findings support the theory that lateral banking minimises the body lateral lean required to maintain high velocities (Neie, 1981) and reduce ankle eversion/inversion (Luo & Stefanyshyn, 2012b) and thus may reduce injury risk as well as improve SVs (Chapter 4).

From an injury risk perspective: peak L-R (inside) ankle eversion angles of 23-25° were observed in Lane 2 Bank and Lane 4 Bank respectively, whilst peak values in Lane 2 Flat and Lane 4 Flat were 37-40°. These large eversion angles exceed the values deemed excessive (~ 13°) (Clarke et al., 1984), where repeated exposure may lead to injuries (Beukeboom et al., 2000). Furthermore, research has associated greater eversion angles and duration of time spent in eversion whilst treadmill running with greater risk of Achilles injury (Becker et al., 2017). Therefore, the reduction in body lateral lean angles and ankle eversion angles of ~15° has the potential to minimise frontal and transverse plane stress on joint soft tissues that may increase the likelihood of injury (Stefanyshyn et al., 2006).

RQ5.2: What are the within-limb effects of lane radius on joint kinematic variables when bend sprinting?

For R-L steps, body lateral lean was significantly greater in Lane 2 Flat than Lane 4 Flat whilst a trend for non-significantly greater lean at TD and TO for L-R steps was observed on the tighter radii. However, no differences were found in hip, knee, and ankle kinematics between lanes, supporting the previous Chapter where minimal changes occurred for the L-R and R-L steps due to the change in radius. The findings of the present research and those of Churchill et al. (2018) confirm a tendency for more inward lateral lean on tighter radii at TD for both L-R and R-L steps. Therefore, it is possible that greater inward lean will minimise the amount of space in relation to the CoM and the ground leading to greater adaptations outside the sagittal plane in order to prepare for the subsequent TD. However, the change in radius of 2 m between lane 2 and lane 4 may not be enough to alter within-limb between lanes, or differences may only be exposed at maximal sprinting velocities.

RQ5.3: What are the effects of lane radius and lateral banking on inter-limb differences in joint kinematic variables when bend sprinting?

Greater body lateral lean was observed at both TD and TO for the L-R step compared to the R-L in Lane 2 Bank, Lane 4 Bank, Lane 4 Flat. This is contrast to outdoor radii where greater body lateral lean is observed during the R-L step (Churchill et al 2018)**.** Nonetheless, this discrepancy in findings is likely due to the large difference in radius between indoor and outdoor competition, with the tighter indoor radii requiring greater lean during L-R stance to direct GRF inwards and follow the path of the bend. Furthermore, larger ES were observed in the banked conditions than the flat conditions suggesting that the lateral banking aids in reducing the overall lateral lean required but increases the differences in body lateral lean between L-R and R-L steps.

The flat conditions were typified with greater hip L-R adduction and greater L-R eversion, whilst, in the banked conditions, the L-R stance displayed greater knee adduction and greater ankle eversion compared to the R-L, specific to Lane 2 Bank, greater R-L hip external rotation was observed, whilst in Lane 4 Bank, more L-R hip flexion was observed. These results suggest that greater L-R eversion was present in both banked and flat conditions, whilst kinematic asymmetry shifts from the hip on banked conditions to the knee under flat conditions of equal radii. Greater external rotation of the R-L hip occurred during stance; thus, the external rotation of the L-R limb occurs at the ankle during L-R stance and the hip during R-L stance. This has bearing for force generation, where alteration of joint positions outside the sagittal plane can impact muscle activity in muscles acting within the sagittal plane (Coqueiro et al., 2005). However, this study is the first to provide continuous kinematic data across the stance phase on radii representative of indoor competition.

Despite the reported asymmetries and injuries associated with counter-clockwise bend running, it is not clear how this relates to performance. Therefore, future research should seek to further understand the relationship between key variables and performance for both the L-R and the R-L steps, and to investigate the relationship between athlete asymmetry and bend sprinting performance.

Phase 1 Summary

Phase 1 increased understanding of altering task demands during bend sprinting representative of indoor competition. However, Phase 1 highlighted that future research should seek to further understand the relationship between key variables and performance for both the L-R and the

R-L steps, and to investigate the relationship between athlete asymmetry and bend sprinting performance. Since the pinnacle of athletics is the Olympic games and athletes typically prioritise the outdoor season over the indoor season, Phase 2 looks at the drivers of performance during maximal bend sprinting on radii representative of outdoor competition.

8.3 Phase 2:

The first Chapter of Phase 2 – Chapter 6: aimed to explore the relationships of external kinetics, step frequency and step length with SV during bend sprinting, and to examine the relationship between inter-limb asymmetry and SV on the bend.

Eight well-trained sprinters undertook maximal effort sprints in lane 1 on outdoor athletics track bend radii. Kinematic and kinetic data were captured to calculate step characteristics and assess GRF production across the L-R and R-L stance phases. To address aims 6.1 and 6.2, the following research questions where posed:

RQ6.1 What is the relationship between step length and frequency, and SV during bend sprinting?

For the L-R step, SL was significantly positively correlated to SV whilst a large positive but non-significant correlation existed between SF and SV. Ohnuma et al. (2018) highlighted that some athletes can maintain SV on the bend in comparison to their straight velocity by maintaining the same kinematics and kinetics in the sagittal plane as on a straight path. Therefore, it may be that athletes who are more successful are strong enough to maintain sagittal kinetics and kinematics that contribute to SL despite the necessary frontal plane adaptations. Sašek et al. (2024) found 59% of variance in bend sprint deficit (defined as deficit of bend to linear 30 m sprint times) was explained by hip abduction and knee flexor strength suggesting that on small radius (9 m), hip abduction strength is an important factor for bend sprinting. This supports previous research that suggests hip stabilisation in the frontal plane is a limiting factor during bend sprinting (Chang & Kram 2007). Previous research has highlighted altered quadricep muscle activity when hip angles have been changed in the frontal plane (Coqueiro et al., 2005). Nonetheless, research is yet to understand if this altered muscle activity because of altered frontal plane kinematics can be improved through improved muscle strength in these positions. For example, Judson et al. (2020c) suggests it may be beneficial for bend sprint athletes to increase plantar flexor strength in internally rotated positions representative of bend sprinting. Further research is required to determine if longer L-R SLs during bend sprinting are related to technique (kinematics) or muscle strength.

For the R-L step, SF was significantly positively correlated to SV whilst a moderate non-significant correlation existed between SL and SV. Unlike the present findings, previous research reports that both SF (r = 0.55; $p < 0.05$), and SL (r = 0.83; $p < 0.01$) were significantly correlated with R-L SV (Ishimura & Sakurai, 2016). One potential explanation for the finding that no significant correlation between SL and SV was observed is that an interaction between steps exists. For example, Churchill et al. (2016) reports that R-L SV was reduced on the bend as a result of shorter SL. Shorter R-L potentially occur as a result of the less effective repositioning the L-R leg for the next TD, evidenced by the greater L-R TD_D observed (Churchill et al., 2016). Therefore, it is possible that the faster bend sprinters produce short GCT to compensate for the reduced SL (and thus FT) to prepare for L-R TD and as a result, produce faster R-L SF. However, future investigations are required to determine the mechanism for faster R-L SV on the bend. Differing lane radius is a possible reason for discrepancies compared to the present findings (36.5 m vs 43.51 m in Ishimura & Sakurai, 2016). Furthermore, it could be that tighter radius inhibits the outside limb's ability to maintain larger SLs due to the amount of turning required with each step, thus producing faster R-L SF increases the number of foot contacts over the course of the bend that could minimise the turning and inward force required with each step. Interestingly, Churchill et al. (2018) found SLs to increase and SF to decrease when comparing lane 5 and lane 2 thus, SV remained similar. Nonetheless, Churchill et al. (2018) goes on to suggest, similar to Ohnuma et al. (2018) that some athletes are better able to maintain SV in addition to the inward force required to follow the path of the bend.

RQ6.2 What external kinetic variables are related to bend sprinting performance (Step Velocity)?

Significant negative correlations were observed between propulsive duration and R-L SV. Churchill et al. (2016) found that the duration of propulsion was significantly longer for the L-R step on the bend compared to the straight, whilst this is the other limb it may indicate a relationship between better bend sprinters being able to minimise contact time, particularly the duration of propulsive force generation. This is supported by previous linear sprint research where a non-significant (likely detrimental) relationship between propulsive time and SV was observed (von Lieres Und Wilkau et al., 2020). Therefore, athletes that can minimise the time on the ground during this phase are likely to produce faster SF and thus contribute to increased SV.

For the L-R step, in contrast with previous bend sprinting research (Churchill, (2012), peak inward force was significantly correlated to SV for the L-R step. Faster sprinting velocities (SV) on curved tracks require greater centripetal force (as shown in equation 6.3). Previous research has emphasized the importance of inward forces during bend sprinting, demonstrating that peak inward forces on the curve are approximately twice as large as the medial-lateral forces observed on straightaways, for both L-R and R-L steps. (Churchill et al., 2016). Additionally, previous research has highlighted that inward force is significantly greater during L-R stance compared to R-L and thus aids generation of turning achieved during stance (Churchill et al., 2016). Therefore, since greater inward forces positively correlated with SV for the L-R step, how athletes produce large inward forces during L-R stance should be investigated in future research.

Average vertical and resultant forces were not significantly positively correlated with SV for L-R or R-L steps. Previous research has highlighted vertical force to be significantly correlated with SL, but not SF for the L-R step (Churchill, 2012). Therefore, it is possible that a lack of, or negative relationship to SF means that vertical force does not significantly correlate with SV. In linear sprinting, vertical force contributed to the majority of total variance (59%) of a regression model for SV (von Lieres Und Wilkau et al., 2020). Further research has shown that greater mean vertical force is associated with faster top running velocities (6.2-11.1 m/s) (Weyand et al., 2000), and within a homogenous group of well-trained sprinters (Nagahara et al., 2018). Since bend sprinting requires horizontal force in the inward direction it may be that these additional demands change the requirements to maintain sufficient bend sprinting velocity and reduced the contribution of vertical force to maintaining SV on the bend.

RQ6.3 What are the inter-limb differences in force production of L-R and R-L limbs during the stance phase?

The results of this study highlighted that the braking demands of the L-R and R-L limb are comparable across the stance phase during bend sprinting on an outdoor competition radius bend, supporting research in the acceleration phase (Judson et al., 2019).

For inward force the R-L step produces greater inward forces during early stance whilst the L-R step stabilises laterally before producing greater inward forces prior to TO, supporting previous research on the importance of inward force during L-R stance (Churchill et al., 2016;

Millot et al., 2024). The greater inward force trend reversing was also observed during the acceleration phase on the bend (Judson et al., 2019); however, the duration of greater L-R inward force in the present study is much greater. It’s possible that the longer duration of greater L-R inward force is an consequence of the bend related asymmetries that may develop as athletes approach maximum velocity further toward the apex of the bend (Judson et al., 2019).

Vertical force was greater during early R-L stance (1-5%) compared to L-R stance. Since previous research reports only discrete variables, this novel finding highlights the intricacies of vertical force production during maximal velocity bend sprinting. Churchill et al. (2016) reported no differences in peak and mean vertical force or vertical impulse between L-R and R-L stance. Nonetheless, both vertical impulses (L-R = 2.15 ± 0.23 m/s; R-L = 2.30 ± 0.36 m/s) and the peak vertical forces appear similar between L-R (3.27 ± 0.27 BW) and R-L (4.03 ± 0.91 BW) stance. This supports the conclusion of Churchill et al. (2016) that peak vertical force is consistent between limbs on the bend, whilst the finding that R-L vertical force is greater during early stance is potentially one of the reasons for shorter R-L GCT and faster R-L SF (Clark & Weyand, 2014).

RQ6.4 What is the relationship between asymmetry of step length and step frequency, and mean SV (L-R and R-L) during bend sprinting?

There were no significant relationships between asymmetry of SL or SF to mean SV suggesting that there is no consistent ratio of SL or SF between L-R and R-L steps that contributes to faster overall SVs. These findings are similar to Exell et al. (2017) study of asymmetry during linear sprinting, where no group consistent trend for asymmetry was observed in step characteristics or the relationship with SV (Exell et al., 2017). Therefore, like linear sprinting (Salo et al., 2011), it may be that athletes produce their individual ratio of SL and SF to produce their best bend sprinting step velocities. However, Churchill et al. (2016) reports that R-L SV was reduced on the bend due to shorter SL, and that this possibly occurred as a result of repositioning the L-R leg for the next TD, where TD_D are often greater. Therefore, it is possible that the faster bend sprinters emphasise short R-L GCT to compensate for the reduced SL (and thus FT) and or are more able to effectively reposition and avoid an early and less active L-R TD and as a result, produce longer R-L SL.

RQ6.5 What is the relationship between kinetic asymmetry and mean SV (L-R and R-L) during bend sprinting?

For asymmetry of kinetic variables, no significant relationships were observed with mean SV. This finding supports previous research during the acceleration phase on the bend Judson, (2019). Nonetheless, where the current study and previous research have highlighted significantly greater inward force during L-R stance (Churchill et al., 2016; Diaz et al., 2024), it is potentially surprising that asymmetry of peak inward force production was not correlated to SV. One potential reason for this is that with the discrete measures utilised, it is not possible to indicate precisely at which point in the stance phase these differences occur. RQ6.3 highlighted that L-R inward force was significantly greater than R-L between 27-41% and 68-98% of stance. The L-R peak inward force occurred at 38% (0.81 BW), whilst R-L peak inward force occurred at 10% (0.70 BW), at the equivalent point of stance the inward force was 0.42 BW, thus the difference between these points, or a measure of the total inward force may be a better measure of inward force production and have a clearer relationship to mean SV.

Chapter 7

The second chapter of Phase 2 aimed to investigate kinematic and kinetic variables that influence bend sprinting performance (SV) or determinants of bend sprinting performance (SL and SF). Thus, the purpose was to inform coaching on the kinetic variables with the greatest bearing on bend sprinting performance and the techniques that impact the development of these kinetic variables.

The following research questions were raised based on the findings of Chapter 6:

RQ7.1 What are the key determinants and kinetic variables that relate to R-L SF?

In contrast with Ishimura & Sakurai's (2016) findings, SF was significantly correlated with ground contact time (GCT) but not FT for the R-L step during bend sprinting. Vertical impulse was also significantly correlated with R-L SF, reinforcing the importance of greater vertical force and rate of application during early right stance (RQ6.2) and minimising GCT for faster R-L step velocities. While FT wasn't significantly correlated with SF, an optimal ratio of short FT for faster SF and longer FT for SL is likely necessary.

RQ7.2 What kinematic variables relate to duration of propulsive force and kinetic variables that relate to R-L SF?

Greater hip flexion at TD was associated with longer propulsion durations, suggesting less active TD positioning. Peak knee flexion and flexion at TD correlate positively with propulsive duration, indicating that excessive flexion may reduce limb stiffness and slow force production (Thompson et al., 2009; Kunz & Kaufmann, 1981). Furthermore, less knee flexion at TD has been associated with faster R-L SF (Churchill, 2012), therefore less knee flexion at TD could be indicative of reduced contact time and thus, shorter propulsion durations. MTP joint plantar flexion at TO, in combination with greater peak knee extension velocity at TO highlights that short propulsive durations were associated with good proximal to distal sequencing of knee extension and MTP plantar flexion to achieve high angular velocity at TO.

Greater vertical impulse is associated with peak knee extension velocity, hip extension angle at TO, and plantar flexion at TO. Faster extension velocities have been shown to contribute to higher vertical forces, that if applied quickly can minimise contact times (Clark et al., 2020; Kunz & Kaufmann, 1981). Thus, the greater joint extension suggests athletes have achieved greater vertical impulse to travel through full extension quickly. Further, greater plantar flexion at TD and TO, and achieving greater peak dorsiflexion related to greater vertical impulse. Thus, at maximum velocity perhaps greater plantar flexor moment generation abilities enable athletes to make greater use of the dorsiflexion stretch-shortening cycle and generate greater vertical impulse.

Knee abduction-adduction RoM was linked to greater vertical impulse, suggesting control in the frontal plane enables greater vertical force. Stabilisation in the frontal plane has been highlighted as a limiting factor during bend sprinting on tight radii (Chang & Kram, 2007). Therefore, generating faster extension angular velocities likely requires the ability to control movement in the frontal plane, as highlighted by (Coqueiro et al., 2005) during modified degrees of abduction/adduction and muscle activity during squatting movements.

RQ7.3 What are the key determinants and kinetic variables relate to L-R SL?

Different athletes may use varying techniques to achieve greater SLs, as stance and flight distances did not correlate significantly with L-R SL. Whilst Churchill et al. (2018) found SL remained similar across radii, it is possible the change in radius impacts the contributions from stance and flight phases to bend sprinting performance and explains discrepancies with previous research (Ishimura & Sakurai, 2016).

L-R SL was significantly positively correlated with inward impulse. This suggests that not only the magnitude but also the duration of inward force application is crucial for producing large SLs that contribute to L-R step velocities (SVs).

RQ7.4 What kinematic variables relate to peak inward force and kinetic variables that relate to L-R SL?

Ankle external rotation angle at TD, peak ankle inversion velocity and ankle external rotation velocity of the L-R ankle at TO were positively correlated with peak inward force. This suggests that the L-R ankle generates turning forces through external rotation and that greater rotation velocity at TO was associated with larger inward force. Chapter 5 and previous research have highlighted large eversion during the L-R stance, therefore the finding that athletes were more able to achieve larger inversion velocities are better able to produce inward force suggests that athletes who are able to forcefully invert as they approach TO produced larger inward forces and thus greater SL. Smaller hip adduction velocity at TD was associated with larger inward forces. Previous research has highlighted stabilising in the frontal plane as a potential limiting factor bend sprinting (Chang & Kram, 2007). Therefore, it is possible that being able to minimise hip adduction velocity at TD reduces the stabilisation demands during the L-R step and allows for more effective force production.

Additionally, hip and knee extension at TO were positively correlated with inward impulse, with earlier initiation of hip extension and later peak knee extension associated with greater inward impulse, indicating more effective proximal-distal sequencing and a more active TD (Churchill et al., 2015). Churchill (2011) found that longer L-R SLs were related to more extended L-R knee at TD, highlighting that this may result in better positioning of the extensor muscles to exert force (Mero & Komi, 1985) and contributing to produce longer SLs. Thus, it is possible that the knee and hip extension velocities are the consequence of optimal positions for rapid force application.

Peak knee adduction during stance was negatively correlated with inward impulse. This suggests that for the L-R step, inward force generation may be more dependent on body lateral lean, hip, and ankle actions rather than knee movement. Greater frontal plane stability at the knee may enable smoother force transfer and rapid hip and knee extension at TO (Chang & Kram, 2007).

Chapter 7 highlighted the importance of optimising ankle rotation, hip and knee extension velocities, and frontal plane stability for effective bend sprinting performance. These findings reinforce previous suggestions that improving bend sprinting performance relies on differing techniques and capabilities rather than solely trying to mimic linear sprinting technique. For example, Judson et al. (2020) highlights that the ability to generate plantar flexion moments in internally rotated positions may be beneficial whilst the present findings add that potentially, the ability to externally rotate and generate forceful inversion during the L-R stance may enable the plantar flexors to generate greater moments. Thus, athletes who can adapt to the altered frontal and transverse plane demands of the bend may achieve better performance and so future research and coaching interventions should focus on developing these specific kinematic patterns to enhance bend sprinting performance.

Phase 2 Summary

Phase 2 highlighted that SL and peak inward force in the L-R step, and SF and duration of propulsive force generation for the R-L step are the key determinants of SV during bend sprinting. Furthermore, novel information on the differences in force production between limbs were highlighted where: R-L step produced greater inward forces during early stance whilst the L-R step stabilises laterally before producing greater inward forces prior to TO and vertical force was greater during early R-L stance (1-5%) compared to L-R stance.

Chapter 7 emphasised the kinetic drivers of L-R SL (inward impulse) and R-L SF (vertical impulse) and the joint kinematic techniques that influence bend sprinting performance (SV) or determinants of bend sprinting performance (SL and SF). Chapter 7 highlighted the requirements of athletes to generate sufficient angular velocities in the sagittal, frontal and transverse planes with the appropriate angular positions at TD and TO to achieve faster SVs. Therefore, because of the additional frontal and transverse plane demands of the bend, coaches and practitioners should seek to make training specific to the bend. Increased specificity could be achieved with plyometric drills on the bend such as bounds for speed or distance that may develop ability to produce high vertical force early in stance and shorter duration of propulsion on the bend. Furthermore, wearable resistance during normal training or adapting existing strength training exercises to induce body lateral lean and improve the ability to produce greater external rotation and inversion velocities at TO. Future research could investigate the effectiveness of training exercises and is discussed in section 8.6.

8.4 Critical Reflection on Methodology

8.3.1 Study Design

A similar threshold of performance set for males (and using IAAF ranking points for females) enabled collection of similar athletes to enable comparisons with previous research (200 m pb < 23.5 s). Thus, the samples of n = 8 and 7 in Phase 1 and 2, respectively are comparable to similar research (n = 6-12) (Alt et al., 2015; Churchill et al., 2015; Judson et al., 2019; Ohnuma et al., 2018). Therefore, it was deemed appropriate to maintain the participant performance thresholds rather than increase the sample size with a lower level of participant.

Whilst research has highlighted kinematic differences between sex during cutting manoeuvres (James et al., 2004), the differences in sprint performance appear to be related to performance level (Ciacci et al., 2017; Zhang et al., 2022). In Mero et al's. (1992) review of sprinting the authors highlight that there are no sex differences regarding SF but that men have a longer SL. Furthermore, during linear sprinting, in a recent study, male and female athletes were combined into one group as the relationships between the performance measures and the mechanics (e.g., force production) of the skill were not considered to be influenced by sex (von Lieres Und Wilkau et al., 2020). Therefore, this programme of research considered that the overall performance output may differ between male and female participants, the mechanical variables that determine their performance are the same. On the other hand, Churchill (2012) separated male and female participants. Since research is yet to fully understand sex differences during bend sprinting, this may be one potential reason for differing results in that females may apply a different strategy to maintaining SV on the bend.

Additionally, whilst female participants were not excluded, the status and effects of the menstrual cycle were not tracked. Previous research has highlighted predicable and measurable variations in the female sex steroids that have variable effects on different body systems (Constantini et al., 2005). However, whilst the effects of menstrual cycle stage on biomechanical variables and sprinting are less evident (García-Pinillos et al., 2021), it has been shown that joint laxity particularly at the knee can be impacted (Herzberg et al., 2017). Since stability in the frontal plane appears to be a limiting factor for bend sprinting performance, with knee abduction-adduction ROM related to vertical impulse for the R-L step and peak knee adduction related to less effective inward force production for the L-R step, this is an area for future research.

It was not deemed appropriate to ask participants to sprint maximally on flat bends of ~14-16 m radii based on consultations with athletes and coaches prior to commencement of data collection. Whilst familiarisation was given during athlete warm ups, since velocity of maximum effort compared to fast sub maximal effort may give different step characteristic and joint kinematic results (Alt et al., 2015; Churchill et al., 2015), this perhaps limits some of the generalisations of these findings. Nevertheless, this is the first research to comprehensively report step characteristics and joint kinematics on conditions representative of indoor competition that can aid coaches and practitioners in their preparation of athletes for the indoor season.

The decision to analyse a single trial or the mean of two trials throughout the thesis can impact the interpretation of biomechanical data in sprint research. While using the mean of two trials was utilised in phase one, as this may provide a more representative picture of an athlete's typical adaption to the change in condition. For Phase 2 analysing the fastest trial available was selected in order to capture the distinctions of the individual’s best performance and inform the kinetics and kinematic that produced the best performance as has been utilised in previous sprint research (King et al., 2023; Nagahara et al., 2018b).

Cross-sectional designs only provide an observation of biomechanical variables at a single time point. However, as highlighted, to standardise with previous research, a maximum 200 m personal best time of 23.5 s for males was set whilst 27.44 s was set for female participants. This was chosen as it gave the equivalent IAAF points, thus representing equal abilities across genders (731) (Spiriev, 2017). Therefore, whilst participants were experienced bend sprinters whose technique is likely reflective of their natural form, it's important to recognise that even elite athletes can exhibit technique variations between training sessions. This variability should be considered when extrapolating results from single-trial or limited-trial analyses to broader conclusions about sprint biomechanics. Nevertheless, data were collected during one session for each participant as the reliability of the marker set has been shown to be reduced when tested across multiple days (Judson et al., 2018).

8.4.2 Data Collection Methods

As highlighted in 6.3.1, data were collected during one session for each participant as the reliability of the marker set has been shown to be reduced when tested across multiple days (Judson et al., 2018). To minimise the influence of marker attachment to the athlete, all participants completed their warm up with markers attached.

An additional limitation of the 3D optoelectronic motion capture methods used throughout the thesis is related to calculation of some variables limited by the ability to reliably create a 3D capture volume without marker drop out of segments at the periphery. For example, turn of the centre of mass and the multi-segment foot. Developments in inertial measurement units and marker less motion capture have the possibility to overcome these limitations which may enable more data collection of greater number of steps, transitions between phases and between bend and straight. Furthermore, this may increase ecological validity, reduce time spend applying markers and thus reduce the burden/time commitment to taking part, thereby increasing the number of athletes willing to take part and or enable researchers to assess the effects of training interventions. Nevertheless, at present, RMSE in joint angles of 2.3 – 4.7° have been reported for kinematics during running when comparing IMU systems to optoelectronic motion capture systems (Reenalda et al., 2016; Wouda et al., 2018), with a recent review highlighting IMUs can provide measurement of running gait spatiotemporal parameters, but IMU-based measurement of running kinematics on lower extremity joints needs to be reported with caution in healthy adults (Zeng et al., 2022). This is further exacerbated by the increased velocities, and 3D nature of bend sprinting. On the other hand, to track centre of mass velocity using an IMU system, Millot et al. (2023) found that an IMU-based system tested slightly underestimated bend centre of mass velocity, through narrow limits which supports its utilisation. Therefore, IMU based systems may enable calculation of step characteristics and velocity during bend sprints and enable greater number of data collections, trials, and participants to be collected. Nevertheless, in order to implement IMU and marker less kinematic data collection systems, sufficient validation in the context of maximal velocity bend sprinting is required.

For external kinetics, previous research has highlighted that IMU methods may be used to estimate sagittal plane components and magnitude of step-average force, however, the medio-lateral component of step-average force was not sufficiently accurate (Gurchiek et al., 2017). As a result a pilot study was undertaken using a single inertial measurement unit to estimate GRF during running (White et al., 2020), however it was deemed the accuracy at velocities representative of well-trained bend sprinters (8-10 m/s) would not be sufficient for use throughout the thesis. Nevertheless, development and validation of such systems is an area for future research.

8.4.3 Data Analysis Approaches

Whilst the TD methods used were different for the L-R and R-L steps, these were chosen as the most accurate methods for each step respectively. Nonetheless, the slight differences in accuracy may induce similarities or differences in the calculation of GCT and FT using the separate methods that were the most accurate reflects the kinematic differences between limbs previously highlighted during maximal velocity bend sprinting (Alt et al., 2015; Churchill et al., 2015; Ishimura & Sakurai, 2016; Ohnuma et al., 2018). Furthermore, it was not possible to determine the effect of the lateral banking on the effectiveness of the kinematic methods for detecting TD and TO, thus this is a potential area for future research.

As alluded to in 8.3.1 thresholds for performance were included in the participant inclusion criteria. Whilst these thresholds ensured a well-trained population took part to determine the effects of different bend conditions in Phase 1 and descriptors of performance in Phase 2 without introducing too much variability into the sample, the limited number of participants in this study presents challenges related to statistical power. A smaller sample size inherently increases the risk of Type II errors, potentially masking statistically significant findings. To address this limitation, in line with previous bend sprint research (Judson et al., 2019), effect size was calculated using Hedges' g, which incorporates a correction factor for smaller samples (Lakens, 2013). This approach provides a more nuanced interpretation of the results beyond mere statistical significance.

The use of Bivariate Pearson correlation coefficients for RQs in Phase 2 allowed for a straightforward assessment of relationships between variables. However, this approach assumes linear relationships and does not account for potential confounding factors or more complex interactions. The interpretation of these correlations using Hopkins' (2003) thresholds provides a standardized framework for assessing the strength of relationships, which enhances comparability with other studies in the field (King et al., 2023; von Lieres Und Wilkau et al., 2020). The use of a 0.10 threshold for the smallest worthwhile effect and 90% confidence intervals aligns with previous research in sprint biomechanics, enhancing comparability. However, this approach may be considered less conservative than traditional significance testing, potentially increasing the risk of Type I errors. Therefore, the magnitude-based inferences (MBI) were used as a guide to interpret the significant findings. For example, peak inward force could be deemed significantly positively correlated with L-R SV (Chapter 6), with the MBI as very likely beneficial. It's important to note that while these methods provide valuable insights, they are primarily correlational and cannot establish causality. Furthermore, as alluded to, the sample size, could significantly impact the reliability and generalisation of the results. Readers should interpret the findings considering these methodological considerations, recognising both the strengths and comprehensive analysis, as well as the limitations in inferring causal relationships and potential sensitivity to sample size effects.

8.5 Novel Contributions to Knowledge and Practical Implications

8.5.1 Methods development for use in bend sprinting research

Chapter 3 highlight that the most accurate kinematic event detection methods for TD were different for the L-R and R-L steps. This reinforces the previously reported kinematic differences between the L-R and R-L steps (Alt et al., 2015; Churchill et al., 2015). The same method was deemed the most accurate for detecting TO for both steps. Thus, the methods were chosen as the most accurate methods for each step respectively and were utilised throughout the thesis and inform future bend sprinting research.

8.5.1 Biomechanics of Indoor Bend Sprinting

The investigation into the effects of lane radius and lateral banking on bend sprinting performance and joint kinematics revealed critical insights into inter-limb differences, kinematic adaptations, and practical training implications. Notably, while SV did not show significant differences across lanes, a 2% reduction was observed in Lane 4 Bank compared to Lane 2 Bank for the L-R step. Interestingly, this contrasted with existing literature indicating that tighter radii can negatively impact performance due to reduced SF and SL (Chang & Kram, 2007; Churchill et al., 2018). Reduced L-R SV in Lane 2 Bank compared to Lane 4 Bank suggested that despite being well trained bend sprinters that had competed indoors within the past 6 months, familiarisation with the banked conditions and potential adaptation may be important to gain the mechanical advantage of an outer lane. Nevertheless, the study also found that lateral banking significantly enhances running speeds, with a notable 6.95% reduction in SV observed in flat conditions compared to banked conditions. Chapter 5 found that greater body lateral lean, hip adduction and ankle eversion occurred in flat conditions compared to banked conditions, suggesting that banking minimises body lateral lean and reduces kinematic alterations in the frontal plane, ultimately allowing athletes to maintain higher velocities. Furthermore, the reduction in ankle eversion angles on banked tracks may also help minimise the risk of injury by reducing stress on joint soft tissues (Becker et al., 2017; Stefanyshyn et al., 2006).

This research highlights the effect of lane radius and banking on inter-limb differences, R-L steps generally exhibited greater SV due to higher SF, while L-R steps had longer FTs. The longer FTs for L-R steps indicate that athletes may take more time to reposition for TD, potentially due to altered kinematics required for centripetal force during bend sprinting as highlighted in Chapter 5 by the greater body lateral lean, hip adduction and ankle eversion compared to the R-L step, supporting previous research on outdoor radii (Alt et al., 2015; Churchill et al., 2015). Kinematic inter-limb differences increased on the tighter radii, suggesting perhaps asymmetry has bearing on bend sprinting performance.

Furthermore, the findings suggest that athletes may benefit from training on banked tracks of varying radii to ensure they are prepared for the different conditions, thereby optimising their performance in indoor competitions. Additionally, a progressive approach in line with theories of specificity and overload (Ball & Herrington, 1998; Brazil et al., 2020) could involve avoidance of tight and or flat radii during early pre-competition training phases and slowly integrating tighter radii at faster velocities.

8.5.2 Bend Sprinting performance

Phase 2 highlighted novel information that in lane 1 of outdoor athletics track SF was the key determinant of SV for the R-L step. The ability to produce short duration of propulsive force was associated with faster SV, whilst greater vertical impulse was associated with greater SF. These kinetic characteristics were related to hip and knee positions at TD, such as minimising hip and knee flexion, that were associated with shorter propulsive durations and enhanced force production. Hip extension at TO and knee extension velocity were related to more effective force generation and shorter GCTs highlighting, the importance of proximal-to-distal sequencing. Athletes initiating stance with greater plantar flexion and achieving greater dorsiflexion produce higher vertical impulse, potentially utilising the stretch-shortening cycle of the Achilles tendon. In the frontal plane, knee abduction-adduction movements are linked to greater vertical impulse, suggesting that frontal plane stability is crucial for force production during bend sprinting. These novel findings highlighted the complex interplay between joint kinematics and kinetics in bend sprinting performance, emphasising the need for athletes to optimise their technique across multiple planes of motion in order to develop bend sprinting performance.

The primary determinant of L-R SV was SL, which itself was strongly related to peak inward force. Inward impulse was significantly correlated to SL, reinforcing the L-R step’s role as an inward force generator. Chapter 6 confirmed this role for the L-R step for the majority of stance but in addition to vertical force, inward force was significantly greater during the R-L step during early stance. This potentially explains the R-L steps reliance on faster SF as greater early stance phase force is an indicator of greater performance (Clark & Weyand, 2014).

To produce greater peak inward force and inward impulse, Chapter 7 found that the L-R ankle generates turning forces through external rotation, contributing to the turn of the centre of mass. Greater peak inversion velocity was also significantly beneficial to inward force production, potentially this has a role in counteracting the large eversion angles observed during L-R stance. Smaller hip adduction velocity at TD was associated with larger inward forces, therefore, potentially reduced velocity minimises the stabilisation demands and allows for more effective force production. Along with the greater magnitudes, optimal timing of hip and knee extension velocities were related to greater inward forces. Furthermore, as suggested by (Chang & Kram, 2007), stabilisation in the frontal plane is a potential limiting factor, this was supported by the finding that peak knee adduction during stance was negatively correlated with inward impulse.

These findings highlight the importance of optimising ankle rotation, hip and knee extension velocities, and frontal plane stability for effective bend sprinting performance. Future research and coaching interventions should focus on developing these specific kinematic patterns to enhance bend sprinting performance. This could involve wearable resistance (Feser, Bezodis, et al., 2021), plyometric drills such as the speed bounds for distance (Washif & Kok, 2020) being undertaken on the bend, and modifying existing training exercises to mimic bend demands, such as the modified lateral split squat (Maddy, 2020).

8.6 Directions for Future Research

This thesis has furthered understanding of bend sprinting performance on conditions representative of indoor and outdoor competition and highlighted kinetic and kinematic drivers of performance. Further research is required to assess the effectiveness of interventions at improving bend sprint velocities by developing the kinetics and kinematics highlighted within this thesis that contribute to faster SV for the L-R and R-L steps. Previous research focused on the sprint start has assessed the biomechanical specificity of training exercises (Brazil et al., 2020) and could be used as a template for drills and exercises to develop the kinetic and kinematic drivers of bend sprinting SVs. As highlighted, this could be made easier with developments and validation of marker less and or IMU based motion capture systems. One additional mismatch between practice and research is coach's perception of technique and training methods. One avenue to further the research area of bend sprinting performance is to investigate elite long sprint coaches' perceptions of bend sprinting to gather their existing approaches to running the bend. Similar research has gleaned insight into coaches perception of linear sprint technique and resistance training (Bolger et al., 2016; Thompson et al., 2009).

Recent research by Churchill et al. (2018) uncovered several spatiotemporal differences between the inner, middle and outer lanes. Meanwhile, World Athletics has recently updated lane assignment rules for 200m and 400m races to optimise performance. In the 200m, lanes 5-7 are now considered most favourable, followed by lanes 8, 3, and 4, with the lowest-ranked athletes in lanes 1-2; while in the 400m, top-ranked athletes are assigned to lanes 4-7, next-ranked to lanes 3 and 8, and remaining athletes to lanes 1-2. Therefore, the lane allocations at major competitions now provide greater advantage to the highest qualifying athletes. Whether the two events are related is unknown, however the greater body of bend sprinting literature appears to aid the evidence-based decision making at major competitions.

Finally, the current research body has increased understanding of the demands of the bend despite some of the acknowledged limitations. To increase the number of athletes that fulfil the inclusion criteria (injury free and 731 IAAF points), future researchers should seek to encourage collaboration of research projects across multi-site data collections to increase the participants available for inclusion. Of particular benefit would be increasing female participants. As highlighted in 6.3.1, female participants were not excluded from the present body of work and two participants included in Chapters 4-5 and one included in Chapters 3, 6, 7 were female. Whilst it is assumed that the dictators of performance are the same across sexes, larger groups would enable this to be confirmed on the bend.

8.7 Thesis Conclusion

This thesis presented a validated method for detecting gait events using kinematic data on the bend. Phase 1 provided novel understanding of altering the task demands during indoor bend sprinting whilst Phase 2 identified original associations with kinetics and kinematics and bend sprinting performance.

In Phase 1 trends for faster SV were found on tighter radii on the banked bend. This trend suggests that athletes require training to be specific to the competition demands and that familiarisation with banked bends would be beneficial for performance. Nevertheless, kinematic inter-limb differences increased on the tighter radii, suggesting perhaps asymmetry has bearing on bend sprinting performance. Reduced magnitudes of frontal and transverse plane kinematic occurred as a result of lateral banking and may have contributed to the increased SV observed in the banked conditions compared to the flat. These findings highlight that both performance and injury risks may be optimised in comparison to flat equivalents.

Phase 2 demonstrated differing contributors of SV, SF and SL reinforcing the asymmetrical demands and differing roles of the L-R and R-L steps during bend sprinting. Novel insights into the role of the R-L on inward and vertical force during early stance were observed, whilst the mechanism for these through optimal hip and knee angles and angular velocities were reported. For the L-R step, this thesis reinforced that the L-R step is the primary inward force generator on bends representative of indoor competition. Peak inward force and inward impulse were positively related to SV and SL respectively. Greater inward forces were achieved by greater ankle external rotation angles and velocities, greater peak inversion velocity was also significantly beneficial to inward force production, suggesting as a mechanism for counteracting the large eversion angles observed during L-R stance (Alt et al., 2015). Minimising hip adduction velocity at TD was associated with larger inward forces suggesting that this is associated with reduced stabilisation demands going through the stance phase.

Coaches should be aware of the different demands on the L-R and R-L step and adapt training to be specific to the bend. Whilst asymmetry of kinetics appeared to have no relationship with performance, inter-limb differences were observed throughout the thesis, and thus, the effect of increased asymmetry is not fully understood during bend sprinting. To develop the kinetics and kinematics found to correlate with SV and or determinants of SV that are highlighted in this thesis, coaches could look to implement specific plyometric drills adapted to the bend. For example, speed bounds for distance (Washif & Kok, 2020) undertaken on the bend or implement novel wearable resistance (Feser, Bayne, et al., 2021; Feser, Bezodis, et al., 2021) during bend sprint training that may develop ability to produce high vertical force early in stance and shorter duration of propulsion on the bend. Furthermore, the use of wearable resistance during normal training or adapting existing strength training exercises may also induce greater body lateral lean and improve the ability to produce greater external rotation and inversion velocities at TO. Furthermore, coaches could adopt existing strength training exercises, such as the modified lateral split squat (Maddy, 2020) or adopt the use of harnesses, cables and or resistance bands to induce lean and or internal rotation to improve strength and stability in bend specific positions (Churchill et al., 2015; Judson et al., 2019).

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Appendices

Appendix 1

Participant information sheets and written informed consent form Ethical approved was gained from the University Research Ethics Committee. Appendix A1 contains example participant information sheets and written informed consent form. These forms were provided to all athletes that participated in the studies within this thesis. The consent form was used to obtain written informed consent from each athlete prior to testing.

Appendix 2

MATLAB functions used to process data throughout the thesis.

Definitions:

GaitEvents_JW – Calculate gait events using kinematic and or kinetic data

ChallisAutoCorrelation – Run autocorrelation (Challis, 1999) to determine the optimum cut-off frequency

ANOVA_PostHoc_Discrete – Collate variables and run two-way repeated measures ANOVA and appropriate post-hoc tests for step characteristic data

ANOVA_PostHoc_SPM– Collate variables and run two-way repeated measures ANOVA and appropriate post-hoc tests using statistical parametric mapping (Pataky et al., 2010) for joint kinematic or kinetic data

JW_ShadedSignificantFigures – Plot continuous data with shaded areas representing periods of significant differences determined by SPM.

Appendix A1

PARTICIPANT INFORMATION SHEET

SFEC Reference No:
Study Title: A comparison between traditional and specific training and bend sprinting.

Name and Contact Details of Supervisor:

Dr Tim Exell - (Tim.Exell@port.ac.uk) - 02392 845294

Department of Sport and Exercise Science,
School of Science,
Spinnaker Building,
PORTSMOUTH,
PO1 2ER

Principal Investigator: Jonathan White
Telephone: 02392 842711
Email: jonathan.white@port.ac.uk

We would like to invite you to take part in our research study. Before you decide we would like you to understand why the research is being done and what it would involve for you. Please ask if anything that you read is unclear or you require further information.

We are from the School of Sport, Health and Exercise Science. We are looking for well-trained sprinters aged between 18 and 39 years of age. Participants should partake in regular bend sprinting and resistance training. They should be healthy with no known musculoskeletal injuries, cardiovascular or respiratory diseases. Additionally, participants should have no known medical adhesive allergy.

What is the purpose of the study?

This study aims to investigate traditional and specific resistance training exercises and compare them to bend sprinting. Resistance training is commonly undertaken as a method for developing sprinting performance, however there is yet to be a study that compares traditional exercises to bend sprinting. As well as this, the use of Wearable resistance has been proposed to overload the athlete whilst performing normal training, therefore maintaining the same technique, however this is yet to be confirmed during bend sprinting. The aim of this research is to compare traditional and more specific resistance training exercises to bend sprinting to assess the specificity and overload of training methods.

Why have I been invited?

You have been invited to participate in this study as you are healthy with no known musculoskeletal injury, cardiovascular or respiratory diseases, are aged between 18 - 39 and partake in regular bend sprinting and resistance training.

Do I have to take part?

No, your participation in this research is completely voluntary. It is entirely up to you to decide if you would like to participate in this study. If you do agree to take part, we will then ask you to sign the attached consent form.

What will happen to me if I take part?

To complete this study, you will be required to attend the laboratory on one occasion. It is expected that participation will require a time commitment of approximately 2 hours.

The visit to the laboratory will involve: participant information being recorded (height, mass, age, gender), preparation for data collection involving placement of small reflective markers using double-sided tape on the feet, legs and hip, attachment of EMG (electromyography) sensors on the upper thighs and lower legs. Data will then be collected from two different resistance training exercises. Following this, three 60 m sprints will be collected in four conditions (12 trials). The four conditions are: Counter-clockwise bend sprints unloaded, clockwise bend sprints unloaded, and then bend sprints with calf, and then thigh wearable resistance. The wearable resistance garments will be cleaned and sterilized between each use.

What will the trials consist of and what measurements will be taken?

During the visit to the laboratory, you will be required to complete 12*60 metre sprints (three in each of the following conditions: Unloaded straight and unloaded bend and then bend sprints with calf, and then thigh wearable resistance.) (see figure 1.) each lasting 30 seconds, and two different resistance exercises (single leg squat and an adapted single leg squat), of which you will complete two sets of six repetitions. The adapted single leg squat is altered through the use of resistance bands to increase lateral body lean and stabilisation in the frontal plane similar to that of bend sprinting. The load for the squats will be self-guided using the repetitions in reserve method. The loaded sprints will involve the secure attachment of 0.1-0.4 kg to the shank and or thigh and be carried out on the indoor athletics track at the National Indoor Athletics Centre in Cardiff following a self-paced warm up. You will be provided adequate rest between each of these tests and training on how to complete the different resistance exercises will be provided before the testing begins to make sure they are completed safely and correctly.

Figure 3. Lower leg calf compression sleeves providing shank wearable resistance.

Upon entry to the laboratory your mass, height and age will be recorded. You will then be prepared for data collection; this will involve placement of small reflective markers on your feet, legs and hip. In addition, EMG sensors will be attached onto your skin at various points on your upper and lower legs.

Due to marker placement and potential sensor interference, participants will be asked to perform both sprinting tasks and all the resistance training exercises in their normal running shorts and shoes.

The optoelectronic cameras capture data by picking up the reflective markers placed on the body, these are then used to recreate body segments in a 3D space. Therefore, no video capture is required.

What are the possible disadvantages of taking part?

As with any exercise and physical activity, there is a risk of musculoskeletal injury. This risk is elevated due to the maximal velocity sprinting tasks, however ensuring adequate rest is provided in-between exercises and a good warm-up and cool-down will be conducted to reduce these risks. Participants will also be coached on how to complete the resistance training exercises correctly to reduce the injury risk.

What are the advantages of taking part? / Expenses and payments?

By completing this study, you will receive a 3D assessment of your running gait. From this, you can analyse your technique to identify areas of improvement and identify factors that may increase risk of injury. You will also be helping identify how effective resistance training exercises and resistance clothing is at targeting the muscles used in maximal velocity sprinting. Finally, you will also gain first-hand experience in the biomechanics laboratory. This is something that will be great value to anyone completing a sport or biomechanics-based degree.

Will my taking part in the study be kept confidential?

The raw data, which identifies you, will be kept securely by the by the Principal Investigator before being anonymised during data analysis. Your data will be stored as paper records and as an electronic copy. Paper records will be stored in the project file maintained by the principle investigator and once the study has been completed will be stored in a locked storage facility within the department. Electronic records will be stored on a computer and hard disk drive that are password protected (University Google drive).

The data, when made anonymous, may be presented to others at scientific meetings and conferences, or published as a project report, academic dissertation and/or scientific paper or book. Anonymous data, which does not identify you, may be used in future research studies approved by an Appropriate Research Ethics Committee. The raw data, which would identify you, will not be passed to anyone outside the study team without your express written permission. The raw data will be retained for at least 30 years. When it is no longer required, the data will be disposed of securely (e.g. electronic media and paper records / images) destroyed.

What will happen if I don’t want to carry on with the study?

You are free to withdraw from the study at any point, both during testing and in between trials. If you do withdraw from the study after some data have been collected you will be asked if you are content for the data collected thus far to be retained and included in the study. If you prefer, the data collected can be destroyed and not included in the study. Once the research has been completed, and the data analysed, it will not be possible for you to withdraw your data from the study.

What if there is a problem?

In the event of an injury or emergency, all Departmental protocols will be followed, a qualified first aider will be present within the Spinnaker building at all times.

If you have a query, concern or complaint about any aspect of this study, in the first instance you should contact the researcher(s) if appropriate. As the researcher is a PhD student there the first supervisor (an academic member of staff) is also listed whom you can contact. If there is a complaint, please contact the Supervisor with details of the complaint. The contact details for both the researcher and any supervisor are detailed on page 1.

If your concern or complaint is not resolved by the researcher or their supervisor, you should contact the Head of Department:

The Head of Department	Prof. Richard Thelwell
Sport and Exercise Science Department	023 9284 5164
University of Portsmouth	Richard.thelwell@port.ac.uk

Spinnaker Building, Cambridge Road, Portsmouth, PO1 2ER

However, if the complaint remains unresolved, please contact:

The University Complaints Officer

023 9284 3642 complaintsadvice@port.ac.uk

Who is funding the research?

This research is funded by the University of Portsmouth

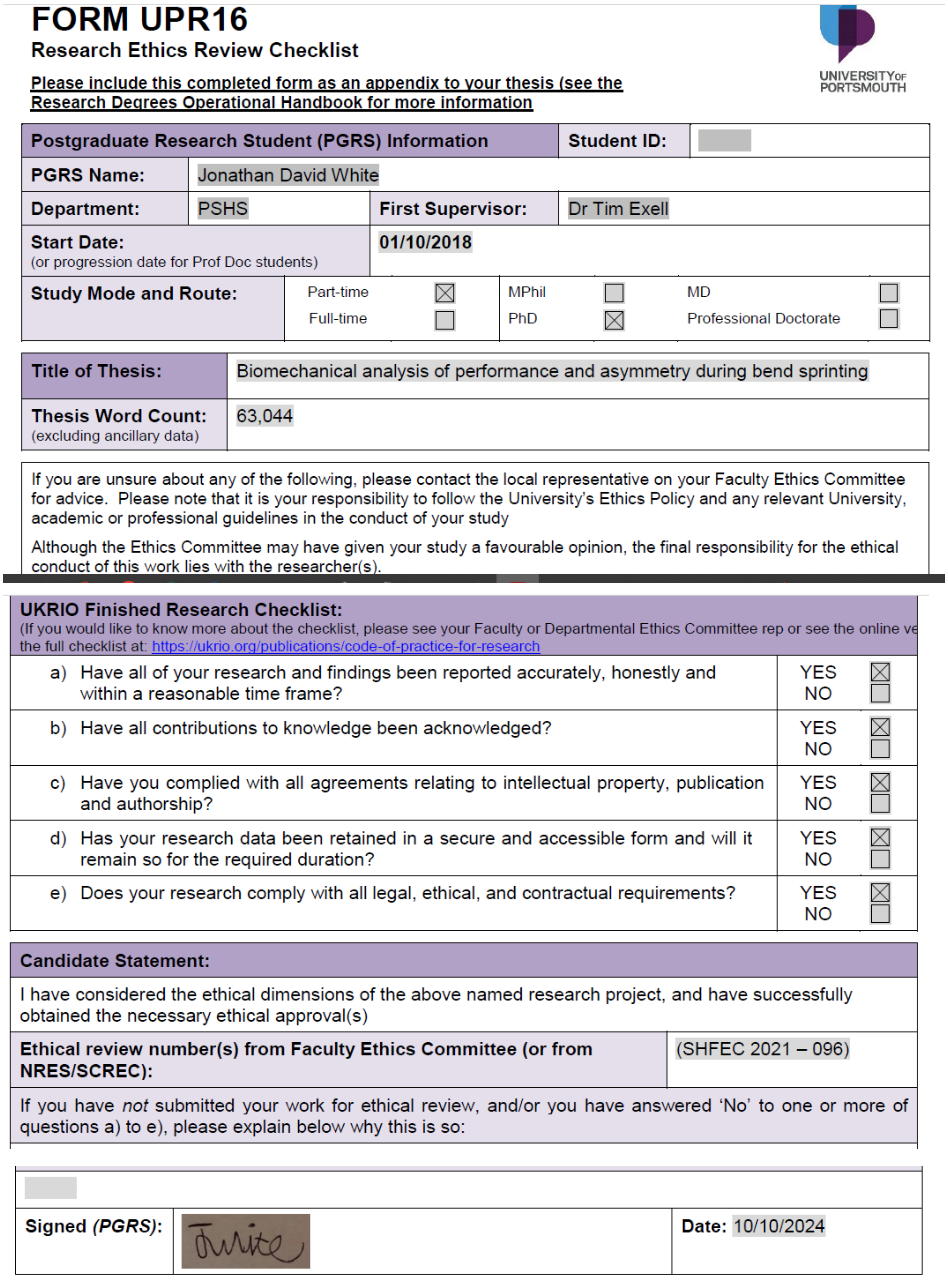
Who has reviewed the study?

Research involving human participants is reviewed by an ethics committee to ensure that the dignity and well-being of participants is respected. This study has been reviewed by the Science Faculty Ethics Committee and been given favourable ethical opinion.

Thank you

Thank you for taking the time to read this information and for considering volunteering to be involved with this research. If you do agree to participate then your consent will be sought on the following page. You will then be given a copy of this information sheet and your signed consent form, to keep.

Appendix 3 Research Ethics Review Checklist



FORM UPR16

Research Ethics Review Checklist

Please include this completed form as an appendix to your thesis (see the Research Degrees Operational Handbook for more information

UNIVERSITY OF PORTSMOUTH

Postgraduate Research Student (PGRS) Information		**Student ID:**	
PGRS Name:	Jonathan David White		
Department:	PSHS	**First Supervisor:**	Dr Tim Exell
Start Date: (or progression date for Prof Doc students)	01/10/2018		
Study Mode and Route:	Part-time ☒ Full-time ☐	MPhil ☐ PhD ☒	MD ☐ Professional Doctorate ☐

Title of Thesis:	Biomechanical analysis of performance and asymmetry during bend sprinting
Thesis Word Count: (excluding ancillary data)	63,044

If you are unsure about any of the following, please contact the local representative on your Faculty Ethics Committee for advice. Please note that it is your responsibility to follow the University's Ethics Policy and any relevant University, academic or professional guidelines in the conduct of your study

Although the Ethics Committee may have given your study a favourable opinion, the final responsibility for the ethical conduct of this work lies with the researcher(s).

UKRIO Finished Research Checklist:
(If you would like to know more about the checklist, please see your Faculty or Departmental Ethics Committee rep or see the online ve the full checklist at: https://ukrio.org/publications/code-of-practice-for-research

a) Have all of your research and findings been reported accurately, honestly and within a reasonable time frame?	YES NO	☒ ☐
b) Have all contributions to knowledge been acknowledged?	YES NO	☒ ☐
c) Have you complied with all agreements relating to intellectual property, publication and authorship?	YES NO	☒ ☐
d) Has your research data been retained in a secure and accessible form and will it remain so for the required duration?	YES NO	☒ ☐
e) Does your research comply with all legal, ethical, and contractual requirements?	YES NO	☒ ☐

Candidate Statement:

I have considered the ethical dimensions of the above named research project, and have successfully obtained the necessary ethical approval(s)

Ethical review number(s) from Faculty Ethics Committee (or from NRES/SCREC):	(SHFEC 2021 – 096)

If you have *not* submitted your work for ethical review, and/or you have answered 'No' to one or more of questions a) to e), please explain below why this is so:

Signed ***(PGRS):***	JWhite	**Date:** 10/10/2024