Biomechanical Comparisons Between Straight and Bend Sprinting in Athletic Sprint Events

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Abstract

During bend sprinting, the continuous need to change direction affects athletes' whole-body mechanics. Continuously changing direction results in athletes not being able to achieve the same velocities on the bend as seen during straight-line sprinting. The aim of this thesis was to identify technique and performance differences between bend and straight-line sprinting. Two studies were conducted, one empirical study with experienced bend sprinters and one scoping review synthesising the existing bend sprinting literature.

No differences were found in performance, push time, or most kinetic variables when analysing the effect of the bend during block starts compared with straight-line sprinting. However, there were reductions in vertical force on the bend compared with straight-line sprinting, which may negatively impact initial steps after block exit by reducing step length. Therefore, the bend reduces performance in subsequent race phases after block exit, potentially because athletes line their blocks up straight to increase anterior velocity.

The results from the scoping review found that the effectiveness of strength training, which targets the performance descriptors, lower body kinematics, and ground reaction forces, should be further explored. A focus should be how athletes can better maintain variables closer to those during straight-line sprinting. Determining which variables are closely related to performance in sprinters who have greater velocities on the bend, and sprinters who can better maintain their velocity on the bend compared with straight-line sprinting, would help improve all bend sprinters. Additionally, statistical analysis such as statistical parametric mapping would provide additional information on the characteristics of the waveform that differentiate performers that may be lost when analysing discrete variables. Finally, advancements in technology should be explored by biomechanists to capture data ecologically during training and competition.

Overall, changes in performance on the bend occur post block exit. However, a decrease in vertical force may impact the first few steps by reducing step length and, therefore, velocity. Variables related to better bend sprinters need to be identified using statistical analysis such as parametric mapping and advances in technology. An intervention study could then evaluate the effectiveness of strength training targeting the performance descriptors, lower body kinematics, and ground reaction forces, providing insights into improving bend sprinting performance.

Publications:

Conference Presentations:

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Dedication

In memory of my grandparents, Betty A. Turner and Walter E. Turner.

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Chapter One: THESIS INTRODUCTION

1 Thesis Introduction

Sprinting is running over a short, predefined distance (100 – 400 m) in as short a time as possible. During the Olympics and other major events, including the IAAF World Championships and the European Championships, sprinting makes up a large component (25% not including hurdles or sprint events in heptathlon or decathlon) of the track and field programmes. Within these events, small margins, commonly hundredths of a second, can be the difference between medals. For example, 2nd and 4th (the difference between a medal and no medal) were separated by 0.01 s in the men's 200 m at the 2018 European Championships and 0.12 s between 1st and 3rd in the men's 200 m at the 2020 Tokyo Olympics. As the cost of winning an Olympic medal continually increases (Hogan & Norton, 2000) and medalling often dictates subsequent funding opportunities, exploration of sprint performance to explore how to go faster is of paramount importance.

Unlike the 100 m race that takes place entirely on the straight, 200- and 400-m races include a portion on the bend that accounts for approximately 58% of the total distance covered (Meinel, 2008). Events including the Great City Games provide an opportunity to compare sprinters' performance across the same distance during bend and straight-line sprinting. For example, Tyson Gay currently holds the record for the men's 200 m in straight-line sprinting with 19.41 s (Manchester, 2010), 0.17 s faster than his personal best on the bend (19.58 s, New York, 2009). The difference in time between straight-line sprinting and the bend demonstrates the effect of the bend on race performance. Whilst there are several factors that could cause such differences (such as differences in race locations, time, season, etc.), previous literature suggests that there are fundamental differences in the sprinting mechanics when running on the bend as opposed to straight-line sprinting, that could be contributing to this time difference.

During a period of 28 years (from 1968 to 1996), the 200 m world record reduced from 19.83 s to 19.66 s. It improved to 19.32 s and then further improved to 19.19 s in 2009, which still stands as the current world record. When Usain Bolt ran 19.19 s to break the World Record, he stated that he could break the 19 s barrier. Research is required to investigate where performance improvements could be made for a sprinter to potentially break the 19 s barrier.

Bend sprinters continuously alter their whole-body mechanics to run around the bend while trying to maintain maximum velocity. The continuous need to change direction during bend sprinting alters spatio-temporal, kinetic, and kinematic variables during the acceleration (Judson et al., 2019; Judson et al., 2020a) and maximal effort phases (Churchill et al., 2015, 2016; Ishimura & Sakurai, 2016) and joint kinetics during the acceleration phase (Judson et al., 2020) compared with straight-line sprinting. The left and right legs also perform different functional requirements during bend sprinting. The role of the left leg is associated with achieving a change in direction whereas the right leg appears to be associated with producing force in the anterior direction (Judson et al., 2019). However, it is not known where in the race other changes occur in technique and performance between the bend and straight-line sprinting. Such understanding could contribute to improving training and performance outcomes. Therefore, research is required to identify where technique and performance differences emerge between bend and straight-line sprinting.

1.1 Aims and objectives

The aim of this programme of research was to identify technique and performance differences between bend and straight-line sprinting.

The objectives were:

- To investigate the effect of the bend on performance, push time, and kinetics during the block phase of the sprint start compared with straight-line sprinting (chapter three).

- To scope out the existing bend sprinting research and identify gaps for future research (chapter four).

1.2 Organisation of thesis chapters

1.2.1 Chapter two – Literature review

Chapter two discussed and critiqued existing literature on bend sprinting biomechanics. To begin with, the kinetic effects of bend sprinting were introduced and discussed in the acceleration and maximal effort phases. Since no research has been conducted on the starting block phase during bend sprinting, block starts during straight-line sprinting were discussed and then possible changes on the bend were suggested using existing bend sprinting literature. Spatio-temporal variables and lower body kinematics were also introduced and discussed, similar to kinetics. Joint kinetics during the acceleration phase and sub-maximal velocity during bend sprinting were also introduced and discussed. The review of literature presented in chapter two underpinned the development of the overall research aim.

1.2.2 Chapter three – Effect of the bend on performance, push time, and kinetics of the sprint start

Understanding the effect of the bend on the block start was initiated in chapter three. An empirical study of traditional biomechanical analysis of performance, push time, and kinetics was undertaken. The findings of chapter three provided information on when the bend initially affects technique and performance. This could then be advanced by comprehensively reviewing the existing bend sprinting literature and identifying gaps for future research using a scoping review in chapter four.

1.2.3 Chapter four – Biomechanics of bend sprinting: A scoping review

Chapter four utilised a scoping review to review the existing bend sprinting literature and identify gaps for future research. The current bend sprinting research was summarised, and recommendations were provided for athletes and coaches to better understand how to optimise bend sprinting performance.

1.2.4 Chapter five – Discussion and conclusion

The final discussion and conclusion in chapter five gave an overview of this programme of research. The limitations and implications of this programme of research were discussed, and recommendations were given for further research.

Chapter Two: LITERATURE REVIEW

2 Literature Review

2.1 Chapter overview

This literature review details the kinetic, kinematic, and joint kinetic adaptations that occur during the acceleration and maximal effort phases in bend sprinting. The work conducted into the kinetics, kinematics, and joint kinetics associated with technique and performance during the starting block phase in straight-line sprinting will be discussed and how the bend may affect technique and performance using existing bend sprinting literature.

2.2 Bend sprinting kinetics

The underlying causes of motion are the forces that the sprinter generates during ground contact using Newton's second law of motion (i.e., $\sum F = m \times a$). The amount of force produced has also been proposed as the best measure of an athlete's leg strength and the quality of their mechanics (Mann & Herman, 1985). Force production has previously been shown to be related to straight-line sprinting performance (Weyand et al., 2000, 2010) and therefore, it is important to understand the patterns and magnitudes of the ground reaction forces during bend sprinting.

Several authors have considered the effect of the bend on force production during sprinting in conditions representative of elite athletics performance (Churchill et al., 2016; Ishimura & Sakurai, 2016; Judson et al., 2019; Ohnuma et al., 2018). Empirical research has demonstrated that the amount of force that can be produced during bend-sprinting, compared with straight-line sprinting, is different for the left and right legs (Alt et al., 2015; Churchill et al., 2015; Ishimura & Sakurai, 2016; Judson et al., 2019). The left leg demonstrated less resultant force on the bend compared with the right (Churchill et al., 2016). Churchill et al.

(2016) found peak resultant force was lower for the left step on the bend (3.61 ± 0.45 BW) compared with straight-line sprinting (3.82 ± 0.53 BW), a finding that supports previous research at smaller radii (Chang & Kram, 2007; Smith et al., 2006). Moreover, although not statistically significant, resultant peak force during the right step increased from 3.66 ± 0.29 BW on straight-line sprinting to 4.19 ± 1.29 BW on the bend (Churchill et al., 2016). In contrast to the maximal effort phase, Judson et al. (2019) found no changes in resultant force during the acceleration phase between bend and straight-line sprinting. Differences between the acceleration and maximal effort phases might be expected because greater forces are achieved during the maximal effort phase as force is proportional to a change in velocity. Additionally, resultant force has been found to not contribute to sprint performance during the acceleration phase (Morin et al., 2011). Therefore, differences between the bend and straight-line sprinting are unlikely to be as great during the acceleration phase as they are during the maximal effort phase. The differences between the left and right legs for resultant force demonstrate that the two legs perform different roles during bend sprinting. Therefore, to meet the requirements of bend sprinting, bend-specific strength and technique training is essential to improve performance.

Although the resultant magnitude of the ground reaction force holds importance during sprinting, the orientation of the forces provides further information as to the effectiveness of the force. The largest component of the total ground reaction force is the vertical ground reaction force. Vertical forces have been found to be related to sprint performance because of the need to accelerate the centre of mass towards the ground and produce upward movement into the next flight phase. However, changes have been demonstrated between the left and right legs on the bend concerning the direction in which sprinters turn,(Alt et al., 2015; Churchill et al., 2015; Ishimura & Sakurai, 2016; Judson et al., 2019) with the left leg demonstrates less vertical force on the bend compared with the right (Churchill et al., 2016; Ishimura & Sakurai, 2016). Furthermore, a significant decrease in vertical force was found for the left step on the bend compared with straight-line sprinting because of inward lean while simultaneously applying a vertical force to counteract gravity (Churchill et al., 2016). In contrast to maximal effort, Judson et al. (2019) found no changes in vertical force during the acceleration phase between bend and straight-line sprinting. Differences between the acceleration and maximal effort phases might be expected because, despite its importance at maximum speed (Weyand et al., 2010), vertical force is not a key variable when trying to improve sprint performance during the acceleration phase (Morin et al., 2011).

Peak braking and propulsive forces have been found to reduce when sprinting on the bend compared with straight-line sprinting (Churchill et al., 2016; Judson et al., 2019). Propulsive force is considered a mechanical determinant of performance as athletes need to increase propulsive force to achieve a greater change in velocity ($A = F / M$) and reduces on the bend during the acceleration (Judson et al., 2019) and maximal effort phases (Churchill et al., 2016) compared with straight-line sprinting. Judson et al. (2019) found a decrease in propulsive force and impulse in both the left and right step but a greater reduction during the left step on the bend. In the maximum effort phase, which is where the athlete can no longer accelerate, the net antero-posterior impulse by default is close to zero and, therefore, would not expect large differences between the conditions (Churchill et al., 2016). However, Churchill et al. (2016) found there was still a statistically significant increase in antero-posterior propulsive impulse between bend and straight-line sprinting for the right step, mainly due to one sprinter. The influence of one athlete demonstrates that athletes have their own individual technique, and is therefore, difficult to determine whether increasing propulsive force in the right foot is an adjustment during bend sprinting. Left step peak anterior force on the bend decreased compared with straight-line sprinting (Churchill et al., 2016). Also, there was an increase in braking impulse and duration of braking for the left step on the bend compared with the left step during straight-line sprinting and the right step on the bend (Churchill et al., 2016). The ability to produce anterior force is impeded in the left step on the bend, but it is not known how to address the reduction and improve performance.

The front and rear foot in the block phase perform different roles during straight-line sprinting (Brazil et al., 2015; Otsuka et al., 2014; Willwacher et al., 2016), similar to the left and right legs performing different roles during the acceleration (Judson et al., 2019; Judson et al., 2020; Judson et al., 2020a) and maximal effort phases (Churchill et al., 2015, 2016; Ishimura & Sakurai, 2016; Ohnuma et al., 2018) in bend sprinting and must be analysed individually. Previous research focused on investigating relationships between variables and performance outcomes during the block phase (Brazil et al., 2015; Willwacher et al., 2016). During the block start, faster sprinters effectively direct their force production in the posterior direction to create anterior force, resulting in a more effective application of force and improved block phase performance (Brazil et al., 2015; Otsuka et al., 2014; Willwacher et al., 2016). When separating the front and rear blocks, significant correlations with normalised average horizontal block power for anterior (r = 0.78), vertical (r = 0.80), and resultant forces (r = 0.80) were only found for the front block (Brazil et al., 2015). Also, Willwacher et al. (2013) identified a greater rate of resultant force development in the front block in faster sprinters (based on personal best (PB)). Rather than investigating relationships between variables and performance, Otsuka et al. (2014) examined differences between performance levels of sprinters (based on best block acceleration) during the block phase. Well-trained (100 m PB 10.87 ± 0.41 s) and trained (100 m PB 11.31 ± 0.42 s) sprinters produced significantly greater mean net resultant and anterior ground reaction forces than non-trained sprinters. However, only a greater mean net anterior ground reaction force for both blocks was found in the well-trained compared with the trained sprinters but did not translate into a significant difference in the mean net resultant ground reaction force (Otsuka et al., 2014). Differences in the level of sprinters or the categorisation of sprinters (grouped on 100 m PB or explicit block performance) between studies could explain inconsistencies in the relationship between block phase performance and force production. The front foot contributes more to total anterior impulse due to a longer push time (Bezodis et al., 2015; Guissard & Duchateau, 1990). There is agreement that the ability to generate large forces, specifically anteriorly, in the front block positively impacts successful sprint starts and improved performance.

Although the front leg produces greater impulse, larger peak forces can be achieved against the rear block (Guissard & Duchateau, 1990) even though the rear leg produces force for only 45% of the block phase on average (Mero & Komi, 1990). Rear block force magnitudes are indicators of block power (Bezodis et al., 2019; Fortier et al., 2005; Willwacher et al., 2016) and are more important than direction (Willwacher et al., 2016). Rear block resultant force and rear block maximal vertical force were significantly greater in faster sprinters than slower sprinters during the block start (Čoh et al., 2017). Fortier et al. (2005) identified rear block peak resultant force as a parameter that determines starting block performance and overall sprint performance between elite (mean 100 m PB = 10.46 ± 0.11 s) and sub-elite sprinters (mean 100 m PB = 11.07 ± 0.30 s). Although the elite sprinters took longer to reach peak rear block force than the sub-elite group (124 vs 119 ms), they spent less total time pushing against the blocks (399 vs 422 ms). An extended leg push time (as a percentage of the whole push phase) was also positively associated (r = 0.53) with greater block power (Bezodis et al., 2015; Bezodis et al., 2019) and evident in sprinters with faster PBs (Fortier et al., 2005). Maximising the rear leg impulse appears to be an important strategy if it does not increase the total block phase duration. This demonstrates an important role for generating greater rear block force. However, like the front block, Otsuka et al. (2014) observed no significant differences in rear block resultant or average anterior force between their well-trained and trained sprinters. Interpreting the relative importance of external force applied to the front and rear block towards overall block performance can be difficult. The differences between studies may be accounted for by different athletes used, statistical analyses, between-group analyses, and the choice of performance categorisation. However, most agree that maximising the rear leg impulse contribution appears to be an important strategy for improving block start performance, provided it does not elongate the total push phase duration.

Ratio of forces (RF) is a meaningful measure of acceleration performance and is key in straight-line sprinting (Morin et al., 2011, 2012; Rabita et al., 2015). This parameter combines both the force applied by the sprinter and their ability to effectively apply this force in the anterior direction (Figure 2.1.1). RF reduces during the acceleration phase of bend sprinting, with Judson et al. (2019) finding the bend elicited an 11% and 22% decrease in mean RF for the left and right steps, respectively. An 8% increase in RF was also found in the right step compared with the left step on the bend. The differences were due to a combination of reduced propulsive force and an essential increase in mediolateral force. This provides further evidence of the asymmetries in force production of the left and right legs during bend sprinting, with force being applied less effectively on the left. Therefore, the generation and orientation of force appears to be a limiting factor during bend sprinting compared with straight-line sprinting. Research should focus on how to apply force more effectively to improve performance.

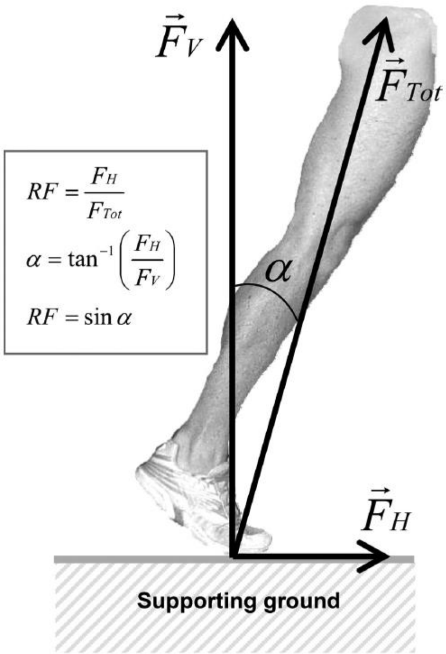

Figure 2.1.1 Schematic representation of the ratio of forces (RF) and mathematical expression as a function of the total (FTOT) and net positive horizontal (FH) (i.e., contact averaged) ground reaction forces. The forward orientation of the total GRF is represented by the angle α (Morin et al., 2011).

The ground reaction force vector (Brazil et al., 2015; Otsuka et al., 2014) and RF (Morin et al., 2011, 2012; Rabita et al., 2015) have been used to objectively represent the effectiveness of sprinters' force application technique in the block phase. Previous research has suggested that a trait of faster sprinters is their greater ability to orientate the total resultant force vector in a more anterior direction because total average anterior force increased without total average resultant force increasing (Brazil et al., 2015; Morin et al., 2011; Otsuka et al., 2014; Rabita et al., 2015). Strong relationships have been demonstrated between RF and block phase performance (Bezodis et al., 2019; Brazil et al., 2015). The direction of force application towards the anterior direction supports the importance of the front leg for forwards propulsion (Debaere et al., 2013) and is more important than in the rear block (Otsuka et al., 2014; Willwacher et al., 2016).

Sprinters with faster PB times generate larger relative horizontal block forces than their slower counterparts (Baumann, 1976), and the front leg contributes 66-76% of the total horizontal impulse (Čoh et al., 2009; Guissard & Duchateau, 1990). Otsuka et al. (2014) found well-trained sprinters had the highest mean net antero-posterior ground reaction force (9.72 ± 0.36 N/kg vs 8.41 ± 0.49 N/kg and 7.32 ± 0.79 N/kg) during the block phase. This contributed to the well-trained sprinters directing their net ground reaction force more anteriorly than trained and non-trained sprinters. Otsuka et al. (2014) assessed differences in three-dimensional force application between sprinters with different levels of block acceleration. In contrast, Brazil et al. (2015) wanted to determine the relationship between block performance and external force characteristics in a group of athletes. The analysis by Otsuka et al. (2014) stated that the resultant force vector angle in the front and not the rear block significantly differed between groups of different performance levels. The different focus of analysis could explain the conflicting findings between the two studies. Direction of force application has not been identified as important in all block phase studies (Bezodis et al., 2019), possibly due to different study designs, statistical analyses, or whether they are comparing different performance levels of sprinters. However, most agree that achieving a smaller resultant force vector angle in the front block demonstrates a superior technical ability between different levels of block performance.

Bend sprinters must generate centripetal force with the ground to continuously change direction around the bend in accordance with Newton 1st law. This requires athletes to focus on generating ground reaction forces that accelerate them towards the axis of rotation of the bend and propel themselves tangentially to the bend. Inconsistencies are present within the literature regarding mediolateral forces on the bend. For example, although research tends to agree that mediolateral forces are greater on the bend than straight-line sprinting (Chang & Kram, 2007; Churchill et al., 2016; Smith et al., 2006), findings assessing between-limb differences are less certain. The left limb produces greater peak inward force (Churchill et al., 2016; Judson et al., 2019; Viellehner et al., 2016). In contrast, greater inward forces in the right limb have been reported (Chang & Kram, 2007; Smith et al., 2006). It is expected that differences in radii are responsible for these different outcomes, with running at tighter radii sharing more similarities with an open cutting manoeuvre (Rand & Ohtsuki, 2000) as opposed to sprinting at larger radii such as those found on a typical outdoor running track. Also, the 'recreationally fit males' (Chang & Kram, 2007) and male soccer players (Smith et al., 2006) may have been more accustomed to performing a cutting action, which appears to be different to the turning method employed by sprinters in athletic events. Churchill et al. (2016) found inward impulse generated on the left step was greater than the right step during bend sprinting. However, Judson et al. (2019) used statistical parametric mapping to provide a more in-depth analysis and found that mediolateral force during bend sprinting was greater in the right step than the left during 1-12% of the stance phase. Later in stance (75-100%), mediolateral force was greater in the left step than the right. The change during the stance phase demonstrates the benefit of statistical parametric mapping analysis, which provides insights that may get lost analysing discrete variables. Ohnuma et al. (2018) found only mediolateral force changed between bend and straight-line sprinting in 'good' sprinters who were better able to maintain their maximum straight-line speed on the bend. It was concluded that better bend sprinters are those who can closely maintain the same sagittal plane kinetics as during straight-line sprinting. Research should focus on how ‘good’ bend sprinters are able to maintain the same sagittal plane kinetics on the bend as straight-line sprinting, therefore, further improving performance.

Mediolateral forces do not directly impact sprinters' ability to generate anterior forces and subsequent block phase performance in straight-line sprinting. Willwacher et al. (2016) found mediolateral force and direction in both the front and rear leg did not significantly improve the predictive power of any of the multiple linear regression models trying to identify the relationship between different force factors and normalised average horizontal block power. The result led Willwacher et al. (2016) to suggest that minimising mediolateral force application to achieve a straighter push-off in the anterior direction would not improve block performance because mediolateral forces are negligible during straight-line sprinting (Debaere et al., 2013; Rabita et al., 2015). Otsuka et al. (2014) found that faster sprinters generated similar mediolateral forces during the block phase to slower sprinters. Although it does not impact performance during the block start in straight-line sprinting, sprinters need to control vertical and mediolateral velocity while aiming to maximise anterior velocity during the transition from block phase to initial acceleration (Debaere et al., 2013). Previous research on bend sprinting has highlighted the importance of producing mediolateral forces and agree they are greater on the bend than straight-line sprinting in different race phases (Chang & Kram, 2007; Churchill et al., 2016; Judson et al., 2019; Ohnuma et al., 2018; Smith et al., 2006). Increases in mediolateral force may affect the effectiveness of force production capacities during the block start and, therefore, impact block phase technique and performance.

Mediolateral forces must be included when calculating RF in all race phases on the bend. Rabita et al. (2015) concluded that mediolateral forces were negligible during straight-line sprinting when including mediolateral forces in their calculation of resultant force. However, in bend sprinting, the generation of mediolateral force is essential to follow the bend. RF, including mediolateral force in the calculation, has been shown to decrease during the acceleration phase on the bend compared with straight-line sprinting (Judson et al., 2019). The increase in mediolateral force may negatively impact the effectiveness of force application technique in the block phase during bend sprinting.

2.3 Bend sprinting kinematics

2.3.1 Direct performance descriptors

It is generally accepted that velocity and speed decrease on the bend compared with straight-line sprinting on athletic specific radii (Churchill et al., 2015; Judson et al., 2020a). Churchill et al. (2015) used absolute speed to measure the athlete's actual performance regardless of the path travelled, demonstrating that any changes are not simply due to athletes following paths longer than the race line. Race velocity (Churchill et al., 2015, 2016) and absolute speed (Churchill et al., 2015) decreased in the left and right steps on the bend compared with straight-line sprinting. However, Judson et al. (2019) found a small 2% reduction in absolute speed on the bend only for the left step compared with straight-line sprinting, although non-statistically significant. Additionally, right step absolute speed was faster than the left step (Judson et al., 2019). Differences in results could be due to the tightness of the radii (37.72 m; Churchill et al., 2015; 36.5 m; Judson et al., 2020a) as controlling whole-body mechanics increases in difficulty with increased tightness of the bend. Churchill et al. (2019), when comparing different radii on the bend, found velocity decreased as bend radius decreased, but only the left step decreased in velocity from lane 5 to lane 2. It appears that as bend radius tightens, reductions in velocity are due to the left step.

Velocity is the product of step length and step frequency (Hay, 1993). Therefore, reductions in race velocity and absolute speed on the bend are due to a decrease in step length and/or frequency. Race step length considers the progression with respect to the official race distance in each step and shortens on the bend compared with straight-line sprinting in both the left and right steps during the acceleration phase (Judson et al., 2020a). The reductions were greater than those found by Churchill et al. (2015) in the maximal effort phase. Greater mechanical differences are introduced when athletes are required to run in lanes with increased tightness of the bend. As radius increases, the amount of centripetal force decreases for the same velocity (centripetal force = mv^2/r). A decrease in centripetal force results in less lean required to counteract the torque which acts to rotate the body away from the centre of the curve. Therefore, athletes running in the outer lanes need less centripetal force to run the bend and can increase their velocity. Judson et al. (2020a) analysed the acceleration phase with athletes' velocity 7.76 ± 0.32 m/s and 7.86 ± 0.27 m/s for left and right steps, respectively, and during a tighter radius (36.5 m). In contrast, Churchill et al. (2015) analysed the maximal effort phase with athletes' bend velocity 9.39 ± 0.45 m/s and 9.33 ± 0.44 m/s for left and right steps, respectively and used a 37.72 m radius. Churchill et al. (2019) found step lengths did not decrease as radii decreased with the shortest step lengths seen in lane 5 compared with lane 8 and lane during bend sprinting. Thus, the relationship between step length and step frequency depends on both velocity and radii. Athletes also try and maintain a straight path for as long as possible during the acceleration phase, which could also impact the differences. Step length is also shorter for the left step than the right step on the bend (Churchill et al., 2015; Ishimura & Sakurai, 2016; Judson et al., 2020a; Maćkala et al., 2015). Churchill et al. (2015) found directional step length reduced for the right step on the bend compared with straight-line sprinting, whereas no changes were found during the acceleration phase (Judson et al., 2020a). Churchill et al. (2015) suggested that the reduction in the right step absolute speed is due to a shorter right directional step length on the bend than straight-line sprinting. Research should focus on how to reduce the reduction in step length to improve performance.

There are inconsistencies between studies with step frequency. Left step velocity has been found to decrease on the bend occur because of a reduction in step frequency compared with straight-line sprinting (Churchill et al., 2015; Ishimura & Sakurai, 2016; Judson et al., 2020a). However, no differences were found in left step frequency on the bend compared with straight-line sprinting (Churchill et al., 2016). Research evaluating sub-maximal velocities (Alt et al., 2015) and smaller radii (Chang & Kram, 2007) found step frequency was not affected by the bend. However, Churchill et al. (2019) assessed only the bend condition but found reductions in performance as bend tightness increased were due to a reduced step frequency in both left and right steps. Furthermore, variability in performance increased between participants, suggesting athletes possess differing abilities to negotiate tighter radii (Churchill et al., 2019). There are also inconsistencies in step frequency between the left and right leg during bend sprinting. Churchill et al. (2019) found no differences between left and right step frequency, but other research reported left step frequency to be lower than right step frequency (Churchill et al., 2016; Ishimura & Sakurai, 2016; Judson et al., 2020a). The radius of the bend might have impacted some of the results. Churchill et al. (2019) assessed lanes 8, 5, and 2 (radii: 45.10, 41.41 and 37.72 m, respectively), whereas generally, Churchill et al. (2015; lane 2 radius 37.72 m), Ishimura & Sakurai (2016; lane 4 radius 43.51 m) and Judson et al. (2020a; lane 1 radius 36.5 m) used smaller radii. Therefore, a decrease in bend radius might be the cause of an increase in step frequency asymmetry between the left and right legs. These results suggest adaptations such as a decrease in step length and step frequency are both velocity and radii specific.

Other spatio-temporal variables such as flight time and contact time, which contribute to step frequency, are fundamental components of sprint performance. Changes in ground contact appear to be more consistent, with previous research demonstrating an increase in left ground contact time on the bend compared with straight-line sprinting (Alt et al., 2015; Chang & Kram, 2007; Churchill et al., 2015, 2016; Ishimura et al., 2013; Ishimura & Sakurai, 2010; Judson et al., 2019; Smith et al., 2006) and for the left step on the bend compared with the right step (Alt et al., 2015; Churchill et al., 2015, 2019; Ishimura & Sakurai, 2016; Judson et al., 2019). Increases in ground contact time usually result in decreases in step frequency as less vertical force is required to generate sufficient vertical impulse (Churchill et al., 2015). The increase in contact time is necessary to maintain constant vertical impulse to compensate for the decrease in vertical force. Since an increase in contact time has been noted within different velocities and radii, it may be a bend specific adaptation. Flight time, however, appears to be velocity specific as faster top speeds can be achieved by travelling further between steps.

Flight time reduces during the right step on the bend compared with straight-line sprinting (Churchill et al., 2015, 2016; Ishimura & Sakurai, 2016), yet Alt et al. (2015) and Ohnuma et al. (2018) reported no difference. During constant velocity, the distance travelled between steps is determined by the amount of force applied to the ground during ground contact. Newton's third law states that for every action, there is an equal and opposite reaction. Therefore, a decrease in vertical force reduces flight time, leading to a shorter step length. (Churchill et al., 2015). Alt et al. (2015) and Ohnuma et al. (2018) found no changes in step length, which explains why no changes in flight time were found and vice versa. Research should further analyse the change in parameters between the left and right legs.

Touchdown distance (horizontal distance from the head of the second metatarsal of the stance foot to the centre of mass; Hunter et al., 2004) has been suggested to have an impact on 200 m sprint performance (Mann & Herman, 1985). Hay (1993) proposed a smaller touchdown distance may be related to a decrease in braking force, which in turn can be associated with a shorter ground contact time (Hunter et al., 2004) and consequently faster speeds (Weyand et al., 2000). Greater touchdown distance occurred in the left step compared with the right step on the bend in both the acceleration (Judson et al., 2020a) and maximal effort phases (Churchill et al., 2015, 2016; Ishimura & Sakurai, 2016) leading to the increase in ground contact time. The increased left touchdown distance on the bend compared with straight-line sprinting has been suggested to be one of the biggest problems affecting the forward velocity of athletes during bend sprinting (Churchill et al., 2015). It would be helpful to understand how touchdown distance can be decreased to improve performance on the bend.

Bend running ability changes between sprinters and can be categorised in two ways: absolute terms (those who run the fastest) or relative terms (those who can maintain a similar velocity on the bend compared with straight-line sprinting). Churchill et al. (2019) found that variability in performance increased between participants as bend radii tightened, suggesting athletes possess different abilities to negotiate tighter radii. Faster bend sprinters (based on fastest trial) have longer step lengths on the bend (Ishimura & Sakurai, 2016). Ohnuma et al. (2018) separated groups of sprinters dependent on their percentage change in speed on the bend compared with straight-line sprinting. ‘Good’ bend runners were those who were able to closely maintain their speed on the bend. Decreases in step length on the bend compared with straight-line sprinting were found only for the ‘poor’ bend sprinters. Ohnuma et al. (2018) found no differences in step length, step frequency, flight time, or ground contact time between conditions in the ‘good’ bend sprinters. Ohnuma et al. (2018) found no change in running speed between the bend and straight-line sprinting. In contrast, a 2% reduction in speed was found in the acceleration phase (Judson et al., 2020a) and a 4.7% reduction in both the left and right legs in the maximal effort phase (Churchill et al., 2015). Therefore, better bend sprinters are those who can closely match parameters that impact velocity on the bend compared with straight-line sprinting. Research should focus on how to reduce the effect of the bend on spatio-temporal variables.

Performance in the block phase during straight-line sprinting is associated with magnitude and technical application (applying force more anteriorly) of external force production (Brazil et al., 2015; Čoh et al., 1998; Otsuka et al., 2014; Willwacher et al., 2016). Block velocity (the anterior velocity of a sprinter’s centre of mass at the instant of block exit) is determined by push phase impulse (product of net propulsive force generated and push duration). Previous research has reported increasing anterior force is more important than increasing the time to generate the force in block starts for a greater anterior velocity (Baumann, 1976; Bezodis et al., 2015; Čoh et al., 1998; Mero, 1988; Mero et al., 1983; Mero & Komi, 1990; Slawinski et al., 2010). However, Ostuka et al. (2014) found significantly faster push times in a well-trained group (0.349 ± 0.019 s) compared with trained (0.379 ± 0.022 s) and nontrained sprinters (0.437 ± 0.066 s). The well-trained group were better starters based on the greatest anterior acceleration of the whole-body centre of mass during the block phase. Thus, the sprinters might be better starters than studies that divided their sprinters based on overall sprint performance variables such as PB, which includes subsequent sprint phases. Consequently, block phase technique should be compared against current performance from just the phase of interest instead of PB (Bezodis et al., 2010). Bezodis et al. (2010) suggested normalised average horizontal block performance to objectively quantify performance because it accounts for the change in velocity and the time taken to achieve the change (i.e., the rate of change in kinetic energy). Forces on the bend are generated using a longer contact time in the acceleration (Judson et al., 2019) and maximal effort phases (Churchill et al., 2016). The necessity to generate inward force may increase the time the sprinter spends pushing in the blocks and reduce block phase performance.

2.3.2 Lower body joint kinematics

Measurement of lower body kinematics describes how individual body segments contribute towards whole-body performance (Mann & Herman, 1985).

During bend sprinting, athletes need to lean inwards to counteract the moment caused by the centripetal force, which athletes must generate to follow the bend. Lateral lean may be responsible for inducing the previously discussed asymmetrical changes in spatio-temporal variables and causes changes to the body's orientation and lower limb kinematics. Body sagittal lean range of motion (range of motion of lean of the angle in the sagittal plane using an angle of a vector between the relevant metatarsophalangeal (MTP) and centre of mass (CoM) is thought to be associated with an increase in contact time during straight-line sprinting (Hunter et al., 2004). Churchill et al. (2015) reported an increase in contact time during bend sprinting, with a greater body sagittal lean range of motion leading to a detriment in sprint performance. Churchill et al. (2015) also reported increased inward (more negative) body lateral lean at touchdown and take-off in both the left and right steps on the bend compared with straight-line sprinting. Body lateral lean was lower in the acceleration phase (Judson et al., 2020a) than the lean angles reported during the maximum effort phase (Churchill et al., 2015). Increased velocity on the bend increases the angle of inward lean. Therefore, changes accumulate during the acceleration phase, resulting in greater changes at faster velocities. Inward lean is a key characteristic of bend sprinting and should be included in bend sprinting analyses.

There is a lack of agreement between studies regarding kinematic adaptations during bend sprinting and in which plane they occur. Churchill et al. (2015) found changes in the sagittal plane with increased left hip flexion/extension at take-off and at peak flexion on the bend compared with straight-line sprinting. Ohnuma et al. (2018) found a difference in the hip joint angle at take-off in the right leg between the bend and straight-line sprinting for ‘poor’ bend sprinters. It was suggested that decreases in anterior-posterior ground reaction force and impulse could affect the reduction in the hip joint extension movement during the stance phase (Ohnuma et al., 2018). However, Alt et al. (2015) did not find any changes in the sagittal plane in the hip, knee, and ankle. Different data collection methods make comparisons between studies difficult. Churchill et al. (2015) measured maximal effort with high-speed video cameras, whereas Alt et al. (2015) and Ohnuma et al. (2018) used more accurate optoelectronic cameras to evaluate sub-maximal velocity and maximal speed sprinting, respectively. Using high-speed video cameras may have caused greater errors in the identification of landmarks which may have influenced calculating joint angles. Additionally, the use of optoelectronic cameras enables the orientation angles of the knee and angle to also be calculated. The radii evaluated also differed from lane one (36.5 m) by Alt et al. (2015), lane one (37.9 m) by Ohnuma et al. (2018) and lane two (37.72 m) by Churchill et al. (2015).

Findings are more consistent regarding adaptations in the frontal and transverse planes (such as hip adduction and ankle eversion) caused by leaning inwards. The left hip adducted more on the bend and further increased with increased velocity (Alt et al., 2015; Churchill et al., 2015; Judson et al., 2020a). Changes in hip adduction have also been found at smaller radii (Chang & Kram, 2007; Luo & Stefanyshyn, 2012). Centripetal force is dependent on the radius of the path and the square of the velocity that the athlete is travelling. Therefore, changes in velocity have a greater impact on centripetal force and, consequently, the amount of lean required to induce frontal plane adaptations at the hip. As well as increased hip adduction, the left hip externally rotates more (Alt et al., 2015; Churchill et al., 2015; Judson et al., 2020a) which, combined with an increase in left ankle internal rotation and eversion during bend sprinting compared with straight-line sprinting (Alt et al., 2015; Judson et al., 2020a), is thought to contribute towards a stabilising function during sub-maximal velocity bend sprinting (Alt et al., 2015). In contrast, adaptations of the right limb during the acceleration phase of bend sprinting can be characterised by an increase in hip abduction (Judson et al., 2020a) and internal rotation (Alt et al., 2015). Luo & Stefanyshyn (2012) introduced a wedged footwear condition during bend sprinting with a 2.5 m radius, creating a 4° decrease in left step ankle eversion with increased sprint speed by 4.3%. The non-sagittal plane adaptations (Alt et al., 2015; Churchill et al., 2015; Judson et al., 2020a) and the increase in performance when the adaptations are removed (Luo & Stefanyshyn, 2012) support the suggestion that sprint performance on the bend is limited by a need to change direction and stabilise the lower limb in the transverse and frontal planes (Chang & Kram, 2007). Results demonstrate that the greatest changes in non-sagittal planes which could negatively impact movements in the sagittal plane and, therefore, reduce performance.

Small changes are found in the knee between the bend and straight-line sprinting. Churchill et al. (2015) only assessed the knee in the sagittal plane as they were unable to reconstruct the knee in three dimensions. Results demonstrated that the left and right knees are more flexed at touchdown on the bend than straight-line sprinting, and the left knee is also more flexed than the right knee at touchdown on the bend. On the other hand, Ohnuma et al. (2018) found no changes in joint angular kinematics of the hip, knee, and ankle, suggesting joint angular kinematics impact velocity changing spatio-temporal variables. Findings from Alt et al. (2015) and Judson et al. (2020a) regarding the knee joint are currently the only published insights into the three-dimensional function of the knee during bend sprinting. An increase in internal rotation of the right knee was reported in comparison to the left and combined with a high external rotation of the right ankle (Alt et al., 2015). Differences in frontal and horizontal planes, but not in the transverse plane, occur between the right and left on the bend (Alt et al., 2015). This led Alt et al. (2015) to suggest that the left limb contributes towards a stabilising function during sub-maximal velocity bend sprinting. However, Judson et al. (2020a) disagreed because no changes were found during peak right ankle external rotation or internal knee rotation during the acceleration phase. Also, Churchill et al. (2015) found that the left ankle was significantly more dorsiflexed at touchdown on the bend than during straight-line sprinting. The lean causes a significant increase in eversion of the left foot on the bend compared with straight-line sprinting, which in turn, with an increase in ankle internal rotation, limits the foot's ability to produce propulsive force (Judson et al., 2020a). Therefore, altering frontal plane kinematics might contribute to sagittal plane kinematics, but it is likely that changes in the transverse plane affect both. Any differences between the bend and straight-line sprinting in the joint angular kinematics of the lower extremity occur mainly in the hip and ankle. It appears that athletes are restricted by their ability to produce force in the non-sagittal planes due to a complex pattern of changes at the foot and ankle. Therefore, understanding how to adapt the force to cope with the adaptation caused by the bend, such as strengthening the muscles, might reduce the restrictions and benefit performance.

A general position of the body in the 'set' position is typically now evident, with the hips above the shoulders and the shoulders ahead of the start line (Mero

& Komi, 1990; Slawinski et al., 2010). ‘Optimum’ angles of the hip, knee, and ankle in the front and rear leg have been suggested as critical determinates of body configuration to generate greater anterior impulses (Mero et al., 1983). Thus, many studies have investigated these angles to identify key factors which differentiate sprinting performance (Atwater, 1982; Bezodis et al., 2014, 2015; Čoh et al., 1998; Debaere et al., 2013; Mero et al., 1983; Mero & Komi, 1990; Milanese et al., 2014; Slawinski et al., 2010). From these investigations, a range of joint angles have been reported for the ankle (front, 94°-107°; rear, 99°-111°), knee (front, 89°-11°; rear, 117°-136°), and hip (front, 41°-52°; rear, 75°-89°), in sprinters with 100 m PB times ranging from 9.98 s to 11.85 s. It is difficult to conclude an optimal ‘set’ position because large standard deviations in set position kinematics have been reported, suggesting large variability, even in homogenous groups. Bezodis et al. (2019) found only weak or nonsignificant correlations between lower body joint angles in the “set” position and block power. Therefore, it is likely that no single, universally optimum combination of lower body joint kinematics exists (Bezodis et al., 2019; Ciacci et al., 2017), and other contributing factors (e.g., anthropometry, strength, and motor abilities; Mero et al., 1983) might have an effect. The potential of athletes already starting to turn during the block phase to ‘run the bend’ could change the position of the body in the ‘set’ position compared with straight-line sprinting.

Both hip joints are flexed in the ‘set’ position and extend throughout most of the time each leg is spent in contact with their respective block (Bezodis et al., 2015; Debaere et al., 2013; Mero et al., 1983). Previous research agrees on the hip angles of both the front and rear legs but found smaller hip angles for the front leg compared with the rear leg (Bezodis et al., 2015; Ciacci et al., 2017; Debaere et al., 2013; Mero et al., 1983). ‘Set’ position joint angles from groups of sprinters across different ability levels have led to identifying positions adopted by subgroups of faster sprinters. These include more flexed hips (mean = 41° and 80° vs 52° and 89° for the front and rear legs, respectively) for the fastest than the slowest groups (based on their centre of mass velocity at the 2.5 mark of a 10 m sprint; Mero et al., 1983). Variations in strength may explain between-sprinter differences in running velocity. The fastest group displayed a greater percentage of fast-twitch fibres (sampled from the vastus lateralis) and higher scores on strength and power tests (height of rise of centre of gravity in the countermovement jump). Stronger sprinters adopt more acute joint angles in the 'set' position and extend their joints over a greater range in the block phase, using their hip extensors to generate maximal power (Mero et al., 1983). In contrast, Ciacci et al. (2017) found that faster (100 m PB 10.03 ± 0.14 s) sprinters did not have more flexed front and rear hips compared with slower (100 m PB 10.74 ± 0.21 s) sprinters with hip angles of 42° and 66° for the front and rear, respectively. These hip angles are respectively similar and lower (a more flexed hip) than the slower (average 100 m time 10.8 ± 0.3 s) sprinters (front hip: 41°; rear hip: 80°) studied by Mero, Luhtanen, and Komi (1983) which could explain the differences in results. It appears that a more flexed front hip is related to an increase in velocity in separate groups of slower sprinters, but for faster sprinters, it stops being a determinant. Despite their explosive strength capacity, a more flexed hip would not be more beneficial, even for world-class sprinters, as it may increase push times. During bend sprinting, previous research has demonstrated changes of the hip angle in the frontal plane (e.g., hip abduction/adduction) and the transverse plane (internal/external rotation; Alt et al., 2015; Churchill et al., 2015;

Judson et al., 2020a). These necessary changes during bend sprinting might mean the leg is in a less advantageous position to extend quickly and decreases block phase performance compared with straight-line sprinting.

Both knees start flexed in the 'set' position. The knees remain relatively still during the first half of the block phase before undergoing extension during block clearance (Bezodis et al., 2015). Faster sprinters have more flexed knee angles than slower sprinters (Bezodis et al., 2015; Ciacci et al., 2017), approximately 11° for every 1 s decrease of seasonal PB on 100 m (Ciacci et al., 2017). A greater front knee flexion angle in the ‘set’ position to produce greater peak torque is potentially more advantageous. However, this would require exceptionally high levels of explosive strength (Ciacci et al., 2017).

Literature suggests that the rear knee position is particularly variable between athletes, with rear knee angles (90° - 154°, Atwater, 1982; 100° - 126°, Čoh et al., 1998; 130° - 140°, Mero et al., 1983; Mero & Komi, 1990), whereas other studies have attempted to find an optimum technique position by comparing different positions in the ‘set’ position (Milanese et al., 2014; Slawinski et al., 2013). Studies comparing different knee angles have shown that rear knee angles of 90° in the ‘set’ position led to higher block velocities in male and female sprinters with 100 m PBs of 12.0 s and 13.1 s respectively, than more extended (both 115° and 135°) rear knee angles. This was due to a greater rear block push duration without any change in the overall push phase duration (Milanese et al., 2014). However, the observed effect may have been due to compensatory adjustments at the other rear leg joints because block spacings were fixed across all conditions. Individual preferences may reflect the wide range of rear knee angles reported in the previous studies based on the observed starting block technique used by elite sprinters (Milanese et al., 2014). Milanese et al. (2014) assumed that the greater horizontal block velocity was due to increased anterior force production and not an increase in push time against the blocks because no differences were found between the three different rear knee angles during the block phase (90°: 0.354 ± 0.015 s; 115°: 0.348 ± 0.016 s; 135°: 0.355 ± 0.014 s). However, the rear knee starts in a more extended angle than the front knee, limiting its range and duration of extension (Bezodis et al., 2015). A more extended angle may explain why the knee joint angular velocity peaks earlier than the hip and ankle peak angular velocities (Bezodis et al., 2015; Slawinski et al., 2010). Churchill et al. (2015) found that the left and right knees were more flexed at touchdown on the bend compared with the straight in the maximal effort phase. However, this might be because of repositioning the leg prior to touchdown. Block starts initiate from a stationary position and no changes in knee angle would be expected during block starts in bend sprinting compared with straight-line sprinting.

Both ankle joints initially dorsiflex and then plantarflex until block exit (Bezodis et al., 2015; Brazil et al., 2017; Charalambous et al., 2012; Debaere et al., 2013; Slawinski et al., 2010). Slawinski et al. (2010) found that the rear ankle dorsiflexes for longer (50% of the pushing block phase compared with 20% for the front ankle). An ability to purely plantarflex from the start would reduce time in the blocks and potentially improve performance (Slawinski et al., 2010). However, this would also remove the stretch-shortening cycle in both the soleus and gastrocnemius used in the sprint start, a mechanism recognised as important in enhancing final force and, therefore, a powerful block start (Mero et al., 2006). In bend sprinting, changes in ankle inversion, eversion, and rotation have been found (Alt et al., 2015; Judson et al., 2020a). This non-sagittal plane adaptation provides further evidence that sprint performance on the bend is limited by a need to change direction and stabilise the lower limb in the transverse and frontal planes (Chang & Kram, 2007). Therefore, changes in ankle inversion, eversion, and rotation may occur during the block start if athletes are starting to turn to ‘run the bend’ during the block phase.

To conclude, in the blocks on the bend, there might be frontal and/or transverse adaptations that affect sagittal plane kinematics and, consequently, performance. In the starting blocks, stabilising all three planes of motion could also impact block phase technique and performance.

2.4 Joint kinetics

Kinetics cause motion and knowledge of them is crucial for understanding the pattern of lower limb joint kinematics. The current evidence base regarding joint kinetics during bend sprinting is limited. During straight-line sprinting, sagittal plane hip moment was extensor for most of the propulsive phase of stance, becoming flexor dominant towards latter stages of ground contact during early (Bezodis et al., 2014) to mid-acceleration (Johnson & Buckley, 2001) and maximal speed (Bezodis et al., 2008). A similar pattern was found during the acceleration phase in bend sprinting (Judson et al., 2020). A large effect size suggested a trend towards a lower hip flexor moment during sprinting on the bend compared with straight-line sprinting (Judson et al., 2020). The hip has been found to be the largest energy generator and absorber in the frontal and transverse planes when muscle energies of the lower limb during sprinting on the bend were investigated (Heinrich et al., 2016). Moderate effect sizes suggested a trend towards a greater left step peak negative frontal and transverse plane power in the hip on the bend than on straight-line sprinting (Judson et al., 2020). Furthermore, Viellehner et al. (2016) found an increase in left peak hip and knee adduction moment during constant sub-maximal effort bend sprinting compared with straight-line sprinting. Segal et al. (2009) suggested hip power in the frontal plane is needed for pelvic control. Since adaptations in the frontal plane are greater in the maximal effort phase (Churchill et al., 2015) compared with sub-maximal velocity (Viellehner et al., 2016) and the acceleration phase (Judson et al., 2020), it is likely that there will be greater hip power in the frontal plane. Additionally, the pelvis is individually influenced by both limbs, and the left and right limbs have different roles during bend sprinting (Alt et al., 2015; Churchill et al., 2015; Judson et al., 2020a). Therefore, a greater level of pelvis control is likely required to overcome these adaptations.

The ankle needs to be capable of withstanding additional loads in the non-sagittal plane whilst also improving the capacity to generate sufficient power in the sagittal plane (Judson et al., 2020). The ankle has been found to be the largest absorber and generator in the sagittal plane (Heinrich et al., 2016). Additionally, it plays a dominant role during straight-line sprinting (Brazil et al., 2017; Debaere et al., 2015; Dorn et al., 2012; Johnson & Buckley, 2001) and has been found to generate the most power in the sagittal plane compared with the hip and knee joints on the bend (Judson et al., 2020). Large and moderate increases in left step peak positive power were observed at the ankle in the frontal and transverse planes but did not affect positive power in the sagittal plane. The ankle also needs to be able to sustain the increase in joint ankle moments, as demonstrated by the large but non-significant increase in left step peak plantar flexor moment on the bend compared with straight-line sprinting (Judson et al., 2020), supporting the results of sub-maximal velocity bend sprinting (Viellehner et al., 2016). Moment production at the ankle is required to stabilise the shank because of the alterations created in the frontal and transverse plane (Judson et al., 2020). The ankle joint appears to be the main limiting factor in sprint performance on the bend (Judson et al., 2020).

Combinations of average ankle, knee, and hip joint moment and power magnitudes during the push phase explained up to 55% of the variance in block power in 17 sprinters (Brazil et al., 2018). Although it has been suggested that the total kinetic energy of the body could be increased if all segments reached their maximum at the same time (Slawinski et al., 2010), this may not be possible because of the sequencing required to transfer energy most effectively between segments (Bobbert & van Ingen Schenau, 1988). A proximal-distal pattern of peak joint powers has been observed in the front leg during the block start in straight-line sprinting, but a knee-hip-ankle pattern was identified in the rear block (Brazil et al., 2016). However, non-sagittal adaptations found in lower-limb joint kinematics during bend sprinting, such as high peak hip adduction angles (e.g., 13.8°, Alt et al., 2015; 10.6°, Churchill et al., 2015) and high peak ankle eversion (e.g., 12.7°, Alt et al., 2015). Judson et al. (2020) found a proximal to distal sequence of peak extensor power generation during the bend and straight-line sprinting. Therefore, the sequence in the block phase during bend sprinting is not known as the pattern in the rear block during straight-line sprinting is different than during the acceleration phase in bend sprinting.

Each hip contributed to more than 60% of the total positive joint work done by the respective leg (Brazil et al., 2016). The front hip is extensor dominant from movement onset before becoming flexor dominant at about 85–90% of the push phase, thus absorbing energy just before block exit (Brazil et al., 2017). Additionally, it is likely that the front knee resultant joint moment is extensor until just before block exit, thus generating extensor energy (Brazil et al., 2018). There is a negligible knee resultant joint moment in the rear leg, but a rear hip extensor resultant joint moment is dominant throughout most of the push and generates energy (Brazil et al., 2017). Ankle plantar flexion resultant joint moments are dominant in each leg throughout its respective push (Brazil et al., 2017). There is a small phase of energy absorption followed by energy generation at both ankles. If the block start on the bend experiences ankle eversion and hip adduction like during other sprint phases of bend sprinting (Alt et al., 2015; Churchill et al., 2015), this might prevent the limbs from generating the same moments demonstrated in straight-line sprinting.

For bend sprinting, joint kinetics have only been explored during the acceleration phase (Judson et al., 2020) and sub-maximal velocity (Viellehner et al., 2016). The magnitude of changes in joint angular kinematics of the lower extremity and ground reaction forces are greater during the maximal effort phase (Churchill et al., 2015, 2016) compared with the acceleration phase (Judson et al., 2019; Judson et al., 2020a). Joint kinetics would provide an indication of the magnitude of muscular force generation and further insight into joint function during maximal effort bend sprinting to help develop strength and conditioning programmes.

After conducting a rigorous narrative literature review, a clear and obvious gap was identified as the acceleration and maximal effort phases had previously been investigated but the block start was identified as requiring further research. As, whilst previous research found that the differences between the bend and straight-line sprinting increased through the race, the point at which differences first occur remains unclear.

Chapter Three: EFFECT OF THE BEND ON PERFORMANCE, PUSH TIME, AND KINETICS OF THE SPRINT START

THE WORK IN THIS CHAPTER FORMED THE BASIS OF THE FOLLOWING CONFERENCE PAPER:

Bagley, A. J, Churchill, S. M., & Wheat, J. (2018) The effect of the bend on global and spatio-temporal variables during the sprint start on the bend and straight-line sprinting. Oral presentation at the BASES Annual Conference, Harrogate.

3 Effect of the bend on performance, push time, and kinetics of the sprint start

3.1 Introduction

Sprinting success is positively influenced by an effective start followed by achieving and maintaining the highest possible running velocity (Delecluse et al., 1995). Around one-third of the athlete's maximal velocity during a sprint race is achieved during the block phase and subsequent first stance (Harland & Steele, 1997). The best strategy to achieve optimal performance is to attain maximum anterior power from the sprint start to block clearance and further accelerate from block clearance to sprint running (Bezodis et al., 2010a, 2014; Debaere et al., 2013; Golden et al., 2009). Athletes must quickly produce high anterior force to maximise forward velocity during the block exit transition phase (Morin et al., 2011, 2012) while controlling vertical and medio-lateral velocity (Debaere et al., 2013). Therefore, block phase performance is an important component in athletic sprint events (Brazil et al., 2015; Mero, 1988; Willwacher et al., 2016).

The underlying causes of motion are the forces which the athlete generates during ground contact (Bezodis et al., 2019) and have been extensively researched in block starts during straight-line sprinting (Bezodis et al., 2010; Brazil et al., 2015; Čoh et al., 2006; Debaere et al., 2013; Otsuka et al., 2014; Slawinski et al., 2010). There is agreement that the ability to rapidly produce high anterior force (Morin et al., 2011, 2012; Rabita et al., 2015) and generate large rear block resultant force (Bezodis et al., 2019; Fortier et al., 2005; van Coppenolle et al., 1989), improves sprint performance. Instead of the resultant ground reaction force magnitude, RF assesses technique and athletes' effectiveness in applying force in the posterior direction (Morin et al., 2011, 2012;

Rabita et al., 2015). Increasing the resultant ground reaction force magnitude, if the orientation stays the same, or orienting the ground reaction force in a more anterior direction will produce a greater anterior acceleration of the entire body.

In contrast to straight-line sprinting, the sprint start on the bend has attracted little attention, even though sprint events longer than 110 m on a standard outdoor track start on the bend. Starting on the bend, athletes must contend with the immediate bend of the track and the staggered position of all competitors. Athletes lean inwards because they need to apply a lateral force during ground contact to generate centripetal force to follow the bend. Medio-lateral forces are often not considered in straight-line sprinting because of their relatively low magnitude (compared with antero-posterior and vertical forces) and because they do not directly contribute to forward progression (Willwacher et al., 2016). However, medio-lateral forces increase during the acceleration (Judson et al., 2019) and maximal effort phases (Churchill et al., 2016; Ohnuma et al., 2018) of bend sprinting compared with straight-line sprinting. Anterior force and impulse decrease in the acceleration (Judson et al., 2019) and maximal effort phases (Churchill et al., 2016) because of a necessary consequence of the additional requirement to produce centripetal force. RF has also been found to decrease during the acceleration phase of bend sprinting (Judson et al., 2019). Potential increases in medio-lateral force production may affect the magnitude and orientation of vertical and anterior forces, and thus RF. Therefore, the additional requirement of generating inward force may restrict force production technique during the block start on the bend compared with straight-line sprinting.

Understanding the differences in the block phase between bend and straight-line sprinting, using race-specific bend radii and surfaces, may improve the execution of the sprint start on the bend through strength and conditioning programmes. Also, differences between the bend and straight-line sprinting will determine whether athletes need to focus more on the block start on the bend because force application technique and performance from the start may influence subsequent steps. Therefore, the aim of this study was to investigate the effect of the bend on performance (measured by normalised average horizontal block power), push time, and kinetics during the block phase of the sprint start compared with straight-line sprinting. It was hypothesised that push time in the blocks on the bend would increase to generate the required forces, and thus normalised average horizontal block power would reduce. Second, it was hypothesised that athletes would apply the forces less effectively (measured by RF) on the bend, and the magnitude of antero-posterior and vertical forces would reduce but an increase in medio-lateral force.

3.2 Methods

3.2.1 Participants

Ten male sprinters (mean age: 22.2 ± 4.24 years), all experienced in bend sprinting (200 and/or 400 m), volunteered to participate in the study. Anthropometric data were collected of the sprinters' stature (1.77 ± 0.08 m; Marsden Leicester height measure, Rotherham, UK), mass (72.8 ± 7.9 kg; BC543, Tanita, Amsterdam, The Netherlands) and leg-length (0.95 ± 0.04 m; measured in the anatomical standing position using a tape measure from the location of surface markers at the medial malleolus to the anterior superior iliac spine). To standardise ability with previous research (22.60 ± 0.33 s, Alt et al., 2015; Churchill et al., 2015; 22.70 ± 0.49 s, Judson et al., 2019; Judson et al., 2020a) the inclusion criteria required a 200 m personal best of 23.5 s or faster (22.39 ±

0.6 s, range: 21.4 to 23.2 s). All athletes were active in training, competed regularly, and injury-free at the time of data collection. Before data collection, all participants were fully informed of the study's aim, risks, benefits of involvement and experimental conditions and provided their written informed consent. The study procedures were approved by the Research Ethics Committee at Sheffield Hallam University (ER5594144).

3.2.2 Experimental set-up

An observational, cross-sectional, repeated measures study design was implemented. Data collection took place on a standard outdoor 400 m track (IAAF, 2008) during a single session for each athlete. The athletes completed their own coach-prescribed warm-up, including practice starts, before undertaking three maximal effort 10 m sprints on the straight and three maximal effort 10 m sprints on the bend in lane 1 (radius: 36.5 m). The order of straight and bend trials was randomised in a counterbalanced order to minimise order effects. Each athlete wore their own spiked shoes, and, using a standard set of starting blocks, adjusted the blocks' position, spacing, and obliquity to their individual preferences. The measurements were then replicated as closely as possible using instrumented starting blocks. Each athlete lined up their blocks at different angles on the bend relative to the start line (between 90° and 97°). Athletes also had their own preference with which foot forward they started with (five athletes started with their right foot forward and five left foot forward). Athletes were instructed to sprint at maximal effort for the full 10 m. Recovery time between trials was between 5 and 8 minutes to minimise any effect of fatigue (Charalambous et al., 2012; Churchill et al., 2015; Judson et al., 2019; Judson et al., 2020a; Rabita et al., 2015; Slawinski et al., 2012).

Custom-made force instrumented starting blocks (Willwacher et al., 2013) were used to measure external force data. Block inclinations of the front and rear legs were adjusted using separate foot plates. Different block units were available for different block obliquities (50°, 57°, 65°, and 73°). On top of each foot plate was a small, custom-made piezo-electric force platform. A more detailed description of the instrumented starting block can be found in Willwacher et al. (2013). The software provided the starting commands, including the starting signal (*on your marks, set, go*).

3.2.3 Data processing

Force data were sampled at 10,000 Hz (post-processed to 1,000 Hz). Electrical charge signals of the force transducers were externally amplified and converted to voltage signals using two eight-channel charge amplifiers (type 9865, Kistler Instrumente AG, Winterthur, Switzerland). Signals were analogue-to-digital converted (16 bit) and stored on a commercially available laptop computer using customised LabVIEW software (LabVIEW 2011, National Instruments, Austin, Texas, USA; Willwacher, Feldker, et al., 2013).

Three-dimensional force signals were transformed from the local (tilted) starting-block reference system (Figure 3.1.1) to a global coordinate system (Figure 3.1.1, Figure 3.1.2). Antero–posterior direction (x-axis) = direction of travel, medio–lateral direction (y-axis) = pointing to the left along the same surface plane, and vertical direction (z-axis) = perpendicular to the ground (pointed vertically upwards). The transformation of force signals compensated for the different inclinations of the force platforms embedded in each block. Force signals were low pass filtered (recursive 4th order Butterworth, 120 Hz cut-off), chosen with the use of residual analysis (Winter, 2009).

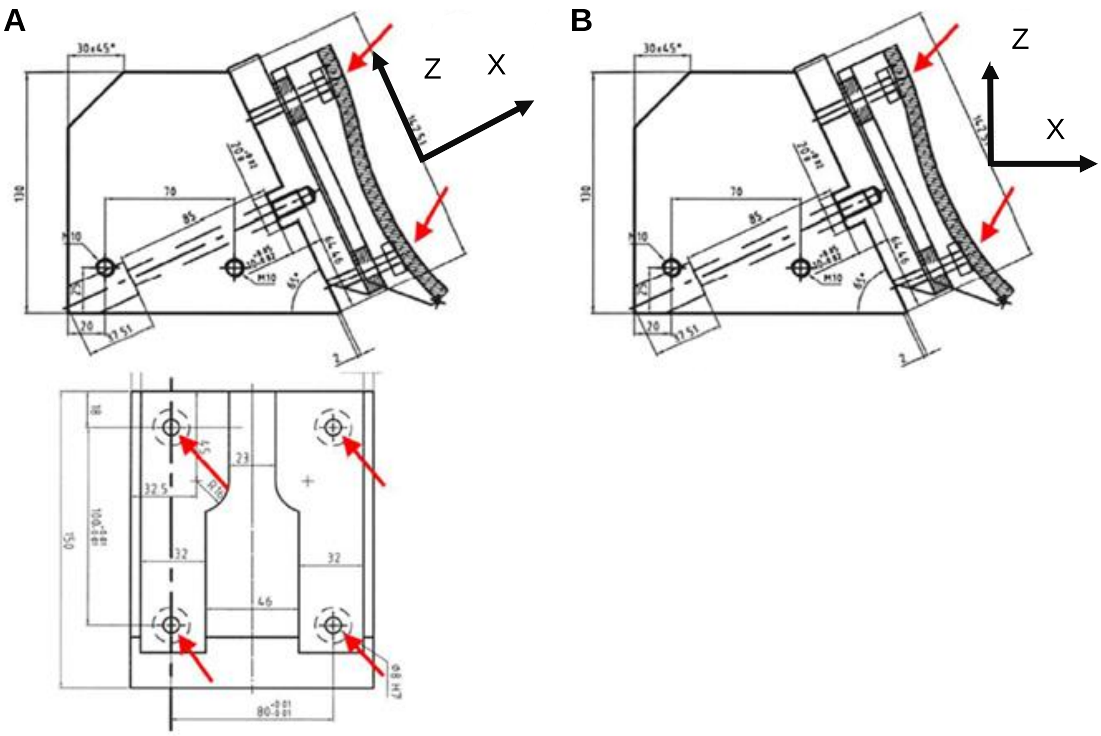

Figure 3.1.1 (A) Technical schematic drawing of one block force measuring unit (including four 3D piezo-type force sensors marked by red arrows) in the sagittal plane (top) and frontal (bottom) plane. Local co-ordinate system displaying vertical (z) and antero-posterior (x) forces (not to scale). Adapted from Willwacher et al. (2016). (B) Transformed forces in the global coordinate system displaying vertical (z) and antero-posterior (x; not to scale). Adapted from Willwacher et al. (2016).

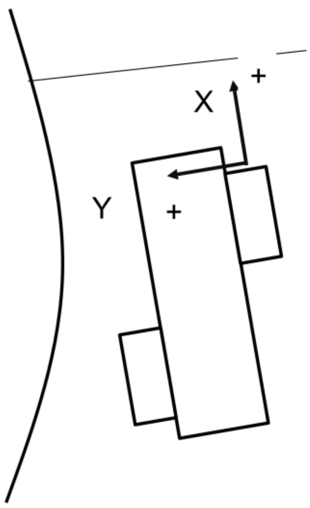

Figure 3.1.2 Transformed horizontal forces in the global coordinate system (not to scale) displaying antero-posterior (x) and medio-lateral (y).

3.2.4 Calculation of variables

Push time for each block and *total push time* were calculated from the force data. Total push time was defined as the time from block start to block exit. The onset of block start was defined as the earliest detection in which the first derivative of either the front or rear block resultant force-time curves > 500 $N.s^{-1}$ and resultant force continued to rise to its maximum value. Block exit was defined as the front block resultant force < 50 N and continued to fall. The total block phase included the front block phase (equal to the total block phase; front leg) and rear block phase (defined between first derivative of resultant force-time curve > 500 $N.s^{-1}$ of the rear leg and last detection of resultant force > 50 N of the rear leg (Figure 3.1.3).

Total horizontal power was calculated from the product of the total horizontal force (antero-posterior and medio-lateral) and horizontal velocity-time signals, with velocity obtained through numerical integration of the total horizontal force signal using the trapezium rule and subsequently divided by body mass.

Normalised average horizontal block power was used to measure block phase performance because it reflects how much a sprinter can increase their block exit velocity and the associated length of time to achieve this (Bezodis et al., 2010). Normalised average horizontal block power was obtained using a mean for horizontal power over the duration of the block phase and normalised to body mass and leg length as smaller sprinters require less power to translate their centre of mass the same extent as a larger sprinter, so body mass and leg length must be accounted for to enable a fair comparison between sprinters of different stature.

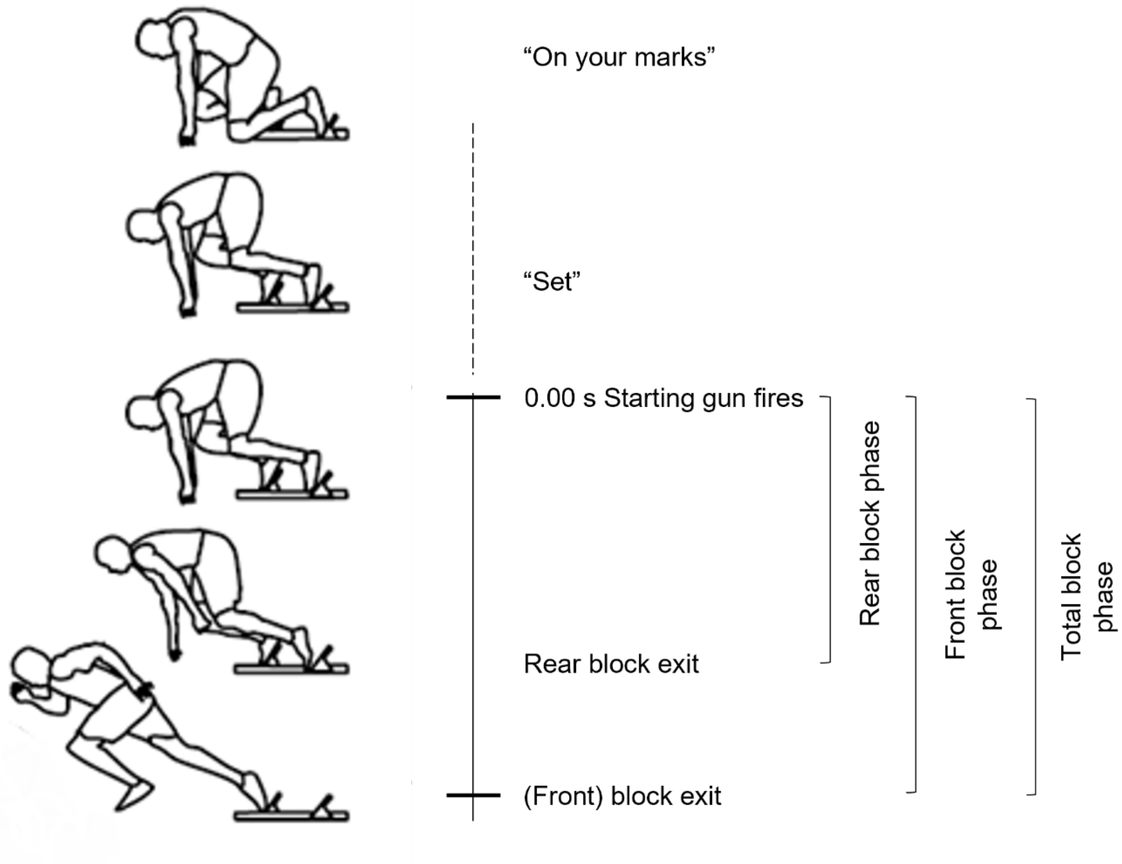

Figure 3.1.3 Schematic representation and definition of the events and associated phases during the sprint start. Adapted from Bezodis, Willwacher, and Salo (2019).

Mean and *peak antero-posterior, vertical, medio-lateral, and resultant forces* were calculated for the front and rear block using the respective front and rear force-time signals and normalised to body mass. Forces in all directions were used to quantify the force application technique on the starting blocks. Medio-lateral forces were defined as follows: positive values corresponded to medial and negative values corresponded to lateral. Because the force was predominantly positive in the front leg and negative in the rear leg, maximal positive values in the front leg and minimal values in the rear leg were considered the maximum medio-lateral forces applied to the blocks (Willwacher et al., 2016).

Inward-outward forces were calculated during the bend trials by transforming the medio-lateral forces using trigonometry when the blocks were not perpendicular to the start line (Figure 3.1.4). This was calculated separately for right and left foot forward starters.

Magnitude of medio-lateral force was calculated as the peak medio-lateral force without direction. This was calculated separately for right and left foot forward starters.

Impulse in each direction was calculated from absolute values using numerical integration of the force data.

Ratio of forces was calculated as the mean RF of the horizontal (in the direction of forward progression) to resultant force (including medio-lateral force; Rabita et al., 2015) during the block phase for each block to specify the effectiveness of force application to the blocks.

Horizontal force angle was calculated as the angle between anterior force and total horizontal force. This was calculated separately for right and left foot forward starters. Horizontal force angle was calculated to determine whether athletes were already starting to turn to 'run the bend' during the block phase (Figure 3.1.5).

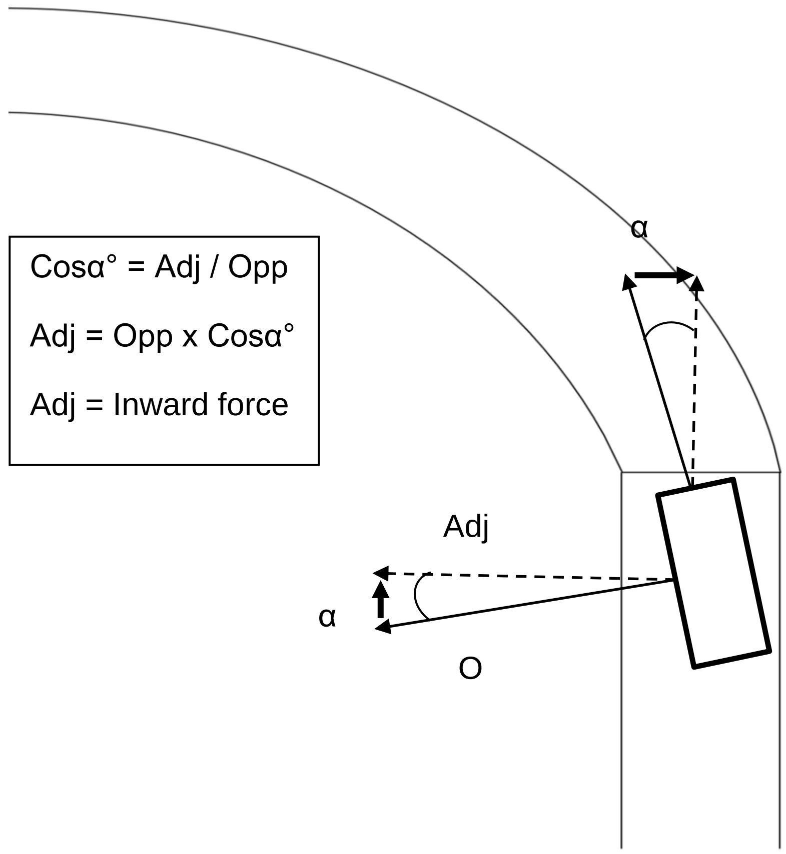

Figure 3.1.4 Schematic showing the calculation of inward-outward force by transforming medio-lateral force (not to scale). The difference in angle between the anterior direction of the blocks and the tangent to the start line is represented by the angle α. Solid line is the original and the dashed line is the rotated axis with the arrowhead showing the direction of rotation.

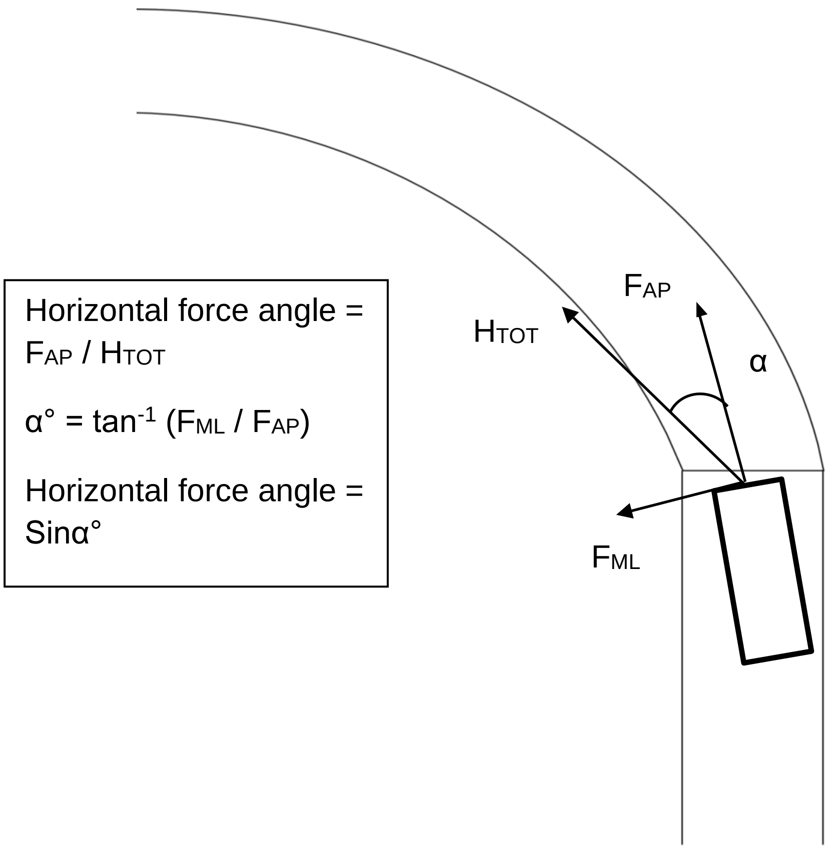

Figure 3.1.5 Schematic showing the calculation of horizontal force angle (α). The difference in angle between the anterior force and the total horizontal force is represented by the angle α.

3.2.5 Statistical analysis

The Shapiro-Wilk normality test ($p > 0.05$) was used to confirm the normal distribution of data. The mean of each athlete's three trials in each condition was used for analysis. For normalised average horizontal block power, push times, anterior, vertical and resultant forces and impulses, a mean for each condition (bend and straight) was calculated. Comparisons of normalised average horizontal block power, push times, mean, and peak forces, impulses, and horizontal force angle between the bend and straight-line sprinting were all made using paired-samples t-tests (SPSS for Windows, version 24; SPSS, Inc. Chicago, Il, USA). The following comparisons were made: front foot on the bend to front foot on straight-line sprinting, and rear foot on the bend to rear foot on straight-line sprinting. To consider comparisons between starting with the right and left foot forward, ML impulse on straight-line sprinting and inward-outward impulse on the bend and horizontal force angle were calculated separately for right and left foot forward starters. For ML impulse, inward-outward impulse, and horizontal force angle, the 10 athletes were separated into two groups (right foot forward starters and left foot forward starters). For each member of the group, a mean individual value was calculated from their three trials, which was then used to calculate a mean for the sub-group in each condition. ML impulse on straight-line sprinting was compared with inward-outward impulse on the bend for right foot forward starters for both the front (right foot) and rear blocks (left foot). Also, front foot horizontal force angle on straight-line sprinting was compared with front foot horizontal force angle on the bend. ML impulse on straight-line sprinting was compared with inward-outward impulse for left foot forward starters for both the front (left foot) and rear bocks (right foot).

Due to a small sample size, the study may be statistically underpowered, so the chance of detecting a true effect is reduced. Unlike inferential tests, effect size emphasises the size of the difference (Coe, 2002). Therefore, results were also interpreted using effect size. Hedges *g* includes a correction for small sample sizes. Effect sizes between the bend and straight-line sprinting for the front and rear foot were calculated for each variable using the equation by Durlak (2009):

$$g = \frac{M_1 - M_2}{SD} \times \left(\frac{N-3}{N-2.25}\right) \times \sqrt{\frac{N-2}{N}} \qquad \textbf{Equation 3.1.1}$$

Where M1 - M2 is the difference between the group means (M), SD is the pooled standard deviation, and N is the total sample size. Cohen's (1988) guidelines were used to assess relative magnitude of the effect, where $g < 0.20$

represents a trivial difference, $0.20 \geq 0.50$ indicates a small difference, $0.50 \geq 0.80$ a moderate difference, and $g \geq 0.80$ a large difference between means.

3.3 Results

There were no statistically significant differences and only trivial effect sizes found between the bend (0.39 ± 0.09) and straight-line sprinting (0.39 ± 0.08) for normalised average horizontal block power ($p = 0.91$, $g = 0.00$). There were also no significant differences in push time for the front and rear foot between the bend and straight-line sprinting (Table 3.1.1).

For the front foot, there were no significant differences between the bend and straight-line sprinting for mean anterior force (Table 3.1.1). However, mean, and peak vertical force were significantly lower on the bend compared with straight-line sprinting by 0.35 N/kg and 0.51 N/kg, respectively (Table 3.1.1), although the effect sizes were small for both. Mean and peak resultant force were also significantly lower on the bend than straight-line sprinting by 0.37 N/kg and 0.56 N/kg, respectively, despite small effect sizes (Table 3.1.1).

For the rear foot, there were no significant differences between the bend and straight-line sprinting for mean anterior force or RF (Table 3.1.1). Furthermore, there were no significant differences for both mean and peak vertical and resultant force for the bend compared with straight-line sprinting (Table 3.1.1).

For both the front and rear foot, there was no significant difference between the bend and straight-line sprinting in the magnitude of medio-lateral impulse (Table 3.1.2).

For athletes starting with their right foot on the front block (right foot forward athletes), for the front foot (i.e., the right foot), there were no significant differences between medio-lateral impulse on straight-line sprinting and inward-outward impulse on the bend or the horizontal force angle, with a trivial and large effect size, respectively (Table 3.1.2). For the rear foot (i.e., the left foot), there was no significant difference between medio-lateral impulse and inward-outward impulse (Table 3.1.2). There was a significant increase in the angle towards the anterior for the rear foot (left foot) of the right foot forward group and total horizontal force, with a small effect size (Table 3.1.2).

For athletes starting with their left foot in the front block (left foot forward athletes), for the front foot (i.e., the left foot), there were no significant differences between medio-lateral impulse and inward-outward impulse, or the angle between anterior and total horizontal force compared with straight-line sprinting (Table 3.1.2). For the rear foot (i.e., the right foot), there were no significant differences between medio-lateral impulse on straight-line sprinting and inward-outward impulse on the bend (Table 3.1.2). There was no significant difference in the horizontal force angle between the bend and straight-line sprinting (Table 3.1.2).

Table 3.1.1 Group mean values (± standard deviation) and Hedges *g* effect sizes for push time, anterior, vertical, and resultant forces, impulses, and RF of the front and rear foot for both the bend and straight-line sprinting.

	Straight		**Bend**		***p* (*g*)**	
	Front foot	**Rear foot**	**Front foot**	**Rear foot**	**Straight vs bend front foot**	**Straight vs bend rear foot**
Push time (s)	0.358 ± 0.023	0.176 ± 0.021	0.362 ± 0.031	0.176 ± 0.024	0.57 (0.12)	0.96 (0.00)
Mean anterior force (N/kg)	5.95 ± 0.79	4.58 ± 0.98	5.77 ± 0.85	4.78 ± 1.03	0.06 (-0.20)	0.17 (0.19)
Mean vertical force (N/kg)	6.98 ± 0.76	4.26 ± 1.21	6.65 ± 0.73	4.44 ± 1.22	0.00* (-0.42)	0.18 (0.14)
Mean resultant force (N/kg)	9.25 ± 0.97	6.42 ± 1.49	8.89 ± 1.02	6.68 ± 1.54	0.00* (-0.35)	0.17 (0.17)
Peak anterior force (N/kg)	9.86 ± 1.38	10.41 ± 2.32	9.56 ± 1.46	10.79 ± 2.51	0.05 (-0.28)	0.32 (0.15)
Peak vertical force (N/kg)	11.62 ± 1.26	8.64 ± 2.42	11.11 ± 1.34	8.85 ± 2.45	0.03* (-0.38)	0.45 (0.08)
Peak resultant force (N/kg)	15.25 ± 1.71	13.54 ± 3.21	14.68 ± 1.88	13.97 ± 3.38	0.02* (-0.30)	0.35 (0.12)
Mean anterior impulse (Ns)	2.12 ± 0.25	0.81 ± 0.24	2.08 ± 0.28	0.86 ± 0.27	0.03* (-0.16)	0.17 (0.16)
Mean vertical impulse (Ns)	2.50 ± 0.32	0.76 ± 0.27	2.40 ± 0.32	0.80 ± 0.29	0.09 (-0.29)	0.18 (0.14)
Mean resultant impulse (Ns)	3.31 ± 0.36	1.14 ± 0.35	3.21 ± 0.40	1.20 ± 0.39	0.05* (-0.26)	0.17 (0.15)
RF (%)	64.27 ± 4.30	71.92 ± 5.74	64.66 ± 3.94	72.02 ± 5.30	0.56 (0.09)	0.87 (0.02)

*Significant at $p < 0.05$

Table 3.1.2. Group mean values (± standard deviation) and Hedges *g* effect sizes of medio-lateral and inward-outward forces and angles of the front and rear foot for both the bend and straight-line sprinting.

	Straight		Bend		*p* (*g*)	
	Front foot	**Rear foot**	**Front foot**	**Rear foot**	**Straight vs bend front foot**	**Straight vs bend rear foot**
Magnitude ML Impulse (Ns)	0.18 ± 0.13	0.03 ± 0.03	0.17 ± 0.08	0.03 ± 0.02	0.54 (-0.15)	0.88 (-0.05)
Right foot forward ML Impulse (Ns)#1	0.05 ± 0.10	-0.02 ± 0.06	-	-	0.24 (-1.12)	0.85 (-0.17)
Right foot forward Inward-Outward Impulse (Ns)#2	-	-	-0.08 ± 0.13	-0.01 ± 0.05		
Left foot forward ML Impulse (Ns)#1	0.28 ± 0.13	0.01 ± 0.03	-	-	0.12 (-0.64)	0.06 (-0.71)
Left foot forward Inward-Outward Impulse (Ns)#2	-	-	0.20 ± 0.08	-0.02 ± 0.03		
Right foot forward Angle from Anterior Impulse (°)#3	1.19 ± 2.78	-1.46 ± 5.17	2.11 ± 3.82	-0.08 ± 4.24	0.38 (-0.26)	0.04* (-0.28)
Left foot forward Angle from Anterior Impulse (°)#3	-6.95 ± 3.01	-0.52 ± 2.07	-5.31 ± 2.36	-1.23 ± 1.35	0.17 (-0.58)	0.65 (-0.39)

Note: #1 +ve is the in the medial direction of the front foot, -ve is in the lateral direction of the front foot, #2 -ve is inwards (directed towards the centre of the bend), +ve is outwards (directed away from the bend), #3 0 is anterior direction, +ve is directed to the left, -ve is directed to the right

*Significant at $p < 0.05$.

3.4 Discussion

The aim of the study was to investigate the effect of the bend on performance (measured by normalised average horizontal block power), push time, and kinetics, during the block phase of the sprint start using novel instrumented starting blocks. No differences were found in normalised average horizontal block power or push time during the block start between the bend and straight-line sprinting. Therefore, there is no detrimental effect on block phase performance when athletes start on the bend during bend sprinting. This may be because anecdotal evidence suggests coaches instruct athletes to line up their blocks to allow them to run in a straight line for as long as possible to maximise anterior velocity and may not actually be starting to run the bend in the starting blocks This finding provides support for accepting the study's null hypothesis that block phase performance does not decrease on the bend. This was because there was no change in push time in the blocks on the bend to apply the necessary medio-lateral forces.

The direction of force application is important for block phase performance. Čoh et al. (1998) found the front leg contributes more to horizontal block exit velocity due to higher impulse generation, primarily because of a longer push duration than the rear leg. Greater block accelerations are attributed to athletes optimising their force production in the anterior direction (Brazil et al., 2015; Otsuka et al., 2014; Willwacher et al., 2016). As such, larger anterior forces applied to the front block are associated with better performance, and directing force more effectively is just as important as increasing the magnitude of the resultant force (Brazil et al., 2015; Otsuka et al., 2014; Willwacher et al., 2016). For the front block in the current study, RF indicated no differences in the direction of force application in block starts between the bend and straight-line sprinting. This is coherent with the finding that there was no change in performance between bend and straight-line sprinting. This support the notion that this aspect of block phase technique is transferable between bend and straight-line starts and athletes do not need to engage in specific bend start training, and straight-line starts would suffice. However, this is speculative and requires further work from a motor learning perspective and research that considers the first steps of the race following block exit.

Resultant force in the rear block is also important for performance during the block phase. Larger forces (Guissard & Duchateau, 1990) and greater magnitude of resultant force applied to the rear block compared with the front block are associated with better performance (Bezodis et al., 2019; Willwacher et al., 2016). In the rear block, the ability to generate larger forces is more important than the ability to direct the forces in a more anterior direction (Willwacher et al., 2016) . However, no differences were found in the magnitude of resultant force in the rear block between the bend and straight-line block starts. This is coherent with the finding that there was no change in performance between the bend and straight-line sprinting. Consequently, known spatio-temporal and kinetic changes in bend sprinting (e.g., Churchill et al., 2015, 2016; Judson et al., 2019; Judson et al., 2020a; Stoner & Ben-Sira, 1979) occur post-block exit, in later stages of the sprint.

A significant decrease in mean and peak vertical and resultant force for the front block on the bend compared with straight-line demonstrates that some changes do occur in the force application of athletes starting on the bend. However, these changes did not affect block phase performance. Colyer et al.

(2019) also stated that vertical force production does not directly contribute to sprint performance per se but found that vertical force production in the initial parts of the block phase and shortly after rear block exit (19–33% and 54–74% of the block push, respectively) were positively related to average horizontal external power. Vertical force is needed to increase vertical velocity and raise the athlete's centre of mass during the first stride. This allows the athlete enough time to prepare for first ground contact (Colyer et al., 2019) and to counteract the effects of gravity (Harland & Steele, 1997). Vertical force overtime produces impulse and, in turn, increases vertical velocity. The effectiveness of the initial acceleration phase depends on the execution of the first step, particularly the length of the step and the position of the foot in the contact phase (Kugler & Janshen, 2010). Higher vertical forces in the block phase results in either shortened support phases or longer flight phases during the subsequent steps after block exit (Kugler & Janshen, 2010). A decrease in vertical force application on the bend in the current blocks compared with straight-line sprinting might affect subsequent steps following block exit by decreasing flight time and consequently a shorter step length during the initial acceleration phase. Previous bend sprinting research has found shorter step lengths during the acceleration phase on the bend compared with straight-line sprinting (Judson et al., 2020a; Stoner & Ben-Sira, 1979). A shorter step length on the bend could then cause a decrease in anterior velocity compared with straight-line sprinting if step frequency does not increase to compensate. Therefore, the changes found in force application in the starting blocks on the bend compared with straight-line sprinting on subsequent steps requires further investigation.

Mediolateral forces increase on the bend compared with straight-line sprinting as a mandatory adjustment of bend sprinting to follow the bend (Churchill et al., 2016; Judson et al., 2019; Ohnuma et al., 2018). The choice of which foot forward does not change the horizontal direction of force application technique. Additionally, no changes in medio-lateral force application and impulse on the bend compared with the straight demonstrates that sprinters do not start turning during the block phase compared with straight-line sprinting to ‘run the bend’ and instead, try and run in a straight line to increase anterior velocity. Previous increases in contact time on the bend were required to apply greater medio-lateral force to generate sufficient inward force to counteract the centripetal force required to follow the bend (Churchill et al., 2016; Judson et al., 2019). During straight-line sprinting, Willwacher et al. (2016) suggested that altering an athlete's starting block technique to minimise medio-lateral force application to achieve a straight push-off in the forward direction would not increase performance. The lack of differences in the present study suggests that coaches should continue to anecdotally instruct their athletes to try and run straight for as long as possible when exiting the blocks and do not need to generate inward force and start turning. This finding suggests that when athletes are starting on the straight, it should not be detrimental to block phase performance on the bend and vice versa. The skills would transfer between the bend and the straight.

3.5 Limitations

There were several limitations which could have influenced the results of this study. First, the sample size of 10 is small. Smaller differences during bend sprinting compared with straight-line sprinting have been found in the acceleration phase (Judson et al., 2019; Judson et al., 2020a) than in the maximal effort phase (Churchill et al., 2015, 2016). Therefore, differences are likely to be smaller during the block start. Trained bend sprinters were required for the study; thus, the generalisability of the study is likely to be limited. While a larger sample size would have been preferable, it was important that the effects measured could be confidently attributed to the influence of the bend rather than the novelty of the task. Increasing the cut-off time to include less-skilled sprinters may have also introduced greater variability into the sample. Therefore, evaluating a smaller, more homogenous sample size was thought more appropriate than to increase the sample size by lowering the experience level. Future studies should focus on larger sample sizes when possible. A smaller sample size is associated with a loss of statistical power, which inflates the risk of a type II error, reducing the chance of a statistically significant result being found. To overcome this risk, effect size (Hedge's g) was also used to aid in the interpretation of the results, which includes a correction for smaller sample sizes (Lakens, 2013). Second, the study did not differentiate between the choice of athlete’s foot selection on the front and rear blocks for performance, push time, anterior, vertical, and resultant forces, and impulses, and RF. Asymmetries have been found in previous bend sprinting studies. Therefore, which foot forward athletes started with may have impacted technique in the blocks.

3.6 Conclusion

In conclusion, there were no differences in performance (normalised average horizontal block power), push time, and the technical application of force (RF) during the block phase between the bend and straight-line sprinting. These results show that differences between the bend and straight-line sprinting occur after block exit. However, decreases in vertical force on the bend may reduce step length post-block exit and affect spatio-temporal and force application in the subsequent initial acceleration phase and should be the focus of future research. The skills from block starts on straight-line sprinting in training would transfer to the bend because no differences in performance or important aspects of technique were found when starting on the bend compared with straight-line sprinting. Rather than athletes in one session completing starts on the bend and straight-line sprinting, they could all be completed on straight-line sprinting but incorporate starts on the bend into a wider training period.

There is little difference in block start performance between the bend and straight-line sprinting. As a result, further research on the bend was not deemed appropriate. Given the importance of the bend phase to events longer than 100 m, and the fact there has been comparatively little research on the bend, it was felt that further research on the bend is warranted. However, due to the COVID-19 pandemic, further experimental research was not possible. Therefore, to provide a focus for areas for future research, a rigorous scoping review was considered to be an appropriate next step in the program of research.

Chapter Four: BIOMECHANICS OF BEND SPRINTING: A SCOPING REVIEW

4 Biomechanics of bend sprinting: A scoping review

4.1 Introduction

Previous sprinting research has mainly focused on 60- and 100-m straight-line sprinting with far less focus on the bend, despite the bend portion of the race being a potentially important source of performance improvement. Research investigating bend sprinting has focused on spatio-temporal, kinetics, and kinematics during different phases in bend sprinting such as the acceleration and maximal effort phases and demonstrated where the changes occur (e.g., Alt et al., 2015; Churchill et al., 2015, 2016; Ishimura & Sakurai, 2016; Judson et al., 2019; Judson et al., 2020; Judson et al., 2020a; Ohnuma et al., 2018). Functional differences between the left and right legs have also been shown (Alt et al., 2015; Churchill et al., 2015, 2016; Judson et al., 2019; Judson et al., 2020a). Chapter three identified that no changes occurred during the block phase and therefore, changes between bend and straight-line occur post-block exit on the bend. Experimental studies have shown the track's geometry has a substantial influence on an athlete's performance, with velocity decreasing in the acceleration (Judson et al., 2019; Judson et al., 2020a) and maximal effort phases (Churchill et al., 2015, 2016) compared with straight-line sprinting. Also, mediolateral force increases during the acceleration phase (Judson et al., 2019) and further increases in the maximal effort phase (Churchill et al., 2016; Ohnuma et al., 2018) during bend sprinting. However, it is not known what other areas are most important for future research in bend sprinting.

Analysing bend sprinting technique can be challenging. Investigating international-level athletes' performance during in-competition, which generally reflects peak performance level in a pressurised situation, is ideal. Collecting data from an international-level athlete sample often results in possessing less control over national-level and non-trained athletes. Restrictions include obstructive views, athlete access resulting in small sample sizes, the often-invasive data collection methods of attaching markers to the athlete, and international-level athletes and coaches are sometimes more resistant than national-level and non-trained athletes to have their training time or structure changed for research. Researchers generally aim to replicate a competitive environment as closely as possible using a representative design. However, lab or training-based studies are not the settings where the sprinter typically performs, and the novelty of the environment may influence the movements being measured. Additionally, even though the environment can be controlled which helps minimise measurement error, the competitive situation cannot be replicated where a sprinter is likely to produce their maximal effort. Environments in which data can be collected are also limited because of factors, for example, force plates having to be mounted on top of, or embedded underneath, a running track when collecting ground reaction force data and the number of cameras and laboratory space available when collecting joint kinematic data of a complete sprint. New technology, including multiple inertial measurement units (IMUs) to estimate ground reaction forces and measure kinematics and markerless motion capture to capture kinematic data without the use of markers, would allow data to be collected at athletics tracks during training sessions or competitions, increasing ecological validity.

Between a growing body of literature and advancements in technology which would allow more data to be collected less invasively, understanding the current literature landscape was deemed worthwhile. A scoping review can help evaluate and identify gaps in current knowledge and thus guide future research towards currently unexplored areas. Therefore, there was a clear need to review the current knowledge of the biomechanics of bend sprinting and identify the most important areas for future research. The purpose of this scoping review was to critically appraise and comprehensively synthesise the existing literature related to bend sprinting and identify areas for future research.

4.2 Methods

The review process proposed in 2020 by the Joanne Briggs Institute (Peters et al., 2015) and the preferred reporting items for systematic reviews and meta-analyses extension for scoping reviews (PRISMA-ScR; Tricco et al., 2018) checklist for reporting were used.

4.2.1 Search strategy

A literature search was conducted using the following databases to identify relevant papers: PubMed, Scopus, SPORTDiscus, and Web of Science. Figure 4.1.1 provides a schematic representation of the search method in accordance with the PRISMA guidelines. Two sets of search terms were used. The first one was as follows:

(1) run* or sprint AND (2) path or curve* or bend AND (3) biomechanic* OR kinetic* OR force OR impulse OR pressure OR moments OR power OR kinematic* OR angle* OR technique OR muscle* OR mechanic* OR asymmetr* OR characteristics OR velocit* OR activ* OR perform*

The second was as follows:

(1) “200 m*” OR 200m* OR “400 m*” OR 400m* OR relay AND (2) run* OR race OR sprint* AND (3) biomechanic* OR kinetic* OR force OR impulse OR pressure OR moments OR power OR kinematic* OR angle* OR technique OR muscle* OR mechanic* OR asymmetr* OR characteristics OR velocit* OR activ* OR technique OR perform*.

Reference lists of those relevant articles included in the scoping review analysis were hand-searched to identify any additional articles. Searches were conducted between 13 May 2021 and 4 March 2022.

4.2.2 Inclusion criteria

Articles were included if they met the following population, concept, and context criteria:

- Types of population: Included human, able-bodied athletes of any age, males and/or females. Articles where disabled athletes were included if they also included able-bodied participants.

- Concept: Articles needed to be about sprint running.

- Context: Articles needed to be related to biomechanics of bend sprinting and at a radius and on surfaces representative of competitive outdoor athletics bend sprinting.

- Selection of sources of evidence: Considering potential difficulties translating articles written in different languages, only original articles written in English were considered. This review considered articles that were empirical in nature and peer-reviewed data, including quantitative research, prospective cohort articles, and mixed-methods.

4.2.3 Exclusion criteria

Articles were not included if they were either 1) a review of the literature including systematic review, scoping review, narrative review, meta-analyses, or validation of a protocol or instrument, or 2) case reports, conference proceedings, and poster presentations due to potential limitations in reporting quality and/or duplication.

4.2.4 Study selection

Articles that matched the eligibility criteria were imported into the bibliographic manager Mendeley™ (Elsevier, Netherlands) to store articles, remove duplicates, and facilitate the screening process. The review process consisted of three levels of screening: (1) title, (2) abstract review, and (3) full text. Two authors independently screened the articles for all three levels, with conflicts resolved by consensus.

4.2.5 Data Extraction

For each outcome, key information from the included texts were extracted into a data form that was related to the biomechanics of bend sprinting. The information included participant characteristics (trained/untrained, age, gender, number, PB) and article characteristics (author, year, study design, sprint phase and radius, aim, protocol, equipment, measures, and results). For a comprehensive study breakdown, see Table 4.1.1.

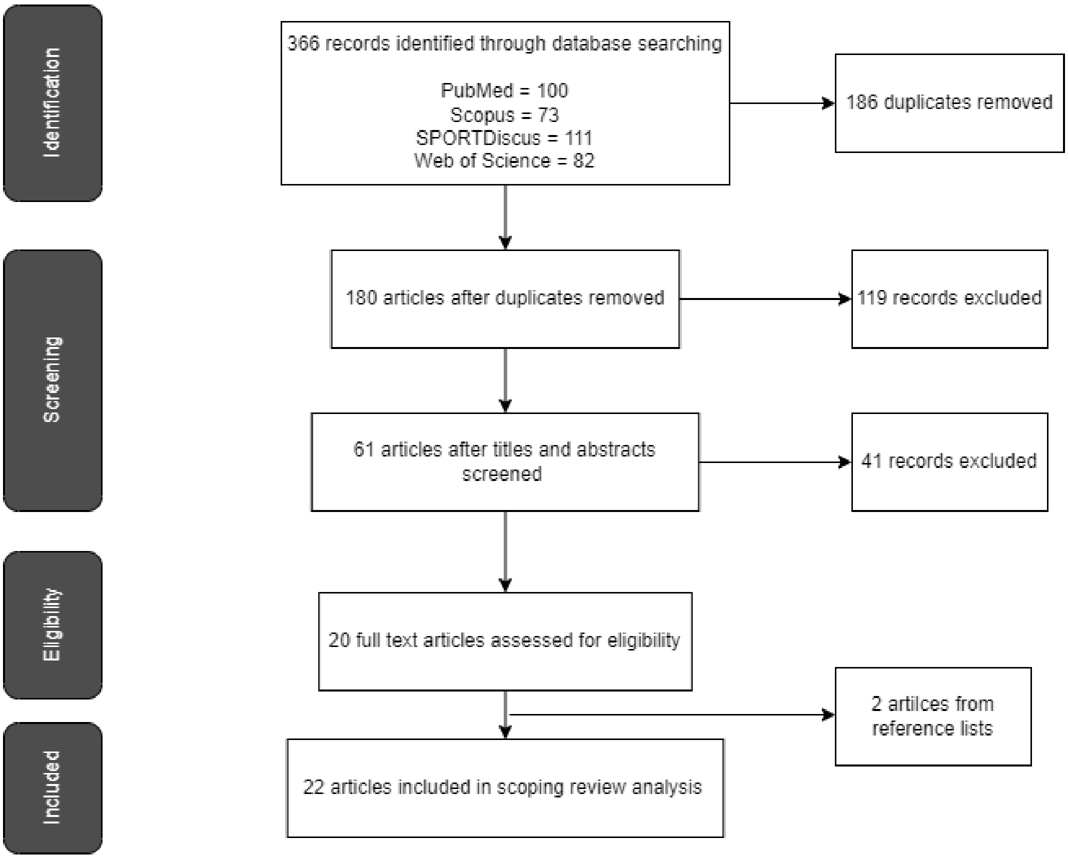

Figure 4.1.1 PRISMA-ScR Flow chart of extracted, included, and excluded articles.

4.3 Results

Initial database searches resulted in the identification of 366 articles. After removing duplicates, 180 articles were retained for initial screening. Title and abstract screening resulted in 119 articles being excluded. The remaining 61 articles were further examined using the inclusion/exclusion criteria, and 41 articles were excluded, resulting in 20 articles to assess for full-text eligibility. A further two articles were found by manually screening reference lists of the fully read articles, leaving a total of 22 articles included in this review (Figure 4.1.1). All the articles included in this review were original research articles. Summaries of the papers reviewed are documented in Table 4.1.1.

Eight studies compared bend and straight running in the 200 m. Out of those studies, one study investigated the block start, four researched either the initial acceleration or acceleration phase, three studied maximal effort, and one analysed sub-maximal velocity. Four studies used the bend as the only condition. Out of those studies, one investigated the block start, three studies studied maximal effort, one researched different lanes, and radii on the bend, and one assessed the reliability of variables on the bend. Four studies included the whole 200 m, one investigated indoor vs outdoor 200 m, and the final seven studies explored the total 400 m.

The studies have used most lanes of the track, but radii differ even using the same lane number. Seven studies used lane 1 (radii 36.5 m to 37.9 m), three studies used lane 2 (radius 37.72 m), one study used lane 4 (radius 43.51 m), one study used lane 5 (radius 41.41 m), one study used lane 6 (radius unknown), and one study used lane 8 (radius 45.10 m). Also, one study used the middle lane (lane number unknown), four studies used all lanes, six studies did not state which lane they used, and three studies did not state the radii but stated the lane used.

The sample sizes of the studies were notably low, ten participants or fewer (16 studies). The other six studies assessed between 11 and 50 participants. 18 studies used only male participants, one used only female participants, and four included both males and females. 13 studies used bend sprinting specialists (200 m and 400 m) only, two used non-bend sprinting specialists only, eight included both bend sprinting specialists and non-specialists, one included able-bodied and amputee and five studies compared different levels of performance between-athletes.

A selection of measurement equipment were used to assess both the effect of the bend and different types of strategies used during the 400 m. Two studies used data collected of finals from publicly available internet broadcasts, two used a manual stride measurement method, five used timing gates/photocells, six used video cameras, three used high-speed video cameras, seven used optoelectronic cameras, six used force plates, seven used electromyography (EMG), two used a biaxial accelerometer, and one used a vertical jump measuring device.

21 studies investigated performance using either a single or a combination of variables (either time (n = 8), speed (n = 6), or velocity (n = 14)). Eighteen studies measured spatio and/or temporal variables, three measured body lean angles, four measured ground reaction forces, 10 measured joint angular kinematics of the lower extremity, one measured joint moments, one measured joint powers, four measured muscle activity, one measured leg spring stiffness, one measured leg strength, and one measured physical fitness.

Table 4.1.1 Summary of data extraction from biomechanics of bend sprinting articles included in the review.

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Abdelbaky, 2012	n = 3. 4 males (200 m PB 22.77 ± 0.25 s).	Block start and initial acceleration (first three steps). Lane 1	To identify the spatio-temporal and kinematic variables which affect 200 m performance during the block start and initial acceleration.	Athletes performed 200 meters from the blocks and the first 3 strides for both straight-line and bend sprinting analysed (9 attempts). Implemented a training program to improve 200 m times.	2 video cameras sampled at 25 Hz.	Performance (time). Step length and step frequency. Joint angular kinematics of the lower extremity.	Block reaction times ranged from 0.20 – 0.24 s. Descriptions of the time, step length, and step frequency of each sprinter from initialisation in the blocks to the 3rd step. Descriptions of the ankle and knee angles in the front and rear blocks.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Alt et al., 2015	n = 6. 6 males (200 m PB 22.60 ± 0.33 s).	Sub-maximal – 90% of the athletes' perceived maximal linear sprint velocity. Lane 1 (radius 36.5 m).	To identify the differences in the three-dimensional joint kinematics of the lower extremity between straight-line and bend sprinting and to describe the differences between the inside and outside leg during bend sprinting.	Athletes performed 3 valid trials of both straight-line and bend sprints at a constant sub-maximal sprinting velocity which was attained after an approach run of 40 m.	Timing gates. 16-camera optoelectronic marker-based motion capture system sampled at 250 Hz.	Performance (velocity). Step length, stance time, flight time, step frequency. Joint angular kinematics of the lower extremity.	No difference in sprinting velocity between bend and straight trials. No change in flight time, step length, and step frequency between bend and straight trials. ↑ stance time for the left leg on the bend compared with the right leg on the bend. ↓ stance time for the right leg on the bend compared with the right leg on straight-line sprinting. ↑ left and right stance phase during bend sprinting in the ankle, knee, and hip of the lower extremity in the frontal and horizontal plane but unchanged in the sagittal plane. ↑ peak hip adduction of the left leg on the bend compared with straight-line sprinting and the right leg on the bend. ↓ hip adduction angle of the right leg on the bend compared with straight-line sprinting. ↑ hip joint peak external rotation of the left leg compared with the right leg on the bend. No difference in joint angles of the knee between the bend and straight-line sprinting. ↑ maximum internal rotation of the right knee compared with the left knee on the bend. ↑ peak eversion angle of the ankle joint of the left leg on the bend compared with the left leg on straight-line sprinting and the right leg on the bend. ↓ peak eversion angle of the ankle of the right leg on the bend compared with straight-line sprinting. ↓ ankle external rotation of the right leg on the bend compared with straight-line sprinting. ↑ peak external rotation of the ankle of the right leg compared with the left leg on the bend.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Churchill et al., 2015	n = 7. 7 males (200 m PB 22.15 ± 0.93 s; range from 21.18 to 23.90 s).	Maximal effort at 40.00 – 47.50 m. Lane 2 (radius 37.72 m).	To understand the changes in performance and technique that occur during maximal effort bend sprinting compared with straight-line sprinting.	Athletes performed three 60 m maximal effort sprints on the bend and straight-line sprinting. The conditions were completed during separate sessions (no more than 3 days apart). 8 minutes rest was given between-trials. 2 consecutive steps were achieved.	2 high-speed video cameras sampled at 200 Hz.	Performance (speed and velocity). Directional step length, race step length, step frequency, ground contact time, flight time, and touchdown distance. Body lean angles. Joint angular kinematics of the lower extremity.	↓ absolute speed and race velocity on the bend compared with straight-line sprinting. ↓ directional step length and race step length for the right step on the bend compared with straight-line sprinting. ↓ step frequency for the left step on the bend compared with straight-line sprinting. ↑ mean left ground contact time on the bend compared with the left step on straight-line sprinting and the right step on the bend. ↓ flight time for the right step on the bend compared with straight-line sprinting. ↑ touchdown distance and body sagittal lean for the left on the bend compared with the left step on straight-line sprinting and the right step on the bend. ↑ larger thigh separation at left touchdown on the bend compared with right touchdown on the bend. ↑ adduction at touchdown and at peak adduction of the left hip on the bend compared with the right hip on the bend. ↑ turning of the centre of mass occurred during left ground contact on the bend compared with the right ground contact on the bend.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Churchill et al., 2016	n = 7. 7 males (200 m PB 22.04 ± 0.74 s; range from 20.89 to 22.90 s)	Maximal effort at 40.00 – 47.50 m. Lane 2 (radius 37.72 m).	To determine whether the constant limb force hypothesis occurs during maximal effort bend sprinting.	Athletes performed up to six 60 m maximal effort sprints. 8 minutes rest between-trials. 1 successful left step and 1 successful right step on the bend and the same on straight-line sprinting were achieved.	2 high-speed video cameras sampled at 200 Hz. Two 0.90 m x 0.60 m force plates sampled at 1000 Hz.	Performance (velocity). Race step length, step frequency, ground contact time, and flight time. Ground reaction forces. Joint angular kinematics of the lower extremity.	↓ mean race velocity on the bend compared with straight-line sprinting for both the left and right steps. ↓ mean right race step length on the bend compared with straight-line sprinting. ↑ step frequency for the right step on the bend to left step on the bend which was not seen on straight-line sprinting. ↑ turning during the left step than the right step on the bend. ↓ mean peak resultant force during the left step on the bend compared with the left step on straight-line sprinting. ↑ mean peak resultant force during the right step on the bend compared with the right step on straight-line sprinting. ↑ braking impulse and the duration of braking during the left step on the bend compared with the left step on straight-line sprinting and right step on the bend. ↑ mean peak inward force and net inward impulse during the left step on the bend compared with the right step on the bend.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Churchill et al., 2019	n = 9. 8 males (200 m PB; range from 21.1 to 22.6 s). 1 male (400 m PB 47.36 s).	Maximal effort at 40.00 – 48.00 m. Lanes 8, 5, and 2 (radii: 45.10 m, 41.41 m, and 37.72 m respectively).	To investigate the effect of running in different lanes on bend sprinting performance and kinematic variables.	Athletes performed two 60 m maximal-effort sprints around the bend in 3 different lanes. 2 athletes completed over 2 training sessions. 8 minutes rest between-trials within a lane and 15 minutes between-lanes. 2 consecutive steps were achieved.	2 high-speed video cameras sampled at 200 Hz.	Performance (velocity). Race step length, step frequency, ground contact time, flight time, touchdown distance, and turning of centre of mass. Body lean angles.	General trend for race velocity and absolute speed to ↓ as bend radius decreased from lane 8 to lane 2. Significant ↓ absolute speed from lane 8 to lane 5 and from lane 8 to lane 2 for the left step. ↓ mean race velocity as bend radius decreased from lane 8 to lane 5 for both the left and right steps. ↓ race velocity from lane 8 to lane 2 for left and right step, statistically significant for the left step. ↑ in race velocity for the left step than the right step for lanes 8 and 5. Shortest race and directional step lengths in lane 5 for both the left and right steps. Step frequencies for left and right steps within a lane were similar in all lanes. General trend for ↓ step frequency as bend radius decreased, significant between lane 5 and 2 for the left step. General trend for ↑ in mean ground contact time during the left step as bend radius ↓, significant difference between lanes 8 and 2. No change in ground contact time during the right step in all lanes. Statistically significant ↑ in ground contact time between left and right in all lanes. ↑ in turning of the centre of mass during the left ground contact phase compared with the right ground contact phase in all three lanes. Significant ↑ in turning of the centre of mass for the right step in lanes 5 and 2 compared to lane 8. No change in touchdown distance, thigh separation at touchdown, and body sagittal lean range of motion between-lanes. ↑ inward body lateral lean at touchdown as radius decreased for both the left and right steps. No change in knee kinematics between-lanes. ↑ in maximum right knee angle during contact in lane 2 and right knee angle at take-off in lane 5 and 2 compared with the left.

							No significant differences for the ankle, MTP, or rearfoot kinematics between-lanes. ↑ trend in inward body lateral lean at touchdown as radius decreased for both the left and right steps. Not statistically significant between lane 5 and lane 2 for the left step. ↑ inward lean at touchdown for the right step compared with the left step within each lane.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Ferro & Floria, 2013	n = 33. 17 males (indoor 200 m 21.85 ± 0.50 s; outdoor 200 m 21.43 ± 0.22 s). 16 females (indoor 200 m 24.87 ± 0.45 s; outdoor 200 m 24.50 ± 0.21 s).	200 m indoor and outdoor distance. All lanes	To conduct a split-time analysis of athletes during 200 m indoor and outdoor competitions to provide information to athletes and coaches which splits are important during indoor 200 m to improve training strategy.	2 indoor and 2 outdoor 200 m finals (women's and men's) in the 4 most important Spanish championships held over a period of 5 years. 24 races altogether.	5 synchronised video cameras every 50 m sampled at 50 Hz.	Performance (time, velocity).	↑ in race time indoors compared with outdoors in both the men's and women's race. ↑ in time to run the 0- to 50-m section indoors than outdoors in men and women. ↑ in time to run the 100- to 150-, section indoors than outdoors in men and women. ↓ in relative average velocity (percentage of average velocity relative to the maximum velocity reached in the fastest section 50-100 m) indoors than outdoors.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Hanon & Gajer, 2009	n = 30. 15 males (split into equal groups of world-class, national, and regional levels). 15 females (split into equal groups of world-class, national, and regional levels).	Complete 400 m. All lanes.	To evaluate the time course for both performance and spatio-temporal variables every 50 m during 400 m events during competition. Also, to compare 3 different levels of performance to determine what discriminates world-class runners from their less experienced counterparts.	World-class level athletes: IAAF pictures recorded during world championships. National and Regional level athletes: an official meeting during the competitive season.	World-class: 9 video cameras every 50 m sampled at 50 Hz. National and Regional: 16 videotape recorders every 25 m sampled at 50 Hz.	Performance (velocity). Stride length and stride frequency.	Peak velocity was reached for all athletes between the 50- and 100-m mark. ↑ velocity of the world-class group compared with the national and regional level groups from 0 to 50 m and remained greater until the 150- to 200-m section in the women and until the 350- to 400-m section in the men. The ↓ in velocity during the last 100 m was greatest for the world-class level, particularly in the women's group. ↑ in stride length as performance levels ↑. Greatest stride length during 100-150 m section except for the national-level runners. The stride lengths of the world-class runners were longer than the national and regional level groups, except in the 350- to 400-m section. Maximum step frequency between 50- to 100-m when the velocity was maximal. Maximum step frequency ↓ with performance level. Except for the last two 50-m runs, the differences in step frequency were not significant between the groups of runners. Step frequency was never significantly difference between the men's groups. Stride length contributed to the decrease in velocity between 200 and 300 m. Both stride length and frequency contributed to the decrease in velocity between 300 and 350 m. Stride frequency contributed to the decrease in velocity between 350 and 400 m.

Table 4.1 – *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Hobara et al., 2010	n = 8. 8 males (2 100 m sprinters, 1 110 m hurdler, 3 400 m sprinters, 1 800 m runner, 1 endurance runner).	Complete 400 m. Lane 6.	To measure both the vertical and leg stiffness continuously over an entire 400 m sprint. Also, to investigate the relationships between leg spring stiffness and running velocity, stride frequency, or stride length.	Athletes were instructed to run 400 m as fast as possible.	1 panning camera sampled at 60 Hz. Biaxial accelerometer (placed on right heel) sampled at 1000 Hz.	Performance (time and velocity). Stride length, stride frequency, ground contact time, and flight time. Leg spring stiffness (vertical stiffness, leg stiffness).	Participants ran the 400 m in 57.62 ± 0.92 s. Forward velocity peaked in the 50-100 m section, and then ↓ from through the rest of the race. Vertical stiffness peaked in the 50 - 100 m section and consistently ↓ thereafter. Mainly associated with an ↑ in estimated vertical centre of mass displacement rather than a ↓ in estimated peak vertical force. Leg stiffness peaked in the 0 – 50 m section and remained constant from the next 50 m section to the finish. Mainly associated with an ↑ in estimated compression of the leg spring. Vertical stiffness and forward velocity decreased by about 40% and 25% respectively from the 50 to 100 m section to the 350 to 400 m section. Time from take-off to touchdown of the same leg was unchanged from the middle to the later part of the 400 m, contact time ↑, resulting in a ↓ of stride frequency. Stride length peaked during the 50-100 m interval and then ↓. Stride frequency and stride length decreased to about 83% and 90% of their maximum values, respectively, in the 350-400 m section. Positive linear relationship was found between stiffness and forward velocity and stride frequency, but not stride length. No significant positive linear relationship was found between stiffness and forward velocity, stride frequency, and stride length. Stride frequency and stride length were significantly correlated with forward velocity.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Hobara et al., 2015	n = 50 50 males (16 able bodied sprinters, 13 T44 class sprinters, 5 T43 class sprinters, and 16 T42 class sprinters).	Complete 200 m. All lanes	To examine whether the difference in forward velocity of a 200 m sprint between able-bodied sprinters and individuals with lower extremity amputations is due to a shorter step length rather than a lower step frequency.	Data collected of finals from publicly available internet broadcasts of men's 200 m races.	N/A	Performance (velocity). Step frequency and step length.	Horizontal velocity ranged from 10.0 m/s - 10.3 m/s in able bodied sprinters. Step frequency ranged from 4.2 - 4.5 Hz in able bodied sprinters. Step length ranged from 2.20 - 2.45 m in able bodied sprinters. Significant negative and positive linear relationship were found between horizontal velocity and step frequency and horizontal velocity and step length in able bodied sprinters.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Ishimura & Sakurai, 2016	n = 18. 10 males (30 m time 3.23 ± 0.13 s). 8 F (30 m time 3.62 ± 0.16 s).	Maximal velocity at 40 to 55 m. Lane 4 (radius 43.51 m).	To investigate the potential asymmetries between the outside and inside legs in the determinants of bend sprinting.	Athletes performed 3 60 m trials with 2nd 30 m timed and the fastest trial selected for analysis. A sequence of at least 2 stride cycles (4 steps) was obtained from each subject. 5- to 10-minutes rest between-trials.	Photocell system. 19-20-camera optoelectronic marker-based motion capture system sampled at 250 Hz.	Performance (speed and time). Step length, step frequency, stance distance, flight distance, step time, stance time, flight time, touchdown distance, foot movement distance, and take-off distance. Joint angular kinematics of the lower extremity.	No difference in the average speeds between the left and right leg. Running speed determinants of the left and right legs were asymmetric. ↑ step length for the left leg compared with the right leg. ↑ step frequency for the right leg compared with the left leg. Faster runners had an ↑ step length for both sides and had the highest step frequency in only the right leg. No interactions between step length and step frequency on the bend. ↑ stance and flight distance for the left compared with the right leg. The ratio of stance distance and flight distance between the right and left legs were the same. For both legs, the longer step length included a longer flight distance. ↑ step, stance, and flight times for the left step compared with the right step. No differences were found in the ratio of stance and flight time between the 2 sides. ↑ touchdown and foot movement distance for the left leg compared with the right leg, but no difference in take-off distance. ↑ ratio of touchdown and foot movement distance for the left leg compared with the right leg. ↓ in take-off distance for the left leg compared with the right leg. ↑ take-off angle, relative height for the left leg, and the symmetric take-off speed compared with the right leg. ↑ vertical velocity and centre of gravity height at take-off for the left leg compared with the right leg. ↑ outward velocity at touchdown for the right leg than for the leg, whereas ↑ anterior velocity at touchdown for the left leg than for the right leg. Greater change of direction during the right foot stance than during the left foot stance caused by greater centripetal force.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Iwańska et al., 2021	n = 11. 11 males (400 m PB unknown)	Complete 400 m. Lane number unknown.	To assess the effect of the bend on fatigue symmetry and lower limb muscle activity while considering the maximum velocity running kinematics of elite Polish athletes.	Athletes performed 400 m accompanied by another competitor who did not take part in the experiment.	Surface EMG obtained from tibialis anterior, lateral gastrocnemius, rectus femoris, and biceps femoris of the left and right legs sampled digitally sampled at 1926 sa/s. Accelerometers located in two Trigno sensors position at the ankle over the Achilles tendons to calculate spatio-temporal variables.	Performance (velocity). Stride time, stride length, stride frequency. Root mean square. Symmetry index. Muscle fatigue index.	No effects of the interactions between right and left lower limbs as well as the end and straight sections. ↑ in root mean square through the race. Largest change in root mean square was 2nd bend and 2nd straight for both legs. Greater change in the left limb. Highest symmetry index in the first two sections of the run (1st bend and 1st straight) but not significant. Left leg had greater muscle activity. Greater fatigue found for the right leg. Largest fatigue asymmetry occurred for tibialis anterior. Smallest fatigue in biceps femoris for both legs. Significant differences in fatigue between biceps femoris and rectus femoris as well as in tibialis anterior. Lowest fatigue values found in the 1st bend. No effects from the interactions between the limb and track trajectory with any kinematic variables. Stride duration ↑ of the right leg compared with left leg. ↑ stride length for the right leg. Running velocity decreased through the 400 m.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Judson et al., 2019	n = 9. 9 males (200 m PB 22.70 ± 0.49 s; range from 21.8 to 23.43 s).	Acceleration phase (10 – 17 m). Lane 1 (36.5 m).	To investigate horizontal force production, foot kinematics, and MTP axis use during bend sprinting compared with straight-line sprinting. Also, investigate potential asymmetries between the outside and inside legs during bend sprinting.	Athletes performed a maximum of 6 trials (3 left, 3 right) at maximal effort for 30 m in each condition (bend and straight). 8 minutes rest between-trials. A minimum of 1 successful right and left step on the bend and on straight-line sprinting were achieved. 1 successful trial per condition and per athlete was analysed.	15-camera optoelectronic marker-based motion capture system sampled at 200 Hz. One 0.90 m x 0.60 m force plate sampled at 1000 Hz.	Performance (speed). Ground contact time. Ground reaction forces. Joint angular kinematics of the lower extremity.	↑ contact time on the bend compared with straight-line sprinting. ↑ contact time on the bend was due to ↑ for the left step compared with the right step. ↓ anteroposterior force on the bend compared with straight-line sprinting in both the left and right steps at 37-44% of stance. ↑ mediolateral force for most of the stance phase (3-96%) on the bend compared with straight-line sprinting. ↑ mediolateral force for the right step than left at 1-12% of stance. ↑ in mediolateral force for the left step than right at 75-100% of stance. ↓ propulsive impulse on the bend compared with straight-line sprinting. ↑ higher mean ratio of forces on straight-line sprinting than bend. Mean mediolateral centre of pressure position was more lateral in relation to the 2nd metatarsal head in the left step on the bend compared with straight-line sprinting, indicating the oblique axis was used for push-off at the MTP joint. ↑ left step peak ankle internal rotation on the bend compared with straight-line sprinting and the right step on the bend. ↓ left step peak ankle inversion on the bend compared with straight-line sprinting. ↑ in peak midfoot eversion in the left step on the bend compared with straight-line sprinting, and a ↓ in the right step on the bend compared with straight-line sprinting. ↑ in right step peak midfoot inversion on the bend relative to straight-line sprinting and the left step on the bend.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Judson et al., 2020b	n = 6. 4 males (200 m PB 22.76 ± 0.95 s; range from 22.00 to 24.10 s). 2 females (400 m PB 64.00 ± 0.00 s).	Maximal velocity at 38-45 m section of 60 m sprints. Lane 1 (radius 36.5 m).	To determine the within- and between-day reliability of bend sprinting using 3D optoelectronic motion capture with a lower limb and trunk marker set.	Athletes performed 5 trials at maximal effort for 60 m. The test protocol was repeated 2 days to 1 week later, with the second session occurring at approx. the same time of day. Approximately 8 minutes rest between-trials. .	12-camera optoelectronic marker-based motion capture system sampled at 240 Hz. One 0.90 m x 0.60 m force plate sampled at 1000 Hz.	Directional step length, step frequency, ground contact time, flight time, and touchdown distance. Joint angular kinematics of the lower extremity.	Descriptions of spatio-temporal, ground reaction forces, and kinematic variables. For between-day reliability, all but two spatio-temporal variables were fair to excellent. Right touchdown distance and left step length were poor to excellent. For all variables, within-day reliability was greater than between-day reliability. Right step frequency displayed a between-day minimal detectable difference (MDD) of 0.16 Hz, whereas right and left contact time had a between-day MDD of 0.02 s. Contact time also demonstrated a small between-day standard error of measurement (SEM) (0.006–0.007 s). Within-day SEM and minimal detectable difference were smaller when compared to between-day values. For joint kinematics, 29 of 44 variables demonstrated excellent between-day reliability when analysing the 95% CI (0.780–0.999). Six frontal and transverse plane variables (left knee internal rotation, right hip external rotation, right knee abduction, right knee adduction, right knee external rotation, right ankle external rotation) demonstrated poor to excellent reliability (0.075–0.985). Within-day reliability (ICC 3, 1: 0.228–0.999) was greater than between-day variability (ICC 3, k, 0.075–0.999) for most joint kinematic variables. MDD ranged from 1–11° across all variables. Between-day SEM values were < 4° across all conditions, however within-day SEM and MDD were smaller.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Judson et al., 2020a	n = 9. 9 males (200 m PB 22.70 ± 0.49 s; range from 21.8 to 23.43 s).	Acceleration phase (10 – 17 m). Lane 1 (radius 36.5 m).	To investigate the effect of bend sprinting on the spatio-temporal and kinematic variables of the lower limb during the acceleration phase.	Athletes performed a maximum of 6 trials (3 left, 3 right) at maximal effort for 30 m in each condition (bend and straight). 8 minutes rest between-trials. A minimum of 1 successful right and left step on the bend and on straight-line sprinting were achieved. 1 successful trial per condition and per athlete was analysed.	15-camera optoelectronic marker-based motion capture system sampled at 200 Hz. One 0.90 m x 0.60 m force plate sampled at 1000 Hz.	Performance (speed and velocity). Directional step length, race step length, step frequency, ground contact time, flight time, and touchdown distance. Ground reaction forces. Joint angular kinematics of the lower extremity.	No main effect for condition with absolute speed and race velocity. ↓ in race step length on the bend compared with straight-line sprinting. ↓ step frequency for the left step on the bend compared with the left step on straight-line sprinting and the right step on the bend. ↑ left step touchdown distance on the bend compared with straight-line sprinting. ↑ in body lateral lean at touchdown in both the left and right step on the bend compared with straight-line sprinting. ↑ peak hip abduction joint angle of the right limb on the bend compared with straight-line sprinting. ↑ peak left step hip adduction on the bend compared with the left step on straight-line sprinting and the right step on the bend. Non-significant, but large effect size, ↑ in peak left hip external rotation on the bend compared with straight-line sprinting. ↑ left step peak ankle internal rotation on the bend compared with straight-line sprinting and the right step on the bend. Large, but non-significant, ↑ in peak left step ankle eversion on the bend compared with the straight. No significant interactions for any variables at the knee.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Judson et al., 2020	n = 7. 7 males (200 m PB 21.8 – 23.43 s).	Acceleration phase (10 – 17 m). Lane 1 (radius 36.5 m).	To investigate the effect of the bend on lower limb joint kinetics compared with straight-line sprinting.	Athletes performed a maximum of 6 trials (3 left, 3 right) at maximal effort for 30 m in each condition (bend and straight). 8 minutes rest between-trials. A minimum of 1 successful right and left step on the bend and on straight-line sprinting were achieved. 1 successful trial per condition and per athlete was analysed.	15-camera optoelectronic marker-based motion capture system sampled at 200 Hz. One 0.90 m x 0.60 m force plate sampled at 1000 Hz.	Performance (velocity). Joint moments. Joint powers.	Although non-significant, a large and moderate ↓ in peak hip flexor moment was observed for the left and right steps on the bend compared with straight-line sprinting, respectively. ↑ in peak left step hip adductor moment on the bend compared with straight-line sprinting. Trend towards an ↑ in left step peak positive hip power in the frontal plane on the bend than straight. A moderate effect size suggests a trend towards an ↑ in left step peak negative hip power in the transverse plane during bend sprinting relative to straight-line sprinting. A large, but non-significant, ↓ in left step peak knee flexor moment of bend sprinting compared with the right. A large effect size, but non-significant, suggests a trend towards an ↑ peak left step ankle plantar-flexion moment on the bend compared with straight-line sprinting. Trend towards ↑ in left step peak ankle eversion moment on the bend compared with the right step on the bend. Large, but non-significant, ↑ in left step sagittal plane ankle energy absorption on the bend compared with straight-line sprinting. A large effect size suggests a greater left step peak ankle eversion moment on the bend than straight. Moderate ↑ in peak positive left step ankle power in the transverse plane during bend sprinting relative to straight-line sprinting. Moderate and large ↑ in left step peak midfoot eversion moment were observed during bend sprinting compared with straight-line sprinting and right step on the bend. ↑ in peak positive midfoot power in both the left and right step on the bend compared with straight-line sprinting. ↑ in peak negative midfoot power in the left step compared with straight-line sprinting. Non-significant interaction for peak MTP joint plantar-flexor moment. ↑ in plantar-flexor moment in the right MTP joint than left on the bend.

							Moderate and large effect sizes suggest a trend towards a greater plantar-flexor moment on the bend than straight in the right and left MTP joints, respectively. Large and moderate ↑ in peak negative joint power of the MTP for the left and right step, respectively, compared with straight-line sprinting. ↑ in MTP joint energy absorption on the bend compared with straight-line sprinting.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Maćkała et al., 2010	n = 6. 6 males (1 Senior, 2 Juniors, 3 School-boys; 100 m PB 11.18 ± 0.17 s; best result 10.78 s).	Complete 200 m.	To compare stride length between the outside and inside legs of different performance levels during 200 m bend sprinting.	200 m sprint. Standing 5 jumps, Sargent vertical jump, and standing long jump to determine leg strength.	Manual stride measurement method. Interval times recorded at each 50 m.	Performance (time and velocity) Stride length and stride frequency. Leg strength	No significant difference in race time between seniors and juniors, although schoolboys ↓. ↑ in stride length and number of strides for seniors, followed by juniors, and then schoolboys. ↑ in step length during the first three 50 m sections. Seniors longest stride length occurred during 100-150 m section, other two groups 50-100 m section. ↓ in step length between bend running (40-90 m) and straight running (140-190 m).
Maćkala et al., 2015	n = 8 8 males 200 m performance (23.80 s ± 2.16 s; best results 21.40 s). Split into advance-national and regional level (n = 4) and beginner sprinters (n = 4).	Complete 200 m and 50 m sprint.	To examine the relationship between 200 m and anthropometric characteristics and motor abilities in different levels of male sprinters.	Athletes performed maximal 200 m sprint and anthropometric measurements on day 1. All maximal sprint tests, flexibility, and 4 kg shot overhead throw, and lower extremity explosive power tests were completed on day 2. Athletes ran one 50m from both a standing and a flying start to determine maximal speed. 48 hours rest and 5-minute rest between maximal sprint trials	Timing system, marks placed for each 50 m interval. Custom-made manual stride measurement devices. Vertical jump measuring device.	Performance (time and velocity) Stride length and stride frequency. 4kg shot overhead throw, countermovement jump, single leg countermovement jump, and standing five jumps.	↓ in time for mature compared with beginner sprinters. ↑ in velocity, stride frequency, and stride length for mature compared with beginner sprinters. 200 m sprint significantly related to experience and body mass. 200 m sprint time significant related to 150 m time and the 50 m from standing and flying start. Smallest differences between the two groups were seen in time of 50 m from standing start and in time of 1-50 m during 200 m sprint. Advanced sprinters dropped less speed between 100-150 m. Advanced sprinters ↑ in velocity during the second 50 m section.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Mastalerz et al., 2012	n = 4. 4 males 400 m runners. (400 m PB 47.66 ± 0.60 s)	Complete 400 m.	To evaluate the effectiveness of estimating fatigue for individual muscles of lower extremities during the run with various intensities.	Athletes performed 400 m with four different intensities. The 1st covering the distance in 90 s, the 2nd in 70 s, the 3rd in 60 s, and the last was performed with a maximal speed until exhaustion. The last, athletes obtained maximum speed as soon as they could and then to maintain this speed during the whole distance. 30 minutes rest between-trials.	Electronic timing every 100 m. Surface EMG obtained from rectus femoris, and the long heads of biceps femoris of the right and left thighs sampled at 1000 Hz	Mean power frequency and mean power amplitude.	Significant differences between the slopes of the regression lines for the muscles of the left and right limbs were noticed. For both rectus femoris and biceps femoris, the slopes of the regression line rose, depending on the velocity of the race. Larger rise for the left limb. Extension of the time and intensity of running is associated with a negative slope of the regression lines indicating a steady increase in muscle fatigue (described by the slopes of the regression lines). Differences between the left and right limbs greater for the rectus femoris muscle. Positive slope was observed in the 1st running for all muscles, but only during the run with the lowest intensity. An increase in the slope of the regression line is linear – a slope increases with the intensity of the race. Greater muscle fatigue in the left limb. Strongest effect was observed for the biceps femoris muscle. During the run with the highest velocity a 30% difference between the left and the right biceps femoris (11% for rectus femoris) fatigue was observed in the first 25 seconds of the race, and it decreased to 3% (9% for rectus femoris) after the 25th second of the race.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Mero & Peltola, 1989	n = 3 3 males 2 100 m (PB 10 .89 s and 11.40 s). 1 400 m (PB 50.96 s).	Complete 400 m.	To investigate the running technique and as well as neural activation in fatigued and non-fatigued conditions during 100- and 400 m running.	2 athletes performed maximally 2 times 100 m and then supramaximal (using a towing system) 2 times 100 m. Fastest maximal and supramaximal run of each subject were selected for further analysis. 1 athlete ran maximally two times 400 m. Cameras recorded 50 m and 90 m for 100 m and 130 m and 380 m for 400 m. 35 minutes rest between 100 m conditions and 120 minutes between 400 m conditions.	2 cameras sampled at 100 Hz perpendicular at 50 m and 90 m for 100 m and 130 m and 380 m for 400 m. Film analyser. Surface EMG obtained from the medial gastrocnemius, biceps femoris, gluteus maximus, rectus femoris, and vastus lateralis.	Performance (velocity). Stride length, stride rate, contact time, flight time, and touchdown distance. Minimum and maximum muscle activity, muscular relaxation.	Highest velocity from 50 to 100 m. Decreased thereafter but from 250 to 300 m there was a slight increase in velocity. Step rate was greatest during 50 to 100 m and then decreased thereafter but step length increased to 150 m and then decreased towards the end of the run. Difference in step length but not step rate between non-fatigued and fatigued conditions. ↑ in step length in non-fatigued conditions was associated with a ↓ in contact time, ↓ in braking distance, ↓ in vertical oscillation of centre of gravity and ↓ in deceleration of running velocity during the braking phase. ↑ in contact time during the fatigued phase. In fatigued conditions velocity ↓ more in maximal sprinting. Step length contributed more to ↑ in velocity during supramaximal running compared with step frequency. Step length slightly ↑ in fatigued phase. The deceleration of running velocity in the braking phase increased slightly in the fatigued conditions. Maximal neural activation of the leg muscles during contact ↓ in the fatigued conditions of short sprint running. Maximal neural activation of the five leg muscles was approximately at the same level ruing both runs and increases were observed at the end of the runs (23.4%). Maximal neural activation of the leg muscles during contact increased with increasing fatigue in long sprint running. The muscular relaxation deteriorated with ↑ fatigue especially in bend running.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Ohnuma et al., 2018	n = 12. 12 males (track and field athletes including jumpers and sprinters).	Maximal velocity (45 m). Lane 1 (radius 37.9 m).	To determine the ideal running technique when sprinting on a bend by comparing the biomechanical characteristics between good and poor bend runners.	Athletes performed 8 trials running 60 m, 2 for each leg and path (straight and bend) during the same day. More than 10 minutes rest between-trials. Kinematic and ground reaction force data of the fastest trial for each leg and path were used for detailed analysis. Participants were separated into 'good' or 'poor' based on the running speed on the bend relative to straight-line sprinting path.	15-camera optoelectronic marker-based motion capture system sampled at 250 Hz. 2 force plates sampled at 1000 Hz.	Performance (speed). Step length, stance distance, step frequency, ground contact time, flight time, and flight distance Ground reaction forces. Joint angular kinematics of the lower extremity including joint angular velocities.	Percentage difference of the running speed in the poor bend sprinting group was lower than in the good bend sprinting group. ↓ in running speed on the bend than on straight-line sprinting in the poor bend sprinting group. Step frequency, stance time, and flight time did not differ between the groups or the conditions. ↓ in step length, and flight distance of the right leg on the bend than straight-line sprinting only in poor bend sprinters. No significant differences in spatio-temporal variables between the groups. No significant differences in lower limb movements during the flight phase between the conditions and groups during the flight phase. Hip joint angle at foot release for the right leg on the bend was smaller than the in poor bend sprinters. Minimum knee, ankle joint angles, and maximum knee joint extension angular velocity of the left leg on the bend were significantly smaller and faster than on straight-line sprinting in the poor bend sprinters. Smaller hip joint angle at foot contact for both legs on the curved path than on straight-line sprinting path in both groups. No significant differences in lower limb movements during the stance phase between the two groups. No significant differences in the vertical component between the groups or the conditions. ↓ in maximum posterior ground reaction force and the impulse on the bend than on straight-line sprinting path in poor bend sprinters. ↑ in maximum and minimum medial ground reaction force and impulse during bend sprinting for both good and poor bend sprinters. No significant differences in ground reaction force during the stance phase between the two groups.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Saraslanidis et al., 2011	n = 8. 8 males (physical education students with previous experience as track runners) 200 m time 24.6 ± 1.2 s.	Complete 400 m. Middle lanes.	To compare and evaluate pacing strategies during 400 m sprinting, with respect to (a) the stimulation of the lactate system, and (b) the alterations to running kinematics due to fatigue.	Athletes completed a maximal 200-m sprinting test to retrieve a reference running speed value before each athlete performed three 400 m running tests aiming at maximum performance. The tests consisted of (a) 400 m, with the first 200 m pace set at 98% of the effort for a 200-m maximal test, (b) 400-m sprint, with the first 200 m pace set at 95% of the effort for a 200-m maximal test, and (3) 400-m sprint, with the first 200 m pace set at 93% of the effort for a 200-m maximal test. After the 200-m mark, subjects were asked to cover the distance with maximum effort. Tests were spaced 4 days apart. Recordings included three consecutive support phases of the participants.	5 pairs of photocells. Electric chronometer. Two digital video cameras sampled at 100 Hz, placed at 125- and 380 m marks of each 400 m test.	Performance (time). Stride length, stride time, stride frequency, ground contact time, and flight time. Joint angular kinematics of the lower extremity. Body lean angles.	Fastest 400 m race was ran when the slowest 1st 200 m pacing strategy (93%) was used. Running speed peaked in the 100-200 m section of the race in all 3 pacing strategies and significantly ↓ in every pacing strategy, being the lowest in the last 100 m of the race. No significant difference between the running speed of the 200 m tests and the running speed of the first half of the 400 m. Last 100 m, running speed ↑ in the 93% strategy compared with 95% and 98% strategies. 95% ↑ than 98% strategy. ↓ in step frequency and step length at the 380 m mark, when compared with those at the 125 m mark. 98% pacing strategy, both step frequency and step length ↓ by approximately 13%. 93% strategy, step frequency dropped by 2.4% and step length by 9.2% at the 380 m mark. Stride time and contact time ↑ in the 2nd half of the 98% and 95% strategies. Flight time ↓ at the 380 m mark in the 93% strategy. Knee angle at take-off ↑ at the 380 m mark than 125 m mark in all pacing conditions. Knee angle at touchdown and maximum amortization ↓ in the 2nd half of 98% and 95% strategies. Ankle angle ↑ at take-off in 93% strategy. Only ankle joint kinematics that was significantly different. Minimum knee angle was greater at the 380 m mark than the 125 m mark in 98% and 95% conditions, but no difference between pacing tactics. Angular velocity of knee ↓ and angular velocity of the thigh ↑ at 380 m mark compared with the 125 m mark.

Table 4.1 - *continued*

Reference	Participants	Sprint Phase and Radius	Aim	Protocol	Equipment	Measures	Results
Yousif et al., 2019	n = 5. 5 males (non-athletes).	Complete 400 m.	To measure leg muscle fatigue using EMG during different 400 m strategies.	Athletes performed 3 strategies. The first strategy: the first 200 m running 85-93% of full speed and the last 200 m sprinting (full speed), second strategy: the first 300 m running 85-93% of sprinting and the last 100 m sprinting, and third strategy: running 85-93% of sprinting for 400 m. Each strategy was performed on a different day.	Surface EMG obtained from the rectus femoris, biceps femoris, gluteus maximus, gastrocnemius lateralis, gastrocnemius medialis sampled at 2000 Hz	Performance (time). Instantaneous mean frequency and instantaneous median frequency to detect muscle fatigue.	Rectus femoris and gastrocnemius medialis significantly increased during the 1st 100 m as the distance ran at 85-93% velocity increased using instantaneous median frequency. Gastrocnemius lateralis, biceps femoris, and rectus femoris did not significantly change between the running strategies for the 1st 100 m of running using instantaneous mean frequency. Biceps femoris significantly increased during the 2nd 100 m as the distance ran at 85-93% velocity increased using instantaneous median and mean frequency. No significant differences for all strategies at the 3rd and 4th 100 m of running using instantaneous median and mean frequency. For the 4th 100 m, the rectus femoris, biceps femoris, gluteus maximus, and gastrocnemius lateralis had less fatigue as the distance ran at 85-93% velocity increased. The gastrocnemius medialis fatigued less during the 4th 100 m. During the 1st, 2nd, and 3rd 100 m, most of the selected muscles fatigued less using the 1st strategy. Lowest fatigue and highest recovery times were during the 1st strategy for most selected muscles.

4.4 Discussion

The purpose of this scoping review was to critically appraise and comprehensively synthesise the existing literature related to bend sprinting and identify gaps in the literature. Recommendations for future research will include: 1, how athletes and coaches can better understand how to optimise bend sprinting performance and 2, how recent improvements in technology can enhance the knowledge of bend sprinting research.

The number of studies conducted using female sprinters is limited despite the number of bend sprinting studies available. Four studies included both female and male participants, and only one study used only female participants. Females are characterised by slower 100 m race times than males (Tatem et al., 2004). Anthropometric parameters, particularly a decrease in height, shorten step lengths, reduce velocity, and increase race times in female sprinters compared with male sprinters (Brechue, 2011). However, Ciacci et al. (2017) concluded that ability explains more differences in start kinematics than sex. Additionally, anatomical differences in females including greater hip width to femoral length ratio (Horton & Hall, 1989), may cause changes in the frontal plane (such as greater hip adduction angles (Ferber et al., 2003) during bend sprinting, which are not necessarily important during straight-line sprinting. Future research should include female sprinters to determine whether there are differences between female and male bend sprinters of the same performance level.

Nine studies included non-specialist bend sprinters who are subjected to the learning process, and effects measured could be attributed to the novelty of the task. Otsuka et al. (2014) found that non-trained sprinters generated significantly less mean net resultant and antero-posterior ground reaction forces during the starting block phase. Trained bend sprinters are likely to have developed a more effective technique to handle the adaptations required for bend sprinting. Therefore, future research should only include specialist bend sprinters if the aim is to determine the effect of the bend and improve performance.

Only two studies included World-class sprinters (e.g., international finalists). The biomechanical factors that distinguish performance at the very highest level of competition are unknown. This would provide an insight into the mechanics of the fastest bend sprinters on the planet. Analysing World-class bend sprinters would assist in developing an understanding of the key factors that can aid coaches and scientists in designing technical training programs to develop and facilitate optimal performance in all bend sprinters.

Increased left touchdown distance on the bend compared with straight-line sprinting has been suggested to be one of the biggest problems affecting forward velocity of athletes (Churchill et al., 2015). Increased touchdown distance increases ground contact time in straight-line sprinting (Hunter et al., 2004), and two studies have found the same in bend sprinting (Churchill et al., 2015; Judson et al., 2020a). Previous straight-line sprinting research has found a smaller touchdown distance to be related to superior sprint performance (Mann & Herman, 1985). Therefore, coaching strategies should focus on athletes maintaining an active touchdown (i.e., reducing the forward horizontal velocity of the foot relative to the ground, immediately before ground contact) to reduce touchdown distance.

During bend sprinting, athletes lean inwards to follow the bend. Increased velocity on the bend increases the angle of inward lean for two reasons: first, the angle of lean is dependent on the magnitude of the centripetal force, which itself is dependent on the radius of the bend, the square of the velocity that the athlete is travelling and the mass of the athlete. Thus, for the same mass, greater centripetal force is required for higher velocities, which requires greater inward lean. Second, inward lean places the contact foot more towards the outside of the bend than the athlete's centre of mass. This foot placement is probably advantageous for centripetal force generation, which may allow athletes to travel at a greater velocity whilst still following the bend and remaining within their lane. Therefore, greater inward lean of faster runners may be both the result of and beneficial for superior performance.

Most studies have explored the effect of the bend on performance descriptors, lower body kinematics, and ground reaction forces. A better understanding of the relationship between variables and performance on the bend would identify which variables are key to improving performance. Ishimura et al. (2016) created a deterministic model of bend sprinting average speed to investigate the asymmetries between the left and the right leg and how bend sprinting speed is affected. Understanding the determinants of bend sprinting, both for faster bend sprinters (velocity) and for better bend sprinters (% change in velocity), would help improve the performance of all bend sprinters and help identify potential weaknesses and variables that do and do not change during each race phase of bend sprinting. Training and strength and conditioning coaches could then focus on the mechanics which influence the found variables. However, only one study has separated participants dependent on ability. Ohnuma et al. (2018) found sprinters with similar running velocities on the bend compared with straight-line sprinting did not need to adapt their spatio-temporal variables. Key variables were not assessed, including asymmetries between the left and the right legs on the bend and inward lean, which has implications on joint angular kinematics of the lower extremity. Athletes also included non-bend sprinting specialists such as long jumpers. Mann & Herman (1985) suggested higher step frequency was the major difference between three Olympic 200 m finalists. Churchill et al. (2019) found variability in performance increased between participants as bend radius tightened, suggesting athletes possess differing abilities to negotiate tight radii. Adaptations that occur because of the bend are more apparent as bend radii decreases (Churchill et al., 2019). Therefore, future research should focus on understanding which spatio-temporal variables, including asymmetries and inward lean, separate levels of bend sprinters using bend sprinting specialists and in lane one.

Joint kinetics have only been explored during the acceleration phase in bend sprinting (Judson et al., 2020) and sub-maximal velocity (Alt et al., 2015). The magnitude of changes in joint angular kinematics of the lower extremity and ground reaction force was greater during the maximal effort phase (Churchill et al., 2015, 2016) compared with the acceleration phase (Judson et al., 2019; Judson et al., 2020a). Therefore, it is likely that similar will be found for joint kinetics. This would help determine what limits vertical and resultant ground reaction force production on the bend because differences were only found in the maximal effort phase, not the acceleration phase. Joint kinetics would provide an indication of the magnitude of muscular force generation and further insight into joint function during bend sprinting to help develop strength and conditioning programmes.

Previous bend sprinting literature have suggested coaching points and areas to focus on, but none of the reviewed research assessed whether they are successful. Ishimura et al. (2016) suggested jump training may improve bend sprinting performance as they found a high correlation between step length and leg strength. Cavanga et al. (1976) and Farley & Gonzalez (1996) found that vertical and leg stiffness increase at high step frequencies. Therefore, plyometric training might improve bend sprinting performance by producing a stiffer leg. Judson et al. (2020a) suggested the high peak hip adduction might be a precursor for injury. Therefore, strength and conditioning programmes should aim to ensure the hip joint can withstand high loads and prevent long-term implications. Judson et al. (2019) suggested that athletes appear to be restricted by their ability to produce force in the non-sagittal planes due to a complex interaction of adaptations at the ankle and foot joints. Practitioners should focus on strengthening muscles in a combination of all three planes, which may address the reductions (Judson et al., 2019; Judson et al., 2020a). The left and right limbs have different functions on the bend, and limb specific training should be considered when developing training programmes. Churchill et al. (2016) suggested that using ropes or harnesses in training to provide resistance in a leaning position might benefit performance. Additionally, undertaking representative strength and technique training performed at high velocity on the bend to further promote specificity is essential to meet the requirements of bend sprinting (Judson et al., 2020a). Consequently, an intervention study to evaluate the effectiveness of strength training targeting the performance descriptors, lower body kinematics, and ground reaction forces would provide insights in improving bend sprinting performance and reduce injury potential.

Apart from one study, all studies that assessed ground reaction forces used discrete variables. Information might be lost with the analysis of discrete values that are restricted to peak or average characteristics of the underlying force signals. Only Judson et al. (2019) has used alternative statistical methods during bend sprinting, such as statistical parametric mapping to look at thresholds during the stance phase and demonstrated differences between stages of the stance phase during the acceleration phase. Using functional data analysis could identify specific features of force production during the contact phase that may not be apparent in the analysis of average or peak forces as previously demonstrated during the block phase in straight-line sprinting (Bezodis et al., 2019; Colyer et al., 2019). Functional data analysis considers the entire function of the waveforms and identifies characteristics of the curves of different performers. Using alternative techniques such as functional data analysis or statistical parametric mapping enables the variability in continuous function to be described and used as inputs to assess associations with dependent measures (Warmenhoven et al., 2017). Statistical analysis such as statistical parametric mapping would provide new insights into the analysis of bend sprinting that might be lost when using discrete variables.

Previous research has focused on assessing kinetics, kinematics, and joint kinetics during specific race phases to determine the effect of the bend. Variables have been shown to increase from the acceleration phase (Judson et al., 2019; Judson et al., 2020a) to the maximal effort phase (Churchill et al., 2015, 2016). Therefore, research should focus on the changes across the whole race. However, challenges related to capturing data may have previously prevented it. Assessing ground reaction forces during bend sprinting has been restricted to one step per trial (Churchill et al., 2016; Judson et al., 2019; Ohnuma et al., 2018). Increasing the number of steps would require more force plates or an increase in the number of trials focused on different distances each trial, similar to Morin et al. (2015), but these may not be available or desirable options. Capturing kinematic data of multiple race phases is also restricted because of the number of cameras required to capture a large field of view. Analysing multiple race phases would provide information on the step-to-step changes that occur through the bend proportion of the sprint and identify where focus should be made to improve performance. Six studies used video cameras, and three studies used high-speed cameras. The amount of data that can be processed and the quality of subsequent analysis is limited to the time-consuming process and liability to subject error when using video cameras (Hay, 1993). Seven studies have used optoelectronic cameras, which remains the choice for quantifying human movement within laboratories. However, the limited research may be related to the challenges in quantifying 3D lower body kinematics of an athlete's performance in realistic conditions. The field of view required to capture multiple sprint phases is beyond the capability of marker-based systems that are often limited to laboratory environments. Additionally, wearing markers may also alter natural movement patterns (Hay, 1993). The placement of markers is subject to inter-session and inter-tester variability (Tsushima et al., 2003), and the data capture technique is both time and resource intensive. Although the published literature regarding bend sprinting is insightful, there are also key methodological and research design limitations that must be acknowledged to improve the understanding of the effect of the bend.

New technology is constantly being developed that could identify and understand new important features of bend sprinting performance and remove current restrictions on capturing biomechanics data. Markerless motion capture

(Choppin & Wheat, 2013; Mündermann et al., 2006) and inertial measurement units (IMUs: combined magnetic and gyroscope sensors) are increasing in popularity in sports research. The use of markerless motion capture shows greater potential to facilitate large scale movement studies in real-world, ecologically valid environments where previous methods of data capture have not been feasible (Kanko et al., 2021) or impede quantitative human movement research. Additionally, assessing motor performance of athletes, including technique, velocity, or strength, either outdoors or in a large venue where athletes train using IMUs to estimate temporal, ground reaction forces or kinematic parameters (Camomilla et al., 2018; Lebel et al., 2013; Teufl et al., 2019; Wouda et al., 2018) could be explored. However, the error in the data must be critically considered as there are currently greater systematic and random differences in running than walking and jumping (Needham et al., 2021). The development of more accurate algorithms and validation for IMUs during bend sprinting is also required. Markerless motion capture and IMUs could alleviate some of the technical and practical concerns of biomechanics data collection, but further development is needed before their performance even matches marker-based motion capture and force plates, respectively.

4.5 Limitations

A selection of terms was used for the scoping review (chapter four) related to bend sprinting since bend sprinting is too broad as a term and would therefore have led to too many results. By using a selection of terms instead of bend sprinting, there is a possibility that some articles were missed. However, the area was covered which interested in by a wide selection of terms and further searched the reference list of reviews that were found as well to make sure no articles were missed.

4.6 Conclusion

This review shows that several bend sprinting studies have been performed in recent years, highlighting changes in performance, spatio-temporal, kinematics, kinetics, and joint kinetics between the bend and straight-line sprinting. There is a gap assessing performance levels on the bend and determining what variables are closely related to performance in sprinters who have greater velocities on the bend and those who can better maintain their velocity on the bend compared with straight-line sprinting. Research analysing multiple race phases during the same data collection session has been restricted due to technology. However, recent advancements in technology would soon allow greater assessments to determine what kinetic and kinematics changes occur through the race. Lastly, statistical analyses such as statistical parametric mapping would provide additional information into the characteristics of the waveform that differentiate performers, which may be lost with the analysis of discrete variables.

Chapter Five: OVERALL DISCUSSION

5 Overall discussion

5.1 Introduction

The aim of this programme of research was to identify technique and performance differences between bend and straight-line sprinting. A series of objectives were devised in chapter one to meet this aim and directed the focus of the investigations outlined in chapters three and four. Consequently, these aims were addressed, and the main findings of this thesis are discussed in this chapter. Furthermore, a discussion of the appropriateness of the methodological approach to meeting this aim is provided, the practical implications of the research are highlighted, and potential future investigations suggested.

5.2 Addressing the aim

Push time, anterior forces, and RF did not change during the block phase, and contribute to no differences in performance being found on the bend compared with straight-line sprinting (chapter three). Previous research (Otsuka et al., 2014; Rabita et al., 2015; Willwacher et al., 2016) demonstrated increased mean force application to the blocks in the anterior direction is associated with increased levels of performance which explains why no differences in both anterior force and performance were found in chapter three. Therefore, the bend does not influence performance during the block start, and performance improvements in block starts generally are likely to positively affect block starts on the bend. When athletes start on the bend, it should not be detrimental to their straight-line performance.

The bend does not appear to significantly affect technique during the block start compared with straight-line sprinting with no changes in medio-lateral forces on the bend compared with straight-line sprinting. This demonstrates that athletes do not generate inward force and start turning during the block phase to ‘run the bend’ and instead, try and run in a straight line to increase anterior velocity.

The only changes found in chapter three were a significant decrease in mean and peak vertical and resultant force for the front block on the bend compared with straight-line sprinting. These changes might affect subsequent steps out of the blocks. Bend training is important for athletes to be able to cope with the demands in transition between different race phases such as the block start to the acceleration phase where the bend does have an effect (Judson et al., 2019; Judson et al., 2020; Judson et al., 2020a).

Chapter four comprehensively synthesised the biomechanical differences during the bend compared with straight-line sprinting found in the existing bend sprinting literature. Previous studies have demonstrated kinetic, spatio-temporal, kinematic, and performance differences to meet the demands of the bend compared with straight-line sprinting and how these change during the acceleration (e.g., Chang & Kram, 2007; Judson et al., 2019; Judson, et al., 2020; Judson et al., 2020a), and the maximal effort phase (e.g., Churchill et al., 2015, 2016; Ishimura & Sakurai, 2016). However, changes in joint kinetics between the bend and straight-line sprinting have only been found during the acceleration (Judson et al., 2020) and sub-maximal velocity phases (Viellehner et al., 2016).

Increases and decreases have been found for vertical and resultant forces in the right and left step, respectively, on the bend compared with straight-line sprinting (Churchill et al., 2016). However, during the acceleration phase, the resultant or vertical force does not change (Judson et al., 2019) and have been found to not contribute to sprint performance during the acceleration phase in straight-line sprinting (Morin et al., 2011). Research showed that the right leg is associated with producing movement in the anterior direction whereas the left leg is concerned with achieving a change in direction (e.g., Alt et al., 2015; Churchill et al., 2015, 2016; Judson et al., 2019; Judson et al., 2020; Judson et al., 2020a).

5.3 Discussion of the methodological approach

There were various limitations which could have influenced the results of this programme of research that are worthy of discussion.

Lane one was used for evaluation in chapter three because it has the tightest bend radius (36.5 m). Therefore, any changes that occur because of bend radius were expected to be more apparent in lane one. Churchill et al. (2019) demonstrated decreases in kinematic modifications across lanes and therefore possible that changes shown in chapter three would become even less prominent as the radius of the lane increase.

Force instrumented starting blocks were used in chapter three to directly collect three-dimensional external force data during the block start from the front and rear blocks. The starting blocks allowed externally valid performance data to be collected that was not restricted to laboratories or the limited number of track surfaces with embedded force plates.

A group design was undertaken in chapter three. This is the first study to research the effect of the bend during block starts and wanted to understand which temporal and kinetic variables were related to performance. Group designs can mask individual differences in data (Dixon & Kerwin, 2002). However, a group design was thought the best approach to determine if the bend affected technique and performance during the block start.

A scoping review was performed in chapter four. Previous research has investigated the biomechanics of bend sprinting and a scoping review can help identify gaps in knowledge and evaluate the current literature and thus guide future research towards currently unexplored areas. It was felt a broader search was needed to cover the whole of bend sprinting research rather than asking a specific question using a systematic review. A meta-analysis was also deemed inappropriate as sufficient research has not been conducted into each race phase of bend sprinting where the results of quantitative studies could be statistically combined.

A selection of terms were used for the scoping review (chapter four) related to bend sprinting (as stated in the methods in chapter four) since bend sprinting is too broad as a term and would therefore have led to too many results. The area was covered by using a wide selection of terms and reference lists of found articles further searched to try and ensure that no articles were missed. However, this cannot be guaranteed.

5.4 Practical applications

There are practical implications from the findings of this thesis, which may help to inform coaching practice. Athletes can focus on block starts either during straight-line or bend sprinting, and the skills would transfer when completing block starts during the other condition. However, sprinters would still need to perform block starts on the bend as the reduction in vertical force may impact subsequent steps. Therefore, to effectively transition bend sprint phases, training on the bend is important and when athletes to start on the bend, it should not be detrimental to technique and performance of block starts during straight-line sprinting. The scoping review in chapter four revealed that the bend does impact technique and performance during race phases after block exit compared with straight-line sprinting.

5.5 Future research

It has been demonstrated that the demands of sprinting on the bend do not occur during the block start. Therefore, it might be worthwhile focusing on other race phases that occur post block exit.

There is little difference in block start technique and performance between the bend and straight-line sprinting. Athletes tend to try and maintain a straight path post block exit for as long as possible but the best strategy for exiting the blocks is not known, whether to increase anterior velocity as much as possible or take the shortest path and whether the same strategy applies to all lanes.

Investigating joint kinetics during the maximal effort phase would help determine what limits vertical and resultant force production on the bend because differences in vertical and resultant force were only found in the maximal effort phase (Churchill et al., 2016) and not the acceleration phase (Judson et al., 2019). Joint kinetics would provide an indication of the magnitude of muscular force generation and a further insight into joint function during bend sprinting to help develop strength and conditioning programmes.

Future research should focus on understanding which spatio-temporal, kinetics, kinematics, and joint kinetic variables separate both bend sprinters who are faster on the bend and better bend sprinters who have a closer match between velocities on the bend and straight-line sprinting. Additionally, asymmetries between left and right legs should be researched to determine differences between levels of sprinters. Furthermore, identifying performance factors that most closely relate to achieving a similar velocity on the bend compared to straight-line sprinting would give a greater insight into aspects of technique that help a sprinter to improve their bend sprinting performance by identifying areas of improvement.

In addition, various studies have suggested coaching points and areas to focus on (Churchill et al., 2016; Ishimura & Sakurai, 2016; Judson et al., 2019; Judson et al., 2020a). An intervention study aimed at evaluating the effectiveness of strength training targeting the performance descriptors, lower body kinematics, and ground reaction forces would provide insights in improving bend sprinting performance.

If collecting ground reaction forces using force plates, using advanced research methods such as statistical parametric mapping to look at thresholds and analysis sprint performance across the whole ground contact phase. This would provide additional information and new insights that may be lost with the analysis of discrete values such as where during ground contact the contribution of horizontal force production is most crucial (Colyer et al., 2018, 2019) and greater mediolateral force during the stance phase (Judson et al., 2019).

The bend of a track does not have force plates embedded within and therefore, multiple trials are needed to collect more than one foot contact of data (Morin et al., 2015). A possible option to alleviate this problem would be the use of multiple IMUs to predict ground reaction forces. Markerless motion capture has the potential to alleviate some of the technical and practical concerns of marker-based motion analysis. Still, such technology requires further development of algorithms before its performance even matches marker-based motion capture.

Therefore, research should focus on developing more accurate algorithms and validation during bend sprinting.

5.6 Conclusion

This thesis provided information on technique and performance differences between bend and straight-line sprinting. Novel instrumented starting blocks were used to quantify the forces applied to the starting blocks in both legs. Performance during the block phase of the sprint start does not change between the bend and straight-line sprinting. Only a decrease in mean and peak vertical and resultant force for the front block was found on the bend compared with straight-line sprinting. Although these changes did not impact performance, a decrease in vertical force may impact the first few steps after block exit by reducing step length, and consequently velocity. Therefore, changes in performance during bend sprinting compared with straight-line sprinting occur after the sprinter has left the blocks as they try to run straight for as long as possible to increase anterior velocity.

In the acceleration and maximal effort phases, how typical straight-line mechanics and lower limb adaptations have adapted to meet the demands of bend sprinting have previously been found. Additionally, the existing evidence related to bend sprinting during athletic sprint events has been evaluated and the most important areas for future research identified. Asymmetries between left and right steps during bend sprinting are prevalent throughout the acceleration and maximal effort phases. However, there are gaps in knowledge related to which variables are key to improving performance and how they can be transferred into coaching or training practice to improve performance. An intervention study could evaluate the effectiveness of strength training targeting the performance descriptors, lower body kinematics, and ground reaction forces which would provide insights in improving bend sprinting performance. Finally, the use of new technologies could be used to alleviate previous issues when capturing data.

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Appendix A. Example consent form

Participant Informed Consent Form

STUDY: **The effect of the bend on the global kinetic and spatio-temporal variables during the block phase of the sprint start on the bend and the straight**

Please answer the following questions by ticking the response that applies

		YES	NO
1.	I have read the Information Sheet for this study and have had details of the study explained to me.	☐	☐
2.	My questions about the study have been answered to my satisfaction and I understand that I may ask further questions at any point.	☐	☐
3.	I understand that I am free to withdraw from the study at any time, without giving a reason for my withdrawal or to decline to answer any particular questions in the study without any consequences to my future treatment by the researcher.	☐	☐
4.	I agree to provide information to the researcher under the conditions of confidentiality set out in the Information Sheet.	☐	☐
5.	I wish to participate in the study under the conditions set out in the Information Sheet.	☐	☐
6.	I consent to the information collected for the purposes of this research study, once anonymised (so that I cannot be identified), to be used for any other research purposes.	☐	☐

Participant's Signature: ______________________________ **Date:** __________

Participant's Name (Printed): ______________________________

Contact details: ______________________________

____

Researcher's Name (Printed): ______________________________

Researcher's Signature: ______________________________

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Please keep your copy of the consent form and the information sheet together.