The Biomechanics of Rugby Place Kicking

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Abstract

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Approximately 45% of the points scored in international Rugby Union matches are the result of place kicks (Quarrie & Hopkins, 2015). However, the key technique characteristics underpinning this skill are not well understood. The aim of this thesis was therefore to investigate rugby place kicking technique and performance, and understand how these differ between successful and less successful place kickers.

In order to objectively quantify place kick performance outcome from data collected in a laboratory environment, a novel performance measure representative of the maximum distance that any given place kick could be successful from was developed. This measure combined initial ball flight data with previously published aerodynamic forces and was shown to predict ball location with a mean error of 4.0%. Full body motion capture and ground reaction force data were then collected from 33 experienced (amateur to senior international level) kickers and three groups of kickers were identified based on their performance outcome: long, short, and wide-left kickers. Differences were observed in the initial ball flight characteristics between the three groups and specific aspects of technique were then analysed to understand how these different performance outcomes were achieved.

The long and wide-left kickers used different strategies to achieve comparable forward kicking foot velocities and initial ball velocities. The wide-left kickers used a hip flexor strategy: greater positive hip flexor work which was facilitated by a stretch across the trunk at the top of the backswing, followed by longitudinal rotation throughout the downswing. In contrast, the long kickers used a knee extensor strategy: greater positive knee extensor work and a more consistent trunk orientation throughout the downswing. Although both strategies led to comparably high initial ball velocity magnitudes, the hip flexor strategy led to greater longitudinal ball spin and an initial ball velocity vector directed towards the left-hand-side. Kickers who achieve fast ball velocities but miss left could potentially benefit from technical interventions to address their trunk kinematics or development of their kicking knee extensor involvement.

The long kickers achieved faster kicking foot and initial ball velocities than the short kickers. The long kickers took a more angled and faster approach to the ball compared with the short kickers. This enabled the pelvis to be less front-on at the top of the backswing, meaning that the kicking foot was further away from the ball at this point and subsequently travelled a longer path to initial ball contact. The long kickers also demonstrated greater horizontal whole-body CM deceleration between support foot contact and initial ball contact and performed greater hip flexor and knee extensor positive work than the short kickers during the downswing. Kickers who cannot generate fast ball velocities could potentially benefit from interventions to their approach direction and velocity, or from development of their kicking hip flexor and knee extensor involvement. This thesis has provided a comprehensive understanding of rugby place kicking technique and recommendations for both coaching practice and research.

Peer-reviewed conference papers

Atack, A., Trewartha, G., & Bezodis, N. E. (2015). Development and evaluation of a method to quantify rugby place kick performance from initial ball flight data. *International Society of Biomechanics in Sports Conference Proceedings, 33,* 768-771. Retrieved from https://ojs.ub.uni-konstanz.de/cpa/article/view/6513/5878.

Atack, A., Trewartha, G., & Bezodis, N. E. (2014). A biomechanical analysis of the kicking leg during a rugby place kick. *International Society of Biomechanics in Sports Conference Proceedings, 32,* 296-299. Retrieved from https://ojs.ub.uni-konstanz.de/cpa/article/view/5992/5473.

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Table of contents

Word count: 79052

List of figures

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 8

Appendix D

List of tables

Chapter 2: Literature review

Chapter 3: Development and evaluation of a measure of overall rugby place kick performance from initial ball flight data

Chapter 4: General methods

Chapter 5: Understanding place kick performance through an investigation of initial ball flight characteristics

Chapter 6: The approach to the ball and motion of the kicking foot: comparisons between successful and less successful rugby place kickers

Chapter 1: Introduction

1.1. Context

Rugby Union (hereafter 'rugby') is a global sport; there are 131 member national unions of its governing body across six continents (World Rugby, 2016) and it was estimated that the 2015 Rugby World Cup was broadcast to over 4 billion viewers and 780 million homes worldwide (Arnold & Grice, 2016). In terms of participation, in England alone, more than 2000 clubs and over 2.5 million rugby players are registered (Rugby Football Union Annual Report, 2015). The primary goal for a rugby team is to score more points than the opposition through grounding the ball past the opponent's goal line (i.e. a try) or kicking the ball between the posts (i.e. a place kick or a drop goal). Place kicks are an option whenever a penalty is awarded (three points) or as a conversion (two points) following the scoring of a try (five points). In an analysis of 582 international rugby matches between 2002 and 2011, 45% of the total points scored were found to come from place kicks (Quarrie & Hopkins, 2015). Furthermore, if the success percentage of the two competing teams' place kicks had been reversed in each match over this time, 14% of the match outcomes would have changed (Quarrie & Hopkins, 2015). Although other factors must be considered, place kick performance is clearly an important factor in the outcome of a match, and an understanding of place kicking technique is important for improving performance levels and team success.

1.2. Overview of existing research

Despite the value of accurate place kicking in rugby, relatively few researchers have investigated the technical requirements of this skill. Aitchison and Lees (1983) were the first to investigate rugby place kicking technique, performing a two-dimensional (2D) kinematic analysis of the kicking leg. Since this initial study, five further studies have been published investigating rugby place kicking technique through three-dimensional (3D) analyses (Baktash, Hy, Muir, Walton & Zhang, 2009; Bezodis, Trewartha, Wilson & Irwin, 2007; Cockcroft & van den Heever, 2016; Sinclair et al., 2014; Zhang, Liu &

Xie, 2012). Baktash et al. (2009) investigated the influence of support foot position on ball velocity, Bezodis et al. (2007) analysed the role of the non-kicking-side arm on ball velocity and accuracy, Cockcroft and van den Heever (2016) assessed the variability in the final step towards the ball and support foot position during the approach phase, whilst Sinclair et al. (2014) and Zhang et al. (2012) investigated the relationships between selected kicking leg kinematics and the velocity of the ball or kicking foot, respectively. Although these studies have provided some understanding of the influence of specific variables on selected aspects of place kick performance, the complete kicking action remains poorly understood, particularly in terms of how successful overall performance is achieved. Investigating the technique differences between kickers who achieve varying levels of outcome success would extend the understanding of the factors that may be important for improving place kick performance.

The above studies primarily considered the effects of technique variables on ball velocity magnitude. However, maximising ball velocity magnitude is not the sole requirement of rugby place kicking as the ball must pass between two vertical goalposts (5.6 m apart) and above a horizontal crossbar (3.0 m above the ground). Unsuccessful place kicks either drop below the height of the crossbar or pass outside one of the goalposts; it is therefore important to consider the direction of the 3D ball velocity vector in addition to its magnitude when determining place kick performance. If the full flight path of the ball cannot be tracked (as has been the case in previous studies), a measure that represents overall place kick performance must be determined from the initial ball flight data that are recorded. Two studies (Ball, 2010; Holmes, Jones, Harland & Petzing, 2006) have described selected initial ball flight characteristics of rugby place kicks, and a third (Linthorne & Stokes, 2014) has simulated the optimum ball launch angle for obtaining maximum distance. However, as a place kick can be unsuccessful for different reasons and the outcome is affected by a combination of ball flight characteristics, investigating how the magnitude and direction of the velocity vector and ball spin differ between place kicks with different outcomes will provide an important understanding of performance before the kickers' techniques are investigated in detail.

Despite the importance of place kicks in determining the outcome of a rugby match, there is currently a limited understanding of how successful performance is achieved. If the key technical factors associated with successful place kick performance can be identified and explained, this knowledge will provide information which can impact the training practices of kickers and coaches. The overall aim of this thesis was therefore *to investigate rugby place kicking technique and performance, and understand how these differ between successful and less successful place kickers.*

1.3. Research questions

In order to address the thesis aim, a series of research questions was developed. To investigate rugby place kicking technique in sufficient detail, including consideration of the external kinetic contributions, a laboratory-based data collection is necessary. This means that the accurate quantification of overall place kick performance is a key first consideration. Previous laboratory-based studies have typically quantified place kick performance as the magnitude of ball velocity immediately post-contact, but this does not provide a true representation of overall performance due to the inherent accuracy demands of the skill. A novel performance measure must therefore be developed which quantifies place kick performance by considering the magnitude and direction of the initial ball velocity vector and the aerodynamic effects on the ball during its flight. Therefore, the first research question to be addressed is:

i. **How accurately can overall place kick performance outcome be estimated from initial ball flight data?**

Whilst some of the initial ball flight characteristics which determine the outcome of a place kick have previously been reported as mean values from entire groups (Ball, 2010; Holmes et al., 2006) or theoretically investigated for a single sub-elite individual (Linthorne & Stokes, 2014), differences in ball flight characteristics between kicks with different performance outcomes have not been investigated. Such an analysis would yield important insight in to place kick performance which would provide greater context for the subsequent investigations of the techniques which cause these differences in performance. Therefore, the second research question to be addressed is:

ii. **How do the initial ball flight characteristics differ between place kicks with different performance outcomes?**

Once these differences in post-contact ball flight characteristics have been understood, the techniques of kickers who achieve different performance outcomes can be investigated. Previous research investigating kicking technique in other football codes has identified a number of variables relating to the approach of the kicker towards the ball which can influence performance. These include the kickers' whole-body centre of mass (CM) velocity as they approach the ball (Andersen & Dörge, 2011; Isokawa & Lees, 1988; Kellis, Katis & Gassis, 2004; Scurr & Hall, 2009), the peak magnitudes of the 3D ground reaction forces recorded between support foot contact and initial ball contact (e.g. Ball, 2013; Kellis et al., 2004; Orloff et al., 2008), the deceleration of the kickers' horizontal whole-body CM velocity between support foot contact and initial ball contact (Potthast, Heinrich, Schneider & Brüggemann, 2010) and the length of the final step towards the ball (Ball, 2008; Lees & Nolan, 2002). However, these studies determined successful performance simply as a fast ball velocity post-contact without imposing an accuracy constraint. As accuracy is an inherent requirement of rugby place kicking, and additional accuracy demands have previously been shown to alter a soccer kicker's approach (Lees & Nolan, 2002; Teixeira, 1999), the above effects in other football codes may not transfer to rugby place kicking. Therefore, the third research question to be addressed is:

iii. **How does whole-body motion prior to initial ball contact differ between successful and less successful kickers?**

This whole-body motion during the approach is ultimately intended to facilitate the desired kinematics of the kicking foot, the distal end of a complex linked-segment system, when it contacts the ball. A relationship between the kicking foot velocity magnitude at initial ball contact and ball velocity magnitude post-contact has been well established in other football codes (e.g. Levanon & Dapena, 1998; De Witt & Hinrichs, 2012) and thus Zhang and colleagues (2012) investigated how the motion of certain body segments contributed to the velocity of the kicking foot at initial ball contact in rugby place kicking but without an accuracy requirement. Kicking foot velocity has also been shown to be affected when an accuracy constraint was imposed in soccer (Lees & Nolan, 2002; Teixeira, 1999). Furthermore, whilst there may be a strong relationship between the magnitude of the kicking foot velocity vector and ball velocity, the direction of this kicking foot velocity vector has not previously been investigated. It is important to understand how the motion of the kicking foot differs between successful and less successful rugby place kickers, and therefore the fourth research question to be addressed is:

iv. How does kicking foot motion from the top of the backswing to initial ball contact differ between successful and less successful kickers?

As the motion of the kicking foot is determined by the rotations of a number of linked segments throughout the kicking phase, the motion of the joints within the kicking leg have typically been the focus of investigations of kicking technique. An analysis of the predictors of ball velocity magnitude in amateur rugby place kickers identified that peak knee extension velocity explained 48% of the variation in ball velocity magnitude (Sinclair et al., 2014). Furthermore, studies of kicking within other football codes have also identified greater kicking hip flexion velocity when faster ball velocities are achieved (e.g. Ball, 2011; Kawamoto, Miyagi, Ohashi & Fukashiro, 2007; Shan & Westerhoff, 2005). As well as considering the kinematic descriptors of joint motion, it is important to investigate the underlying joint kinetics which explain how these observed motions are achieved. No studies have comprehensively investigated the kicking leg joint kinetics in rugby place kicking, although aspects of them have been described in other football codes (e.g. Lees, Steward, Rahnama & Barton, 2009; Nunome, Asai, Ikegami & Sakurai, 2002). How the kicking leg mechanics of kickers who achieve successful place kick performances differs from those who are less successful remains unclear, and an understanding of these differences could direct the focus of coaches and players when seeking to improve performance. Therefore, the fifth research question to be addressed is:

v. **What are the kicking leg joint mechanics during the downswing and how do these differ between successful and less successful kickers?**

Whilst the motion of the kicking leg joints have been the primary focus of previous research into kicking skills, the orientation of both the pelvis and the trunk have also been investigated in soccer instep kicking (Lees & Nolan, 2002; Scurr & Hall, 2009; Shan & Westerhoff, 2005). The pelvis and trunk are more proximal within the linked-segment system, and their rotations therefore affect the motion of the more distal segments and ultimately the kicking foot. Previous research in soccer instep kicking has identified that greater longitudinal rotation of both the pelvis and trunk segments as the kicking leg is retracted is associated with faster kicking foot and ball velocities (Lees & Nolan, 2002; Shan & Westerhoff, 2005). Whilst the movement of the torso was not a primary focus of their investigation, Bezodis et al. (2007) reported that accurate kickers typically possessed minimal trunk longitudinal angular momentum at initial ball contact. An investigation of the motion of the torso would indicate whether relative trunk-pelvis motion is important in generating faster kicking foot velocities and if the torso plays a role in maintaining an accurate kick. Therefore, the final question to be addressed is:

vi. **How does the motion of the torso during the downswing differ between successful and less successful kickers?**

These six research questions provide a focus for the thesis around which experimental investigations and analyses can be systematically conducted. The results of these investigations will allow the research questions to be addressed and the thesis aim to be met. These investigations and the methods used are reported in subsequent chapters within this thesis.

1.4. Organisation of chapters

1.4.1. Chapter 2 - Literature review

A critical review of the literature relevant to this thesis is provided in this chapter. A discussion of the current research concerning rugby place kicking technique is provided which includes studies investigating initial ball flight characteristics, support foot position, kinematics of the kicking leg and motion of the non-kicking-side arm as well as an initial description of the last step the kickers take prior to initial ball contact, and the anthropometric and strength characteristics of kickers. However, as peer-reviewed empirical research concerning rugby place kicks is currently sparse, potentially relevant aspects of technique from other kicking skills are considered, as is selected experiential information from rugby coaching sources. The full-body motion of the kicker is discussed, with a focus on kicking technique during both the approach and the kicking phases. Based on the available evidence, a conceptual model is then proposed which identifies aspects of technique that may be important for successful rugby place kick performance. Additionally, methodological issues related to the collection and analysis of data relevant to the investigations undertaken in this thesis is addressed.

1.4.2. Chapter 3 - Development and evaluation of a measure of overall rugby place kick performance from initial ball flight data

This chapter develops and evaluates a method for obtaining a measure that represents overall rugby place kick performance using initial ball flight data which are typically available within a laboratory setting. A mathematical model is developed that simulates the flight of a rugby ball using initial ball flight data and equations of motion accounting for the aerodynamic forces acting. Experimental rugby place kick ball flight data are collected to calibrate the model through the identification of aerodynamic force coefficients from previously published wind tunnel experiments which provide the closest matching outputs. The model is then verified to ensure that systematic alterations to model inputs and constants result in realistic alterations to the model output. Finally, the model is validated against additional experimental data to check the accuracy and consistency of the model outputs and to confirm the accuracy with which the model can be used to obtain a single performance measure that represents the maximum distance that any given place kick would be successful from.

1.4.3. Chapter 4 - General methods

With the ability to obtain a relevant performance measure using data from just the initial ball flight, place kicking technique and performance can be experimentally investigated in detail in a laboratory environment. This chapter details the general methods employed to obtain the kinematic and kinetic data used in the subsequent experimental chapters as well as the additional considerations that were made in an attempt to replicate aspects of the field environment where possible. The participants, the experimental setup and procedures, and the data processing and analyses are all described in detail in this chapter.

1.4.4. Chapter 5 - Understanding place kick performance through an investigation of initial ball flight characteristics

An investigation of the initial ball flight characteristics of rugby place kicks is presented in this chapter. Initially, a correlation analysis is performed between the measured ball velocity magnitude and the estimated maximum kick distance (determined using the methods developed in Chapter 3) to critique the outcomes of previous research that has used ball velocity magnitude as the performance criterion. The estimated maximum kick distances are then used to objectively group the kickers to facilitate subsequent comparisons of the techniques of successful kickers against those who were less successful. Three distinct groups are identified: 'long' kickers who achieved a maximum distance of greater than 32 m, 'wide-left' kickers who would have missed the left-hand goalpost before the ball had travelled 32 m, and 'short' kickers for whom the ball would have dropped below the height of the crossbar before it had travelled 32 m. Finally, the initial ball flight characteristics are compared between the three groups in order to understand why the specific performance outcomes occurred.

1.4.5. Chapter 6 - The approach to the ball and motion of the kicking foot: comparisons between successful and less successful rugby place kickers

This chapter investigates the whole-body motion prior to initial ball contact and the motion of the kicking foot during the downswing, including how these differ between the three previously identified groups of kickers. The kickers' whole-body CM position and velocity are considered at three key events (kicking foot take-off, support foot contact and initial ball contact), and the length and direction of the final step that the kickers take towards the ball from kicking foot take-off to support foot contact as well as the position of the support foot relative to the ball are analysed and compared between the three groups. The ground reaction forces recorded from underneath the support foot are presented for the first time in rugby place kicking and these time-histories are compared between the groups to understand how the kickers' changed their whole-body motion between support foot contact and initial ball contact. Finally, the kicking foot motion from the top of the backswing to initial ball contact is investigated, to initially explain some of the differences observed in the ball flight characteristics before progressing to the more proximal segments in the next chapter.

1.4.6. Chapter 7 - Understanding kicking leg and torso motion during the downswing to explain differences in place kick performance outcome

This chapter presents the kicking leg joint kinematics from the top of the backswing to initial ball contact as well as the joint kinetics, calculated through an inverse dynamics analysis, with those patterns exhibited by the long kickers compared with those of the two less successful groups to identify and understand the different strategies employed by the kickers. The orientations of the kickers' body segments at initial ball contact are presented and differences between the three groups are identified. The motion of the pelvis and the trunk segments over this period are also explored in relation to both the generation of a fast kicking foot velocity and the achievement of an accurate kick.

1.4.7. Chapter 8 - General discussion

The main findings from this thesis are discussed in this chapter and key conclusions are drawn. The research questions are briefly addressed in turn before the methodological approaches used throughout the thesis are discussed. The key technique differences between the long kickers and each of the less successful groups are then discussed. The conceptual model proposed in Chapter 2 is revisited and revised to incorporate these findings to provide a framework to discuss the practical implications for coaches and kickers if they were lacking accuracy or distance, respectively. Future research directions that would continue to further the understanding of rugby place kicking are then proposed.

1.5. Chapter summary

This chapter introduced the previous studies that have investigated biomechanical aspects of rugby place kicking technique and thus the current understanding in the field, leading to the thesis aim. Six research questions were then posed that will be sequentially addressed to meet the thesis aim. Finally, the organisation of the thesis chapters are briefly described which will allow the research questions to be addressed.

Chapter 2: Literature review

2.1. Introduction

In the search for rugby place kicking technique literature, directly relevant articles in peer-reviewed journals were first retrieved. However, relatively few studies have been published in this area and each has focussed on a different specific area of interest, meaning there is limited empirical evidence available to direct and support the current understanding of rugby place kicking technique. It was therefore decided to consider information from selected coaching-related sources which contain experiential evidence regarding the technical factors considered to be important to kicking technique. In order to support some of this experiential evidence and to identify additional biomechanical factors that may be of interest, information from relevant research articles investigating the technique of kicking skills in other football codes (Rugby League, soccer and Australian Rules football) was also critically reviewed. Although there are differences in the constraints between these skills (e.g. level of accuracy required, open or closed skill, different balls used), it is plausible that some information from other football codes can be relevant to rugby place kicking. Using this wide-ranging sample of literature, this review will now commence by discussing the determination of rugby place kick performance.

2.2. Determination of performance

The need for accurate measurement of performance is critical when investigating the technical factors which contribute to successful performance. Typically, sports biomechanics research studies are conducted in laboratories enabling integrated ground reaction force and 3D kinematic data to be collected (discussed further in Section 2.4) but where space constraints would often limit the ability to track the full flight path of a rugby ball following a place kick. Consequently, researchers typically record the initial flight of the ball and make an inference as to the expected overall performance.

The flight of the ball is directly determined by the initial ball flight characteristics (the magnitude and direction of the linear ball velocity, and the ball's angular velocity) and the aerodynamic forces acting on the ball. Holmes et al. (2006) measured some of the initial ball flight characteristics of place kicks performed by elite rugby players - the 2D resultant ball velocity magnitude (in the forward and vertical directions), the ball angular velocity about its medio-lateral axis (hereafter termed 'end-over-end spin') and the ball launch angle (above the horizontal when viewed from the side; see Table 2.1). The ball velocity magnitudes recorded in this study were comparable with those recorded by Bezodis et al. (2007), Linthorne and Stokes (2014) and Sinclair et al. (2014) for both amateur and professional rugby kickers and by Ball (2010) for Rugby League players (Table 2.1). However, Zhang et al. (2012) recorded slower ball velocities as did Baktash et al. (2009), likely representative of the less experienced kickers who participated in these studies (although the precise ball velocities were not reported in the latter study, they appeared to range between 15.0 and 20.0 m/s). Furthermore, the recorded mean ball launch angles ranged from 30 to 36° across the previous studies (Ball, 2010; Bezodis et al., 2007; Holmes et al., 2006; Linthorne & Stokes, 2014; Sinclair et al., 2014). Holmes et al. (2006) was the only study to report the end-over-end ball spin and no studies to-date have recorded the longitudinal spin (the spin rate about the ball's longitudinal axis) nor resolved the velocities into their individual components.

Table 2.1. Ball launch characteristics of rugby place kicks as reported in the literature (mean ± SD).

	Participants	2D/3D Data	Ball velocity (m/s)	Launch angle (°)	End-over-end spin (°/s)
Ball (2010) *	7 professionals	2D	25.2 ± 4.0	36 ± 3	
Bezodis et al. (2007)	5 amateurs	3D	24.5 ± 1.0	35	
Holmes et al. (2006)	14 professionals	2D	26.4 ± 3.0	30 ± 4	1440 ± 252
Linthorne & Stokes (2014)	1 amateur	2D	26.2 ± 1.7	31 ± 5	
Sinclair et al. (2014)	20 amateurs	3D	26.6 ± 1.6	34 ± 2	
Zhang et al. (2012)	7 amateurs	3D	17.8 ± 2.5		

* The studied participants were Rugby League players

Whilst these data represent some of the ball flight characteristics which affect place kick performance, previous research investigating place kicking technique has generally quantified performance using solely linear ball velocity magnitude (Baktash et al., 2009; Sinclair et al., 2014; Zhang et al., 2012). However, a place kick taken 32 m from the centre of the goalposts (the average distance place kicks were taken from in international matches between 2002 and 2011; Quarrie & Hopkins, 2015) would not be successful if the lateral deviation in the ball's trajectory was 5° from the centre of the posts, and this margin for error reduces as the angle the kick is taken from increases or the distance from the posts increases. Clearly the accuracy of the kick is an important consideration for overall place kick performance in addition to the magnitude of the ball velocity. Only one of the previous studies investigating place kicking technique has quantified the accuracy of the kicks, through simple measurement of the lateral deviation of the ball relative to a target 10 m away from the kicking tee (Bezodis et al., 2007), and no studies have combined both of these critical components of the ball velocity vector to quantify overall performance using a single measure.

2.2.1 Methods used to simulate ball trajectory

When in-flight, the path of a rugby ball is governed by equations of motion based on the gravitational and aerodynamic forces acting on it. Therefore, if the initial ball flight characteristics are known and the forces acting on the ball can be accurately estimated, the trajectory of the ball flight could be simulated and overall place kick performance can be predicted. Previous studies have used this knowledge to simulate the flight of sporting projectiles such as soccer and rugby balls and discuses (e.g. Bray & Kerwin, 2003; Carré, Goodwill & Haake, 2005; Seo, Kobayashi & Murakami, 2006b; Hubbard & Cheng, 2007). The aerodynamic forces acting on a projectile cannot currently be directly measured in-flight and must therefore be estimated through other methods. Previous research using an optimisation approach identified the best values to represent the aerodynamic forces for individual soccer kicks when averaged across their complete flight (Bray & Kerwin, 2003; Carré et al., 2005). The spherical shape of a soccer ball means the orientation of the ball is likely to have little effect on the aerodynamic forces acting on it (particularly as the seams connecting the panels are distributed regularly around the ball) and as such, the drag and lift forces may be assumed to be constant throughout flight (Bray & Kerwin, 2003). Conversely, the prolate spheroid shape of a rugby ball means that both the angle of attack and yaw angle of the ball affects the wind flow across the surface and therefore the aerodynamic forces acting on it. Thus, in the case of a spinning rugby ball where both of these angles may be constantly changing at different rates, the aerodynamic forces cannot be assumed to be constant throughout flight.

Wind-tunnel experiments have been conducted to directly measure the aerodynamic forces acting on a rugby ball (e.g. Alam, Subic, Watkins, Naser & Rasul, 2008; Seo, Kobayashi & Murakami, 2006a; Seo, Kobayashi & Murakami, 2007). Alam and colleagues (2008) mounted a rugby ball on a turntable within a wind tunnel, allowing it to be placed at different yaw angles relative to the direction of the wind flow (depicted in Figure 2.1b). The three aerodynamic forces (drag, lift, and side) and the three aerodynamic moments (yaw, pitch and roll) acting on the ball were measured using a force sensor. The aerodynamic data were measured for wind speeds between 16.7 m/s and 38.9 m/s, a range containing the ball speeds previously recorded for place kicks (Table 2.1). However, as the ball was stationary in these trials the effect of ball spin about any of the three principal axes was not considered. The forces recorded may therefore not be representative of a spinning rugby ball (as demonstrated by Seo, Kobayashi & Murakami, 2004), which is typically the case in a place kick, where the air flow around the ball is likely to be constantly changing.

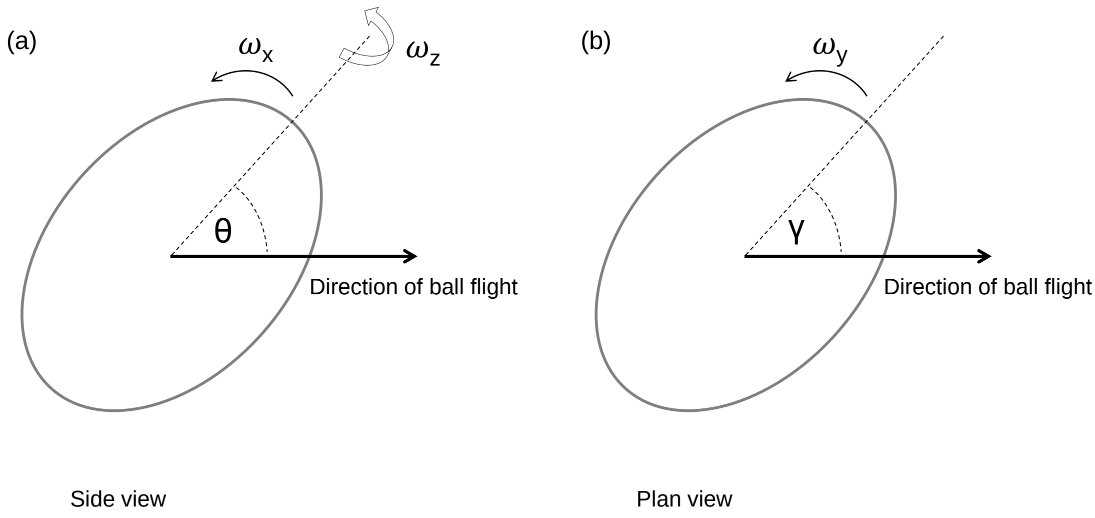


Figure 2.1. The definition of the pitch angle (θ), pitch angular velocity (ω_x) and rolling angular velocity (ω_z) as viewed from the side (a) and the yaw angle (γ) and yaw angular velocity (ω_γ) as seen from the plan view (b).

During the ball flight phase of a place kick, the ball typically rotates predominantly about its medio-lateral axis (end-over-end spin) and it is therefore important to consider the aerodynamic forces and moments acting when the ball is rotating in this manner. Seo et al. (2007) rotated a rugby ball about its medio-lateral axis using a motor and measured the aerodynamic forces and yawing moment acting on the ball at 1000 Hz at wind speeds of 15 and 20 m/s and for yaw angles of 45° and 90° to the direction of wind flow (depicted in Figure 2.1b). The measured drag, lift and side forces and the yawing moment data were fitted with polynomial equations as a function of both a spin coefficient (first order) and yaw angle (first order for the drag and lift forces, third order for the side force and second order for the yawing moment).

A curved ball trajectory is not an outcome typically desired by elite coaches in place kicking (Bezodis & Winter, 2014; Greenwood, 2003; Wilkinson, 2005). However, it clearly can occur based on the curve (typically a right to left ‘draw’ shape for right-footed kickers) sometimes seen in place kick trajectories, and is caused by longitudinal ball spin imparted by the kicker during the ball contact phase. It is also therefore important to understand these effects. In a similar experiment to the one described above, Seo et al. (2006a) recorded aerodynamic data for a ball spinning about its longitudinal axis between 1 and 10 revs/s, at wind speeds from 15 to 30 m/s and at pitch angles from 0 to

90° (see Figure 2.1a for a depiction of pitch angle). The authors found that the drag and lift forces and pitching moment were almost unaffected by both wind speed and spin rate and therefore average data across all conditions were presented at each pitch angle (Seo et al., 2006a). The data were then fitted with polynomial functions, with the drag and lift forces and pitching moment calculated as a function of pitch angle (fourth, third and second order polynomials, respectively) and the side force calculated as a function of both pitch angle (third order) and roll angular velocity (first order). At high pitch angles (greater angle above the horizontal), a difference of around 10% was observed in the measured drag force compared with that recorded by Alam et al. (2008) which Seo et al. (2006a) believed may be due to the additional rotation of the ball in their experiment. Given the differences observed in the drag forces measured for a ball spinning about its transverse axis (Seo et al., 2007) and a non-spinning rugby ball (Seo et al., 2004) at various yaw angles, there are clearly differences in the two cases. This suggests that the forces measured by Seo et al. (2006a; 2007) provide a more accurate representation of those in a true place kick when the ball is spinning. The aerodynamic forces obtained were used to simulate the flight of a rugby place kick and to investigate the optimal initial conditions for each kick (Seo et al., 2006b), but these simulations were not evaluated against experimental data and therefore the accuracy of the estimated aerodynamic forces remains unknown.

If an appropriate combination of aerodynamic force coefficients from these wind-tunnel experiments can be identified and incorporated into a simulation model, an accurate representation of ball flight from any given rugby place kick could be obtained from empirical initial ball flight kinematics. This would allow overall place kick performance to be determined from data collected in a laboratory environment where kicking technique can be investigated in greater detail and with greater accuracy.

2.3. Kicking technique

Sporting skills are often considered in phases, which occur between identified key events, to provide a more focussed analysis framework (Burkett, 2010). It is proposed that a rugby place kick can be broadly separated into four sequential phases: the approach, the kicking phase, the ball contact phase and the follow-through phase (Figure 2.2). The approach commences when the kicker moves from their stationary preparatory position. During this phase, the kicker takes their final step towards the ball which is identified as the final time the kicking foot leaves the floor (kicking foot take-off) and the phase concludes once the kicking foot reaches the top of the backswing, which signals the start of the kicking phase. During the kicking phase, the kicking leg swings down towards ball contact. The ball contact phase is the time from initial contact between the foot and the ball (initial ball contact) to when the ball leaves the foot and is in-flight. The follow-through is then the motion of the kicker once the ball is in-flight.

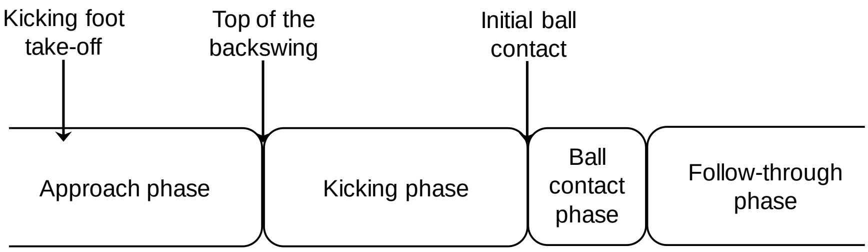


Figure 2.2. The four phases identified in a rugby place kick and the key events that distinguish them or occur during them.

Whilst the motion of the kicker during a rugby place kick is not yet well understood, movements during these four phases have been described and investigated within kicking skills in other football codes, in particular soccer instep kicking. Specific technique aspects during the approach and the kicking phases have been identified as being important in determining kicking performance due to the influence they have on the motion of the kicking leg, the end of which (i.e. the kicking foot) ultimately contacts the ball and directly determines the motion of the ball post-contact. Whilst the motion of the more proximal joints of the kicking leg have also been described during the ball contact phase, only the motion of the kicking foot has been specifically investigated (to understand injury mechanisms and footwear design). Additionally, once the ball is in-flight, the motion of the kicker can no longer affect the ball and it has been suggested by an elite rugby kicking coach as simply being a *"release mechanism... at the end"* (Bezodis & Winter, 2014). The key technical factors investigated within the literature and identified through coaching-related sources in each of the phases will now be reviewed in turn.

2.3.1. The approach phase

Simple observation of rugby place kickers indicates that they typically take a two or three step approach from an angle behind and to the side of the ball. To date, no research has been published investigating the effect of the whole-body approach on rugby place kick performance. However, it is a feature discussed within the coaching literature and there is general agreement that the kicker should approach the ball from an angle (Greenwood, 2003), with Wilkinson (2005) suggesting an angle of 45˚ relative to the desired line of ball flight. Soccer players also often take an angled approach to kicking a stationary ball but experimental manipulations of their approach angle have revealed inconclusive effects on resultant ball velocity magnitude and accuracy (Andersen & Dörge, 2011; Kellis et al., 2004; Isokawa & Lees, 1988; Scurr & Hall, 2009). However, making acute extreme adjustments to a kickers' approach will likely affect many aspects of their technique and therefore a cross-sectional study of skilled and less skilled kickers may be more insightful in understanding how approach angle may affect place kick performance. Whilst Scurr and Hall (2009) found no significant differences in either the ball velocity magnitude or accuracy of soccer instep kicks taken from different approach angles by amateur players, the kickers did display a more longitudinally rotated pelvis at the top of the backswing when they approached from greater angles. Greater longitudinal pelvic rotation at the top of the backswing is thought to enable the kicking foot to be positioned further away from the ball prior to initiation of the downswing (Scurr & Hall, 2009). De Witt (2002) suggested that kickers may obtain a faster kicking foot velocity at initial ball contact if the kicking foot is positioned further away from the ball at the top of the backswing as it would likely then take a longer path down towards the ball, providing the kicking leg joints more time to rotate. However, they did not present any empirical data to support this assertion and so evidence is required to appraise it.

Research in Australian Rules football punt kicking found a longer final step length to be moderately associated with longer kick distances (*r* = 0.41; Ball, 2008). The final step length was also moderately related to both maximum kicking thigh angle and peak kicking knee flexion angle (*r* = 0.41 and *r* = 0.37). The authors suggested that a longer final step enabled greater kicking hip extension and knee flexion at the top of the backswing with the subsequent greater thigh and shank range of motion during the kicking phase increasing the potential to develop a faster kicking foot velocity at initial ball contact. The results of these studies appear to suggest that a longer final step length may be an important determinant of the ball velocity magnitude achieved in kicking skills and the angle of this step may also be worthy of consideration. However, it must be considered that the approach of the kicker has been found to alter when an accuracy constraint is imposed in soccer instep kicking (Lees & Nolan, 2002); the final step length of two professional soccer players was shorter when performing instep kicks with a focus on an accurate kick compared with when the focus was on maximising ball velocity (final step lengths of 0.53 - 0.55 m and 0.72 - 0.81 m, respectively; Lees & Nolan, 2002) and when female soccer kickers took a curve kick which requires greater accuracy compared with an instep kick (1.50 ± 0.12 m and 1.55 ± 0.40 m, respectively; Alcock, Gilleard, Hunter, Baker & Brown, 2012). There is a noticeable difference in the final step lengths recorded by Lees and Nolan (2002) and those recorded by Alcock et al. (2012) as well as in Australian Rules punt kicking (1.74 ± 0.15 m; Ball, 2008) and most importantly, rugby place kicking (1.52 ± 0.12 m; Cockcroft & van den Heever, 2016). Some of these differences may be explained by the methods used to measure the final step length in these studies, however, further analyses of the results reported by Lees and Nolan (2002) is limited as they did not report the anthropometrics of the kickers nor the methods they used to measure the final step length. Nevertheless, given the results of Alcock et al. (2012) supported the assertion that there were differences in the final step length when there was an additional accuracy requirement to the task, as well as differences in both the whole-body and kicking leg motion (which will be discussed in greater detail in Section 2.3.2), an investigation into the approach of the kicker towards the ball will be important when investigating rugby place kick performance where both the ball velocity magnitude and direction are important in determining the success of the skill.

The kicker's velocity magnitude as they approach the ball has been found to explain 40% of the variance in kicking foot velocity magnitude at initial ball contact (which itself had a strong relationship with kick distance, r = 0.68) in Australian Rules football punt kicking (Ball, 2008). However, the effect of approach velocity on the performance of other kicking skills has been largely unexplored. Anderson and Dörge (2011) found that amateur kickers were able to obtain their fastest ball velocities when performing soccer instep kicks at their self-selected approach velocity, and ball velocity reduced when this approach velocity was increased or decreased. Furthermore, Lees and Nolan (2002) found that the approach velocity of two professional soccer kickers was significantly slower when they performed instep kicks with a focus on accuracy than on maximum ball velocity (with a mean difference of approximately 0.9 m/s), as did Alcock et al. (2012) when comparing the motion of female soccer kickers performing a curve kick compared with an instep kick (mean difference of 0.3 m/s). These results suggest that the approach velocity magnitude of the kicker may be an important consideration in rugby place kicking when maximising the ball velocity is not the sole consideration for the kickers. Potthast et al. (2010) extended this and suggested that it was in fact the deceleration of the kickers during the kicking phase that was more important in determining kicking foot velocity than the velocity they approached with *per se*. This deceleration of whole-body velocity is caused by the forces exerted between the support foot and the floor throughout this phase. These ground reaction forces have been shown to differ depending on the angle of the approach taken by the kicker in soccer instep kicking (Isokawa & Lees, 1988; Kellis et al., 2004). There were observed differences in both the peak medio-lateral and antero-posterior forces and the corresponding time-histories (assessed qualitatively, but not using quantitative statistical analyses) up to initial ball contact when the kickers approached the ball from different lateral positions (as may be expected given the differences in whole-body CM velocity in these two principal directions). The ground reaction forces recorded during the kicking phase will be discussed in detail in Section 2.3.2.

The position of the support foot relative to the ball is one aspect of the approach that has been described in rugby place kicking. Cockcroft and van den Heever (2016) presented the support foot positions relative to the ball on the tee for 15 professional rugby kickers. The support foot was observed to land approximately 0.33 ± 0.03 m to the left and 0.03 ± 0.07 m behind the back of the tee, but no association was made between these positions and place kick performance. In contrast, Baktash et al. (2009) experimentally manipulated the support foot position of amateur kickers and measured the effects on ball velocity and specific aspects of kicking technique. Four positions were identified and marked on the laboratory floor and the authors hypothesised that faster ball velocities would be attained when the support foot landed 0.30 m lateral to, but in line with the ball in the forward direction (comparable to that reported by Cockcroft & van den Heever, 2016 and hereafter considered the reference position), compared with positions 0.30 m in front of, behind, and to the left of this reference position. The results in this study showed no significant difference in ball velocity magnitude or peak kicking hip and knee flexion-extension angles or peak kicking knee flexion-extension resultant moment between support foot positions. However, the positions used in this study were extreme manipulations, representing positions that were much further from the ball than those observed across a group of rugby place kickers (Cockcroft & van den Heever, 2016) and the participants were three amateur kickers who achieved much slower resultant ball velocities than other previously published studies investigating rugby place kicking. These results should therefore be treated with caution. When compared between kickers and considered in relation to performance in Australian Rules football (Ball, 2008), the self-selected support foot positions of kickers who were able to drop punt a ball further was more lateral to the ball compared with the shorter kickers. Investigation of the differences in self-selected support foot position on place kick performance would provide an initial understanding of how it might influence kicking technique rather than employing acute manipulations which would require longer-term training of the kicking skill from each position.

The approach of the kicker towards the ball has not been widely investigated in rugby place kicking, but there are clearly a number of factors related to the approach that may be important in determining place kick success. Both the velocity that the kicker approaches the ball with and the final step taken by the kicker have been suggested as potentially affecting the success of soccer instep and Australian Rules punt kicking through the effect they have on whole-body motion and that of the kicking leg. Furthermore, the length of the final step may interact with the above variables to affect the position of the support foot relative to the ball and the orientation and configuration of the kicker at the top of the backswing, both of which may potentially affect the movement of the kicker throughout the ensuing kicking phase towards initial ball contact.

2.3.2. The kicking phase

The motion of the kicking leg throughout a rugby place kick is of interest as ultimately it is the end of this limb (i.e. the kicking foot) that contacts the ball and directly affects ball flight. To date, no studies have provided a comprehensive analysis of the motion of the kicking leg in rugby place kicking. In contrast, the motion of the kicking leg in the soccer instep kick has been widely reported. Wickstrom (1975) provided the first description - forward rotation of the pelvis about the longitudinal axis, followed by hip and knee flexion, initiating forward motion of the thigh towards the ball. Hip flexion is then decelerated and the knee is extended up to initial ball contact, by which point the thigh is near stationary. This pattern of soccer kicking leg movements has since been reported in investigations of both male and female and experienced and inexperienced kickers (e.g. Ball, 2011; Kawamoto et al., 2007; Lees et al., 2009; Levanon & Dapena, 1998; Lyle, Sigward, Tsai, Pollard & Powers, 2011; Sakamoto, Hong, Tabei & Asai, 2012; Shinkai, Nunome, Isokawa & Ikegami, 2009) and clear parallels exist between this description and that described by an elite rugby kicking coach (Bezodis & Winter, 2014). The motion of the kicking foot will be discussed first before the rotations of the kicking leg joints are considered, followed by the torso segments, the support leg and the ground reaction forces recorded underneath the support foot. Finally, the relationships identified between the anthropometrics, strength and power of the lower limbs and kicking skills are briefly discussed.

Kicking foot motion

To date, no research has been published that has specifically investigated the motion of the kicking foot in rugby place kicking. As the end of the linked-segment system that directly contacts the ball and subsequently dictates the flight of the ball, the magnitude and direction of the linear velocity vector and the orientation of the kicking foot relative to the ball at initial ball contact are important to consider when investigating rugby place kicking technique.

Previous research in soccer instep kicking has investigated the linear velocity of the kicking foot prior to and throughout the ball contact phase and the subsequent relationship with kicking performance. The linear velocity of the kicking foot increases throughout the kick, peaking at initial ball contact (De Witt & Hinrichs, 2012; Dörge, Andersen, Sorensen & Simonsen, 2002; Nunome, Lake, Georgaki & Stergioulas, 2006), where a strong positive relationship between the peak kicking foot velocity and ball velocity post-contact has been established (i.e. r = 0.71 - 0.83; Levanon & Dapena, 1998; De Witt & Hinrichs, 2012; Nunome et al., 2006). The strength of this relationship between kicking foot velocity at ball contact and ball velocity post-contact has prompted studies to investigate the technical factors that contribute to a fast kicking foot velocity at initial ball contact in both rugby place kicking (Zhang et al., 2012) and other football codes (Anderson & Sidaway, 1994; Ball, 2011; Young & Rath, 2010). However, a number of studies have also reported that kicking foot velocity is reduced by between 2.2 and 4.6 m/s in soccer instep kicks when an accuracy constraint is imposed (Lees & Nolan, 2002; Teixeira, 1999). Therefore, whilst a fast kicking foot velocity would be desirable in rugby place kicking, in order to achieve a fast ball velocity, the inherent accuracy requirement of the skill may mean the kickers cannot solely focus on generating a fast foot velocity as the direction of the foot velocity vector at initial ball contact will likely influence the direction of the ball flight post-contact.

The path of the kicking foot prior to initial ball contact has been highlighted as an important technical factor of rugby place kicking by an elite rugby kicking coach (Bezodis & Winter, 2014). In a semi-structured interview, the coach stated that the foot should travel in a *“straight line going through... towards the target... from six to twelve inches behind the ball [until]... six to twelve inches after impact”*. This kicking foot path is anecdotally discussed by Wilkinson (2005) who identifies two styles of swing, the ‘J-shape’© and the ‘C-shape’©. These swing shapes are named based on the path of the kicking foot during the downswing and through the ball contact phase when viewed from above for a right-footed kicker (the ‘C-shape’© is inverted – ‘Ɔ’). Wilkinson (2005) advocates the ‘J-shape’© swing because the straighter approach of the foot to the ball is proposed to increase the amount of time that the foot is travelling in the desired direction of ball flight thereby increasing the likelihood that the ball will travel towards the centre of the target after it has left the foot, a coaching premise also supported by Greenwood (2003). In contrast, the curvature of a ‘C-shaped’© path is thought to reduce the amount of time that the foot is travelling in the desired direction of ball flight, thereby increasing the likelihood of it travelling in an inappropriate direction during contact (Wilkinson, 2005). Based on these definitions, it would appear that the coach interviewed by Bezodis and Winter (2014) also advocated the ‘J-shaped’© path. Although it appears to be widely considered in an applied rugby kicking setting, the path of the kicking foot is a currently un-researched area in rugby place kicking. Analysis of the kicking foot path and the direction of its velocity vector at initial ball contact may help to explain differences observed in the ball velocity post-contact.

In soccer instep kicking, the kicking foot has been shown to contact the ball on the inside of the foot, just in front of the ankle, near the foot's centre of mass (Tol, Slim, Soest & Dijk, 2002). This identified location corresponds to the suggested contact location in rugby place kicking of *"toe down, laces up; promote the hard part of the foot striking* *through the ball"* (Bezodis & Winter, 2014). Differences between the kicking foot orientation at initial ball contact in successful and less successful kicks have not been investigated in any football codes as studies of foot orientation have focussed on injury mechanisms (Asami & Nolte, 1983; Tol et al., 2002) and influencing factors such as footwear design (Sterzing, Kroiher & Hennig, 2008). However, this would appear to be worthy of consideration based on the principles of impact mechanics, whereby the size and specific area of the kicking foot that makes contact with the ball affects the coefficient of restitution and therefore the subsequent ball flight post-contact (Andersen, Kristensen & Sorensen, 2008).

Kicking hip, knee and ankle joint mechanics

Whilst the motion of the kicking foot at initial ball contact directly determines the motion of the ball post-contact, the foot is the end of a linked-segment system and its motion is therefore affected by that of the more proximal segments. Aitchison and Lees (1983) conducted a 2D analysis of the kicking actions performed by skilled (amateur), less-skilled and unskilled rugby place kickers and identified that the skilled kickers demonstrated a two-stage acceleration of the kicking shank. The first stage of this acceleration, up to the point when the thigh was perpendicular to the ground, was attributed to the effect of gravity (however, no details were provided with regards to how this was determined). The second stage of acceleration, from this point, was considered to be due to the power transferred from the thigh to the shank, a technical characteristic often termed proximal-to-distal sequencing. The importance of this proximal-to-distal sequencing in maximising ball velocity is widely reported in soccer kicking research (Browder, Tant & Wilkerson, 1991; Dörge et al., 2002; Lees & Nolan, 2002; Levanon & Dapena, 1998; Nunome et al., 2002; Patritti & Lees, 1999; Putnam, 1991) and was also highlighted by the elite rugby kicking coach: the *"hip leads the knee, then 'snaps' the shank that 'snaps' the foot through the ball underneath it"* (Bezodis & Winter, 2014).

The study by Aitchison and Lees (1983) provided some initial indication of how skilled kickers may be able to achieve faster ball velocities. However, they did not consider the accuracy of the kicks nor motion that occurred in non-sagittal planes. This latter point is important since place kicking is clearly a 3D movement (Bezodis et al., 2007). Two studies have subsequently analysed the influence of the motion of the kicking leg on ball and kicking foot velocity magnitudes in place kicks through 3D analysis (Sinclair et al., 2014; Zhang et al., 2012). Zhang et al. (2012) assessed the contribution of the individual kicking leg segmental velocities and both the linear and angular velocities of the pelvis segment to the linear kicking foot velocity magnitude at initial ball contact through a velocity decomposition method (previously used to analyse the development of racquet-head speed in tennis; Sprigings, Marshall, Elliott & Jennings, 1994). This method states that the magnitude of the linear kicking foot velocity is determined by the linear velocity of the pelvis, and the sum of the tangential velocities of the kicking leg segments. Knee extension velocity was identified as the largest contributor to foot velocity magnitude at initial ball contact (75 ± 8%) whilst hip flexion velocity, linear pelvis velocity and pelvis rotation (the specifics of which were undefined) were smaller contributors (13 ± 1%, 9 ± 1% and 2 ± 1%, respectively). A proximal-to-distal sequencing of segmental motion was also observed for all trials recorded for the seven amateur kickers analysed. However, all data were reported with linear velocity units, representative of the tangential velocities of the kicking leg segments but associated to the angular motion of the kicking leg joints and with no clear description of how these percentages were calculated across the complete duration of the kick, making further interpretation of the results difficult. The second study (Sinclair et al., 2014) which investigated rugby place kicking technique of amateur kickers identified peak knee extension velocity as the only significant predictor of ball velocity magnitude ($R^2 = 0.48$) when all 3D kicking and support leg joint kinematic peak angles and angular velocities and values at initial ball contact were considered (i.e. 72 discrete data points). However, no mention was made of the variables that were entered into the forward stepwise regression after assessment of the co-linearity of the variables, which may have eliminated potentially important variables from the final model.

These aforementioned rugby place kicking studies which identified relationships between the ball/kicking foot velocity magnitudes and knee extension velocity instructed their participants to execute maximal kicks and included no accuracy requirement within the task. In such cases where the direction of ball travel is not a principal concern of the kicker, neither is the direction of the kicking foot velocity vector. However, studies that have compared the joint mechanics of the kicking leg during soccer instep kicks when speed was the focus versus when there was an accuracy constraint have identified differences in kicking technique. Lees and Nolan (2002) reported significantly reduced peak kicking leg joint angular velocities for two professional soccer kickers when taking accurate kicks as opposed to when maximising ball velocity magnitude (by approximately 30%, 18% and 55% for the hip, knee and ankle joints, respectively), which resulted in a slower kicking foot velocity at initial ball contact. However, slower joint rotations may have allowed the kickers to control the motion of the kicking foot prior to initial ball contact in order to direct the ball towards the target more accurately. Furthermore, a study of female soccer players taking instep and curve kicks found the kickers demonstrated a significantly larger peak knee extension velocity at initial ball contact when taking curve kicks that require a more precise foot-ball contact (Alcock et al., 2012). The authors believed this may have been a strategy employed by the kickers to allow the muscles crossing the hip joint to adjust the path of the kicking foot early in the downswing before rapidly extending their knee in order to achieve a fast kicking foot velocity at initial ball contact (Alcock et al., 2012). Thus, in order to fully understand the influence of the kicking leg joint kinematics on the motion of the kicking foot during the kicking phase and the motion of the ball post-contact in rugby place kicking, it is important that an accuracy constraint is imposed on the kickers as is present in true rugby place kicking.

Whilst the joint kinematics describe the motion of the kicking leg joints and some knowledge of the effect of these on ball velocity magnitude in rugby place kicking exists, it is the underlying kinetics that explain how this motion is achieved and these are not well understood in rugby place kicking. The only mention of the joint kinetics in rugby place kicking is by Baktash et al. (2009) who presented knee flexion-extension joint moments of place kicks performed with experimentally-manipulated support foot positions. However, these authors only presented a figure depicting the knee joint moment time-history of an individual kicker from each of the support foot positions and reported that there were no significant differences in the peak values recorded from each position across the kickers. There were also no details provided regarding how the joint centre locations were determined and the time-histories were not compared (or time-normalised). The joint kinetics of the kicking leg during rugby place kicking remain unknown and their potential influence on performance appears worthy of consideration given what is known about them from evidence in other football codes.

The resultant moments about the kicking leg ankle, knee and hip joints were recorded during soccer instep kicks by both Nunome et al. (2002) and Lees et al. (2009). Kicking leg ankle moments were small compared with both the knee and hip joints but a resultant plantar flexor moment was observed for the majority of the kicking phase which became dorsiflexor dominant in the final 5% of the phase prior to initial ball contact. A small resultant inversion moment was also observed at the ankle joint throughout the kicking phase (Nunome et al., 2002), however, this was accompanied by negligible ankle inversion suggesting it was working to negate other forces (e.g. due to the inertia of the foot segment). A resultant knee extensor moment was observed (peak normalised[*] moment of 0.09 at approximately 50-75% of the kicking phase), up to around 95% of the phase when a resultant flexor moment became dominant just before initial ball contact (Nunome et al., 2002). The timing of this flexor moment varied between the two studies, with Lees et al. (2009) reporting that it occurred earlier, during approximately the final 20% of the kicking phase. These discrepancies may be due to methodological differences in that Lees et al. (2009) reported the joint mechanical time-histories throughout the kick including the ball contact phase, which if not treated appropriately can lead to errors in the data preceding initial ball contact (Nunome et al., 2006). In contrast, Nunome et al. (2002) only recorded motion prior to initial ball contact and as such the data would not be affected by such errors. They did, however, only filter their data in one direction towards

[*] To facilitate comparisons between these studies in this literature review, all kinetic data were normalised using the equations presented by Hof (1996), but using height as opposed to leg length which is infrequently presented in the literature.

initial ball contact, shifting the data closer to initial ball contact (by 10-25 ms). Thus, neither studies likely provide an accurate representation of this change from knee extensor to knee flexor dominance and further investigation is required that uses appropriate data processing techniques. Nunome et al. (2002) also recorded the knee joint internal/external rotation kinematics and kinetics, but these motions were negligible. During the majority of the kicking phase a resultant flexor moment was observed at the hip, peaking at approximately 50% of the kicking phase (peak normalised flexor moment of 0.22). This resultant flexor moment then decreased and a resultant extensor moment became evident prior to initial ball contact. As with the knee flexor moments described above, differences were observed in the timings of the peak hip extensor moments in the two studies, likely due to the described methodological differences (the likely time shift in this peak was 15 ms towards initial ball contact in the study by Nunome et al., 2002). The hip joint also demonstrated a resultant external rotator and adductor moment throughout the kicking phase (peak normalised values of 0.03 and 0.09, respectively; Nunome et al., 2002); however, minimal motion was observed about both of these axes throughout the kicking phase. The estimates of joint motion about these axes has been shown to be erroneous in other sporting movements when using automatic motion capture systems (Cappozzo, Catani, Della Croce & Leardini, 1996; Schache, Baker & Lamoreux, 2008) and the manual digitising process used by Nunome et al. (2002) likely increased this error, meaning these data should be interpreted with caution.

Although comprehensively described, the effect of these kicking leg joint moments has not been investigated in the context of performance in soccer instep kicking. However, the differences in the kicking leg moments of experienced and inexperienced soccer players performing a soccer side-foot kick have been investigated (Kawamoto et al., 2007). Whilst there is less emphasis on generating a fast ball velocity than in an instep kick and the focus of the player is typically to achieve accuracy in a side-foot kick (Kawamoto et al., 2007), the players were instructed to kick the ball with maximum effort whilst maintaining accuracy. The differences seen in the technique between the two groups are therefore potentially of interest when considering rugby place kicking. First, the experienced kickers generated a significantly faster ball velocity (21.4 ± 1.5 m/s) compared with the inexperienced kickers (16.0 ± 1.0 m/s). The experienced kickers also generated a significantly greater peak hip flexor moment, knee extensor moment and ankle plantar flexor moment compared with the inexperienced kickers (differences in normalised peak moments of 0.08, 0.01 and <0.01, respectively). Whilst the peak normalised joint moments recorded for the experienced side-foot kickers are smaller than those recorded in previous studies investigating instep kicks, likely due to the greater need for accuracy, the lower joint moments of the inexperienced kickers suggest that the technique of these kickers did not allow them to generate as fast a kicking foot velocity at initial ball contact which subsequently led to a reduced ball velocity post-contact. It could therefore be important that, in addition to describing and understanding the general kicking leg joint moments in rugby place kicking, differences between the more successful rugby place kicks (where fast ball velocities are achieved and the kick is accurate) and those kicks that lack one of the two necessary components (either velocity or accuracy) are also investigated.

A resultant joint moment will be associated with either positive or negative joint power depending on whether that joint is flexing or extending. This is quantified as the product of joint moment and angular velocity, but has not been widely reported in previous kicking studies aside from the soccer instep kicking study of Lees et al. (2009). Negligible positive or negative power was evident at the ankle joint during the kicking phase apart from a small period of positive power by the ankle plantar flexors in the final 20% of the kicking phase (normalised peak power of 0.01). The joint power time-history of the kicking knee revealed two periods of negative power and one period of positive power. For approximately the first 50% of the kicking phase, negative power by the knee extensors was observed. This reduced the flexion velocity of the knee before initiating a period of positive power as the knee began to subsequently extend. As the knee continued to extend, a flexor moment then became dominant, resulting in a period of negative power by the knee flexors up to initial ball contact (peaking at initial ball contact with a normalised peak power of 1.42). Lees et al. (2009) suggested that this second period of negative power may provide the kicker with two potential benefits. The first is a protective mechanism due to the anatomical constraint (van Ingen Schenau, Bobbert & Rozendal, 1987) at the knee joint, requiring the kickers to exert a flexor moment as the knee approaches maximum extension to prevent potential injury due to hyperextension. The second theory suggested that a less than fully extended knee position may have enabled the kicker to externally rotate the shank and, therefore, allowed them to obtain a more precise orientation of the kicking foot prior to initial ball contact (Blankevoort, Huiskes & de Lange, 1988). This second theory may be particularly important when considering the technique differences of accurate and inaccurate rugby place kickers. The kicking hip joint power time-history demonstrated positive hip flexor power throughout the kicking phase, peaking at approximately 40% (normalised peak power of 0.51), before reducing to a minimal amount in the final 20%, prior to initial ball contact.

The time-integral of the joint power time-histories quantifies the work done at the joint; for each period of positive or negative power, the total positive or negative work done at the joint can be calculated. This variable has also rarely been reported for investigations into kicking skills, with only two published abstracts containing joint work data (Nunome, Ikegami, Asai, Sakurai & Terashima, 2001; Robertson & Mosher, 1985). Robertson and Mosher (1985) presented the total positive and negative work done by both the hip and knee flexors and extensors from the initiation of the backswing through to after ball contact; unfortunately the work done solely during the kicking phase cannot be identified to understand how the motion of the kicking foot prior to initial ball contact is achieved. Nunome et al. (2001) calculated the positive work done by the knee extensors and the hip adductors, flexors and external rotators in both soccer side-foot and instep kicking from the initiation of the backswing to initial ball contact. Significantly more positive work was done by the knee extensors in the instep kick compared with the side-foot kick, whilst the hip external rotators did significantly more positive work in the side-foot kick compared with the instep kick. Although the kicking foot velocities were not reported in this study, the previously reported relationship between knee extension velocity and ball velocity magnitude and the requirements of the two kick styles studied by Nunome et al. (2001) indicates that the greater positive work done by the knee extensors in the instep kick likely aided in the generation of a faster kicking foot velocity at initial ball contact and therefore the subsequent ball velocity. The greater positive work done by the hip external rotators in the side-foot kicks likely orientated the kicking foot so that it would contact the ball on the more medial aspect of the foot which has been suggested to ensure the force applied to the ball by the kicking foot is directed in the desired direction (Asai, Carré, Akatsuka & Haake, 2002). However, these latter data should be treated with some caution given the previously reported errors when analysing motion about the longitudinal joint axis.

These investigations that have reported the joint kinetics of the kicking leg in soccer kicking have provided some insight as to how the more proximal joints contribute to the linear kicking foot velocity, as well as identifying differences when a more controlled foot-ball contact is needed, such as in the side-foot kick. Given these findings, understanding how the motion of the kicking leg enables rugby place kickers to generate both a fast foot velocity and maintain a controlled foot-ball contact is clearly worthy of detailed investigation. The identification of differences that may exist between more and less successful kickers could be highly valuable for guiding coaching practice.

Torso kinematics

The motion of the pelvis and trunk segments (considered here to comprise the 'torso') has also been identified as important in kicking (Wickstrom, 1975). As highlighted previously, longitudinal rotation of the pelvis appears important in determining the position of the kicking foot at the top of the backswing and subsequently the path that it takes down towards the ball and potentially through the ball contact phase (Scurr & Hall, 2009). If the pelvis is more longitudinally rotated away from a front-on position when the kicking foot is at the top of the backswing it should have a greater range of motion through which to rotate, potentially generating a faster kicking hip linear velocity and subsequently linear kicking foot velocity at initial ball contact. The kicking foot would also likely then take a longer path towards the ball, providing the kicking leg joints more time to rotate through a greater range of motion, also theorised to lead to a faster foot velocity at initial ball contact (De Witt, 2002). Therefore, a more longitudinally rotated pelvis at start of the kicking phase may enable a faster kicking foot velocity to be achieved at initial ball contact. This was empirically supported by Lees and Nolan (2002) who reported that the range of motion of the pelvis about the longitudinal axis was significantly greater (by approximately 10°) for two professional kickers when performing maximal speed instep soccer kicks where a faster kicking foot velocity at initial ball contact was achieved compared with when they performed accurate instep kicks and their kicking foot velocity was reduced. It is believed that both the length of the final step towards the ball and the angle of the approach may influence this longitudinal pelvis rotation prior to the kicking phase as was discussed in Section 2.3.1.

The relative motion of the pelvis and trunk segments has also been identified as an important technique factor in generating a fast kicking foot velocity in soccer instep kicking. Shan and Westerhoff (2005) reported that experienced soccer instep kickers created a ‘tension arc’ across the torso whereby longitudinal rotation of the pelvis and extension of the kicking hip at the top of the backswing are accompanied by longitudinal trunk rotation (towards the left-hand-side for a right-footed kicker, opposing the longitudinal rotation of the pelvis) and maximal horizontal extension and abduction at the non-kicking-side shoulder, creating a stretch across the torso. An elite rugby kicking coach also identified the non-kicking-side arm position at the start of the kicking phase being *“taut and pulled up right across the body from the kicking leg”* as a fundamental aspect of successful rugby place kicking (Bezodis & Winter, 2014). This stretch is then released as the kicking leg swings towards the ball, accompanied by longitudinal trunk rotation (towards the right-hand-side, and a more similar orientation to the pelvis), and non-kicking-side shoulder horizontal flexion and abduction. The muscles that were previously stretched at the top of the backswing (primarily the trunk flexors and hip flexors) are able to contract with more force during the release through the stretch-shortening cycle mechanism (Komi, 1984), thereby assisting the generation of a faster kicking foot velocity at initial ball contact. In contrast, the inexperienced kickers studied by Shan and

Westerhoff (2005) did not demonstrate a significant difference in the trunk and pelvis orientations between the approach to the ball or the kicking phase, suggesting that they did not create a 'tension arc' as they approached the ball. Whilst this 'tension arc' appeared to enable the experienced kickers to generate a faster kicking foot velocity at initial ball contact, the kickers also demonstrated significantly greater trunk flexion and longitudinal rotation during the kicking phase. Ball velocity magnitude was the primary consideration in this study and so the potentially negative effect that this trunk motion may have on the accuracy of the kick was not considered. It has been suggested in the rugby coaching literature that longitudinal trunk rotation should be controlled prior to initial ball contact (Greenwood, 2003), indicating that the longitudinal trunk rotation observed during the release of the 'tension arc' may not be desirable in maintaining an accurate kick, although empirical data is required to objectively assess this.

A number of authors have commented on the importance of a ‘strong posture’ throughout the rugby place kick, as it is suggested to be important in ensuring the kicking foot travels along the correct line directing the ball to the target (Greenwood, 2003; Wilkinson, 2005). It appears that a ‘strong posture’ is generally considered to be an upright trunk and extended support leg, maintained throughout the kick with little lateral movement of the trunk (Greenwood, 2003). In contrast, ‘poor posture’ has been suggested to result in the kicker’s weight being transferred to one side, and as such is considered to cause the kicking foot to swing out of the desired line to assist in the balance of the kicker (Greenwood, 2003). This alteration to the kicking foot path would likely lead to the kicking foot velocity vector being mis-directed at initial ball contact, or at least the margin for error in its direction being reduced, which would subsequently affect the direction of the ball velocity vector post-contact, although this is conjecture and has not previously been empirically investigated in rugby place kicking. The suggestion that minimal longitudinal trunk rotation is desirable in order to achieve an accurate kick is supported by the research of Bezodis et al. (2007) who investigated the segmental contributions to whole-body angular momentum. Whilst analysing the motion of the trunk was not the primary objective of this study, minimal longitudinal trunk angular momentum was observed at initial ball contact for more accurate kickers. Bezodis et al. (2007) also identified that accurate kickers displayed greater angular momentum of the non-kicking-side arm about the global antero-posterior axis compared with the inaccurate kickers, bringing the arm closer to the midline of the body. Furthermore, the magnitude of the opposing rotational motion of the non-kicking-side arm about the global longitudinal axis was greater when kickers were instructed to kick as if from a greater distance from the posts, where they had generated greater anti-clockwise rotational motion of the kicking leg about the global longitudinal axis. It was surmised that the motion of the non-kicking-side arm counteracted that of the kicking leg, that the more accurate kickers were able to position their body more appropriately at initial ball contact and that all kickers utilised this non-kicking-side arm motion to greater effect when kicking for distance, potentially to stop over-rotation of the whole-body and to minimise trunk rotation. It therefore seems important to consider the role of longitudinal trunk rotation in rugby place kicking, both for the generation of a fast kicking foot velocity and for maintaining accuracy.

Support leg joint mechanics

Whilst the motion of the kicking leg has been widely investigated in a variety of football codes, the support leg motion has received less attention. The only aspect related to the support leg that has been investigated in rugby place kicking is the position of the support foot relative to the ball following the final step (Baktash et al., 2009; Cockcroft & van den Heever, 2016), as discussed in Section 2.3.1.

Whilst currently unexplored within rugby place kicking, aspects of the joint mechanics of the support leg have been described in soccer instep kicking (e.g. Harrison & Mannering, 2006; Inoue, Nunome, Sterzing, Sinkai & Ikegami, 2014; Kellis et al., 2004; Lees et al., 2009; Lees & Rahnama, 2013; Lyle et al., 2011). However, Lees et al. (2009) were the only researchers to report the complete kinematic and kinetic flexion-extension support leg joint time-histories from support foot contact to initial ball contact (termed the stance phase). Following support foot contact, support knee flexion (peak velocity of approximately 400°/s) was observed up to approximately 80% of the stance phase, which was accompanied by a knee extensor moment and therefore, negative knee extensor power. The support knee then extended up to initial ball contact, and a period of positive knee extensor power was observed. In contrast, the support hip extended throughout the kicking phase through positive hip extensor power. Inoue et al. (2014) also reported motion about the other hip joint axes - hip adduction immediately following support foot contact followed by abduction throughout the stance phase, and similarly rapid external rotation following support foot contact before internal rotation up to initial ball contact. The resultant joint moments about these axes were minimal throughout, but were opposing the observed motion and therefore absorbing energy. The ankle initially displayed rapid plantar flexion, inversion and adduction followed soon after by dorsiflexion, eversion and abduction (within the first 25% of the stance phase), before displaying minimal motion for the second half of the stance phase. A consistent plantar flexor moment was observed throughout the stance phase, opposing the small ankle dorsiflexion velocity meaning there was negative ankle plantar flexor power.

As the support foot is the only point of ground contact throughout the entire kicking phase, the forces it exerts directly determine the whole-body motion of the kicker. The support leg has therefore been suggested to have two major roles in kicking – to resist the ground reaction forces experienced by the player and to transfer the momentum of the kickers' whole-body centre of mass to the thigh of the kicking leg (Inoue et al., 2014). The ground reaction forces recorded underneath the support foot determine the effectiveness of the kicker in achieving both of these but, surprisingly given their evident importance, they have not been quantified in rugby place kicking to date.

The 3D ground reaction forces have been recorded throughout the stance phase in soccer instep kicking (e.g. Barfield, 1995; Inoue et al., 2014; Isokawa & Lees, 1988; Katis & Kellis, 2010; Katis et al., 2013; Kellis et al., 2004; Lees et al., 2009; Orloff et al., 2008; Rodano & Tavana, 1993). Whilst some studies simply reported peak ground reaction force values, Inoue et al. (2014), Katis et al. (2013), Kellis et al. (2004), Lees et al. (2009) and Orloff et al. (2008) presented the complete ground reaction force time-histories throughout the stance phase for amateur and professional soccer players, respectively. The broad patterns reported by the studies were similar in both the vertical and medio-lateral directions, although there were differences in the antero-posterior time-histories between the studies. The vertical force increased from support foot contact to a peak magnitude (approximately 2.0 BW) between 20 and 30% of this phase before being largely maintained up to initial ball contact. The medio-lateral forces have typically been recorded in the lateral direction (towards the left for a right-footed kicker) throughout the kicking phase, decelerating the kicker's lateral velocity caused by the angled approach to the ball (Lees et al., 2009). The peak lateral force was recorded as between 0.5 and 0.8 BW, at approximately 20% of this phase.

The antero-posterior force was typically directed in a posterior direction throughout the kicking phase, peaking at between 0.5 and 1.0 BW approximately halfway through the stance phase (Inoue et al., 2014; Lees et al., 2009; Orloff et al., 2008) and decelerating the kickers' whole-body CM throughout. Katis et al. (2013) also reported an antero-posterior force in a consistent direction throughout the time-history, but did not make clear which direction it was acting in. Kellis et al. (2014) on the other hand, reported that the antero-posterior force was initially directed posteriorly (peaking at 0.37 ± 0.03 BW between 5 and 15% of the phase), serving to decelerate the forward velocity of the kickers' centre of mass, before increasing (after 10-30% of the phase) in the anterior direction up to initial ball contact (to a peak of 0.69 ± 0.10 BW). This finding seems unlikely as it would suggest that the kickers' whole-body CM was accelerating in a forward direction throughout the kicking phase which has not been reported in any previous studies and counterintuitive given the link to the transfer of momentum from a kicker's whole-body CM to their kicking foot (Potthast et al., 2010). Potthast et al. (2010) found that the deceleration (in both the lateral and posterior directions) of the kicker's whole-body CM explained 36% of the variation in ball velocity in soccer instep kicking of 19 experienced soccer players. The authors proposed that the braking of the whole-body CM allows a portion of the whole body impulse to be transferred to the kicking leg thigh, thereby increasing the angular impulse of the segment and subsequently foot velocity, a premise which appears logical and may support their assertion that a fast approach velocity could influence the ball velocity magnitude, provided that the kicker possesses enough support leg strength to decelerate this faster approach velocity. Furthermore, Inoue et al. (2014) suggested that the positive work done at the support hip and knee prior to initial ball contact may raise the whole-body CM enabling the transfer of momentum to the kicking leg, a theory that has recently been experimentally demonstrated by Augustus, Mundy and Smith (2016). Following a technique intervention which aimed to increase the kicker's support leg hip and knee extension and vertical displacement of the pelvis and hips during the kicking phase, kickers generated a faster ball velocity and demonstrated significantly greater extension velocity of the support leg hip and knee joints which raised the support leg hip and passively extended the kicking leg knee faster down towards the ball (Augustus et al., 2016).

Analysis of the ground reaction forces in a rugby place kick would help to identify if a similar deceleration in the kickers' whole-body CM is observed for place kickers who generate faster kicking foot velocities, and whether the approach velocity appears to be a contributing factor to this. Furthermore, as previously suggested, the ground reaction forces may also be affected by the kickers' approach angle which must also be considered in the context of place kick performance.

Strength characteristics

In addition to specific technique analyses, a number of studies have investigated the lower limb anthropometric, strength and power characteristics of rugby players, based on the position that they play and their experience (e.g. Baker & Newton, 2008; Duthie, 2006; Gabbett, 2002; Nicholas, 1997). However, to date, studies have only investigated the relationship between physical characteristics and kicking performance in soccer. Wong, Chamari, Dellal, and Wisloff (2009) identified a moderate significant correlation between body mass and ball velocity ($r = 0.58$) in young soccer players (playing within the U14 years age-group), suggesting that the heavier kickers were able to generate a faster ball velocity. The relationship between quadriceps strength (measured through isokinetic dynamometry) and ball velocity is currently inconclusive with some studies showing a positive relationship (e.g. Cabri, de Proft, Dufour & Clarys, 1988; Narici et al., 1988), some a non-significant relationship (Saliba & Hrysomalis, 2001) and an unclear relationship in another (Cometti, Maffiuletti, Pousson, Chatard & Maffuli, 2001; Mognoni, Narici, Sirtori & Lorenzelli, 1994). In addition to acute cross-sectional studies, the effect of strength training programmes on ball velocity has been investigated in elite soccer players and no significant improvement in ball velocity was found, despite increases in hip flexor and knee extensor strength (Aagaard, Simonsen, Trolle, Bangsbo & Klausen, 1996; Trolle, Aagaard, Simonsen, Bangsbo & Klaysen, 1993).

2.3.3. The ball contact phase

Previous research has not typically investigated the motion of the kicker throughout the ball contact phase and instead has focussed on the technique variables at initial ball contact (such as the magnitude of the kicking foot velocity vector) which have been shown to influence the motion of the ball post-contact. Lees et al. (2009) did report both the kicking and support leg joint mechanical time-histories throughout the kicking, ball contact and follow-through phases. However, Nunome et al. (2006) identified the importance of using appropriate data treatment methods when analysing motion around initial ball contact (different from those that are typically used to process the preceding data) due to the varying frequency components within the data. As Lees et al. (2009) used a standard 12 Hz fourth order Butterworth filter to smooth their data throughout the three phases, the estimated motion around the ball contact phase presented by the authors is unlikely to represent the true motion of the kicker. Nunome et al. (2006) therefore provide the only accurate investigation of any aspect related to the motion of the kicking leg joints during the ball contact phase. Rapid ankle plantar flexion was observed after initial ball contact, after which peak angular shank velocity and peak linear ankle velocity were recorded. This rapid ankle plantar flexion has previously been investigated in order to understand injury mechanisms (due to the position of the contact on the foot segment;

Asami & Nolte, 1983; Tol, et al., 2002) or the influence of footwear design (Sterzing et al., 2008).

The ball contact phase has been identified as lasting approximately 10 ms in soccer instep kicking (Nunome et al., 2006), and thus provides little time for a kicker's technique to alter and subsequently influence ball flight. For this reason, and the challenges associated with obtaining accurate data, the ball contact phase has rarely been investigated in kicking skills. As highlighted in the preceding sections, the kicker's technique prior to initial ball contact is not yet well understood in rugby place kicking and given this earlier motion of the kicker will influence their motion during the ball contact phase, it is important to address the approach and kicking phases first.

2.3.4. The follow-through phase

Following ball contact, a follow-through phase has been identified. However, the motion of the kicker can no longer affect the ball motion and is most likely a *“release mechanism... at the end... to dissipate the energy build up... [due to] the braking forces they’re putting on themselves... a hop or a skip, it may be a run, a step on your kicking foot afterwards, it may be whatever it is but there needs to be a release”* (Bezodis & Winter, 2014). When investigating the technical factors that affect performance outcome in any kicking skill, the kickers' motion during the follow-through is therefore not of primary interest, which is reflected in the fact that it has seldom been focussed on in previous kicking studies in any football codes. The motion of the kicker during this phase is of interest in order to understand injury mechanisms and how the longevity of the kicker may be affected, which is a consideration of elite rugby kicking coaches (Bezodis & Winter, 2014), but beyond the scope of this thesis.

2.3.5. Summary of kicking technique factors and proposal of the conceptual model

Numerous technique factors have been identified which are, or could be, important for rugby place kick performance. Based on this review, a conceptual model is proposed (Figure 2.3), which includes the biomechanical variables relating to kicking technique that have been identified as potentially of most importance for investigating and understanding rugby place kicking. These factors are detailed throughout both the approach and kicking phases as the motion of the kicker prior to initial ball contact appears to be of primary interest when investigating performance in kicking skills.

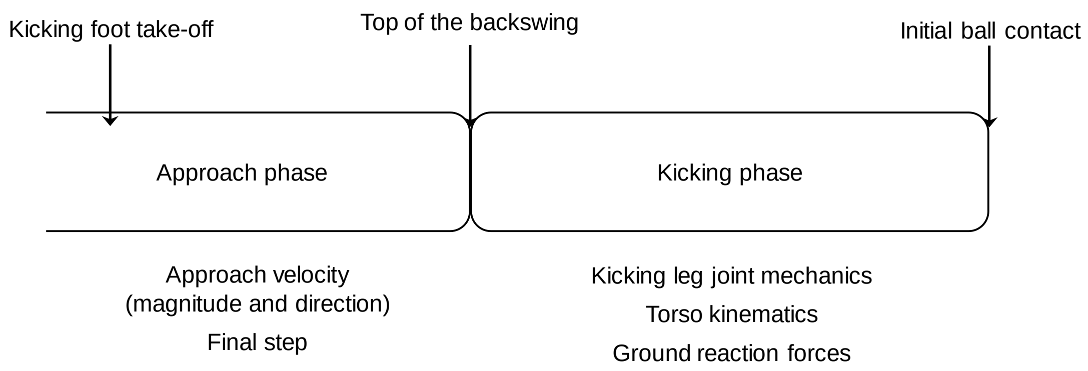


Figure 2.3. Proposed conceptual model including the biomechanical factors identified from the literature as being of primary potential importance to the success of a rugby place kick.

It is clear that rugby place kicking is a 3D action and all analysis should therefore be conducted to record the motion as such. Additionally, whilst some specific analyses have been conducted to investigate technical factors associated with generating a fast ball velocity, it is necessary to further this analysis to incorporate the inherent accuracy constraint in rugby place kicking to understand the effect of these and other factors on all initial ball flight characteristics and overall place kick performance. Furthermore, the forces exerted by the support foot from support foot contact to initial ball contact have been identified as important features of a kickers' technique in other football codes but remain unexplored in place kicking and will likely help to explain differences in the motion of kickers prior to initial ball contact.

2.4. Data collection and processing methodologies

Accurate data collection is important in all biomechanical investigations and the data collected must provide appropriate information to address the research questions. The study design must therefore be carefully considered to ensure that valid data are obtained. Whilst a field-based data collection provides ecological validity, a laboratory setting enables more sophisticated data collection, such as that of ground reaction forces, in a controlled environment. Once these data are obtained, they must be processed appropriately to reduce the effects of the noise that is typically present. Furthermore, subsequent processing may be needed to obtain the specific information of interest, for example, body segment inertia parameters are required if conducting an inverse dynamics analysis to calculate joint kinetic variables. Once the variables of interest have all been obtained, statistical analyses must then be employed in order for objective inferences to be made when comparing between groups of kickers.

2.4.1. Validity

The validity of a measurement tool reflects the degree to which it measures what it is intended to (Thomas, Nelson & Silverman, 2011). Two key components of validity are internal and external validity. The external validity concerns the validity of the experimental environment, ensuring that the results obtained can be extrapolated to the true performance setting. The internal validity of a measurement represents the accuracy of the data collected, and in order to ensure that internal validity is maintained, measurement error and bias must be minimised.

Data concerning the performance of sporting skills would ideally be collected when the skill in question is performed in a competitive situation as this is the true performance of interest - for place kicking, this would mean during a match. However, this poses a number of problems due to the need for an extensive equipment setup in order to maintain the internal validity given the various locations any kick could be taken from on the pitch. A possible alternative would be to collect the data on a rugby pitch during a training session as the equipment could be set up appropriately at a pre-determined kick location. However, this restricts which data can be collected and given that the ground reaction forces are of interest based on the previous review of literature, it is important that these can be collected. Furthermore, an outdoor environment is affected by factors such as weather and degrading ground conditions; these can affect performance through alterations to the flight of the ball and the interaction between the support foot and the ground, meaning that it is difficult to ensure consistency both within and between data collection sessions. A laboratory environment enables researchers to use sophisticated data collection systems to obtain integrated motion capture and force data to provide a comprehensive overview of the skill which is often not possible in a field-setting.

2.4.2. Force platforms

Force platforms are frequently used in studies of human movement in order to understand the underlying causes of movement. Force platforms quantify the ground reaction forces and if they are the only additional external forces acting, when combined with kinematic data in an inverse dynamics analysis, resultant internal joint forces, moments and powers can be calculated. Force platforms have been widely used in studies investigating kicking in other football codes (e.g. Inoue et al., 2014; Katis & Kellis 2010; Katis et al., 2013; Lees et al., 2009; Orloff et al., 2008) in order to aid the understanding of how the observed motion is achieved and will be critical in addressing the previously stated research questions.

2.4.3. Motion capture methods

When analysing sporting technique, the motion of the performer is typically tracked using either automatic or manual methods. If data were collected in a competitive setting, manual video capture must be used as markers cannot be attached to the players. If markers are not used to measure the 3D motion of segments, typically only joint centres can be tracked through manual digitising which does not allow the segmental or joint motions about the three principal axes to be determined. Recently, markerless systems have been introduced to record 3D human motion (e.g. Clark et al., 2012; Corazza, Mündermann, Gambaretto, Ferrigno & Andriacchi, 2010) but the accuracy of these systems for tracking small changes in rapid 3D movements is currently limited.

Automatic motion capture systems offer an accurate and comprehensive method to collect fully 3D kinematic data. Once an appropriate camera setup is established and the volume calibrated, the automatic system collects and reconstructs the displacements of identified markers that are positioned on the kicker, leaving only the data processing to the operator. The location of these markers is therefore critical in obtaining accurate estimates of the underlying anatomy. Moreover, as these systems typically consist of multiple cameras, 3D data in a large capture volume may be collected and some redundancy in the marker tracking is provided, so that more than two cameras are tracking each marker in case one camera view is obscured.

Automatic motion capture systems have been used in studies investigating rugby place kicking technique (Baktash et al., 2009; Bezodis et al., 2007; Sinclair et al., 2014; Zhang et al., 2012). Furthermore, previous studies investigating soccer instep kicking have used an integrated system, allowing simultaneous automatic motion capture and force platform data to be collected (e.g. Inoue et al., 2014; Katis & Kellis, 2010; Kellis et al., 2004; Lees et al., 2009; Lees & Rahnama, 2013; Lyle et al., 2011; Nunome et al., 2006). However, the development of a comprehensive, appropriate for the application, and accurate body segment model is critical in determining the accuracy of the data obtained, particularly when using automatic motion analysis systems which only track markers placed on the skin as opposed to recording the complete motion of the person.

Reconstruction of body segments

Regardless of the motion capture system used, the positions of markers attached to specific anatomical landmarks are tracked in order to reconstruct the underlying anatomy. This reconstruction is subject to instrumental error determined by the methods used and caused by factors including electrical interference, digitising error, landmark or marker occlusion, and skin movement artefact. This error leads to the inclusion of noise in observed values which may mask the true data. However, these effects can be minimised through both careful experimental setup (e.g. camera setup and system calibration) and data smoothing techniques (as higher frequencies typically contain proportionally more noise than the true recorded signal). This noise, whilst present in raw data, is amplified when higher derivatives are calculated (Winter, 2009). Noise will therefore be more apparent when velocities and accelerations (which are required for calculating joint kinetics) are calculated from raw displacement data. There are a number of different smoothing methods that may be employed to reduce the noise in a signal.

Polynomial and spline functions, Fourier analysis and digital filters are all smoothing methods that have previously been used in sports biomechanics research. Both polynomial and spline functions assume that the true signal has a predetermined, identifiable shape and that a function can be fit to the data. Polynomial functions tend to be fitted to raw displacement data, the equations of which can be analytically differentiated in order to calculate higher derivatives of the data (Zernicke, Caldwell & Roberts, 1976). The use of polynomials provide an adequate representation of simple, low frequency movements (such as the flight of a projectile), but may cause over-smoothing of complex, high frequency movements (such as impacts; Burkholder & Lieber, 1996). Spline functions combine a series of polynomials, of varying orders, allowing a closer match to complex high frequency movements (Burkholder & Lieber, 1996) as the signal is separated into sections. Cubic (third order) and quintic (fifth order) splines are most commonly employed in biomechanics research (Wood, 1982). When considering which of these functions to use, the researcher must decide upon the appropriate fit to the data of interest and the degree of smoothing necessary. Furthermore, the inflection points between the individual polynomials that make up the spline must be carefully selected as they may be affected by the noise in the raw data (Winter, 2009).

Another smoothing method that may be utilised by researchers involves Fourier analysis. Fourier analysis requires the transformation of the data into the frequency domain and represents the signal as a series of weighted sine and cosine terms. Presenting the data in this manner allows the identification of the high-frequency noise which can be removed prior to inverse transformation back into the time domain. Hatze (1981) describes the application of the Fourier analysis to human movements, highlighting its effectiveness with movements with a number of degrees of freedom, as it is designed to simultaneously process multi-dimensional data. Furthermore, the Fourier coefficients that are determined during the analysis allow direct computation of subsequent derivations of raw displacement data (Hatze, 1981). However, this analysis requires the data to be periodic in nature (e.g. human gait), which limits its application in more complex discrete asymmetrical movement patterns such as the rugby place kick.

Digital filters, based on a weighted moving average equation (Winter, 2009) filter data of particular frequencies from the signal. As mentioned previously, motion capture data at higher frequencies tend to contain proportionally more noise than the true signal meaning low-pass filters can be applied to remove the data above a specified cut-off frequency (Winter, 2009). The choice of cut-off frequency applied is important to ensure that the majority of the noise is removed without unduly affecting the true signal. There are a variety of methods that may be employed to objectively identify an appropriate cut-off frequency for a data set. These include regression equations (Yu, Gabriel, Noble & An, 1999), methods using the assumption that the noise present is white (Challis, 1999) or a residual analysis of the difference between the filtered and unfiltered data across a range of cut-off frequencies (Winter, 2009). Residual analyses are frequently conducted in biomechanical analyses and whilst quite labour intensive, enable researchers to visually inspect a residual-frequency graph to select the most appropriate cut-off frequency for individual data sets (Winter, 2009). There are a number of factors that must be considered when using digital filters. Firstly, as digital filters use adjacent data points when smoothing a signal, a phase-lag occurs and filters are therefore often run bi-directionally (Winter, 2009). Additionally, errors can occur at the end-points of the data set due to the recursive nature of a filter (Vaughan, 1982) and it is therefore common practise to either collect additional data outside of the period of interest, or to pad the data set at either end. The data may be padded through replication of the data end-point, linear extrapolation or reflection procedures (Smith, 1989). Unlike the other two procedures, data reflection allows the true pattern of the data at the ends of the data sets to be maintained, thereby ensuring no end-point errors occur as may be the case if there are changes in the shape of the data at either the start or the end of the data set. Derivatives of the filtered data may be calculated through finite difference equations, such as the second central difference method (Miller & Nelson, 1973).

When calculating joint kinetics, through inverse dynamics analysis, two sets of data are combined - those describing the segmental kinematics (from marker trajectories) and the external force data (typically ground reaction forces). However, as motion data typically has a lower frequency content than ground reaction forces except for when high frequency motion may occur such as in impacts, care must be taken as to how the data are processed. Some researchers have highlighted the effect of calculating joint kinetics using different cut-off frequencies to smooth these two input data sets during an inverse dynamics analysis (Bezodis, Salo & Trewartha, 2013; Bisseling & Hof, 2006; van den Bogert & de Koning, 1996; Kristianslund, Krosshaug & van den Bogert, 2012). Using two different cut-off frequencies for motion and force led to excessive fluctuations in the calculated resultant joint moments near impacts, but these fluctuations disappeared when the same cut-off frequencies were used to filter both sets of input data. It was suggested that filtering the motion data using a low cut-off frequency causes true high frequency segmental accelerations (typically observed at impacts, e.g. support foot contact) to be removed and spurious joint forces are therefore introduced. Using the same cut-off frequency to process the two sets of data in such an analysis has therefore been advised in studies where impacts occur.

In addition to the instrumental error introduced into the raw data, data collected using markers will also contain soft tissue artefact due to the movement of the marker relative to the underlying bone. Soft tissue artefact may contain both high and low frequency components and as such, only the high frequency components may be distinguishable from the true signal (Winter, 2009). Soft tissue artefacts are therefore considered to be the primary source of error in reconstructed skeletal motion from skin-mounted markers (Cappozzo, Cappello, Della Croce & Pensalfini, 1997). Due to the high forces exerted on the body, the relative movement of the skin is greater during impact situations (such as landing on the ground; Reinschmidt & van den Bogert, 1997). Soft tissue artefact may be minimised through the use of an appropriate protocol, ensuring markers are placed on areas of the skin with minimal relative movement to the bone and through appropriate attachment of the markers to the skin (Cappozzo et al., 1996;

Manal, McClay, Stanhope, Richards & Galinat, 2000; Leardini, Chiari, Della Croce & Cappozzo, 2005).

Marker clusters can also be used to reduce the effects of skin movement artefact. Clusters of three or more markers are placed on a segment, typically away from areas thought to increase skin movement artefacts. The position of these marker clusters relative to anatomical markers defining the proximal and distal ends of the segment that they are tracking are recorded in a static trial. The anatomical markers can then be removed prior to collection of the dynamic trials, removing noise due to the motion of these markers that are typically placed on bony landmarks, and that may obstruct the motion. Marker clusters are then used to track the segments during the dynamic trials, and have been shown to provide a better representation of non-sagittal plane motion than individual markers placed at anatomical landmarks/joint centres (Benoit et al., 2006). In terms of marker cluster structure, previous research (Cappozzo et al., 1997; Manal et al., 2000) has found that four markers provides an accurate representation of the bone movement (Cappozzo et al., 1997) and that the clusters should be positioned towards the distal end of the segment (Manal et al., 2000), away from bony prominences and areas overlying muscle bellies where greater skin movement occurs (Cappozzo et al., 1997). Furthermore, attaching markers to a fixture as opposed to directly onto the skin minimises the relative movement between individual markers thereby reducing the errors introduced from inter-marker movement (Manal et al., 2000). The use of marker clusters mounted on a fixture is therefore proposed as the most appropriate method to track the motion of limb segments in sporting skills.

Body segment inertia parameters

The calculation of joint kinetics requires the inertial properties of each segment in the whole-body model to be specified. This includes the segmental mass, CM location and moment of inertia. The first two of these properties are also required for the calculation of the whole body CM location using a summation of moments approach (Winter, 2009). A number of methods have been used to determine the individual segment properties and their application to the modelling of a rugby player must be considered.

A number of studies have reported segmental inertia parameters determined directly from the dissection of human cadavers (e.g. Dempster, 1955; Clauser, McConville & Young 1969; Chandler, Clauser, McConville, Reynolds & Young 1975). These ratio and regression data are provided as ratios relative to whole body mass (for segmental mass) and segmental lengths (for segmental CM location), both of which can be easily measured for any individual. This method is therefore simple for researchers to apply in any study. However, the cadaver specimens of the original datasets were typically elderly males (Dempster, 1955) who are unlikely to have a similar stature or body composition to the athletic population and so are not typically utilised in sports biomechanics research.

Mathematical models have been developed which represent the human body as a series of geometric solids (e.g. Hanavan, 1964; Jensen, 1978; Hatze, 1980; Yeadon, 1990). Subject-specific anthropometric measurements are required to determine the dimensions of each solid which are then combined with segmental density data obtained from cadaver studies to provide subject specific segment parameters. Unfortunately, the accurate measurement of the segmental dimensions is particularly time-consuming and therefore, rarely practical when working with sporting populations. These methods may therefore be of use if more complex human body models are required (due to the greater number of geometric solids identified as comprising the human body in some models, e.g. Hatze, 1980; Yeadon, 1990) if, for example, there is a focus on investigating specific segments in greater detail, or if the parameters cannot be estimated from previously obtained data using medical imaging techniques, described below.

Various medical imaging techniques have been employed to estimate body segment inertia parameters, based on the tissue distribution of the body (e.g. Durkin, Dowling & Andrews, 2002; Zatsiorsky & Seluyanov, 1983). Images are taken at regular intervals along the body, and the assessment of the tissue properties allows the calculation of the required segmental inertia parameters. However, if these methods are to be used to directly obtain the parameters for other individuals, this process requires specialist equipment and knowledge of scanning techniques, thereby limiting the accessibility to these techniques. Furthermore, if these techniques were used to identify the individual parameters of all participants investigated within a study the process would be particularly time-consuming, which is not practical when analysing sporting populations where the available time with athletes is often limited. They are, however, accurate techniques to obtain individual-specific body segment inertia parameters. Zatsiorsky and Seluyanov (1983) recorded these parameters for a group of young male athletic students which could be applied to a similarly athletic population, and presented the data in ratio form. These ratios can be used to estimate the segmental inertia parameters if the necessary anthropometric measurements were taken. The end-points of the segments identified by Zatsiorsky and Seluyanov (1983) are not easily identifiable, but the data were adjusted by de Leva (1996) who defined the segments using more conventional segmental end-points and adjusted the ratios accordingly. This method therefore offers a viable option for estimating body segment inertia parameters of a young athletic population.

Summary of motion capture methods

The methods that may be employed to collect and process the data necessary to answer the proposed research questions have been considered, including the validity of the data, the methods used to collect motion capture and force platform data, data smoothing methods and how to accurately reconstruct the underlying segmental motion from skin-mounted marker data, using appropriate body segment inertia parameters. Through appropriate selection and implementation of these methods, accurate 3D, full-body data can be obtained from rugby place kickers. In order to then make objective comparisons between successful and less successful kickers, inferential statistics are required.

2.4.4. Inferential statistics

As only a sample of a larger population is typically investigated in a research study, inferences are made regarding how the observed results relate to the complete population. Null-hypothesis significance testing (NHST) is the traditional inferential statistics method used in quantitative research studies to analyse scientific data sets (Biau, Jolles & Porcher, 2010). This approach produces a p-value from an outcome statistic to represent the probability of obtaining an effect equal to or larger than that observed, if the null hypothesis were true (Biau et al., 2010). The effect tested may be either a difference between two groups or an association between two variables and if the obtained p-value is equal to or less than a previously determined cut-off, the null hypothesis can be rejected. However, all analyses are performed on a data sample that is selected as a representation of a true population and no sample can represent a population exactly meaning that any inference made may be wrong (Hopkins & Batterham, 2016). In the case of NHST, a Type I error is made when the null hypothesis is rejected when in fact a null effect is present and a Type II error is made when the null hypothesis is accepted when in fact an effect is present. Researchers ideally wish to minimise both types of error when conducting inferential statistics. The acceptable rates for each type of error are decided in advance of a study and are typically set at an α-level of 5% (Type I error) and a β-level of 20% (Type II error) in scientific, non-clinical research (Hopkins & Batterham, 2016). The p-value cut-off described above for statistical significance is set based on the decided α-level and therefore, a null hypothesis is typically rejected if $p \leq 0.05$, with a 5% Type I error rate.

Whilst the α-level of a test can be set by the researcher, the β-level is affected by the statistical power of a test which is dependent on the sample size, the size of the effect being investigated and the α-level. As the α-level is typically already set and researchers cannot control the size of the effect, they will estimate the appropriate sample size for a study to maintain a β-level of 20%. However, in sport biomechanics research, researchers are often limited to the use of convenience sampling and therefore are not able to obtain the desired sample size meaning their study may not have sufficient statistical power to detect a true effect and any inferences made should be treated with appropriate caution (Hopkins, 2006).

In addition to concerns regarding the conservative nature of NHST some researchers argue that it is not whether there is an effect, rather the size of the effect that is of interest, since there are no truly zero effects in nature (Batterham & Hopkins, 2006). For example, in sport biomechanics an outcome statistic of $p < 0.05$ may represent an effect that is practically irrelevant to sporting performance, but in contrast a non-significant outcome could in fact be important but due to either a small sample size in the study or high measurement variability causing the p-value for the outcome statistic to be greater than 0.05 (Batterham & Hopkins, 2006). The p-value obtained through NHST does not provide the size or direction of the effect, nor an indication of the range of possible values based on the sampling variability (Batterham & Hopkins, 2006). Confidence intervals have been proposed as a more practical approach to represent the likely range in which the true population statistic would fall and when considered alongside an outcome statistic, such as a difference in means or an effect size, can be assessed in relation to values that are considered to be substantial (in either a positive or negative sense; Hopkins, 2010). The probability of the true population statistic being positive, trivial or harmful can then be calculated in order to identify the likely practical importance of the outcome statistic (Batterham & Hopkins, 2006); this approach has been termed magnitude-based inference (MBI; Batterham & Hopkins, 2006). Despite there still being some debate about preferred statistical methods, MBI is now widely used and accepted in sports science research and is therefore considered to be a practically meaningful approach to inferential statistics in sport biomechanics.

In sport biomechanics, both NHST and MBI analysis is typically conducted to compare discrete data points (such as peak values or values at specific events) within a data set despite hundreds or thousands of values across an entire time-history often being collected (Pataky, 2012). Statistical Parametric Mapping (SPM) is a method that allows complete time-normalised, one-dimensional trajectories such as GRFs or joint mechanical time-histories of multiple groups to be analysed (Pataky, 2012), and significant differences in sections of the time-histories to be identified. A statistical parametric map can be devised through computation of the scalar test statistic SPM{*t*} at every time point of the time-histories of interest. SPM{*t*} suprathreshold clusters are then identified topologically using random field theory for time points where the SPM{*t*} curve exceeds the critical *t*-threshold (Adler & Taylor, 2007). The critical *t*-threshold represents the level at which only α-level% of smooth random curves would be expected to cross, meaning the identified suprathreshold clusters represent areas in the time-histories where a significant difference is observed between groups (Pataky, 2012).

To-date, SPM has been used in biomechanical studies such as those investigating the impact of knee modelling approach (Robinson, Donnelly, Tsao & Vanrenterghem, 2013), the justification of pooling sexes when assessing GRFs during walking (Castro, Pataky, Sole & Vilas-Boas, 2015) and the contribution of support leg action to maximal instep soccer kick performance (Augustus et al., 2016). Significant differences have been observed in the time-histories, other than when peak values are observed, which would not be found when discrete data points alone are analysed. Although SPM is based on NHST and is therefore a typically conservative approach due to the aforementioned larger Type II error rates compared with MBI (Hopkins & Batterham, 2016), SPM has two major benefits over the traditional analysis of discrete data which render it of value for sport biomechanics analyses. The first is that the statistics are viewed in the same temporal space as the original data, making the inferences more meaningful (Pataky, 2012) and the second is that it removes the bias of analysing 1D data, such as joint mechanical time-histories and GRFs, using 0D (discrete) methods (such as MBI or traditional NHST; Pataky, Vanrenterghem & Robinson, 2015). The Type I error rate has been shown to increase to 38% from the traditionally accepted rate of 5%, when 1D data are analysed using 0D methods (Pataky, Vanrenterghem & Robinson, 2016). This increase in Type I error rate is due to the lower critical *t*-threshold employed in 0D methods compared with the 1D SPM method. Despite SPM being a conservative approach due to its basis on NHST, the ability to consider the complete 1D time-histories and make comparisons between multiple groups whilst maintaining a Type I error rate of 5% is desirable when analysing biomechanical data such as joint mechanical time-histories and ground reaction forces.

2.5. Chapter summary

This review of literature led to the formulation of a conceptual model identifying the key technical factors that appear important to consider during the approach and kicking phases of a rugby place kick. These factors reflected the 3D, full-body nature of rugby place kicking, the potential importance of the ground reaction forces and the need to measure joint kinetics to fully understand performance. In order to address the proposed research questions a number of considerations must therefore be made with regards to the data collection methodologies employed. Of primary importance is the need to obtain the necessary data to answer the research questions and therefore an integrated, laboratory-based automatic motion capture and force platform system is required. However, this setup does not allow the full path of the ball flight to be completed and as such the final ball position when it crosses the goal line is unknown. A method must therefore be developed that allows place kick performance to be determined in a laboratory.

Chapter 3: Development and evaluation of a measure of overall rugby place kick performance from initial ball flight data

3.1. Introduction

The success of a rugby place kick is determined by the position of the ball when it crosses the try line; a successful kick must be above a crossbar (3.0 m above the ground) and between two upright posts (5.6 m apart). Once the ball leaves the kicking foot it must therefore possess appropriate flight characteristics in order for the kick to be successful from a given location on the pitch. Whilst it is straightforward to observe and quantify rugby place kick success in a field environment, biomechanical analyses are often performed in a laboratory to allow more detailed measurement of technique-related variables. As the tighter spatial constraints of a laboratory setting rarely allow the full flight path of the ball to be tracked, studies have typically determined kicking performance using one of the flight characteristics that contributes to overall performance - the magnitude of the ball velocity vector.

Previous laboratory-based biomechanical research investigating rugby place kicking has quantified performance using the magnitude of the 2D (in the forward and vertical directions) or 3D initial ball velocity (Aitchison & Lees, 1983; Baktash et al., 2009; Bezodis et al., 2007; Holmes et al., 2006; Linthorne & Stokes, 2014; Sinclair et al., 2014; Zhang et al., 2012), and in one instance the lateral position of the ball from the assumed line of the centre of the posts was also separately considered (Bezodis et al., 2007). Whilst these measures quantify some of the initial ball flight characteristics, it is the combined magnitude and direction of the linear ball velocity vector and the ball spin that ultimately determines the success of a rugby place kick. Thus, in order to completely assess rugby place kick performance using a single measure, both factors must be considered. Furthermore, it is vital that any performance measure used is meaningful to coaches and players in order for them to understand the real-world context.

When in-flight, the path of the rugby ball is governed by equations of motion based on the gravitational and aerodynamic forces acting on the ball, as discussed in Section 2.2. Previous studies have used this knowledge to simulate the flight of sporting projectiles but the aerodynamic forces acting on a projectile cannot currently be directly measured in-flight and must therefore be estimated through other methods. Wind-tunnel experiments have been conducted to directly measure the aerodynamic forces acting on a rugby ball (e.g. Alam et al., 2008; Seo et al., 2006a; Seo et al., 2007), and these can be used to provide data for the present work. These studies were discussed in detail in Section 2.2 and the aerodynamic forces obtained have previously been used to simulate the flight of a punt kick, a screw kick and a rugby place kick, and to investigate the optimal initial conditions for each kick (Seo et al., 2006b). However, the models used for these simulations were not evaluated against experimental data and therefore the accuracy of the predictions, or the estimated aerodynamic forces, could not be determined. Furthermore, there were differences in the designs of the studies, whereby the ball was held in a stationary position (Alam et al., 2008) or rotated about either the longitudinal (Seo et al., 2006a) or medio-lateral axis (Seo et al., 2007). As a rugby ball is likely to spin about multiple axes in a rugby place kick, the most appropriate combination of forces that best represent those acting on the ball must be identified and included within a model, the accuracy of which can be assessed to address research question i:

i. **How accurately can overall place kick performance outcome be estimated from initial ball flight data?**

3.2. Methods

A six degrees-of-freedom mathematical model comprising equations of motion was developed in Matlab (v.7.12.0, The MathWorks Ltd., USA; Appendix A) to predict the flight path of a rugby ball from initial flight parameters. Developed models must be validated and verified to evaluate their accuracy, and a general process has been proposed by Hicks, Uchida, Seth, Rajapool, and Delp (2015) for all movement simulations. A modified approach comprising four stages was therefore adopted for the development and evaluation of the current model:

1. *Model development* (Section 3.2.1) to formulate the equations of motion.
2. *Model calibration* (Section 3.2.2) to identify the closest-matching model to experimental data. The combination of aerodynamic force coefficients from previously published wind-tunnel experiments that provided the closest match between the model-estimated and experimentally measured ball position after 22 m of horizontal flight were identified.
3. *Model verification* (Section 3.2.3) to ensure that systematic alterations to input data and model constants resulted in realistic changes in the model output. This stage is typically performed prior to the model calibration (Hicks et al., 2015) but for the current purposes it was more appropriate to do this once the optimal combination of aerodynamic force coefficients had been determined.
4. *Model validation* (Section 3.2.4) to check the accuracy and consistency of the modelled estimates compared with independent experimental data.

3.2.1. Model development

The inputs to the model were immediate post-contact values for 3D ball CM displacement from ball CM position on the kicking tee (d_x, d_y, d_z), linear ball CM velocity (v_x, v_y, v_z), pitch angle (θ), yaw angle (γ) and the end-over-end, yaw, and longitudinal spin velocities of the ball (ω_x, ω_γ, ω_z). The initial roll angle was not included in the model as previous wind-tunnel experiments determined it to have a negligible effect on the aerodynamic force data of a rotating rugby ball (Seo et al., 2004). All variables used in this model (and their nomenclature) are detailed in Table 3.1.

Table 3.1. Definitions and nomenclature of the variables discussed in this chapter.

Variable name	Symbol	Definition	Units
Linear kinematics			
Displacement *	d	Linear displacement of the ball CM	m
Velocity *	v	Linear velocity of the ball CM	m/s
Resultant velocity	$\vec{v}$	3D resultant linear velocity of the ball CM	m/s
Acceleration *	a	Linear acceleration of the ball CM	m/s^2
Angular kinematics			
Pitch angle	θ	Angle of the ball about the medio-lateral axis	°
Yaw angle	γ	Angle of the ball about the antero-posterior axis	°
Roll angle †	β	Angle of the ball about the longitudinal axis	°
End-over-end spin	ω_x	Angular velocity of the ball about the medio-lateral axis	°/s
Yaw spin	ω_y	Angular velocity of the ball about the antero-posterior axis	°/s
Longitudinal spin	ω_z	Angular velocity of the ball about the longitudinal axis	°/s
End-over-end acceleration	α_x	Angular acceleration of the ball about the medio-lateral axis	$°/s^2$
Yaw acceleration	α_y	Angular acceleration of the ball about the antero-posterior axis	$°/s^2$
Longitudinal acceleration †	α_z	Angular acceleration of the ball about the longitudinal axis	$°/s^2$
Aerodynamic forces and moments			
Side force coefficient	C_x	Side force coefficient used to calculate the side force acting on the ball in the medio-lateral direction	
Drag force coefficient	C_y	Drag force coefficient used to calculate the drag force acting on the ball in the antero-posterior direction	
Lift force coefficient	C_z	Lift force coefficient used to calculate the lift force acting on the ball	
End-over-end moment coefficient	Cm_x	End-over-end moment coefficient used to calculate the end-over-end moment acting on the ball about the medio-lateral axis	
Yawing moment coefficient	Cm_y	Yawing moment coefficient used to calculate the yawing moment acting on the ball about the antero-posterior axis	
Longitudinal moment coefficient †	Cm_z	Longitudinal moment coefficient used to calculate the longitudinal moment acting on the ball about the longitudinal axis	
Side force	F_x	Force acting on the ball in the medio-lateral direction	N
Drag force	F_y	Force acting on the ball in the antero-posterior direction	N
Lift force	F_z	Force acting on the ball in the vertical direction	N
End-over-end moment	M_x	Moment acting on the ball about the medio-lateral axis	N.m
Yawing moment	M_y	Moment acting on the ball about the antero-posterior axis	N.m
Longitudinal moment †	M_z	Moment acting on the ball about the longitudinal axis	N.m
Constants			
Ball volume	Vb	The volume of the ball	m^3
Air density	ρ	The air density assuming standard atmospheric conditions	$kg/m/s^2$
Ball mass	m	The mass of the ball	kg
Gravity	g	The vertical acceleration due to gravity	m/s^2
Inertia of the ball about the medio-lateral axis	I_x	The moment of inertia of the ball about the medio-lateral axis	$kg.m^2$
Inertia of the ball about the longitudinal axis	I_z	The moment of inertia of the ball about the longitudinal axis	$kg.m^2$

* The linear kinematics were resolved into their three principal directions, medio-lateral, antero-posterior and vertical (represented by the subscripts x, y and z, respectively)

† The roll angle, longitudinal acceleration and longitudinal moment and coefficient were not included in the model.

In order to estimate the position of the ball in all subsequent time iterations (i, 0.0001 s) the side, drag and lift forces (acting in the medio-lateral, antero-posterior and vertical directions, respectively, and termed F_x, F_y, F_z) were calculated using the following equations (as used by Seo et al., 2006a, 2007):

$$F_{x_{(i)}} = C_{x_{(i)}} \cdot \rho \cdot Vb^{2/3} \cdot 0.5 \cdot \vec{v}^{\,2}_{(i-1)} \tag{3.1}$$

$$F_{y_{(i)}} = C_{y_{(i)}} \cdot \rho \cdot Vb^{2/3} \cdot 0.5 \cdot \vec{v}^{\,2}_{(i-1)} \tag{3.2}$$

$$F_{z_{(i)}} = C_{z_{(i)}} \cdot \rho \cdot Vb^{2/3} \cdot 0.5 \cdot \vec{v}^{\,2}_{(i-1)} \tag{3.3}$$

The volume of the ball (Vb) was included as a constant (0.0048 m^3; Seo et al., 2006a). The air density of the surrounding environment (ρ) was also constant (1.225 kg/m^3) based on the assumption of standard atmospheric conditions at the testing location (9 m above sea level), an atmospheric pressure of 101325 $kg/m/s^2$, and a temperature of 15°C. The 3D resultant ball velocity ($\vec{v}$) calculated in the previous time iteration was calculated using Pythagorean theorem. The three aerodynamic force coefficients (C_x, C_y, C_z) were obtained as a function of pitch angle, yaw angle, longitudinal spin and a spin coefficient from the polynomial equations determined previously in wind-tunnel experiments by Seo et al. (2006a; 2007), the most appropriate of which were determined in the calibration stage (Section 3.2.2).

Longitudinal rotational acceleration of the ball was considered to be negligible due to the negligible longitudinal moment previously identified by Seo et al. (2004). However, Seo et al. (2006a) recorded an end-over-end moment (M_x) when a ball had longitudinal spin and Seo et al. (2007) recorded a yawing moment (M_y) when the ball had end-over-end spin. The end-over-end (M_x) and yaw (M_y) moments were calculated at each time iteration using the following equations:

$$M_{x_{(i)}} = Cm_{x_{(i)}} \cdot \rho \cdot Vb \cdot 0.5 \cdot \vec{v}^{\,2}_{(i-1)} \tag{3.4}$$

$$M_{y_{(i)}} = Cm_{y_{(i)}} \cdot \rho \cdot Vb \cdot 0.5 \cdot \vec{v}^{\,2}_{(i-1)} \tag{3.5}$$

The density and volume constants and the resultant ball velocities included in these equations were the same as those included in equations 3.1-3.3. The end-over-end and yaw moment coefficients (Cm_x and Cm_y, respectively) were calculated as a function of pitch angle, yaw angle and a spin coefficient using the polynomial equations previously determined from wind-tunnel experiments (Seo et al., 2007 and Seo et al., 2006a, respectively). The effect of the inclusion of these equations on the accuracy of the ball model estimates was also assessed during the calibration process, along with the drag, lift and side force coefficients (Section 3.2.2) to identify which combination provided the closest match to experimental data.

The 3D linear accelerations (a_x, a_y, a_z) of the ball CM were determined at each time iteration through the division of the forces acting on the ball by ball mass (m; 0.435 kg, average mass of the ball from the World Rugby laws) and through the subtraction of gravity from the vertical acceleration (g; 9.81 m/s^2):

$$a_{x_{(i)}} = F_{x_{(i)}} / m \tag{3.6}$$

$$a_{y_{(i)}} = - F_{y_{(i)}} / m \tag{3.7}$$

$$a_{z_{(i)}} = (F_{z_{(i)}} / m) - g \tag{3.8}$$

The end-over-end (α_x) and yaw (α_y) accelerations of the ball were then calculated at each time iteration through the division of the moments acting on the ball by the corresponding moments of inertia:

$$\alpha_{x_{(i)}} = M_{x_{(i)}} / I_x \tag{3.9}$$

$$\alpha_{y_{(i)}} = M_{y_{(i)}} / I_x \tag{3.10}$$

The moment of inertia of the ball about the medio-lateral axis (I_x) was included as a constant (0.0033 kg.m^2; Seo et al., 2006a). The end-over-end acceleration of the ball (α_x) was dependent on the pitch angle of the ball so that it was positive when the ball was orientated such that the higher end of the ball was anterior to its CM and negative when the higher end of the ball was posterior to its CM. The yaw acceleration (α_y) was dependent on the yaw angle of the ball. If the leading end of the ball was to the left of the direction of travel, the yaw acceleration acted in an anti-clockwise direction (as viewed from above) and if it was to the right it acted in a clockwise direction.

The calculated linear accelerations (a_x, a_y, a_z) were numerically integrated (trapezium rule) to obtain the instantaneous linear velocities of the ball at each time instant (v_x, v_y, v_z) by calculating the change in ball CM velocity and combining it with the velocity in the previous iteration (equations 3.11-3.13). The angular accelerations were also integrated in this way to obtain the corresponding angular velocities (ω_x, ω_y; equations 3.14-3.15).

$$v_{x(i)} = v_{x(i-1)} + ((a_{x(i-1)} + a_{x(i)}) \cdot 0.5 \cdot t) \tag{3.11}$$

$$v_{y(i)} = v_{y(i-1)} + ((a_{y(i-1)} + a_{y(i)}) \cdot 0.5 \cdot t) \tag{3.12}$$

$$v_{z(i)} = v_{z(i-1)} + ((a_{z(i-1)} + a_{z(i)}) \cdot 0.5 \cdot t) \tag{3.13}$$

$$\omega_{x(i)} = \omega_{x(i-1)} + ((\alpha_{x(i-1)} + \alpha_{x(i)}) \cdot 0.5 \cdot t) \tag{3.14}$$

$$\omega_{y(i)} = \omega_{y(i-1)} + ((\alpha_{y(i-1)} + \alpha_{y(i)}) \cdot 0.5 \cdot t) \tag{3.15}$$

These calculated linear and angular velocities were then numerically integrated (trapezium rule) to calculate the change in linear and angular displacements of the ball from the previous iteration (d_x, d_y, d_z, γ, θ) which were combined with the displacements in the previous time iteration (equations 3.16-3.20), to yield the updated position of the ball.

$$d_{x(i)} = d_{x(i-1)} + ((v_{x(i-1)} + v_{x(i)}) \cdot 0.5 \cdot t) \tag{3.16}$$

$$d_{y(i)} = d_{y(i-1)} + ((v_{y(i-1)} + v_{y(i)}) \cdot 0.5 \cdot t) \tag{3.17}$$

$$d_{z(i)} = d_{z(i-1)} + ((v_{z(i-1)} + v_{z(i)}) \cdot 0.5 \cdot t) \tag{3.18}$$

$$\theta_{(i)} = \theta_{(i-1)} + ((\omega_{x(i-1)} + \omega_{x(i)}) \cdot 0.5 \cdot t) \tag{3.19}$$

$$\gamma_{(i)} = \gamma_{(i-1)} + ((\omega_{y(i-1)} + \omega_{y(i)}) \cdot 0.5 \cdot t) \tag{3.20}$$

The estimated linear ball displacements were updated for each time iteration until d_x had reached either 2.65 m or -2.65 m (the maximum distance in the medio-lateral direction that the ball could still pass between the two goalposts, accounting for the size of the ball, irrespective of its orientation) or d_z fell below 3.15 m (the height of the crossbar, also accounting for the size of the ball). The output of the model was d_y in the penultimate frame of the simulation (when the ball would still have passed between the posts and above the crossbar). This provided a performance measure that was meaningful in a practical setting - the maximum forward displacement of the ball before the kick was unsuccessful, termed 'maximum distance'. For applied feedback to a coach or kicker, this single measure accounts for both the accuracy and speed of a kick, and represents the maximum distance that a rugby place kick could be taken from (directly in front of the posts) and be successful. The reason why the kick would have failed from a greater distance (as it was missing left, missing right or dropping short) could also be identified from the lateral and vertical displacements.

3.2.2. Model calibration

An important step in the process of developing a model is to compare the model predictions against experimental data. Part of this validation process includes calibrating the model, through assessment and adjustment of selected model constants, in order to find the closest match to experimental data (Hicks et al., 2015). Experimental data from multiple rugby place kicks were therefore collected to allow the accuracy of the ball flight model to be evaluated.

Experimental setup

Four proficient rugby place kickers (three male, one female, mean ± SD age 27.8 ± 4.1 years, mass 79.3 ± 6.5 kg, height 1.81 ± 0.09 m, three right-footed, one left-footed) participated in this study which was approved by the local research ethics committee. The participants performed a series of rugby place kicks in an indoor sports hall which allowed environmental factors such as wind and temperature to be controlled until a total of 38 usable trials were recorded. All kicks were taken from a kicking tee placed 22.00 m from a vertical wall, perpendicular to the medio-lateral centre of a target area marked on the wall.

Determination of initial ball flight kinematics

Two high-speed cameras (Phantom V5.2, Vision Research Inc., USA) synchronised to the nearest 1 ms through the illumination of 20 LEDs, recorded the initial 2.50 m of ball flight at 240 Hz and with a shutter speed of 1/1000 s. The cameras were positioned 13.00 m away from the kicking tee, with an angle of 72° between their optical axes and with their fields of view centred on the kicking tee. The cameras were calibrated using a 16-point calibration frame that filled a 1.60 × 2.00 × 2.24 m 3D volume. The positive y-axis (representing the forward direction) was horizontal and directed towards the intersecting point of the hall's floor and wall, aligned with the centre of the target, and was the intended direction of travel of the ball. The positive z-axis was vertical, and the x-axis was the cross-product of these (positive to the right), representative of the medio-lateral direction.

The raw video files of the kicking trials were imported into Vicon Motus (v.9, Vicon Motion Systems, Oxford, UK) and specific points on the rugby ball were digitised at full resolution (1280 × 800 pixels) and 2 × zoom, from a minimum of 10 frames prior to initial ball contact until the ball was no longer in view of the cameras. These points were the top and bottom of the ball and the centre of the visible panels (marked on the ball with tape, Figure 3.1) or the middle of a seam connecting the panels (also marked with tape, Figure 3.1). In addition to this, the position of the fifth metatarsal-phalangeal joint (toe) of the kicking foot was digitised in all recorded frames. Given the importance of the accuracy of these initial ball conditions as model inputs, and the random noise typically associated with manual digitisation of video data, each video clip was digitised 17 times. This was identified as the number of repetitions which provided stable values within a bandwidth of ± 0.25 standard deviations either side of the mean (using the method described by Taylor, Lee, Landeo, O'Meara & Millett, 2015). The 3D displacement time-histories of the digitised points were reconstructed from the two camera views using direct linear transformation (DLT) and .c3d files were exported to allow a rigid ball segment to be reconstructed in Visual3D (v.5, C-Motion, Ltd., Germantown, Maryland, USA). The 3D ball angle was calculated using an XYZ Cardan rotation sequence relative to the global coordinate system. The 3D linear displacements of the ball CM and the ball angles were exported for further analysis. All data from the left-footed kicker were converted to the same convention as the right-footed kickers prior to data analysis.

Figure 3.1. A rugby ball placed on the kicking tee, with one mid-panel seam and two panels visible.

The mean value of the 17 digitisation repetitions was calculated at each frame for each trial. In order to identify ball contact and ball flight, linear ball and toe velocities were calculated from raw ball CM and toe displacement data using the second central difference method. Ball contact was identified as the frame where peak forward toe velocity was recorded (Shinkai et al., 2009). The first frame of ball flight was identified as the first frame that forward ball velocity (calculated from the raw data) decreased following movement onset (Shinkai et al., 2009). Initial in-flight ball velocity was subsequently calculated in each principal direction by fitting a polynomial to the first four frames of raw ball flight displacement data (first order for both horizontal directions, second order for vertical). This number of frames was determined through pilot testing, as it was less affected by errors in the marker reconstruction than if fewer were used (identified as a stable calculated standard deviation in resultant ball velocity across all analysed trials), and provided a closer representation of initial ball velocity than when subsequent frames were included, due to the effect of aerodynamic drag (Appendix B). Initial ball pitch and yaw angles were identified from the first frame of ball flight and the end-over-end, yaw and longitudinal spin rates of the ball were then calculated as the first derivative of the respective ball angles between the first and fourth frames of ball flight.

Determination of ball position after 22 m of flight in the y-axis

Two additional high-speed (200 Hz, shutter speed = 1/1000 s) cameras (Sony FX1000, UK) were positioned 12.00 m directly in front and 13.50 m to the side of the centre of the target to determine the position of the ball when it hit the wall. These two cameras were synchronised to the nearest 1 ms using a separate set of LEDs. The frame in which the ball hit the wall was identified in the side camera and the centre of the ball was digitised in the corresponding frame of the front camera, as well as in one frame either side. The images for the front camera were calibrated through digitising a number of points of known locations over an area of 4.61 m vertically by 9.06 m horizontally on the wall (Figure 3.2). For each trial, the ball position was reconstructed from the front camera data using 2D DLT with lens correction factors through a custom Matlab script. The position of the ball in the frame when it hit the wall was used as the criterion ball position. For trials where the synchronisation lights could only be seen in one camera (due to an obstructed view; n = 8 trials), the video frame where the ball appeared to have rebounded from the wall was identified in the front camera and the centre of the ball digitised for that and the two preceding frames. The mean ball position across the three frames was used as the criterion final ball position for these trials where only one set of lights could be seen.

A panning camera (Panasonic HC-V210 HD camcorder, UK) captured the complete ball flight at 50 Hz. This panning camera was used to identify the frame in which both independent sets of synchronisation LEDs (by the kicking tee and by the target wall) were first illuminated and the number of LEDs seen in this frame. This allowed flight time to be calculated as the time between initial ball flight and the ball hitting the wall using these events identified in the high-speed cameras.

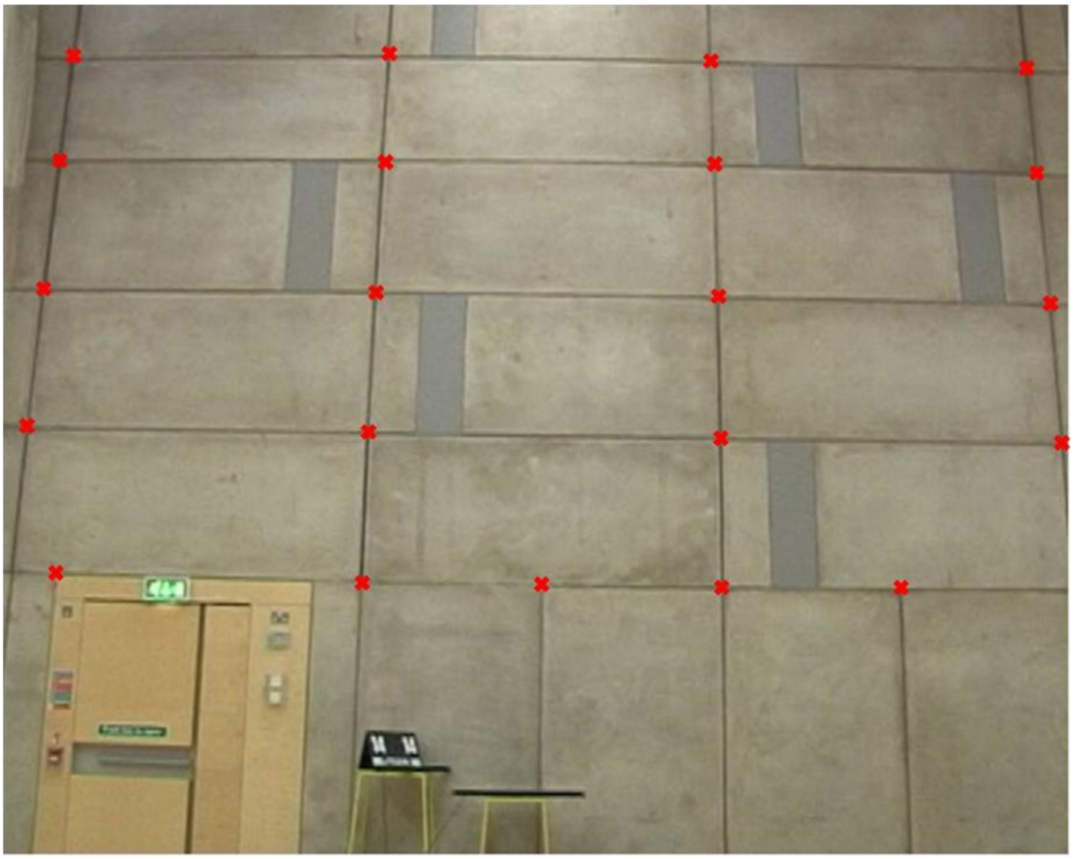


Figure 3.2 The 21 calibration points measured and digitised to calibrate the ‘front’ camera to reconstruct the final 2D ball position (calibration dimensions at their widest point of 4.61 m ✕ 9.06 m).

Identification of aerodynamic force coefficients for inclusion in the model

When developing movement simulations, Hicks et al. (2015) suggested that a model should be calibrated to identify the appropriate constants that produce an output closest to experimental data. A similar approach is important within this study as the aerodynamic forces acting on the ball throughout flight were obtained from previous wind-tunnel experiments rather than being directly measured. Whilst multiple wind-tunnel experiments have been performed which rotated the ball about different axes and against different wind speeds, none singularly represent the flight typically observed during a rugby place kick. It is therefore important to identify which combination of aerodynamic force coefficients should be included in the model to provide the closest estimate of place kick performance.

During ball flight the ball primarily spins end-over-end. It may therefore be assumed that the aerodynamic force data recorded from the study where a ball was rotated in this manner (Seo et al., 2007) would provide the best estimate of those acting on the ball throughout a rugby place kick. Seo et al. (2007) determined the side, drag and lift coefficients (C_x, C_y and C_z, respectively) as polynomial functions of yaw angle relative to the direction of travel (γ) in degrees and a spin coefficient (S, equation C.1, Appendix C) based on wind-tunnel data (equations C.2-C.4, Appendix C). The direction that the side force accelerated the ball was dependent upon the direction of the yaw angle relative to the direction of travel. A yawing moment coefficient (C_n) was also represented as a polynomial function of yaw angle and the spin coefficient (equation C.5, Appendix C).

Seo et al. (2007) did not consider the additional effects of rotations about other axes which may be present in a rugby place kick. Rotations about the longitudinal axis were investigated separately by Seo et al. (2006a) and found to cause a lateral deviation in the flight path of the ball due to a side force when the longitudinal spin rate was greater than 360°/s. It is therefore important to consider the side force data presented by Seo et al. (2006a) as it may be an important feature of kicks where longitudinal spin is present. The side force coefficient was defined as a polynomial function of pitch angle in degrees (θ) and longitudinal spin in revolutions per second (ω_z; equation C.6, Appendix C). The direction that the side force accelerated the ball was dependent upon the direction (anticlockwise or clockwise) of the longitudinal spin. A pitching moment was also recorded by Seo et al. (2006a), which was not recorded when solely end-over-end spin was present, and was represented as a function of pitch angle (equation C.7, Appendix C).

In order to calibrate the model and identify the aerodynamic force coefficients that provided the closest-matching model output to experimental data, a number of permutations were investigated which included various combinations of the above aerodynamic force coefficients within the model. The different permutations are detailed in Table 3.2, ranging from no aerodynamic forces to all of the previously estimated forces being included in the model. As Seo et al. (2006a) only recorded a side force when the ball had greater than 360°/s of longitudinal spin, this particular force was only implemented in such a situation.

For the purposes of model calibration (and validation), the mathematical model was adjusted so that it terminated once the ball had travelled 22.00 m in the forward direction (the distance the ball travelled in the experimental setup before hitting the wall), whilst both lateral and vertical ball displacements were permitted to be infinite. As independent trials are needed to separately calibrate and validate the model (Hicks et al., 2015), the 38 recorded trials were split in to two data sets of 19 trials. For the model calibration, the measured initial ball flight data from one set of 19 experimental trials were used as inputs to the model and the outputs were the estimated lateral and vertical positions when the simulated ball had travelled forward 22.00 m. Eight model permutations (Table 3.2) were used to estimate the final ball position for each kick and the model outputs were compared with the measured positions from the experimental data. The combination of aerodynamic force coefficients which produced the smallest mean difference between the model-estimated and experimentally-measured final ball positions across all 19 trials were considered to provide the closest representation of place kick performance and were therefore used in the model for all subsequent analyses.

Table 3.2. The various permutations of aerodynamic data included within each version of the model for the calibration process.

Model version	Side force coefficient (Seo et al., 2007)*	Side force coefficient (Seo et al., 2006a)*	Drag force coefficient	Lift force coefficient	Pitching moment coefficient	Yaw moment coefficient
1	-	-	-	-	-	-
2	-	-	✓	✓	-	-
3	✓	-	✓	✓	-	-
4	✓	-	✓	✓	-	✓
5	✓	✓	✓	✓	-	✓
6	✓	✓	✓	✓	✓	✓
7	✓	✓	✓	✓	-	-
8	-	✓	✓	✓	-	-

* When both side force coefficients were included in a model version, the coefficient presented by Seo et al. (2007) was applied to those trials where the longitudinal spin of the ball was less than or equal to 360°/s, whilst the coefficient presented by Seo et al. (2006a) was applied to those trials where the longitudinal spin of the ball was greater than 360°/s.

3.2.3. Model verification

Having identified the combination of aerodynamic data which provided the closest match with experimental data, this model was then verified to ensure that observed changes in the model outputs due to systematic changes to the input parameters and constants were realistic. The mean value calculated from 150 rugby place kicks (5 kicks from 30 kickers) obtained within the biomechanics laboratory (Chapter 4) were used as generalisable input data for the model and are detailed in Table 3.3.

Table 3.3. Initial ball flight parameters used as inputs to the model for the verification stage.

Variable	Initial value
Pitch angle	39°
Yaw angle	0°
End-over-end-spin	1754°/s
Yaw spin	64°/s
Longitudinal spin^	574°/s
Lateral ball position*	0.001 m
Forward ball position*	0.353 m
Vertical ball position*	0.373 m
Lateral ball velocity†	-0.5 m/s
Forward ball velocity	22.5 m/s
Vertical ball velocity	13.4 m/s

* All ball positions were with respect to the position of the ball on the tee pre-ball contact.
† A negative lateral velocity indicates it was directed towards the left of the centre of the goalposts.
^ Longitudinal ball spin was directed in an anti-clockwise direction when viewed from above.

The ball flight simulation was run, using the input data detailed in Table 3.3, until the ball was either deemed to fall below the height of the crossbar or no longer pass inside of one of the goalposts and the maximum distance noted (the criterion). Each of the above inputs and the other included model constants (e.g. m, p, V_b, I_L, I_T) were then independently increased and then decreased by 10% and the effect on the ball flight trajectory and the maximum successful kicking distance was determined and compared with the criterion.

3.2.4. Model validation

Once the model had been calibrated to identify the combination of aerodynamic force coefficients which provided the closest match to the experimental data and verified to ensure systematic changes resulted in realistic changes to the model outputs, it was then validated to assess its closeness of match to experimental data (independent trials). The model was re-run using the remaining 19 experimental trials (collected in Section 3.2.2) and the mean difference between the model-estimated and the measured ball positions was calculated. Additionally, the observed differences in ball positions were further analysed in an attempt to understand the sources of the errors.

3.3. Results and discussion

A mathematical model was developed that simulated the flight of a rugby ball from measured initial conditions. Inclusion of the appropriate aerodynamic forces from previous wind-tunnel experiments resulted in the model estimating the final ball position of 19 kicks with a mean resultant difference of 0.87 ± 0.42 m compared with the experimentally measured ball positions. This difference represents 4.0% of the total forward displacement (22.00 m). When validated against a further 19 independent kicks, the mean resultant difference between the model-estimated and measured ball positions was 0.88 ± 0.40 m. Furthermore, systematic changes in the model inputs and constants resulted in realistic changes in the ball flight and model output.

3.3.1. Model calibration

The first stage of the model evaluation process involved the model calibration, identifying which model version provided the closest match to experimental trials and, therefore, which combination of aerodynamic force coefficients from previous wind-tunnel experiments to include. Various combinations of the aerodynamic force coefficients were included in eight versions of the model to estimate the position of the ball after 22.00 m of forward flight for 19 kicks. The calculated differences between the model estimated and the measured ball positions for each model version are detailed in Table 3.4.

Table 3.4. Absolute differences in the estimated and criterion ball positions and flight times for the various model versions used to calibrate the ball flight model (all data presented as mean ± SD).

Model version	Difference in resultant displacement (m)	Difference in lateral position (m)	Difference in vertical position (m)	Difference in flight time (s)
1	1.59 ± 0.54	0.95 ± 0.84	1.06 ± 0.35	-0.23 ± 0.09*
2	1.18 ± 0.68	0.93 ± 0.75	0.53 ± 0.36	0.15 ± 0.06
3	1.72 ± 1.06	1.56 ± 1.08	0.58 ± 0.40	0.16 ± 0.07
4	1.39 ± 0.69	1.15 ± 0.71	0.60 ± 0.40	0.15 ± 0.06
5	1.06 ± 0.60	0.84 ± 0.58	0.60 ± 0.40	0.16 ± 0.06
6	0.99 ± 0.50	0.76 ± 0.54	0.53 ± 0.37	0.12 ± 0.05
7	1.47 ± 1.07	1.29 ± 1.10	0.59 ± 0.39	0.16 ± 0.07
8	0.87 ± 0.42	0.59 ± 0.47	0.51 ± 0.35	0.15 ± 0.05

* A negative flight time indicates the ball reached 22.00 m faster in the simulation than in the experimental trials.

Model version 1 contained no aerodynamic forces and simply simulated the motion of the rugby ball using equations of projectile motion. The absolute difference in the resultant displacement (in the lateral and vertical directions) of the ball between the model estimated and the measured ball positions was 1.59 ± 0.54 m and the estimated flight time was 0.23 ± 0.09 s faster than that measured, due to the absence of aerodynamic forces decelerating the ball in the model. Subsequently, model version 2 included both the drag and lift force coefficients for a ball spinning end-over-end which reduced the difference between the estimated and measured vertical displacements of the ball from 1.06 ± 0.35 m to 0.53 ± 0.36 m and the difference in resultant displacement to 1.18 ± 0.68 m. However, the error in lateral displacement remained just under a metre, suggesting that there was typically some side force acting on the ball in-flight that was not accounted for in the model.

The side force coefficient for a ball spinning end-over-end was included in model version 3. An increase in the difference in the resultant displacements to 1.72 ± 1.06 m was observed, primarily due to the larger difference in the lateral displacement of 1.56 ± 1.08 m. This suggested that solely using the force coefficients may not allow accurate calculation of the forces acting on the ball during a place kick. Model version 4 therefore also included the yawing moment coefficient presented by Seo et al. (2007) in an attempt to more accurately represent the yaw angle of the ball throughout flight. This version showed a slight reduction in the difference in resultant displacement to 1.39 ± 0.69 m, comprising a difference in lateral displacement of 1.15 ± 0.71 m. These results suggested that the side force coefficients used in versions 3 and 4 of the model (from Seo et al., 2007) do not provide an accurate representation of the side forces exerted on the ball during a place kick, which may be due to longitudinal ball spin being exhibited in reality but ignored in this model version.

Longitudinal ball spin has been shown to affect the lateral deviation of the flight path (Seo et al., 2006a) and therefore the lateral displacement of the ball. The side force presented by Seo et al. (2006a) was included in model version 5 for those kicks where the ball was spinning longitudinally at more than 360°/s in addition to the coefficients used in version 4 (i.e. the side force coefficient presented by Seo et al. (2007) for those kicks with longitudinal spin less than 360°/s was retained). The difference in the resultant displacement for this model version reduced to 1.06 ± 0.60 m and the difference in the lateral displacement reduced to 0.84 ± 0.58 m. This model therefore provided a closer match to the experimental trials and highlighted the importance of considering the multi-axial rotations of the ball in place kicking. Following this, model version 6 also included the pitching moment coefficient recorded for a ball spinning longitudinally (Seo et al., 2006a). The difference between the estimated and recorded ball positions in both the lateral and vertical directions were further reduced in this model version to 0.99 ± 0.50 m. However, analysis of the simulated angular rotation of the ball in-flight indicated that the pitching and yawing moments increased the end-over-end and longitudinal spin rates of the ball to unrealistic levels when visually compared with the experimental trials and observation of place kicking in match scenarios. These moments were recorded in wind-tunnel experiments where the ball was not rotating about the axis about which the moment was measured. Therefore, these moments do not appear to be representative of those acting on a rugby ball during the flight of a place kick where the ball is already rotating about multiple axes. This effect may be similar to that observed by Seo et al. (2004) who recorded differences in the aerodynamic forces measured for a non-spinning rugby ball compared with a spinning rugby ball.

Model version 7 was developed to identify whether the motion of the ball throughout flight was more realistically simulated without the inclusion of the pitching or yawing moments, but with all of the aerodynamic forces still included. The difference in the resultant displacement was 1.47 ± 1.07 m, due to an increase in the difference in lateral displacements to 1.29 ± 1.10 m. This increase in lateral displacement error was observed in those kicks where the longitudinal spin of the ball was less than 360°/s, where the simulated kicks tended to curve away from their original trajectory which was not reflected in the measured final ball position of the actual kicks. This suggested that the calculated side force was an over-estimation for these trials. The overestimation may be due to Seo et al. (2007) only recording the forces at yaw angles of 45 and 90° and at wind speeds of 15.0 and 20.0 m/s. As the experimental data often fell outside of these boundaries (the ball yawed through 180° and had initial resultant ball velocities of 22.5 ± 1.3 m/s) the polynomials used to calculate the coefficients may not be an appropriate representation outside of the ranges. Hence, version 8 omitted the side force coefficient for kicks with longitudinal spin less than 360°/s and provided the most accurate estimate of rugby place kick performance with a difference between the resultant estimated and measured final ball positions of 0.87 ± 0.42 m. The differences in the lateral and vertical ball positions of 0.59 ± 0.47 m and 0.51 ± 0.35 m, respectively, were also the lowest of all model versions.

The calibration stage therefore identified version 8 of the model as providing the most accurate representation of rugby place kick performance in terms of both the final ball position and the simulation of the ball motion in-flight. Model version 8 included all of the aerodynamic forces, with the side force calculated using the equations presented by Seo et al. (2006a) for a ball with over 360°/s of longitudinal spin, and no moments acting on the ball (Table 3.2). The flight times for all versions of the model incorporating aerodynamic forces (versions 2-8) over-estimated flight time by between 0.12 and 0.16 s.

This suggests that errors in the aerodynamic force and moment coefficients slow down the simulated flight of the ball compared with the experimental kicks and are therefore likely overestimates. Whilst the complete trajectories cannot be compared, the maximum estimated vertical displacement of the ball for all trials was realistic given the observed trajectories relative to the dimensions of the indoor hall, as were the projected flight paths. Furthermore, this overestimate was systematic across all kicks and all versions of the model and did not alter the relative determination of performance.

3.3.2. Model verification

Once the model was calibrated, the closest-matching model version (version 8 from Section 3.3.1) was verified using independent data to ensure that the simulation was implemented correctly and realistic changes were observed in the model output when systematic alterations were made to input and constant parameters. Selected model input parameters and constants were systematically increased and decreased by 10% and the effect on the estimated maximum distance of the kick was recorded. The direction of certain vectors was also reversed to determine the effect on the model output.

The criterion model output (‘maximum distance’: final ball displacement in the forward direction before it missed wide of the goalposts or dropped short of the crossbar) using the all-trial-averaged input data was recorded as 21.84 m and the model terminated because the ball would not have passed inside the left-hand goalpost. Systematic alterations in the linear kinematic input data produced expected changes in the model output data. Increasing the initial linear velocities of the ball led to changes in the maximum distance of -1, 4 and -3% for the lateral, forward and vertical velocities, respectively. An increase in any of the linear velocities of the ball directly affected the corresponding linear displacement as well as the resultant velocity and therefore the spin coefficient (equation C1, Appendix C) and subsequently the drag and lift forces acting on the ball (equations C2-3, Appendix C). An increase in both the drag and lift force caused the flight of the ball to have a more vertical projection, thereby decreasing the forward displacement at each time iteration. An increase in the initial lateral velocity therefore caused the ball to reach the maximum lateral displacement earlier and subsequently reduced the maximum distance to 21.60 m (1% decrease). Similarly, an increase in the vertical velocity altered the ball flight trajectory as described above (and depicted in Figure 3.3a), reducing the maximum distance (21.02 m, 3% decrease). However, an increase in the forward velocity directly increased the forward displacement of the ball at each time iteration as well as increasing the drag and lift forces and the increase in the forward displacements had a greater effect on the output than the increase in the forces (as seen by the increase in the maximum distance to 22.40 m, 4% change). Reversing the direction of the lateral velocity vector, from left to right, altered the initial direction of the ball flight, opposing the direction of the longitudinal spin. The initial trajectory of the ball in the horizontal plane was therefore less angled towards the left-hand goalpost (Figure 3.3b), allowing the ball to travel further (27.78 m, 27% increase) before it missed.

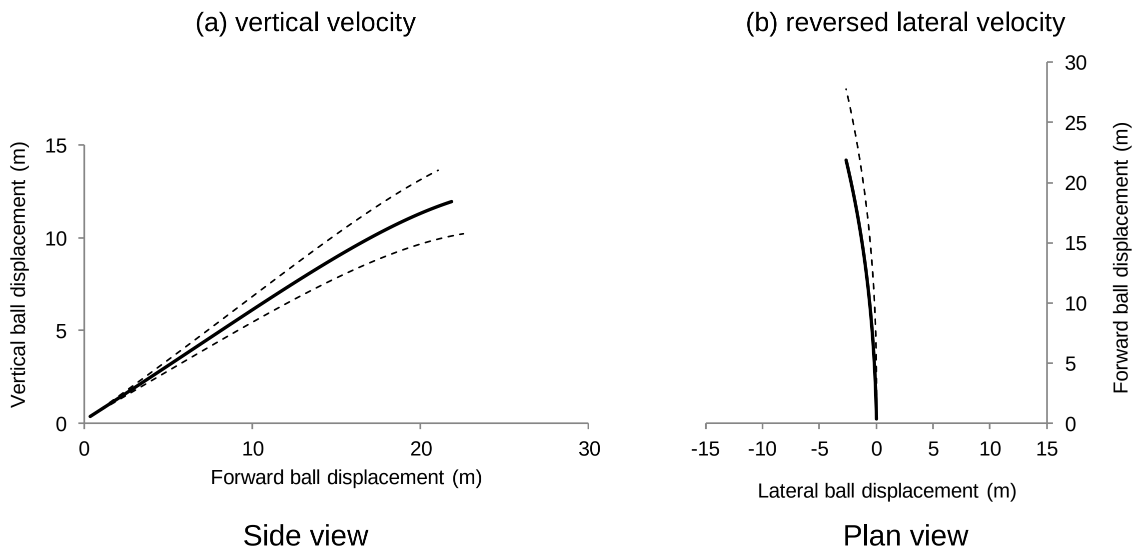


Figure 3.3. The estimated complete ball flight trajectories (dashed line), following systematic changes to selected initial linear ball input parameters, compared with the criterion trajectory (solid line): (a) vertical velocity ± 10%, as viewed from the side, (b) reversed lateral velocity, as viewed from above.

Minimal changes were observed in the ball trajectories or model outputs when systematic changes were made to the yaw and pitch angles and velocities (0 to 1% of the criterion maximum distance). This was expected as the ball continued to rotate through the complete range of ball angles, thereby negating the effect of a change of ball angle on the aerodynamic force coefficients. An increase of 10% to the longitudinal spin rate increased the side force acting on the ball (as it was greater than 360°/s), which increased the lateral velocity meaning it reached the maximum lateral displacement earlier (thereby reducing the maximum distance to 21.60 m; 1% difference compared with the criterion). The directions of both the yaw and longitudinal spin were also reversed and again the change in the yaw angular velocity had a minimal effect on the model (<1% change). However, reversing the direction of the longitudinal spin (from clockwise to anti-clockwise) altered the direction of the lateral linear acceleration of the ball and therefore ultimately reversed the direction of the lateral velocity and displacement of the ball from left to right (Figure 3.4). Subsequently, the ball travelled further forward (27.62 m, 26%) before missing the right-hand goalpost (as opposed to the left-hand goalpost previously).

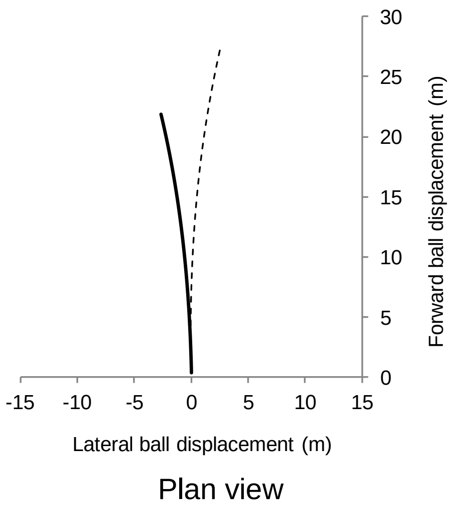


Figure 3.4. The estimated complete ball flight trajectory (dashed line), after the direction of the longitudinal ball spin was reversed (from anti-clockwise to clockwise), compared with the criterion trajectory (solid line), as viewed from above.

Analysis of the effect of alterations to the constant parameters also demonstrated the expected changes. An increase in the ball mass reduced the linear acceleration of the ball in all directions, stemming the reduction in the forward velocity, allowing the ball to travel further before it missed the posts (23.09 m, 6% increase from the criterion). In contrast to this, an increase in both the air density and ball volume caused an increase in all of the aerodynamic forces acting on the ball and therefore, the ball accelerations. The greater side force caused greater curvature in the flight trajectory whilst the drag and lift forces increased the vertical projection of the ball flight and therefore reduced the maximum distance to 20.67 m and 21.05 m, respectively (4 and 5% decreases from the criterion).

3.3.3. Model validation

Having calibrated and verified the model, the final step was to investigate the accuracy and consistency of the model against additional independent data. The model (version 8 from Section 3.3.1) was re-run using data from the other half (n = 19) of the experimental trials (collected in Section 3.2.2). The initial ball flight data were input to the model and the estimated 2D ball positions (lateral and vertical) were compared with those measured after 22.00 m of horizontal ball flight in the forward direction. The difference in the resultant displacement for these trials was 0.88 ± 0.40 m which represents 4.0% of the horizontal displacement, and is very close to the difference of 0.87 ± 0.42 m obtained during the calibration stage (Section 3.3.1). This mean difference of 4.0% is considerably smaller than that recorded by Tanino and Suito (2009) who simulated screw and punt kicks with a mean error of 25.8% of the measured horizontal displacement of the ball, suggesting that the present study provided a more accurate representation of the outcomes of place kicks than that obtained by Tanino and Suito (2009). This may be due to the aerodynamic force coefficients used in the current study, which were based on experimentally measured forces acting on rugby balls, being more accurate than the generic incompressible Navier-Stokes equations used by Tanino and Suito (2009). Furthermore, Tanino and Suito (2009) only considered the spin of the ball about one axis for each kick type (longitudinal spin for the screw kick and end-over-end spin for the high punt kick). As has been shown in this study, and can be seen in the still images presented by Tanino and Suito (2009), the ball typically rotates about multiple axes, and so the inclusion of more degrees of freedom in the initial flight parameters is necessary.

Although the model provided a close estimate of performance, the mean difference of 0.88 m between the estimated and measured displacements reflects error in one or more of the values used in the model. These errors may be due to random human error in the calculated initial ball flight parameters introduced through the digitisation process or due to errors in the aerodynamic force coefficients. The random human error was reduced by taking the mean value of 17 multiple digitisations and would likely be further reduced if using automatic marker tracking. However, it is important to understand any error introduced into the model by the aerodynamic force coefficients and the subsequent effect on the estimates.

When considering the final ball positions of all 38 experimental trials collected in Section 3.2.2, the estimates of the model demonstrated similar errors in both the lateral and vertical displacements of the ball (mean absolute errors of 0.59 ± 0.47 m and 0.51 ± 0.35 m, respectively). This suggested that there was not a specific model input or parameter that was causing greater error in a particular direction. Additionally, when the differences in the lateral and vertical displacements were compared, the error was generally consistent across all final ball positions suggesting there was little systematic bias within the model (Figure 3.5). However, there did appear to be a greater likelihood of the estimated lateral ball displacement of kicks with a final lateral displacement to the left of the centre of the goalposts (i.e. final lateral displacement < 0 m) being exaggerated compared with those that were to the right of the centre of the goalposts (i.e. more lower points towards the bottom-left-hand corner of Figure 3.5a; heteroscedastic random error). This may be due to the estimated side force being larger than that actually exerted on the ball throughout flight, causing a ball with anti-clockwise longitudinal spin to be accelerated towards the left-hand goalpost. A similar effect was seen when comparing the estimated displacements of the 17 repeated digitisations of a kick with a high longitudinal spin rate (greater than 3 rev/s; Figure Da, Appendix D) where all of the repetitions bar one over-estimated the horizontal displacement of the ball. This suggests that the error is unlikely from the digitising process and is instead likely due to the design of the wind-tunnel experiments in which the force was measured. However, the error in estimates is less than if the side force was excluded (Figure Db, Appendix D), and this force was thus retained in the model. Analysis of the differences in the vertical displacements of the ball (Figure 3.5b) suggested that larger errors were observed in those kicks with a higher vertical displacement than those with lower vertical displacements (also heteroscedastic random error). These larger errors may be due to the lift and drag forces being over-estimated within the model due to inherent errors in the aerodynamic force coefficients. Other potential inaccuracies in aerodynamic force coefficients are further highlighted in the error in the estimated flight times. The flight time was over-estimated (mean = 0.15 ± 0.05 s) for all kicks suggesting that the modelled aerodynamic forces were larger than those exerted throughout flight, reducing the forward progression of the ball.

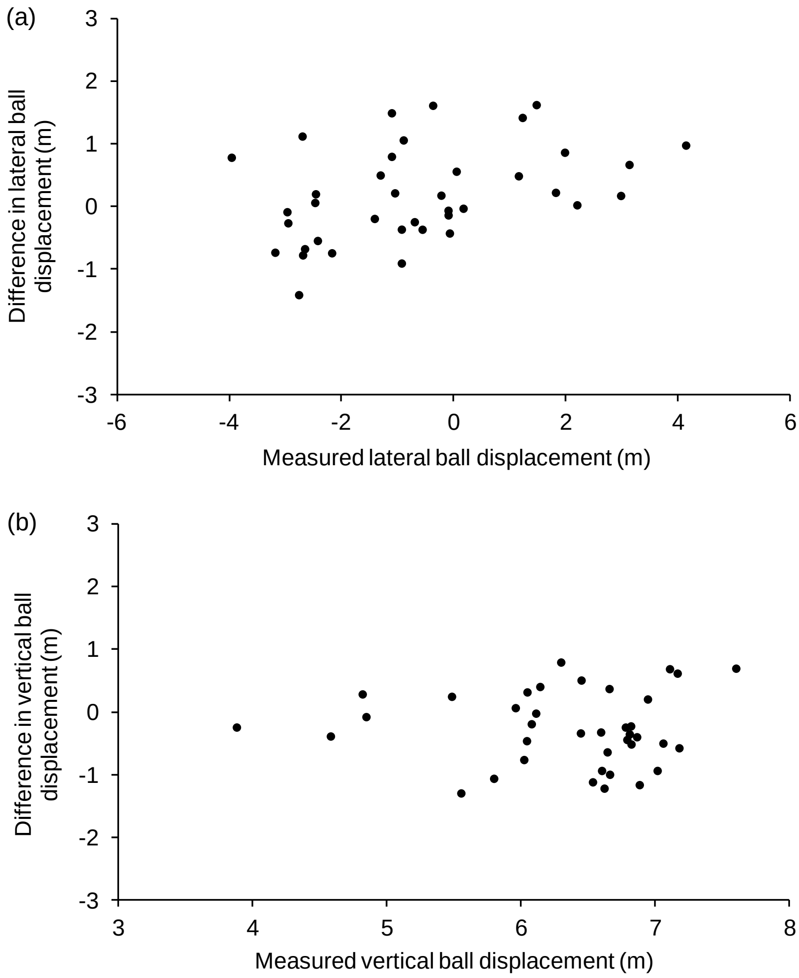


Figure 3.5. The error in estimated and measured ball positions in the (a) lateral direction and (b) vertical direction.

Based on the results of this analysis, it is suggested that the model provides a representation of rugby place kick performance which is appropriately accurate for use as an outcome measure in subsequent analyses of place kicking technique. The model provides a composite measure of overall place kick success, representative of field-based performance and therefore meaningful to coaches and players, from initial ball flight data typically available in a laboratory. Improvements to the model estimates could be made in future studies in a number of ways. Firstly, further wind-tunnel experiments may be conducted that address the methodological issues raised in this study, such as:

- the method used to mount the ball - using a magnetic suspension and balance system as opposed to a mounting rod to avoid flow disturbance around the ball
- the wind-speeds - ensuring they are representative of ball speeds achieved in place kicking
- the range of ball angles - investigating all potential ball angles relative to the wind flow

A comprehensive investigation of the ball flight trajectories of rugby place kicks was beyond the scope of this chapter which sought to establish how accurately overall place kick performance could be estimated from initial ball flight data using previously published equations to estimate the aerodynamic forces and moments acting on the ball. However, future studies may look to optimise the polynomial equations (used to estimate the aerodynamic data) through systematic adjustments to the constants. Given the number of equations used to calculate the forces and the number of constants included within them (Appendix C), care must be taken to ensure the estimated trajectory is realistic once optimum constant values, which produce the minimum error in the estimate, are identified.

3.4. Conclusion

This study aimed to develop and evaluate a method for obtaining a meaningful measure of overall rugby place kick performance using initial ball flight data. This allowed research question i to be addressed:

i. **How accurately can overall place kick performance outcome be estimated from initial ball flight data?**

The developed model was calibrated and verified, and then validated to reveal a mean error in resultant ball displacement of 4.0% of the forward displacement of the ball. This is a substantial improvement from previously evaluated models of rugby ball flight (25.8%). Given this relatively low error magnitude, it is proposed that this model can now be used to quantify rugby place kick performance from the initial 3D linear and angular ball kinematics recorded in a laboratory setting. The model can be used to estimate the maximum distance that any given kick could be taken from and be successful; a single value which incorporates both the speed and accuracy demands of place kicking and is meaningful to both players and coaches as a representation of overall field-based performance.

Chapter 4: General methods

A mathematical model was developed and evaluated in Chapter 3 which enables overall place kick performance to be determined from the initial ball flight data typically obtained in laboratory data collections. The variables proposed as important for understanding rugby place kicking technique in Chapter 2 can therefore be obtained from motion capture and ground reaction force data in a laboratory environment, and understood in the context of a true performance measure. The methods used to collect these data and to address research questions ii - vi in the subsequent chapters of this thesis are detailed in this chapter.

4.1. Participants

Thirty-three competitive rugby players who take place kicks regularly within their training regime and in competitive situations (including amateurs, players in the academies of professional clubs, full senior professionals and one senior international) volunteered to participate. Selected descriptive statistics of these kickers are presented in Table 4.1. All were free from injury and provided their written informed consent to participate (parental consent was also obtained for the two kickers under 18 years of age). The full procedures were approved by the St Mary's University Ethics Committee. Participants' heights were recorded in a neutral standing position using a stadiometer and their masses were calculated from measurements of their weight in a neutral standing position on a force platform (9287BA, Kistler Instruments Ltd., Switzerland). The length of their kicking leg was also determined as the distance between the lateral malleolus and the greater trochanter in a neutral standing position.

4.2. Laboratory setup

All trials were collected in a laboratory using a 10 or 11 camera Vicon motion capture system (7 or 8 MX cameras and 3 MX-3+ cameras, Vicon, Oxford, UK; camera resolution of 659 × 493 pixels), to record motion within an approximate 4.4 m × 6.0 m × 2.0 m capture volume at 240 Hz. The locations of the cameras around the capture volume for both right-footed and left-footed participants are depicted in Figure 4.1 and Figure 4.2, respectively, and these yielded an average resolution of measurement of 0.0009 m (identified in pilot testing by moving a rigid object with known inter-marker distances through the entire volume). Ground reaction forces from underneath the support foot were recorded using a force platform (9287BA, Kistler Instruments Ltd., Switzerland) at a sampling frequency of 960 Hz. The platform was covered with 4 mm thick Mondo Sportflex Sealskin Embossing synthetic track surface (Mondo UK Ltd., Rugby, UK) which was secured using strong double-sided adhesive tape. This was flush with the surrounding surface of the same material and thickness. Vicon Nexus (v. 1.8.3, Oxford, UK) was used to synchronously collect the data from the cameras and the force platform.

Table 4.1. Descriptive statistics of the kickers.

Kicker	Playing level	Kicking foot	Age (years)	Height (m)	Leg length (m)	Mass (kg)
1	Professional	Left	20	1.83	0.97	95.0
2	Academy	Right	19	1.67	0.83	65.9
3	Academy	Right	20	1.75	0.88	90.3
4	Amateur	Right	24	1.90	1.00	91.7
5	Academy	Left	19	1.89	1.01	87.6
6	Academy	Right	18	1.79	0.93	70.3
7	Professional	Right	18	1.84	0.99	92.4
8	Academy	Left	19	1.93	0.99	99.6
9	Academy	Right	19	1.78	0.93	84.5
10	Academy	Right	19	1.80	0.93	78.7
11	Academy	Left	18	1.90	1.01	91.3
12	Academy	Right	19	1.76	0.91	82.6
13	Amateur	Right	25	1.82	0.96	88.7
14	Amateur	Right	23	1.80	0.95	76.0
15	Academy	Right	20	1.80	0.93	85.8
16	Amateur	Right	24	1.80	0.97	84.4
17	Amateur	Right	22	1.88	0.98	90.1
18	Amateur	Left	28	1.77	0.93	82.5
19	Amateur	Left	30	1.88	0.97	103.3
20	Academy	Left	17	1.83	0.98	87.0
21	Amateur	Right	26	1.81	0.98	79.6
22	Academy	Right	17	1.76	0.93	76.5
23	Professional	Right	24	1.92	1.02	103.0
24	Amateur	Right	27	1.77	0.95	86.3
25	Amateur	Right	29	1.94	1.02	85.4
26	Amateur	Right	19	1.86	0.93	72.2
27	Academy	Right	18	1.82	0.97	84.8
28	International	Right	23	1.88	0.99	96.9
29	Academy	Left	21	1.80	0.94	94.3
30	Amateur	Left	31	1.78	0.95	75.2
31	Academy	Right	18	1.81	0.99	84.9
32	Academy	Right	19	1.76	0.92	85.1
33	Academy	Right	19	1.88	0.96	91.7
Mean ± SD			22 ± 4	1.82 ± 0.06	0.96 ± 0.04	86.2 ± 8.8

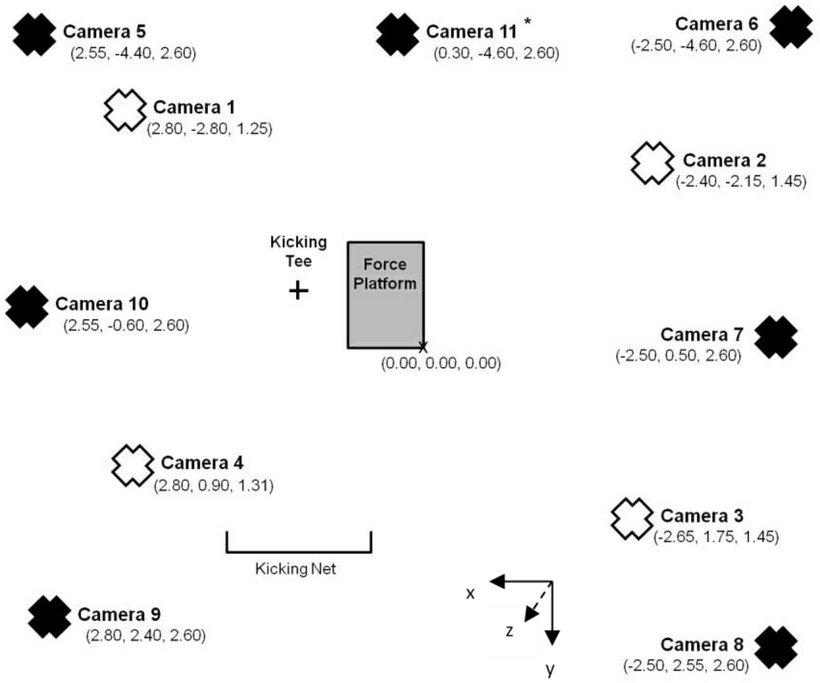


Figure 4.1. Camera setup for right-footed kickers (not to scale; all measurements taken from the corner of the force platform using an (x,y,z) coordinate system). * denotes a camera only used in the 11 camera setup. (Cameras mounted on a rig suspended from the ceiling are marked with a black cross, cameras mounted on a tripod are marked with a white cross).

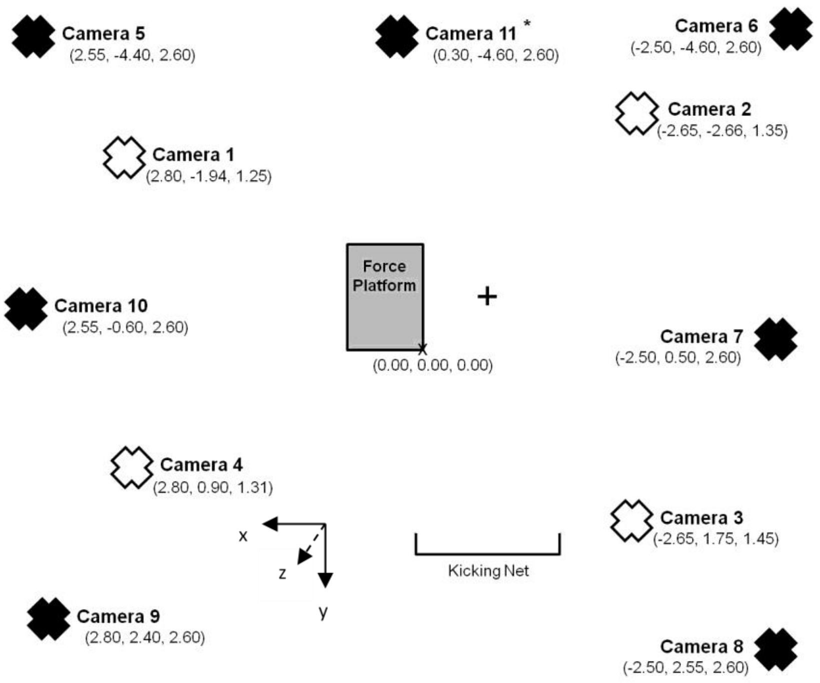


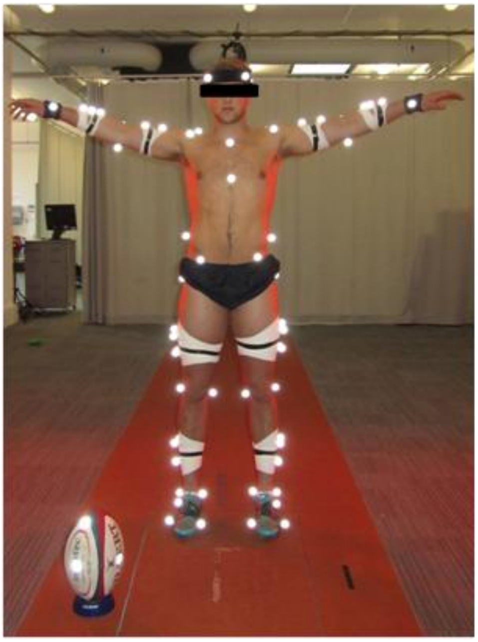
Figure 4.2. Camera setup for left-footed kickers (not to scale; all measurements taken from the corner of the force platform using an (x,y,z) coordinate system). * denotes a camera only used in the 11 camera setup. (Cameras mounted on a rig suspended from the ceiling are marked with a black cross, cameras mounted on a tripod are marked with a white cross).

The global coordinate system was set such that the y-axis represented the antero-posterior direction (forward direction, the intended direction of ball travel for a perfectly straight kick), the x-axis the medio-lateral direction and the z-axis was the cross-product of the two in the vertical direction (depicted in Figure 4.3). Prior to the commencement of the kicking trials, each kicker's tee position was identified to ensure that their full support foot landed on the force platform. A 1.2 m wide by 2.3 m high net (Extra Point Kicking Net; The Net Return LLC, Fairlawn, New Jersey, USA) was positioned 2.00 m in front of the kicking tee. A 1.20 m high by 0.05 m wide weighted ribbon was hung from the top centre of the net; this represented the line of the centre of the rugby posts and provided a target line for the players to aim at (as can be seen in Figure 4.3). All participants used a Gilbert Virtuo Matchball (size 5), with a pressure of 9.5 – 10.0 psi (as required by the Laws of the Game; World Rugby, 2015) and wore their own moulded boots.

Figure 4.3. The set-up in the laboratory for a right-footed kicker, with a ball on the kicking tee positioned next to the force platform.

Seventy-four retro-reflective markers (Vicon, Oxford, UK) with a diameter of 25 mm were used to define and track a 14 segment rigid body model of the kicker (Figure 4.4). Thirty-eight of these markers were attached to the kicker's skin using durable double-sided tape on anatomical landmarks and eight were attached to bands placed on the head and wrists, detailed in Table 4.2.

(a)



(b)

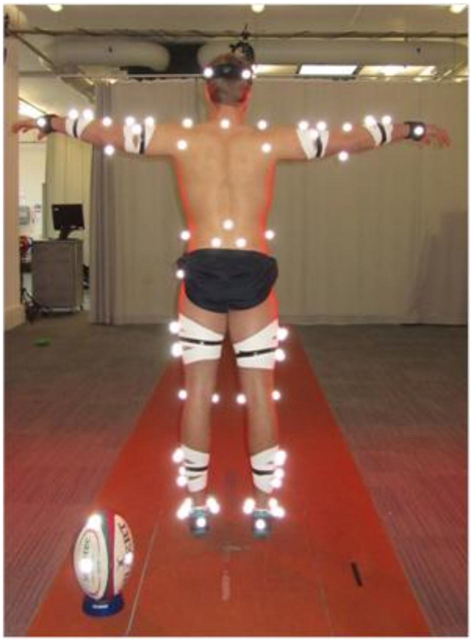


Figure 4.4. The marker setup viewed from (a) the front, (b) the rear.

Additionally, eight customised marker clusters were positioned on the arm and leg segments to track the segmental movements (as suggested by Cappozzo et al., 1997 to minimise movement artefact). The base of the marker clusters was made from Polymorph (Middlesex Teaching Resources Ltd., Hertfordshire, UK), which was identified in pilot testing as being appropriate in reducing the relative movement between four mounted markers whilst being comfortable for the kickers. The clusters attached to the leg segments consisted of four markers (Figure 4.5a), and those attached to the arms consisted of three markers (Figure 4.5b). This reduced number of markers for the arm segments reduced tracking errors associated with close proximity of markers (Cappozzo et al., 1997) yet still provided sufficient markers to accurately track the segment in three-dimensions. Prior to attaching the marker clusters, the skin was sprayed with Tuffner Pre-tape (Mueller Sports Medicine Inc., Prairie du Sac, Wisconsin, USA). The leg clusters were secured with 50 mm Tiger Tear tape (Tiger Tapes, UK) and the arm clusters with 25 mm TEA 009 Premium Tearable EAB (Fit4Sport Ltd., Oldham, UK) as depicted in Figure 4.4. The clusters were placed towards the distal end of the segment, away from bony landmarks and the muscle belly to minimise soft tissue artefact (Manal et al., 2000).

Table 4.2. Anatomical marker locations (adapted from the Vicon Plug-in-Gait marker setup, Vicon, Oxford, UK; detailed in Vicon, 2012).

Marker	Anatomical Position
RFHD / LFHD	Temple
RBHD / LFHD	On a horizontal plane to the temple markers
C7	Spinous process of 7th cervical vertebra
CLAV	Jugular notch
† RACR / LACR	Acromion process
† RAGH / LAGH	Anterior aspect of the glenohumeral joint
† RPGH / LPGH	Posterior aspect of the glenohumeral joint
STRN	Xiphoid process of sternum
T10	Spinous process of 10th thoracic vertebra
† RILC / LILC	Iliac crest
RASI / LASI	Anterior superior iliac spine
RPSI / LPSI	Posterior superior iliac spine
† RMELB / LMELB	Medial epicondyle of the elbow
RLELB / LLELB	Lateral epicondyle of the elbow
RMWRI / LMWRI	Styloid process of the ulna
RLWRI / LLWRI	Styloid process of the radius
† RGT / LGT	Greater trochanter
† RMKNE / LMKNE	Medial epicondyle of the knee
RLKNE / LLKNE	Lateral epicondyle of the knee
† RMANK / LMANK	Medial malleolus
RLANK / LLANK	Lateral malleolus
RHEE / LHEE	Calcaneous, on a horizontal plane with the ankle joint centre
† RMIDFOOT / LMIDFOOT	Lateral aspect of the foot, non-collinear to LANK and 5MTP
† R5MTP / L5MTP	Head of 5th metatarsal phalangeal joint
† R1MTP / L1MTP	Head of 1st metatarsal phalangeal joint

† Additional markers used for the identification of body segments (adapted from the models presented by Chin, Elliot, Alderson, Lloyd & Foster (2009); Lloyd, Alderson & Elliott (2010).

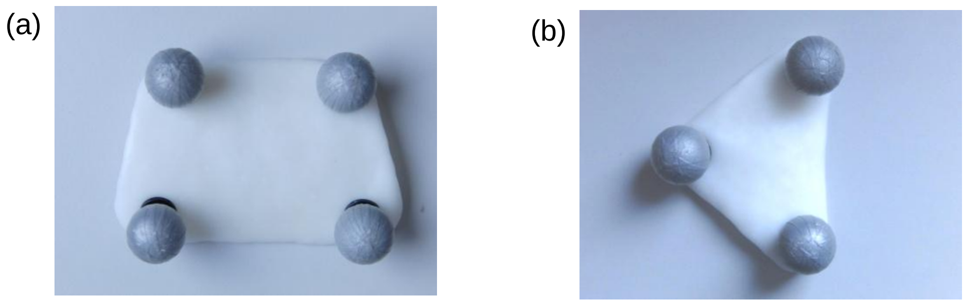


Figure 4.5. The marker clusters which were attached to the leg (a) and arm (b) segments of the participants.

The ball was also tracked as a separate segment and therefore required the attachment of reflective markers. Six circles of reflective tape (25 mm in diameter) were attached to the ball, one in the centre of each of the panels of the ball and two at known locations at the top of opposing panels (Figure 4.6; two of the panel centre markers and one of the markers towards the top of the panels are visible).

Figure 4.6. The rugby ball used by the participants.

4.3. Procedures

A static trial was first collected with all 74 markers on the kicker and six markers on the ball visible. This allowed the segments to be reconstructed through a custom rigid-body model created in Visual3D as detailed in Appendix E. This static trial also allowed the tracking markers used in the dynamic trials to be associated with the segments on which they were located (Appendix E). The markers not required for segment tracking were then removed prior to the kicking trials, leaving the eight marker clusters and 26 individual markers attached to the kicker.

Following a self-directed warm-up, the participants familiarised themselves with the environment by performing as many kicks as needed until they reported that they were comfortable. The kickers were then asked to kick as if from their maximum range in the centre of the goalposts, aiming for the target, for a minimum of seven kicks. After each kick, the kickers were provided with self-selected rest between kicks so that they could complete their kicks at a rate that would be familiar and comfortable based on their typical training.

4.4. Data processing

Positional data of the retro-reflective markers were reconstructed and labelled using Vicon Nexus. Five maximum range kicks taken by each participant were selected for subsequent analysis based firstly on marker visibility and secondly on the subjective rating of the quality of the kick (provided by the kicker after each kick was taken on a scale of 1-10, with 10 representing a perfect kick). Ball contact was identified as the frame in which the raw kicking foot 5MTP marker reached peak velocity in the forward direction (Shinkai et al., 2009) which was calculated from the raw marker trajectory using the second central difference method (Miller & Nelson, 1973). Each trial was cropped so that it ended with the frame prior to ball contact (termed 'initial ball contact) and the positional marker data along with the 3D raw ground reaction force data were exported for processing in Visual3D.

A ball segment model was applied to the static trial of each kicker which allowed the ball to be defined (detailed in Appendix E) and subsequently tracked during the kicking trials. Three-dimensional ball orientations relative to the global coordinate system were calculated using an XYZ Cardan rotation sequence. These orientations and the raw ball CM displacements were exported for all frames from initial ball flight onwards, identified as the first frame where the raw forward velocity of the ball CM first decreased after initial ball contact (Shinkai et al., 2009); which was calculated from the raw ball CM trajectory using the second central difference method (Miller & Nelson, 1973). The initial linear velocity of the ball CM was calculated from polynomial functions fitted to the first four frames of the raw displacement data (first order for both horizontal directions, second order for vertical). The ball angular velocities were calculated in each of the principal directions as the first derivative of the respective ball orientation relative to the global axes between the first and fourth frames of ball flight. The initial 3D resultant ball velocity was calculated using Pythagorean theorem. The launch angle of the ball was calculated using the initial linear velocities of the ball CM in the forward and vertical directions, and the lateral angle was calculated using the initial forward and lateral linear velocities. The model developed in Chapter 3 was then used to determine the 'maximum distance' of each kick and for each kicker, the kick with the largest maximum distance was selected for subsequent analysis as it represented the kicker's best performance of all those completed. In a practical setting, the success of a kicker is typically determined as their maximum 'range', that is the maximum distance from the goalposts that they can be successful from. Thus, the kick representative of the best performance was chosen because this research aimed to investigate differences in the technique of kickers based on the highest level of performance they were capable of achieving.

The 14 segment rigid body model (detailed in Appendix E) was applied to the static trial for each kicker which, when combined with the segmental inertia data of de Leva (1996), defined each segment. Adjustments were made to the inertia properties of both the feet and forearm-hand segments proposed by de Leva (1996). The foot was modelled as a segment from the ankle joint centre to the mid-metatarsal-phalangeal joint as described by Winter (2009) and the average boot mass (0.3 kg) was added to the foot segment. The moment of inertia of the foot segment was then calculated using the equations presented by Winter (2009) based on this combination of foot and boot mass. The hand segment was not included in the model and therefore the mass and inertia of the hand were accounted for in the forearm segment, using the parallel axis theorem and assuming a fixed angle of 0° (full extension) between the hand and forearm segments.

When applying this model to the dynamic trials, gaps in the marker trajectory data of ten consecutive frames or less were interpolated with a cubic spline which used data from three frames either side of the gap; any trials that contained longer gaps were not considered for analysis due to the potential errors introduced when interpolating larger gaps (Howarth & Callaghan, 2010). Following any gap filling, 20 data points were padded by reflection at both the start and end of each data set (Smith, 1989) and these marker displacement data were filtered using a fourth order zero-lag Butterworth filter at a cut-off frequency of 18 Hz. This frequency was determined through residual analyses (Winter, 2009) performed on markers from two randomly selected trials for each kicker. One tracking marker from each of the body segments was randomly selected and the mean identified cut-off frequency of the markers for all kickers was used to filter the marker trajectories across all trials. Soft tissue artefact and measurement error in the reconstructed data were minimised through the use of a global optimisation (Inverse Kinematics) approach to compute segmental pose data using a Quasi-Newton optimiser, based on methods proposed by Lu and O'Connor (1999) within Visual3D. This permitted unconstrained 3D rotations at all joints but translations were prohibited. The cut-off frequency used to filter the estimated segmental poses from the global optimisation was the same as that used to filter the raw marker data (18 Hz). The raw ground reaction force data were also filtered using a fourth order zero-lag Butterworth filter at 125 Hz, identified through residual analysis (Winter, 2009). Residual analysis was performed on the ground reaction force data of the same two randomly selected trials as the marker trajectories, for each participant, and the mean cut-off frequency was used to filter the ground reaction force data.

Three key events prior to initial ball contact were then identified from the processed data:

- Kicking foot take-off: the frame in which the kicking foot last left the ground before initial ball contact based on the kicking foot 5MTP marker being greater than 0.10 m above the ground (Lees et al., 2009).

- Support foot contact: the frame in which the support foot made contact with the force platform, identified when the recorded vertical ground reaction force data first increased, and subsequently remained above, a threshold of 10 N.
- Top of the backswing: the frame where the kicking foot CM reached its highest vertical position prior to initial ball contact.

The kickers' whole-body CM location was calculated using a summation of segmental moments approach (Winter, 2009) and CM displacement and velocity time-histories were determined. The whole-body CM kinematics at kicking foot take-off, support foot contact and initial ball contact were then extracted from these time-histories. The net impulse was calculated in the principal directions through integration of the ground reaction force time-histories (trapezium rule) and divided by the kickers' mass to calculate the deceleration in the whole-body CM between support foot contact and initial ball contact.

Kicking leg hip, knee and ankle joint angular displacements were calculated using the XYZ (flexion/extension, abduction/adduction, internal/external rotation) Cardan rotation sequence as suggested to be most appropriate for kicking actions (Lees, Barton & Robinson, 2010). Full hip and knee extension were defined as 0°, and the ankle angle from each participant’s static trial was defined as 0°. Joint angular velocities were also calculated, with the proximal segment of the joint used as both the reference segment and resolution coordinate system for all joints. Absolute pelvis, trunk and kicking leg segmental angular displacements were also calculated relative to the global coordinate system using the XYZ Cardan rotation sequence. Absolute longitudinal pelvis rotation velocity was calculated, with the global coordinate system used as the reference, but with the pelvis segment as the resolution coordinate system (so that it would be comparable to the calculated longitudinal rotation displacement). Finally, the angular displacement of the trunk relative to the pelvis was calculated using an XYZ Cardan rotation sequence (as suggested by Brown, Selbie & Wallace, 2013, for analysis of the ‘X-factor’ in golf).

Resultant joint moments of the kicking leg hip, knee and ankle joints were resolved into the joint coordinate system (Kristianslund, Krosshaug, Mok, McLean & van den Bogert, 2014) through an inverse dynamics analysis and the joint powers were referenced to the global coordinate system. For the inverse dynamics analysis, separate copies of the raw external ground reaction force data, were filtered using a fourth order zero-lag Butterworth filter at 18 Hz in order to prevent potential artefacts in the subsequently determined joint kinetics (Bezodis et al., 2013; Bisseling & Hof, 2006; van den Bogert & de Koning, 1996; Kristianslund et al., 2012). The total negative and positive work done at each joint was calculated through integration of the joint power time-histories (trapezium rule). The joint moment, power and work data were normalised for comparison between participants using the equations presented by Hof (1996), with height substituted for leg length as described previously (the equation presented for joint power was corrected according to the recommendations of Bezodis, Salo & Trewartha, 2010):

$$\text{Normalised joint moment} = \frac{\text{joint moment}}{(\text{body weight} \times \text{height})} \qquad (4.1)$$

$$\text{Normalised joint power} = \frac{\text{joint power}}{(\text{body mass} \times \text{gravity}^{3/2} \times \text{height}^{1/2})} \qquad (4.2)$$

$$\text{Normalised joint work} = \frac{\text{joint work}}{(\text{body weight} \times \text{height})} \qquad (4.3)$$

The recorded ground reaction force data were normalised by dividing by the participant's body weight (Hof, 1996). The length of the final step towards the ball was calculated as the resultant displacement between the kicking foot CM in the frame prior to kicking foot take-off and the support foot CM at support foot contact. The angle of this step relative to the global antero-posterior axis was also calculated from the forward and lateral components of this displacement. The distance between the support foot CM at support foot contact and the ball CM was also calculated.

All variables measured in the medio-lateral direction and joint rotations about the antero-posterior and longitudinal axes were inverted for the left-footed kickers to allow direct comparison with the right-footed kickers. Initial ball contact was labelled as occurring at 0.0 s and all joint and segment mechanics were time-normalised to 101 samples using an interpolating cubic spline across the downswing phase (from the top of the backswing to initial ball contact) and ground reaction force data to 101 samples across the stance phase (from support foot contact to initial ball contact).

4.5. Statistical analysis

For comparisons between discrete variables, effect sizes were calculated (Cohen, 1988) to assess the magnitude of the difference between the variables. The effect sizes were interpreted as: <0.2, trivial; 0.2 to 0.6, small; 0.6 to 1.2, large and >2.0, very large (Hopkins, Marshall, Batterham & Hanin, 2009). Following this, 90% confidence intervals were calculated and magnitude-based inferences were derived using a spreadsheet (Hopkins, 2007). A threshold of 0.2 was considered to be a practically important effect (Hopkins et al., 2009; Winter, Abt & Nevill, 2014), meaning that substantial positive and negative effects could be determined as follows. If the upper CI was greater than 0.2 and the lower CI did not cross -0.2, the effect was found to be substantially positive. If the lower CI was less than -0.2 but the upper CI was not greater than 0.2, the effect was found to be substantially negative. If the upper and lower CIs crossed 0.2 and -0.2, respectively, the effect was found to be unclear. The likelihood of the true value falling within each classification of positive, trivial and negative was also calculated.

For comparisons between complete time-histories, a statistical parametric mapping two-tailed independent samples t-test (SPM; Friston, Ashburner, Kiebel, Nichols & Penny, 2007) was used. The scalar output statistic, SPM{t}, was calculated separately at each individual time point, and where this crossed the critical threshold which only 5% of smooth random curves would be expected to cross, differences between the time-series were identified. All SPM analyses were implemented using the open-source spm1d code (v.M.0.3.6, www.spm1d.org) in Matlab.

4.6. Chapter summary

This chapter detailed the general methods used to address research questions ii-vi in the subsequent experimental chapters. The characteristics of the participants and the experimental protocol were described, and the data processing methods used to reconstruct the underlying segmental kinematics of these participants during kicking trials was explained, ensuring movement artefact were minimised through the use of marker clusters and global optimisation procedures. The calculations used to obtain the specific kinematic and kinetic variables of interest were described, including how they were normalised to compare between separate groups of participants, and the statistical methods used to perform these comparisons in both discrete variables and complete time-histories were outlined. These methods can now be used to investigate the ball flight and kicking techniques during laboratory-based data collections with a view to understanding differences in technique and performance between successful and less successful rugby place kicks.

Chapter 5: Understanding place kick performance through an investigation of initial ball flight characteristics

5.1. Introduction

A meaningful measure of rugby place kick performance was developed and evaluated in Chapter 3. This quantified the maximum distance from which any given kick could be successful by accounting for the magnitude and direction of the ball velocity vector post-contact, the spin of the ball and the aerodynamic forces acting on the ball throughout flight. This measure allows overall place kick performance to be determined from data collected in a laboratory using the methods detailed in Chapter 4. A more complete understanding of rugby place kicking can then be gained than that previously possible in research which has typically focussed only on the magnitude of the ball velocity when assessing performance (Aitchison & Lees, 1983; Baktash et al., 2009; Sinclair et al., 2014; Zhang et al., 2012).

The combination of the initial ball flight characteristics of a kick ultimately determines its outcome. Whilst maximising the linear velocity of the ball will cause the ball to travel further, if the launch angle of the ball is too low or too high then the ball will drop below the height of the crossbar closer to the kicking tee than it would have with an optimal launch angle. Linthorne and Stokes (2014) previously identified an optimum launch angle of 32.3° (± 1.9°, 95% CI) for obtaining the maximum distance in a rugby place kick through simulations based on a single place kicker. However, even if the launch angle is optimal, if there is a sufficient lateral component to the initial velocity, the ball will pass to the left or right of the goalposts before it drops below the height of the crossbar. Longitudinal spin will also cause the ball to curve away from its initial direction of flight; for a right-footed kicker this is typically in an anti-clockwise direction when viewed from above, causing the ball to 'draw' from right to left.

The initial ball velocity (magnitude and direction) and the spin imparted on the ball during ball contact all combine to determine the outcome of a place kick. There are therefore different possible explanations for why a given kick may miss short, left or right, but these differences in the initial ball flight characteristics have not been investigated. An understanding of these differences would allow practitioners to identify how different performance outcomes are achieved and which components of initial ball flight are key to those successful performers. Grouping the kickers based on their performance outcomes will also enable comparisons to be made between successful and less successful kickers when subsequently investigating and understanding the aspects of technique which influence the ball flight. The next research question to be addressed is therefore:

ii. **How do the initial ball flight characteristics differ between place kicks with different performance outcomes?**

5.2. Methods

Thirty-three male place kickers (mean ± SD, age = 22 ± 4 years, mass = 86.2 ± 8.8 kg, height = 1.82 ± 0.06 m, 24 right-footed, nine left-footed) each performed five maximum range place kicks in a laboratory environment (as described in Chapter 4). Their segmental kinematics were tracked using 54 reflective markers and the motion of the ball was recorded using six attached circles of reflective tape (also described in Chapter 4).

The initial ball flight characteristics were obtained for all trials using the procedures described in Section 4.4 and the maximum distance of the kicks was estimated using the ball flight model developed in Chapter 3. For each kicker, the kick with the greatest maximum distance was identified and selected for further analysis. The initial 3D resultant ball velocity, the launch angle, the lateral angle and the angular velocities about the medio-lateral (termed 'end-over-end spin') and longitudinal axes (termed 'longitudinal spin') were extracted for each of these kicks. All data from left-footed kickers were converted to the same convention as the right-footed kickers prior to data analysis.

Comparison of performance measures

The kicks were firstly ranked in order based on their maximum distance. They were then also separately ranked based on the magnitude of their resultant velocities and a Spearman's rank-order correlation coefficient (ρ) was calculated between these two data sets. The magnitude of the correlation coefficient was interpreted as: <0.1 = trivial, 0.1 to 0.3 = small, 0.3 to 0.5 = moderate, 0.5 to 0.7 = large and >0.7 = very large (Cohen, 1988). 90% confidence intervals (CIs) were calculated from the correlation coefficient and magnitude-based inferences were derived using a spreadsheet (Hopkins, 2007). A threshold of 0.1 was considered to be a practically important effect (based on the magnitude thresholds suggested by Cohen, 1988), meaning any correlation coefficients between -0.1 and 0.1 were deemed to be trivial. If the upper CI was greater than 0.1 and the lower CI did not cross -0.1, the relationship was found to be substantially positive. If the lower CI was less than -0.1 but the upper CI was not greater than 0.1, the relationship was found to be substantially negative. If the upper and lower CIs crossed 0.1 and -0.1, respectively, the relationship was found to be unclear.

Grouping of kickers based on their kick outcome

The kickers were then grouped based on the performance outcome of their best kick. Initially, those kicks with a maximum distance greater than 32 m (the average distance from the posts that a place kick was taken in international matches between 2002 and 2011; Quarrie & Hopkins, 2015) were identified. These kicks were considered to be more successful and were subsequently termed 'long' kicks. Those kicks with a maximum distance less than 32 m were identified as being less successful and were sub-divided based on their reason for the failure. Those which remained straight but dropped short were separated from those which missed left and those which missed right. Four distinct groups of kicks were therefore identified:

1. The **long** kicks - the more successful kicks with a maximum distance greater than 32 m.

2. The **short** kicks - the less successful kicks with a maximum distance less than 32 m because they dropped short of the crossbar.

3. The **wide-left** kicks - the less successful kicks with a maximum distance less than 32 m because they missed the left-hand goalpost.

4. The **wide-right** kicks - the less successful kicks with a maximum distance less than 32 m because they missed the right-hand goalpost.

Comparison of ball flight characteristics

Once the kicks had been categorised, group means and standard deviations were calculated for all initial ball flight variables. Effect sizes were calculated to compare each of the variables between each group pairing (Cohen, 1988), before 90% CIs of these effect sizes and magnitude-based inferences were derived with a smallest important effect determined as an effect size of 0.2 (Batterham & Hopkins, 2006; detailed in Chapter 4).

5.3. Results

Comparison of performance measures

The initial ball flight characteristics (mean ± SD) of the 33 kickers are presented in Table 5.1. A substantially positive relationship was found between the ranking of the kicks based on the maximum distance and the resultant velocity (ρ = 0.52, 90% CI = 0.27 to 0.71). The difference in rankings of the individual kicks between the two performance measures is depicted in Figure 5.1.

Table 5.1. Initial ball flight characteristics of the kickers (mean ± SD).

	Group mean ± SD
Maximum distance (m)	33.74 ± 7.47
Lateral velocity (m/s)*	0.3 ± 1.0
Forward velocity (m/s)	22.5 ± 2.9
Vertical velocity (m/s)	13.6 ± 1.9
Resultant velocity (m/s)	26.4 ± 2.7
Lateral angle (°)*	1 ± 3
Launch angle (°)	31 ± 5
End-over-end spin (°/s)	2359 ± 914
Longitudinal spin (°/s)[†]	469 ± 375

* Directed towards the right-hand-side of the goalposts.
[†] In an anti-clockwise direction when viewed from above

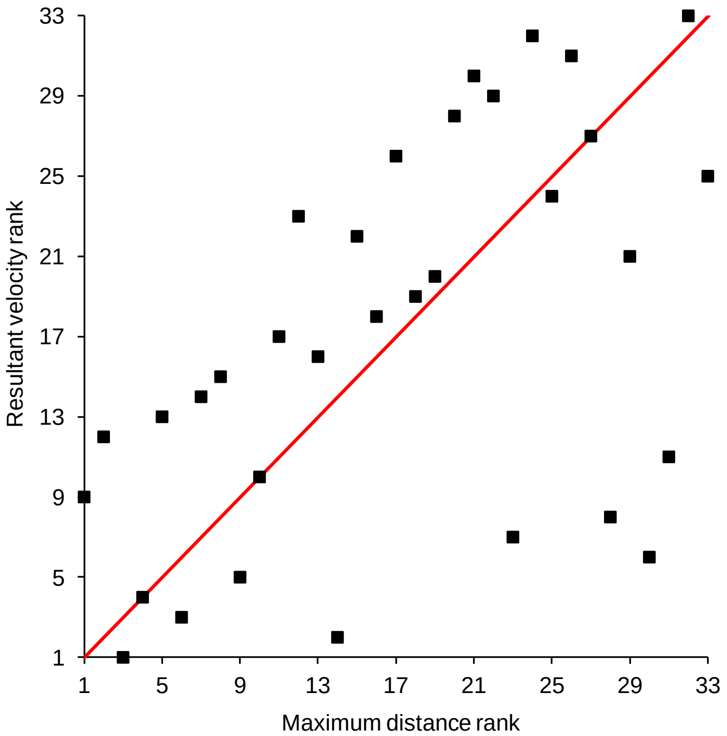


Figure 5.1. The performance rankings of the maximum kicks of 33 kickers based on the maximum distance and the resultant ball velocity. A ranking of 1 represents the best performance and 33 the worst. The red line represents a perfect rank order correlation, those kicks below the line were ranked higher based on their resultant velocity and those above the line on their maximum distance.

Grouping of kickers based on their kick outcome

The kickers were then categorised into the four distinct groups based on their kick outcomes. As two kicks were within 4.0% (the previously determined accuracy of the ball flight model, Chapter 3) of the 32 m maximum distance threshold, they were excluded from all further analysis as they could not be confidently grouped. The remaining kicks were then categorised into the four groups (Table 5.2) and the descriptive characteristics of the kickers who performed the kicks in each of these groups are detailed in Table F.1, Appendix F. As only one kick was classified into the wide-right group, this group was removed from any further analysis. Thirty kicks, classified into three distinct groups, were therefore included in all subsequent analyses.

Table 5.2. Number of kicks classified into each group.

Group	Number of kicks
Long	18
Short	4
Wide-left	8
Wide-right	1

Comparison of ball flight characteristics

The mean ± SD of the initial ball flight characteristics of the kicks within each of the three remaining groups were calculated (Table 5.3) and 90% CIs calculated. The maximum distance of the short and the wide-left kicks was 27.25 ± 3.80 m and 25.88 ± 3.24 m, respectively (Table 5.3). These kicks were substantially shorter than the long kicks (39.30 ± 4.92 m; Figure 5.2). There was no clear difference between the maximum distance of the wide-left and short kicks (Figure 5.2).

Table 5.3. Initial ball flight characteristics of the three groups (mean ± SD).

	Long	Wide-left	Short
Maximum distance (m)	39.30 ± 4.92	25.88 ± 3.24	27.25 ± 3.80
Resultant velocity (m/s)	27.6 ± 1.7	26.9 ± 1.6	20.8 ± 2.2
Lateral velocity (m/s)*	0.3 ± 1.0	-0.3 ± 0.7	0.7 ± 0.7
Forward velocity (m/s)	23.5 ± 1.8	23.6 ± 2.5	16.9 ± 1.6
Vertical velocity (m/s)	14.4 ± 1.2	12.5 ± 2.7	12.0 ± 2.0
Lateral angle (°)*	1 ± 3	-1 ± 2	2 ± 3
Launch angle (°)	31 ± 3	28 ± 7	35 ± 3
End-over-end spin (°/s)	2263 ± 877	2307 ± 663	2070 ± 1377
Longitudinal spin (°/s)	288 ± 206	746 ± 466	473 ± 394

* A negative lateral velocity and lateral angle indicates that the ball was initially travelling towards the left-hand-side of the goalposts, with a positive value directed towards the right-hand-side.

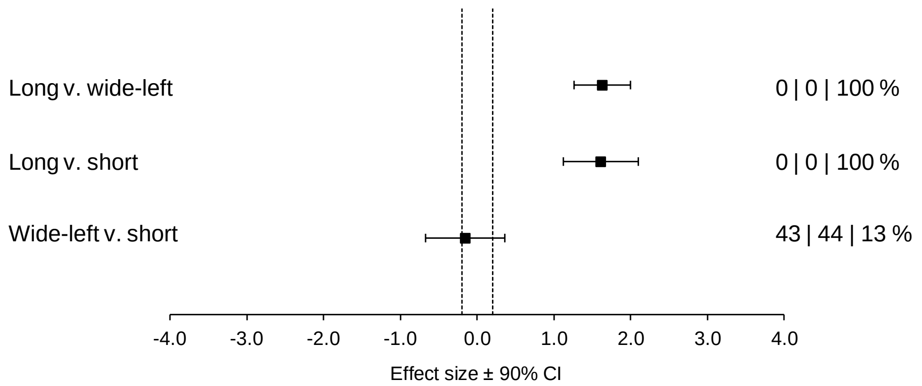


Figure 5.2. Effect sizes (± 90% CI) between the maximum distances of the long, wide-left and short kicks. The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each comparison represent the likelihood that the effect is negative | trivial | positive.

There was no clear difference in the resultant ball velocity magnitudes of the long and wide-left kicks (Figure 5.3). However, the resultant ball velocity of both of these groups of kicks was substantially faster than that of the short kicks (Figure 5.3). There were also differences between the groups when the ball velocity was considered in each of the three principal directions. The lateral velocity of the long kicks was substantially more positive (directed towards the right-hand-side of the goal) compared with the wide-left kicks (Figure 5.4), the lateral velocity of the wide-left kicks was substantially more negative compared with the short kicks, but there was no clear difference between the long and short kicks (Figure 5.4).

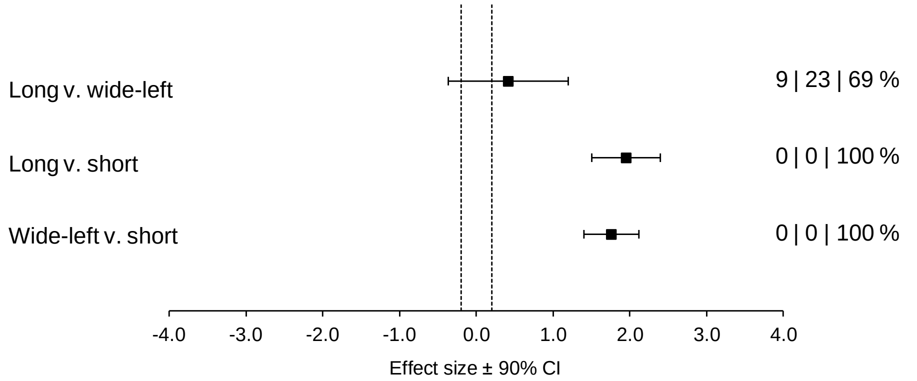


Figure 5.3. Effect sizes (± 90% CI) between the resultant ball velocity magnitudes of the long, wide-left and short kicks. The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each comparison represent the likelihood that the effect is negative | trivial | positive.

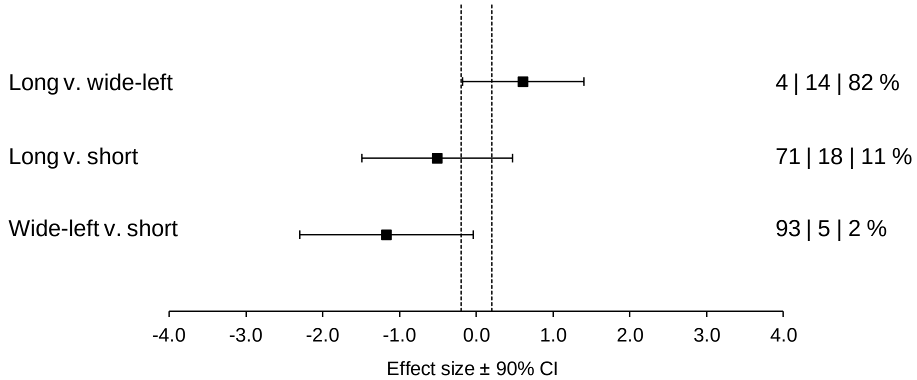


Figure 5.4. Effect sizes (± 90% CI) between the lateral ball velocities of the long, wide-left and short kicks. A negative effect represents a ball velocity directed more towards the left-hand-side of the goal whilst a positive effect was more towards the right-hand-side of the goal. The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each comparison represent the likelihood that the effect is negative | trivial | positive.

There was no clear difference in the forward ball velocity between the long kicks and the wide-left kicks (Figure 5.5) However, the forward velocity of both of these was substantially faster than the short kicks (Figure 5.5). The vertical ball velocity of the long kicks was substantially faster than both the wide-left and short kicks (Figure 5.6) but there was no clear difference in vertical velocity between the wide-left and short kicks.

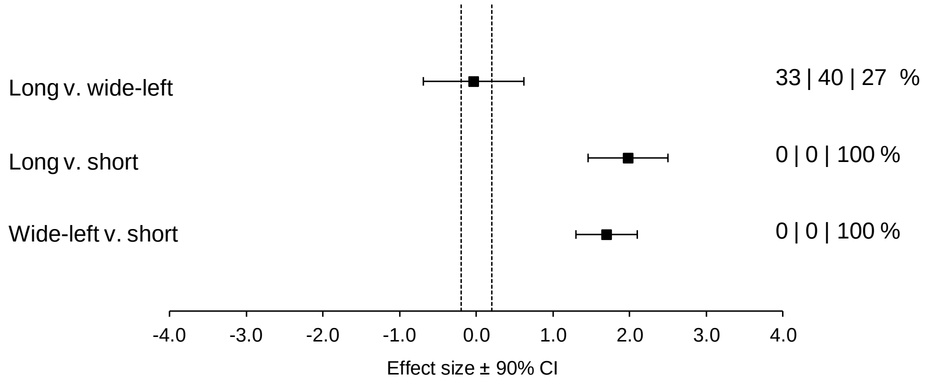


Figure 5.5. Effect sizes (± 90% CI) between the forward ball velocities of the long, wide-left and short kicks. The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each comparison represent the likelihood that the effect is negative | trivial | positive.

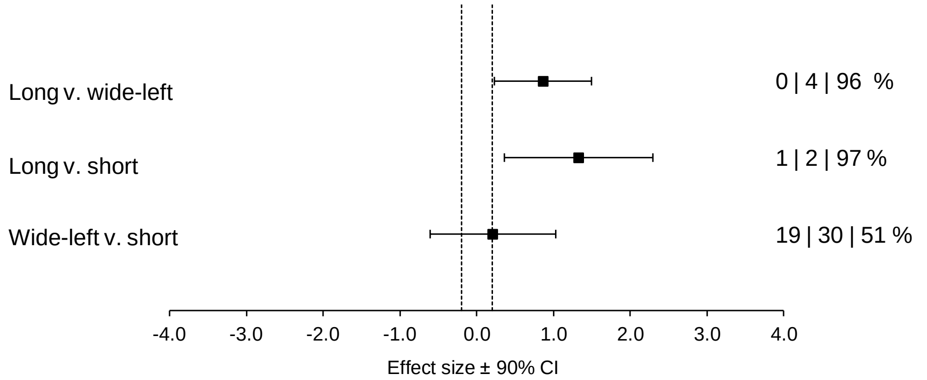


Figure 5.6. Effect sizes (± 90% CI) between the vertical ball velocities of the long, wide-left and short kicks. The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each comparison represent the likelihood that the effect is negative | trivial | positive.

The ball launch angles of both the long and short kicks were substantially higher than those recorded for the wide-left kicks (Figure 5.7). The launch angle of the short kicks was also substantially higher than that of the long kicks (Figure 5.7). The lateral angle of the long kicks was substantially more positive (directed towards the right-hand-side) than the wide-left kicks (which was directed towards the left-hand-side; Figure 5.8), but both the long and wide-left kicks were substantially more negative than the short kicks (Figure 5.8).

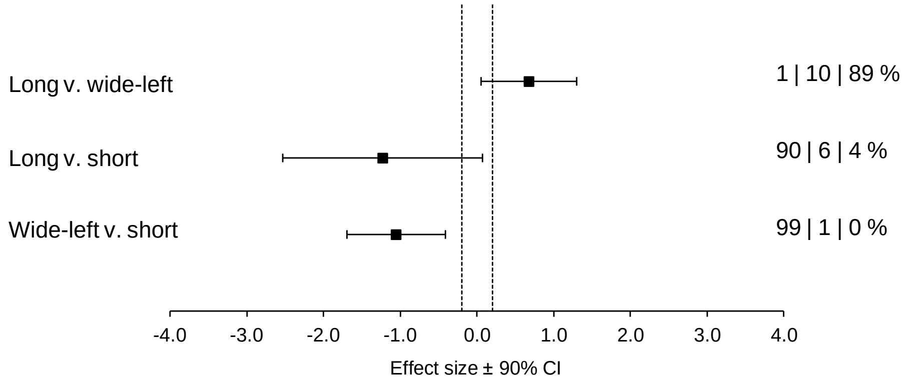


Figure 5.7. Effect sizes (± 90% CI) between the launch angles of the long, wide-left and short kicks. The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each comparison represent the likelihood that the effect is negative│trivial│positive.

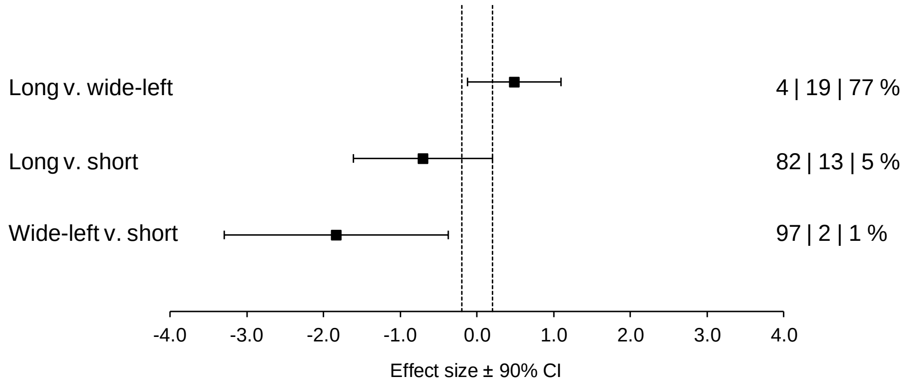


Figure 5.8. Effect sizes (± 90% CI) between the lateral angles of the long, wide-left and short kicks. A negative effect represents a lateral angle directed more towards the left-hand-side of the goal whilst a positive effect was more towards the right-hand-side of the goal. The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each comparison represent the likelihood that the effect is negative│trivial│positive.

There were no clear differences in the end-over-end spin of the ball across the three groups (Figure 5.9). However, for longitudinal ball spin, both the long and short kicks had substantially less spin than the wide-left kicks (Figure 5.10). There was no clear difference in the longitudinal spin of the long kicks compared with the short kicks (Figure 5.10).

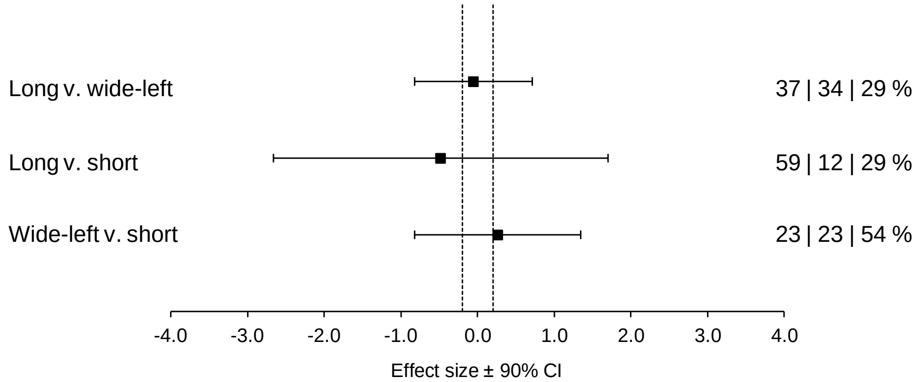


Figure 5.9. Effect sizes (± 90% CI) between the end-over-end spin of the long, wide-left and short kicks. The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each comparison represent the likelihood that the effect is negative|trivial|positive.

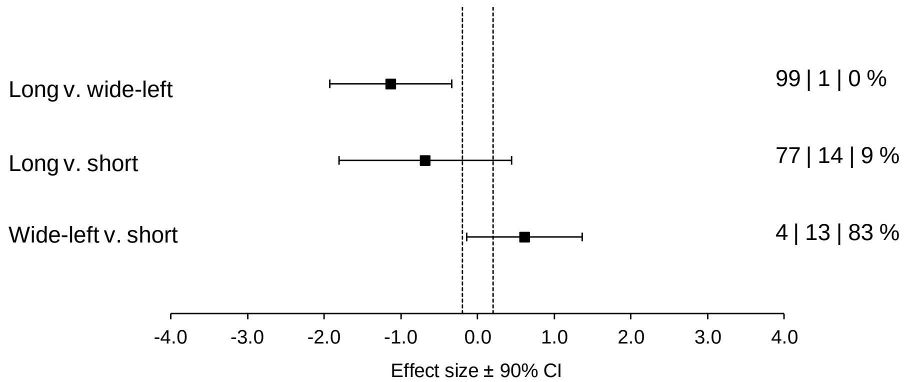


Figure 5.10. Effect sizes (± 90% CI) between the longitudinal spin of the long, wide-left and short kicks. The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each comparison represent the likelihood that the effect is negative|trivial|positive.

5.4. Discussion

Three groups of kickers were determined based on the performance outcomes of their best kick using the mathematical model developed in Chapter 3. This grouping enabled differences in the ball flight characteristics to be identified between the successful (long) kicks and the less successful (wide-left and short) kicks. Furthermore, the rank order of kick success differed when ball velocity magnitude was used as the performance criterion compared with when the maximum distance of the kick was used. The maximum distance of the kick is proposed to provide a more appropriate single performance measure as it represents overall place kick performance by considering the direction of the ball velocity vector and the spin on the ball in addition to just the ball velocity magnitude.

Previous research has typically determined the success of a place kick based on the ball velocity magnitude (Aitchison & Lees, 1983; Baktash et al., 2009; Sinclair et al., 2014; Zhang et al., 2012). Although a large, substantially positive relationship was found between the rankings of the kicks based on the measured resultant velocity of the ball and the maximum distance of the kicks, the correlation coefficient (ρ) of 0.52 demonstrates that there is considerable variation in the relative success of kicks between the two performance measures (Figure 5.1). Whilst the two measures are clearly related and a fast ball velocity will often result in a greater maximum distance, the ball velocity magnitude only explains 27% of the variance in the two rank orders and others factors such as the direction of the ball velocity vector and the ball spin must account for the other 73% of the variance in the rank orders. Therefore, whilst previous studies have considered the ball velocity magnitude as the performance outcome in previous rugby place kicking research, it is clear that other factors influence true overall place kick performance and thus require consideration when seeking to fully understand place kick performance.

The resultant ball velocity magnitude of both the long and wide-left kicks was higher than that recorded in previous studies investigating place kicks taken by both professional and amateur kickers (resultant velocity range of 15-26 m/s; Baktash et al., Bezodis et al., 2007; Holmes et al., 2006; Linthorne & Stokes, 2014; Sinclair et al., 2014; Zhang et al., 2012). Whilst the maximum distance of the long kicks was substantially greater than the wide-left kicks, no clear differences were observed between the magnitudes of the resultant ball velocities and this vital difference in the true performance outcome between these two groups would be overlooked if solely assessing performance based on ball velocity magnitude. Furthermore, although the short kicks' resultant ball velocity was substantially slower than that of the wide-left kicks, there was no clear difference in maximum distance between these groups; if the performance of these groups had been determined simply based on ball velocity magnitude the wide-left kicks would have been considered to be more successful yet in fact the true performance outcome shows that overall performance levels were comparable. These results extend the previously discussed variation in the kick rankings between the two performance measures and provide clear examples supporting the need to use a performance measure that represents overall place kick performance, such as the maximum distance value developed in the current work.

The maximum distance of the place kicks recorded in the current study was shorter than that recorded in the only previous experimental study to directly record them (53.74 ± 5.72 m, Holmes et al., 2006) but similar to the mean distance that kicks were taken from in international matches over a ten year period (Quarrie & Hopkins, 2015, 32 ± 12 m). The difference in the maximum distances achieved in the current study and the previous study by Holmes et al. (2006) may be due to methodological differences in the two studies. Firstly, whilst both studies required kickers to perform maximum range place kicks directed towards a target, Holmes et al. (2006) directly measured the distance to the first bounce of the ball and also did not account for the lateral deviation of the ball meaning the kicks may have only been successful from shorter distances than those reported. Furthermore, Holmes et al. (2006) analysed the kicks of six professional rugby players representing an elite population whereas the current study also included experienced amateur place kickers who may not be successful from as far. Finally, the kickers analysed by Holmes et al. (2006) performed the place kicks on a natural turf training field, maintaining ecological validity, but meaning environmental factors such as wind speed, temperature and humidity will have influenced the ball flight compared with the predicted trajectories made from initial ball flight data collected in a laboratory environment in the current study.

Analysis of the individual components of the ball velocity vector in each of the principal directions revealed further differences between the kick groups. Although there was no clear difference in the resultant ball velocity magnitudes between the long and wide-left kicks, the long kicks had a substantially greater vertical velocity than the wide-left kicks and their lateral velocities were directed in opposite directions relative to the target line; the long kicks had a ball velocity vector directed towards the right-hand-side whereas the wide-left kicks' was directed towards the left-hand-side. In addition to a lateral velocity vector directed towards the left-hand-side, the longitudinal ball spin of the wide-left kicks was substantially greater than the long kicks which led to the ball curving further towards the left-hand-side of the goalposts throughout the flight and ultimately missing the left-hand goalpost. A kick may miss the left-hand goalpost due to either a misdirected ball velocity vector (towards the left-hand-side) or greater anti-clockwise longitudinal ball spin causing the ball to curve from right-to-left and the results of the current study actually indicate that the wide-left kicks did both. These results support the assertion from coaching literature that a curved ball trajectory (caused by longitudinal spin) is undesirable in place kicking (Bezodis & Winter, 2014; Greenwood, 2003; Wilkinson, 2005) and highlights the limitations of studies that have not considered this ball flight characteristic. Previous experimental studies investigating rugby place kicking or soccer instep kicking have not yet directly determined relationships between kicking foot kinematics before initial ball contact and the direction of the ball velocity vector post-contact, but an elite rugby kicking coach has suggested that *"You don't want the leg to go out and then come across the ball"* (Bezodis & Winter, 2014). Given the observed differences in the lateral ball velocity between the two groups, subsequent investigation of the technique differences including the kicking foot kinematics may help to explain how these differences in the initial ball flight characteristics were achieved.

As would be expected based on the performance outcomes of the kicks, both the forward and vertical ball velocities of the long kicks were significantly greater than in the short kicks. Interestingly, however, the short kicks also demonstrated a larger lateral ball angle (directed towards the right-hand-side) compared with the long kicks, and whilst there was no clear difference between the longitudinal ball spin of the two groups, as the short kicks mean longitudinal ball spin was greater than 360°/s this meant the ball curved away from its initial trajectory towards the right-hand-side, dropping below the height of the crossbar before it would have missed the left-hand goalpost. The ball launch angle of the short kicks was also substantially higher than in the long kicks, and 10% larger than the optimum launch angle of 32.3° identified for place kicks by Linthorne and Stokes (2014), suggesting the ball dropped below the height of the crossbar from a shorter distance than if it had a slightly lower launch angle. When the optimum launch angle proposed by Linthorne and Stokes (2014) was resolved, it comprised a forward velocity of 23.6 m/s and a vertical velocity of 14.8 m/s, both of which are larger than those of the short kicks (a difference of 6.7 m/s and 2.8 m/s, respectively). It would therefore appear that although the short kicks were limited by a lower resultant velocity, the larger difference in forward velocity suggests that achieving a lower trajectory may be a primary focus for improving performance. Given the previously stated strong positive relationship between the magnitudes of the kicking foot velocity prior to initial ball contact and the ball velocity post-contact (e.g. Levanon & Dapena, 1998; De Witt & Hinrichs, 2012; Nunome et al., 2006), subsequent analysis of the kicking foot velocity vector prior to initial ball contact would help to identify whether the magnitude or direction of the kicking foot velocity vector at initial ball contact is a potential limitation of the short kickers' technique.

5.5. Conclusion

This chapter investigated the initial ball flight characteristics of rugby place kicks and their subsequent effect on the performance outcome. The first main finding was the fundamental importance of considering the overall performance of the kicks using a more relevant measure of place kick success ('maximum distance') rather than the more commonly used ball velocity magnitude which is only one contributor towards overall performance. This was illustrated by considerable variation in the rankings of kicks depending upon the performance measure used. A grouping based on this measure of maximum distance enabled the most successful (long) kicks to be compared with those that were less successful because they lacked either distance (short) or accuracy (wide-left) in order to address the following research question:

ii. **How do the initial ball flight characteristics differ between place kicks with different performance outcomes?**

The longitudinal ball spin of the wide-left kicks was substantially greater than both the long and short kicks' and as the ball velocity vector of the wide-left kicks was initially directed towards the left-hand-side, the ball curved further to the left-hand-side throughout its flight and ultimately missed the left-hand goalpost before dropping below the height of the crossbar. In contrast, the short kicks' ball velocity vector was initially directed towards the right-hand-side and although the longitudinal ball spin of these kicks caused the ball to curve towards the left-hand-side, the ball dropped below the height of the crossbar before it would have missed the left-hand goalpost. As these initial ball flight kinematics are directly determined by the motion of the kicking foot which strikes the ball, investigation of the kicking foot kinematics prior to initial ball contact may help to explain why the different ball flight characteristics are observed. Furthermore, as the kicking foot is the end segment of a complex linked-segment system, comparisons of the motion of the more proximal segments could provide a more complete understanding of how the different kicking foot kinematics are achieved. Thus, following on from this understanding of rugby place kick performance outcomes based on the initial ball flight kinematics, it is important to now investigate the techniques of the kickers used to generate these performances.

Chapter 6: The approach to the ball and motion of the kicking foot: comparisons between successful and less successful rugby place kickers

6.1. Introduction

In Chapter 5, three distinct groups of place kickers were identified based on their performance outcome. This grouping enabled the ball flight characteristics of the most successful kicks to be compared with those that were less successful because they lacked either distance or accuracy, and the differences to be discussed. Understanding the differences in the techniques of the kickers between these three groups will reveal how these different performance outcomes were achieved and will provide valuable insight for coaches and players. This will then allow specific technical aspects to be identified that could be important for coaches to consider when seeking to improve the performance levels of kickers who lack either distance or accuracy.

Observational analysis of rugby place kicking reveals that kickers take an angled approach to the ball, similar to that observed for kicking skills in other football codes (e.g. Isokawa & Lees, 1988; Kellis et al., 2004; Scurr & Hall, 2009). A number of variables relating to the approach of the kicker towards the ball have previously been investigated in these other football codes. These include the angle of approach (Isokawa & Lees, 1988; Kellis et al., 2004; Scurr & Hall, 2009) and approach velocity (Andersen & Dörge, 2011) in soccer instep kicking, and final step length in Australian Rules football and soccer instep kicking (Ball, 2008; Lees & Nolan, 2002). However, these studies determined successful performance simply as either a fast foot velocity pre-contact or fast ball velocity post-contact, and apart from Lees and Nolan (2002), did not impose any accuracy constraints which have been shown to alter the approach of the kicker (Lees & Nolan, 2002; Teixeira, 1999). The same effects may therefore not be present in rugby place kicking where accuracy is an inherent performance demand as outlined in Chapter 2.

To date, only two studies have investigated aspects related to the approach of the kicker towards the ball in rugby place kicking. Baktash et al. (2009) experimentally assessed the effect of support foot placement on ball velocity and concluded that support foot position did not affect ball velocity magnitude (there was no consideration of kick accuracy). However, the participants were three amateur kickers with limited experience who achieved slow ball velocities (the precise values were not reported but were approximately 15 - 20 m/s), and the experimental manipulations were extreme; although the reference position of 0.30 m to the left of the ball CM was close to the typical values reported by Cockcroft and van den Heever (2016) from 15 professional rugby place kickers (0.03 ± 0.07 m behind and 0.33 ± 0.03 m to the side of the ball), the three manipulations of 0.30 m in front of, behind, and to the left of this reference position are clearly extreme in the context of the variation observed by Cockcroft and van den Heever (2016). Cockcroft and van den Heever (2016) also measured the length and angle of the final step towards the ball (based on foot positions at kicking foot take-off to support foot contact) but did not consider how these relate to performance. As the approach of a kicker towards the ball will influence their body position at the start of the kicking phase, investigating how the approach differs between rugby place kicks with different outcomes will provide a valuable understanding of the initial whole-body motion towards the ball.

Following support foot contact, as the only point of ground contact throughout the kicking phase, the forces exerted by the support foot directly determine the whole-body motion of the kicker. Larger peak ground reaction forces recorded underneath the support foot have been strongly associated with faster ball velocities in both soccer instep kicking (Kellis et al., 2004; Orloff et al., 2008) and Australian Rules football (Ball, 2012). Potthast et al. (2010) suggested that greater deceleration of the whole-body CM over this period may enable the kicker to transfer momentum to the kicking leg, increasing the linear velocity of the kicking foot. Furthermore, the approach angle taken by kickers towards the ball has been shown to influence both the medio-lateral and antero-posterior ground reaction forces in soccer instep kicking (Isokawa & Lees, 1988; Kellis et al., 2004). Thus, an investigation into the ground reaction forces recorded up to initial ball contact will provide an indication as to the whole-body motion of the kicker and how this may influence performance.

At the end of the kicking phase, the kicking foot contacts the ball and directly affects its subsequent flight. Previous soccer kicking literature has consistently demonstrated a strong relationship between the velocity magnitude of the kicking foot at initial ball contact and the ball velocity magnitude post-contact (e.g. $r = 0.71 - 0.83$; Levanon & Dapena, 1998; De Witt & Hinrichs, 2012; Nunome et al., 2006). However, whilst kickers may achieve comparable kicking foot velocity magnitudes at initial ball contact and ball velocity magnitudes post-contact, if there are differences in the directions of the velocity vectors the success of the kick may be affected. Furthermore, the magnitude of the kicking foot velocity at initial ball contact has been shown to be reduced by 2.2 - 4.6 m/s when an additional accuracy constraint is imposed (Lees & Nolan, 2002; Teixeira, 1999), possibly due to the need to ensure an appropriately directed ball velocity vector. How the kicking foot progresses towards initial ball contact - its motion during the kicking phase - is therefore of considerable interest when investigating kicking skills. The motion of the kicking foot at initial ball contact will likely be affected by the position of the kicking foot at the start of the kicking phase and the subsequent path it takes towards the ball during the downswing; the latter is an aspect of technique that has been highlighted as a key consideration by place kicking coaches (Bezodis & Winter, 2014; Wilkinson, 2005). Analysis of the motion of the kicking foot from the top of the backswing to initial ball contact may therefore help to explain the differences observed in the ball flight characteristics of place kicks with different performance outcomes. Such investigations into the differences in the approach taken by the kicker towards the ball and the motion of the kicking foot prior to initial ball contact in rugby place kicks with differing outcomes will allow research questions iii and iv to be addressed:

iii. How does whole-body motion prior to initial ball contact differ between successful and less successful kickers?

iv. How does kicking foot motion from the top of the backswing to initial ball contact differ between successful and less successful kickers?

6.2. Methods

Thirty-three male place kickers (mean ± SD age = 22 ± 4 years, mass = 86.2 ± 8.8 kg, height = 1.82 ± 0.06 m) each performed five maximum range place kicks in a laboratory where their segmental kinematics were tracked using 54 reflective markers and ground reaction forces were recorded from underneath the support foot (as described in Chapter 4).

The 3D positions of the markers were labelled using Vicon Nexus and .c3d files containing the labelled marker trajectories and 3D force vector were exported to Visual3D, as described in Chapter 4. The best kick for each kicker (determined as achieving the furthest maximum distance, Chapter 5) was selected for further analysis. These trials were cropped so that they ended at the frame prior to initial ball contact and three further events (kicking foot take-off, support foot contact and the top of the backswing) were identified for each kick as described in Chapter 4. The raw marker and ground reaction force data were processed as previously described (Chapter 4). The net impulse was calculated in the principal directions using integration procedures as described in Chapter 4. The kickers' whole-body CM location was calculated using a summation of segmental moments approach (Winter, 2009) with the inertia data of de Leva (1996) including adjustments to the hand and foot segments as described in Chapter 4. These data enabled a number of variables to be calculated:

- Position of the kicker at kicking foot take-off, support foot contact and initial ball contact: whole-body CM position of the kicker relative to the ball CM in each of the principal directions and as a resultant value.

- Velocity of the kicker at kicking foot take-off and initial ball contact: linear whole-body CM velocity of the kicker in each of the principal directions (calculated using the second central difference method; Miller & Nelson, 1973) and as a resultant value.

- Change in the velocity of the kicker: division of the net impulse between support foot contact and initial ball contact in the principal directions by mass. The total change in whole-body CM velocity in the horizontal plane was also calculated.

- Final step length and angle: the length of this step was calculated as the resultant distance between the kicking foot CM in the frame prior to kicking foot take-off and the support foot CM at the instant of support foot contact. The direction of this step relative to the global antero-posterior axis was determined, with a positive angle representing a step direction towards the right-hand-side.

- Support foot position: support foot CM position measured relative to the ball CM in the horizontal plane at support foot contact.

- Kicking foot position at the top of the backswing: kicking foot CM position measured relative to the ball CM in each of the principal directions and as a resultant value.

- Kicking foot velocity at initial ball contact: kicking foot CM velocity was calculated in each of the principal directions (using the second central difference method; Miller & Nelson, 1973) and as a resultant value.

- Kicking foot path length: calculated as the sum of the resultant 3D displacement of the kicking foot CM over each frame between the top of the backswing and initial ball contact.

The kickers were grouped as determined in Chapter 5 to enable the above variables to be compared between kicks with different performance outcomes ($n = 18$ for the long kickers, $n = 8$ for the wide-left kickers and $n = 4$ for the short kickers; for the ground reaction forces one wide-left kicker was removed due to incomplete data). Mean ± SD were calculated for all variables for each of the three groups of kickers. Effect sizes were calculated between the group pairings for all discrete variables, before 90% CIs and magnitude-based inferences were derived to allow comparisons between the groups with a smallest important effect determined as an effect size of 0.2 (Chapter 4). The ground reaction force data were normalised to the kickers' body weights due to the substantially lower mass of the short kickers compared with the other two groups (Appendix F). The kinematic data were not normalised as there was no substantial difference in the kickers' heights or leg lengths between the groups (Appendix F) and this also allowed differences to be discussed in more meaningful units from an applied perspective. The ground reaction force time-histories were also time-normalised to 101 points between support foot contact and initial ball contact and analysed using a statistical parametric mapping two-tailed independent samples t-test to assess differences between the groups (with an α-level of 5%, Chapter 4).

6.3. Results

6.3.1. Whole-body motion

Event timings

The timings of kicking foot take-off, support foot contact and the top of the backswing relative to initial ball contact (at time = 0.0 s) for each of the three groups are presented in Figure 6.1. There were no clear differences when comparing the timing of kicking foot take-off of the long kickers with either the wide-left or short kickers (effect size = -0.3 ± 0.7 and effect size = 0.7 ± 1.0, respectively) but kicking foot take-off was substantially earlier for the wide-left kickers compared with the short kickers (0.03 s earlier, effect size = 1.1 ± 1.2). Support foot contact occurred substantially later for the long kickers compared with both the wide-left and the short kickers (0.01 s and 0.02 s later, respectively; effect size = -0.7 ± 0.8 and effect size = -1.3 ± 1.0), however, there was no clear difference when comparing the timing of support foot contact between the wide-left and short kickers (effect size = -0.4 ± 0.8). There were no clear differences when comparing the timing of the top of the backswing across the three groups (effect size = -0.2 ± 0.7 between the long and wide-left kickers, effect size = 0.4 ± 0.9 between the long and short kicks and effect size = 0.7 ± 1.3 between the wide-left and short kickers).

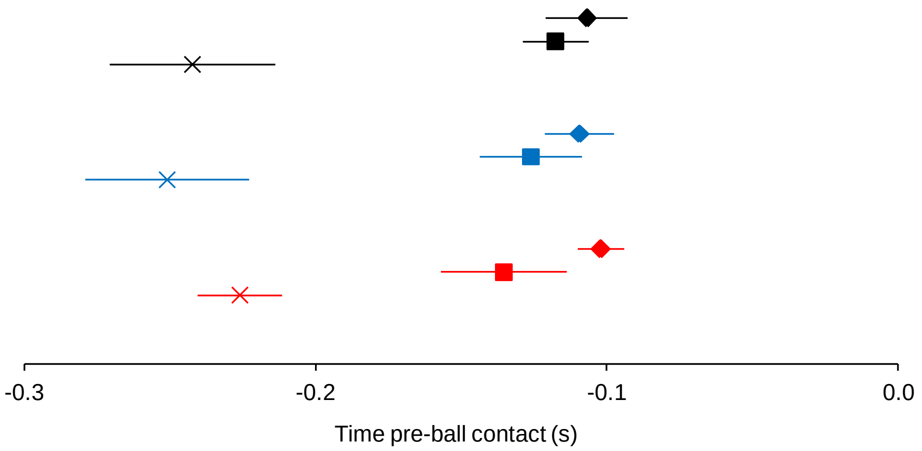


Figure 6.1. The mean ± SD timings of kicking foot take-off (cross), support foot contact (square) and top of the backswing (diamond) relative to initial ball contact (0.0 s) for the long kickers (black), wide-left kickers (blue) and short kickers (red).

Motion of the whole-body CM at kicking foot take-off

All kickers took an angled approach to the ball (Figure 6.2a). The long kickers' whole-body CM was substantially further from the ball at kicking foot take-off compared with the wide-left kickers’ (by a mean difference of 0.05 m; Table 6.1) and both of these groups' whole-body CMs were substantially further from the ball at kicking foot take-off compared with the short kickers' (by 0.16 and 0.11 m, respectively; Table 6.1). When this position was considered in the three principal directions, the long kickers' whole-body CM was substantially further to the left at kicking foot take-off than both the wide-left and short kickers' (by 0.07 and 0.24 m, respectively; Table 6.1) and the wide-left kickers’ whole-body CM was substantially further to the left than the short kickers' (by 0.17 m; Table 6.1). There were no clear differences when comparing the forward positions of the whole-body CM at kicking foot take-off across the three groups (Table 6.1). There were also no clear differences when comparing the vertical positions of the long kickers’ whole-body CM at kicking foot take-off with either the wide-left or the short kickers', but the wide-left kickers’ whole-body CM was substantially higher than the short kickers' (by 0.05 m; Table 6.1).

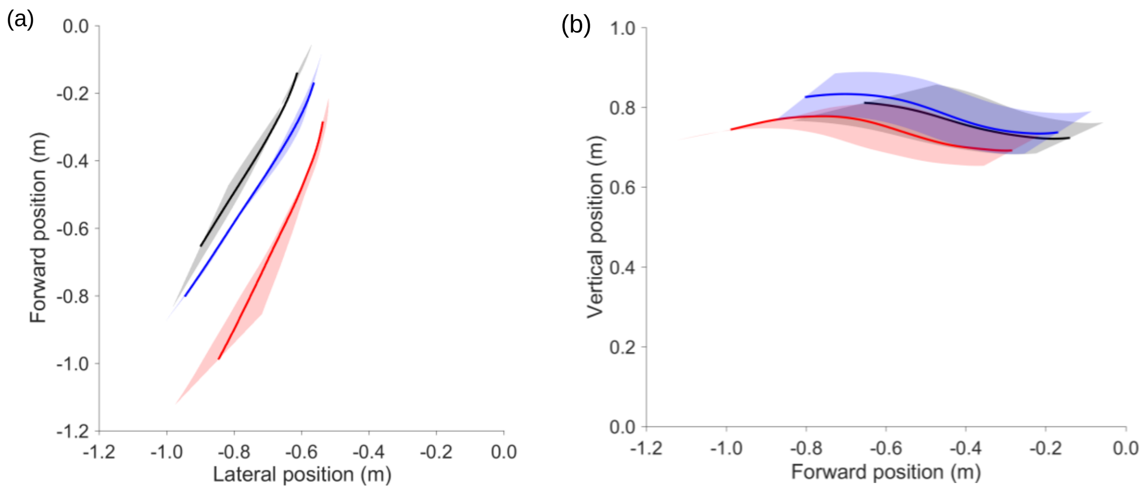


Figure 6.2. The mean ± SD path of the kickers' whole-body CM prior to initial ball contact (a) viewed from above and (b) from the side (relative to the ball CM as [0,0,0]) for the long kickers (black), short kickers (red) and wide-left kickers (blue).

The long kickers had a substantially faster resultant whole-body CM velocity at kicking foot take-off (3.5 ± 0.5 m/s) than both the wide-left (3.1 ± 0.4 m/s; Figure 6.3a) and short kickers (2.8 ± 0.3 m/s; Figure 6.3a) but there was no clear difference between the wide-left and short groups (Figure 6.3a). When resolving the velocity into the three principal directions, there was no clear difference in the lateral whole-body CM velocity at kicking foot take-off of the long kickers (1.9 ± 0.4 m/s) and the wide-left kickers (1.7 ± 0.3 m/s; Figure 6.3b) but both the long and the wide-left kickers had a substantially faster lateral (to the right-hand-side of the goalposts) whole-body CM velocity than the short kickers (1.2 ± 0.4 m/s; Figure 6.3b). The long kickers had a substantially faster forward whole-body CM velocity at kicking foot take-off (2.9 ± 0.6 m/s) compared with both the wide-left (2.5 ± 0.4 m/s; Figure 6.3c) and the short kickers (2.5 ± 0.3 m/s; Figure 6.3c) but there were no clear difference when comparing the wide-left kickers with the short kickers (Figure 6.3c). There was also no clear difference in the long kickers' vertical whole-body CM velocity at kicking foot take-off (0.4 ± 0.2 m/s) compared with the wide-left kickers (0.3 ± 0.14 m/s; Figure 6.3d) but the vertical velocity of both of these groups was substantially faster than that of the short kickers (0.1 ± 0.1 m/s; Figure 6.3d).

Table 6.1. Whole-body CM position relative to the ball at kicking foot take-off, support foot contact and initial ball contact for each group (mean ± SD) and the magnitude-based inferences for the group comparisons.

		Whole-body CM position (m)	Compared with wide-left kickers Effect size ± 90% CI	(% Negative | Trivial | Positive)	Compared with short kickers Effect size ± 90% CI	(% Negative | Trivial | Positive)
Kicking foot take-off						
Resultant						
	Long	1.52 ± 0.14*†	0.5 ± 0.7	(5 | 18 | 77)	1.3 ± 0.8	(0 | 1 | 99)
	Wide-left	1.47 ± 0.04*			2.6 ± 2.7	(5 | 3 | 92)
	Short	1.36 ± 0.05				
Lateral						
	Long	-1.00 ± 0.13*†	-0.7 ± 0.8	(86 | 11 | 3)	-2.0 ± 0.8	(100 | 0 | 0)
	Wide-left	-0.93 ± 0.05*			-2.3 ± 1.4	(99 | 1 | 0)
	Short	-0.76 ± 0.11				
Forward						
	Long	-0.80 ± 0.21	-0.2 ± 0.9	(50 | 28 | 22)	0.0 ± 0.8	(35 | 33 | 32)
	Wide-left	-0.78 ± 0.04			0.4 ± 3.1	(36 | 9 | 55)
	Short	-0.81 ± 0.09				
Vertical						
	Long	0.81 ± 0.05	-0.4 ± 0.7	(70 | 24 | 6)	0.7 ± 1.0	(8 | 13 | 79)
	Wide-left	0.83 ± 0.05*			1.0 ± 1.0	(2 | 5 | 93)
	Short	0.78 ± 0.03				
Support foot contact						
Resultant						
	Long	1.18 ± 0.07	0.4 ± 0.7	(9 | 26 | 65)	0.5 ± 0.9	(9 | 20 | 71)
	Wide-left	1.16 ± 0.04			0.2 ± 1.6	(32 | 17 | 51)
	Short	1.15 ± 0.05				
Lateral						
	Long	-0.77 ± 0.07*†	-0.9 ± 0.8	(94 | 5 | 1)	-1.7 ± 0.8	(100 | 0 | 0)
	Wide-left	-0.72 ± 0.01*			-1.4 ± 1.4	(93 | 4 | 3)
	Short	-0.65 ± 0.09				
Forward						
	Long	-0.44 ± 0.12*	0.1 ± 0.5	(15 | 49 | 36)	1.2 ± 0.9	(1 | 2 | 97)
	Wide-left	-0.46 ± 0.06*			1.7 ± 1.5	(2 | 3 | 95)
	Short	-0.58 ± 0.09				
Vertical						
	Long	0.77 ± 0.04	-0.3 ± 0.6	(61 | 31 | 8)	0.6 ± 1.1	(11 | 16 | 73)
	Wide-left	0.79 ± 0.05*			0.8 ± 1.0	(4 | 10 | 86)
	Short	0.75 ± 0.02				
Initial ball contact						
Resultant						
	Long	0.96 ± 0.04	0.3 ± 0.7	(15 | 29 | 56)	0.2 ± 1.0	(23 | 24 | 53)
	Wide-left	0.95 ± 0.05			0.0 ± 0.9	(37 | 30 | 33)
	Short	0.95 ± 0.05				
Lateral						
	Long	-0.61 ± 0.04*†	-1.4 ± 0.8	(99 | 1 | 0)	-0.8 ± 0.8	(87 | 10 | 3)
	Wide-left	-0.56 ± 0.02			0.4 ± 1.1	(17 | 20 | 63)
	Short	-0.58 ± 0.07				
Forward						
	Long	-0.15 ± 0.09*	0.1 ± 0.7	(23 | 35 | 42)	1.6 ± 0.9	(0 | 1 | 99)
	Wide-left	-0.16 ± 0.07*			1.7 ± 1.1	(1 | 1 | 98)
	Short	-0.28 ± 0.07				
Vertical						
	Long	0.71 ± 0.04†	-0.7 ± 0.7	(87 | 11 | 2)	0.5 ± 1.1	(12 | 17 | 71)
	Wide-left	0.74 ± 0.05*			1.0 ± 0.9	(2 | 4 | 94)
	Short	0.69 ± 0.04				

* Denotes a substantial effect compared with the short kickers † Denotes a substantial effect compared with the wide-left kickers

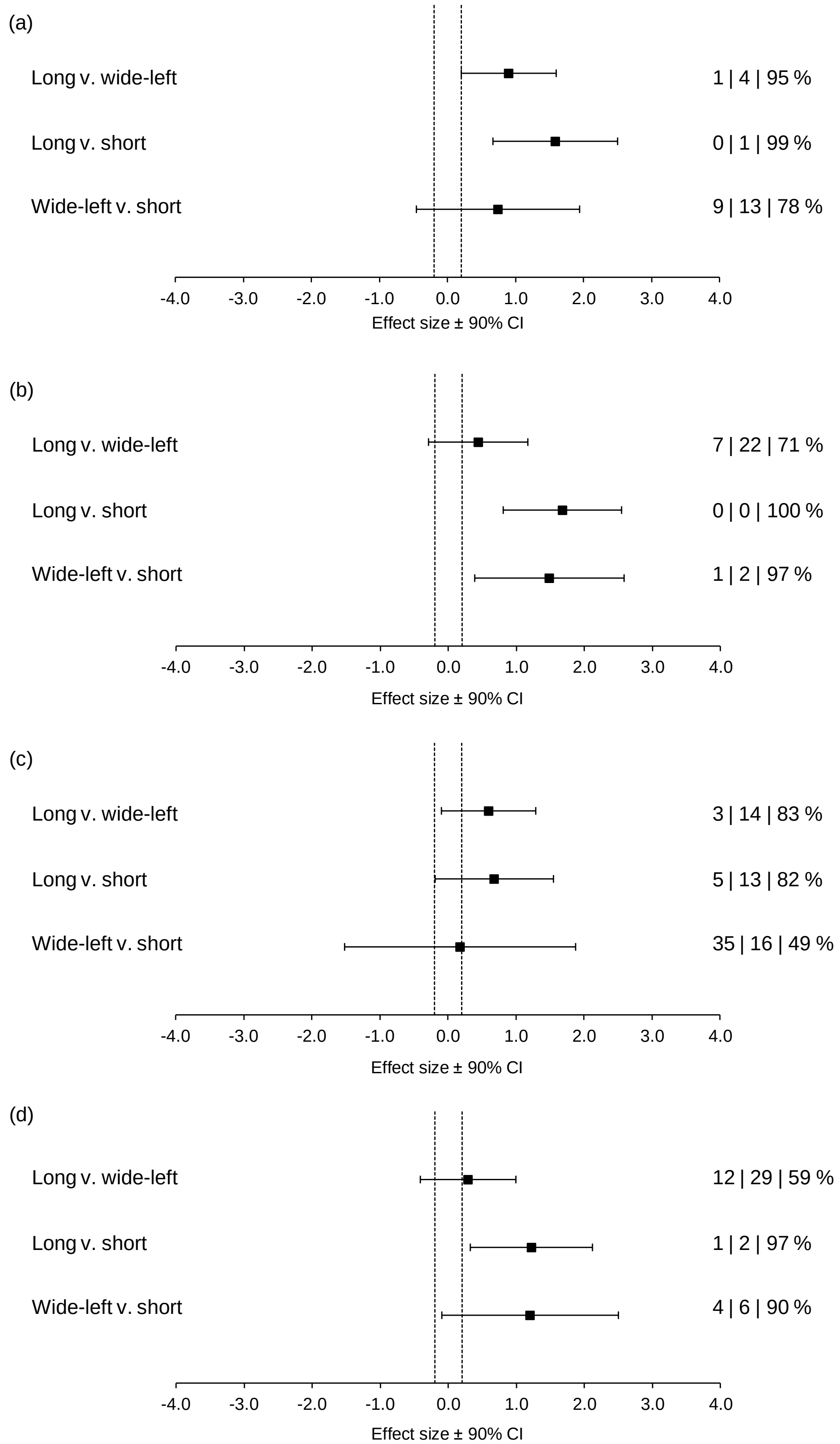


Figure 6.3. Effect sizes (± 90% CI) between the kickers' whole-body CM velocity magnitudes at kicking foot take-off: (a) resultant, (b) lateral, (c) forward and (d) vertical. The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each group comparison represent the likelihood that the effect is negative | trivial | positive.

Final step kinematics (kicking foot take-off to support foot contact)

Following kicking foot take-off, the long kickers took a substantially longer final step to support foot contact (1.69 ± 0.13 m) than both the wide-left (1.51 ± 0.11 m; Figure 6.4a) and the short kickers (1.44 ± 0.10 m; Figure 6.4a) but there was no clear difference in final step length between the latter two groups (Figure 6.4a). Furthermore, this step was directed at a greater angle (towards the right-hand-side relative to the antero-posterior direction), for the long (26 ± 9°) and wide-left kickers (26 ± 4°) compared with the short kickers (15 ± 7°; Figure 6.4b). There was no clear difference between the angle of the final step taken by the long and wide-left kickers (Figure 6.4b). A plan view of the mean ± SD foot CM positions at kicking foot take-off and support foot contact of the three groups is presented in Figure 6.5.

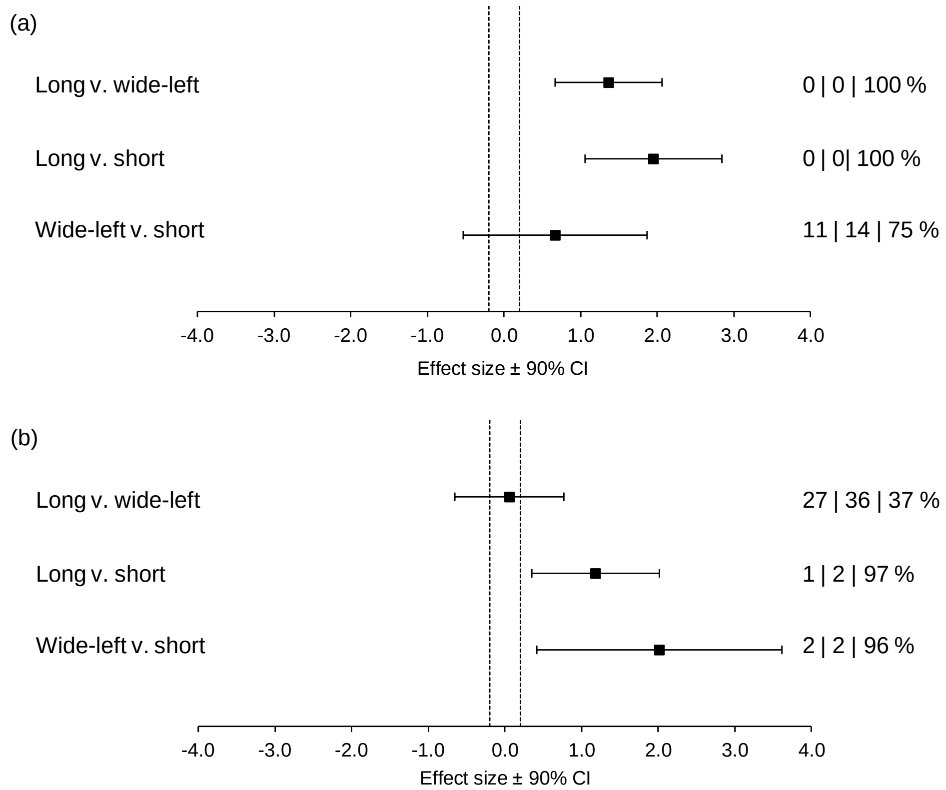


Figure 6.4. Effect sizes (± 90% CI) between the (a) resultant final step length and (b) angle of the final step of the kickers. The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each group comparison represent the likelihood that the effect is negative | trivial | positive.

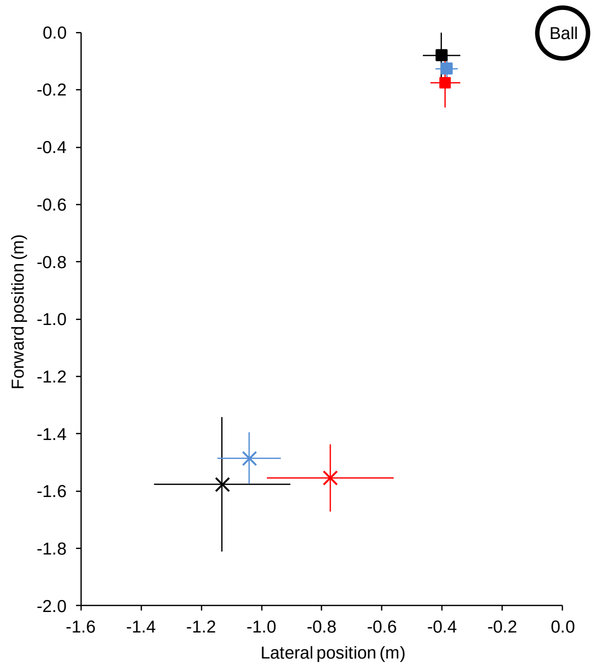


Figure 6.5. The mean ± SD position of the kicking foot CM at kicking foot take-off (crosses) and the support foot CM at support-foot contact (squares) relative to the ball CM for the long kickers (black), wide-left kickers (blue) and short kickers (red).

Support foot and whole-body CM position at support foot contact

At the instant the support foot contacted the ground at the end of the final step, the support foot CM was to the left of, and behind, the ball CM in all groups (Figure 6.5). There were no clear differences when comparing the position of the support foot CM relative to the ball CM between the three groups of kickers either as a resultant 2D value or in the medio-lateral direction (Table 6.2). However, the long kickers positioned their support foot substantially further forward compared with both the wide-left and the short kickers (by 0.04 and 0.09 m, respectively; Figure 6.5 and Table 6.2).

Table 6.2. Support foot CM position relative to the ball at support foot contact for each group (mean ± SD) and the magnitude-based inferences for the group comparisons.

	Support foot CM position (m)	Compared with wide-left kickers Effect size ± 90% CI (% Negative | Trivial | Positive)		Compared with short kickers Effect size ± 90% CI (% Negative | Trivial | Positive)	
Resultant					
Long	0.42 ± 0.06	0.2 ± 0.7	(18 | 34 | 48)	-0.3 ± 0.9	(58 | 25 | 17)
Wide-left	0.41 ± 0.04			-0.8 ± 1.8	(73 | 11 | 16)
Short	0.43 ± 0.03				
Lateral					
Long	-0.40 ± 0.06	-0.3 ± 0.7	(60 | 28 | 12)	-0.2 ± 0.9	(50 | 28 | 22)
Wide-left	-0.38 ± 0.04			0.1 ± 1.5	(35 | 19 | 46)
Short	-0.39 ± 0.05				
Forward					
Long	-0.08 ± 0.08*†	0.6 ± 0.7	(3 | 13 | 84)	1.2 ± 0.9	(1 | 2 | 97)
Wide-left	-0.12 ± 0.04			0.8 ± 1.3	(9 | 11 | 80)
Short	-0.17 ± 0.09				

* Denotes a substantial effect compared with the short kickers † Denotes a substantial effect compared with the wide-left kickers

Similar to the support foot position, there were no clear differences in the resultant distance between the kickers' whole-body CM and the ball CM at support foot contact between the three groups of kickers (Table 6.1). When the position was resolved into the three principal directions, the long kickers' whole-body CM remained substantially further to the left of the ball at support foot contact (as was observed at kicking foot take-off) compared with both the wide-left and the short kickers (by 0.05 and 0.12 m, respectively; Table 6.1) and the wide-left kickers' whole-body CM was substantially further to the left compared with the short kickers (by 0.07 m; Table 6.1). There was no clear difference when comparing the antero-posterior position of the long kickers' whole-body CM and the wide-left kickers', but both of their whole-body CMs were substantially further forward compared with the short kickers' (by 0.14 and 0.12 m, respectively; Table 6.1). There were also no clear differences between the long kickers' vertical whole-body CM position at support foot contact and either the wide-left or short kickers' (Table 6.1) but the wide-left kickers' was substantially higher than the short kickers' (by 0.04 m; Table 6.1).

Normalised ground reaction forces following support foot contact

The time-normalised resultant ground reaction force time-histories of the three groups of kickers from support foot contact (-100%) to initial ball contact (0%), termed the 'stance phase', are presented in Figure 6.6a. For all groups, the mean resultant ground reaction force increased throughout the early stance phase towards its peak of 3.1 and 3.2 BW for the long and wide-left kickers respectively and 2.6 BW for the short kickers (Figure 6.6a). An overall reduction in this force with small fluctuations was observed for both the long and wide-left kickers over the stance phase (Figure 6.6a) whilst the short kickers displayed a reduction following the initial peak, before an increase near the middle of the stance phase. However, no significant differences were observed across all time points when comparing the resultant ground reaction force time-histories between the three groups (Figure 6.6c,e,g; $p > 0.05$).

The ground reaction forces were also considered as their three principal components. The same broad patterns were observed in the vertical ground reaction force time-histories as in the resultant time-histories (Figure 6.6b) and there were no significant differences in these time-histories between the three groups ($p > 0.05$; Figure 6.6d,f,h). The medio-lateral ground reaction force was directed towards the left-hand-side throughout the stance phase for all groups (as viewed from behind the kicker, i.e. towards the direction they had approached from). For the first 20% of this phase, the medio-lateral force increased at the same rate for all groups, before reaching a mean peak of between 1.1 and 1.4 BW (range in group means; Figure 6.7a). This peak force was then largely maintained up to initial ball contact by both the long and wide-left kickers but reduced by approximately 50% for the short kickers (Figure 6.7a). There were no significant differences in the medio-lateral ground reaction force time-histories between the long and wide-left kickers ($p > 0.05$; Figure 6.7c). However, the medio-lateral ground reaction force of the long kickers was significantly greater (to the left) compared with the short kickers in the middle of the stance phase and just prior to initial ball contact ($p < 0.001$; Figure 6.7e). The medio-lateral force was also greater for the wide-left kickers compared with the short kickers in the middle of the stance phase ($p < 0.001$; Figure 6.7g). For the antero-posterior force, there were initial fluctuations during the early part of this phase before it soon became directed posteriorly for all groups (Figure 6.7b). No significant differences were present in the antero-posterior ground reaction force time-histories between the three groups ($p > 0.05$; Figure 6.7d,f,h).

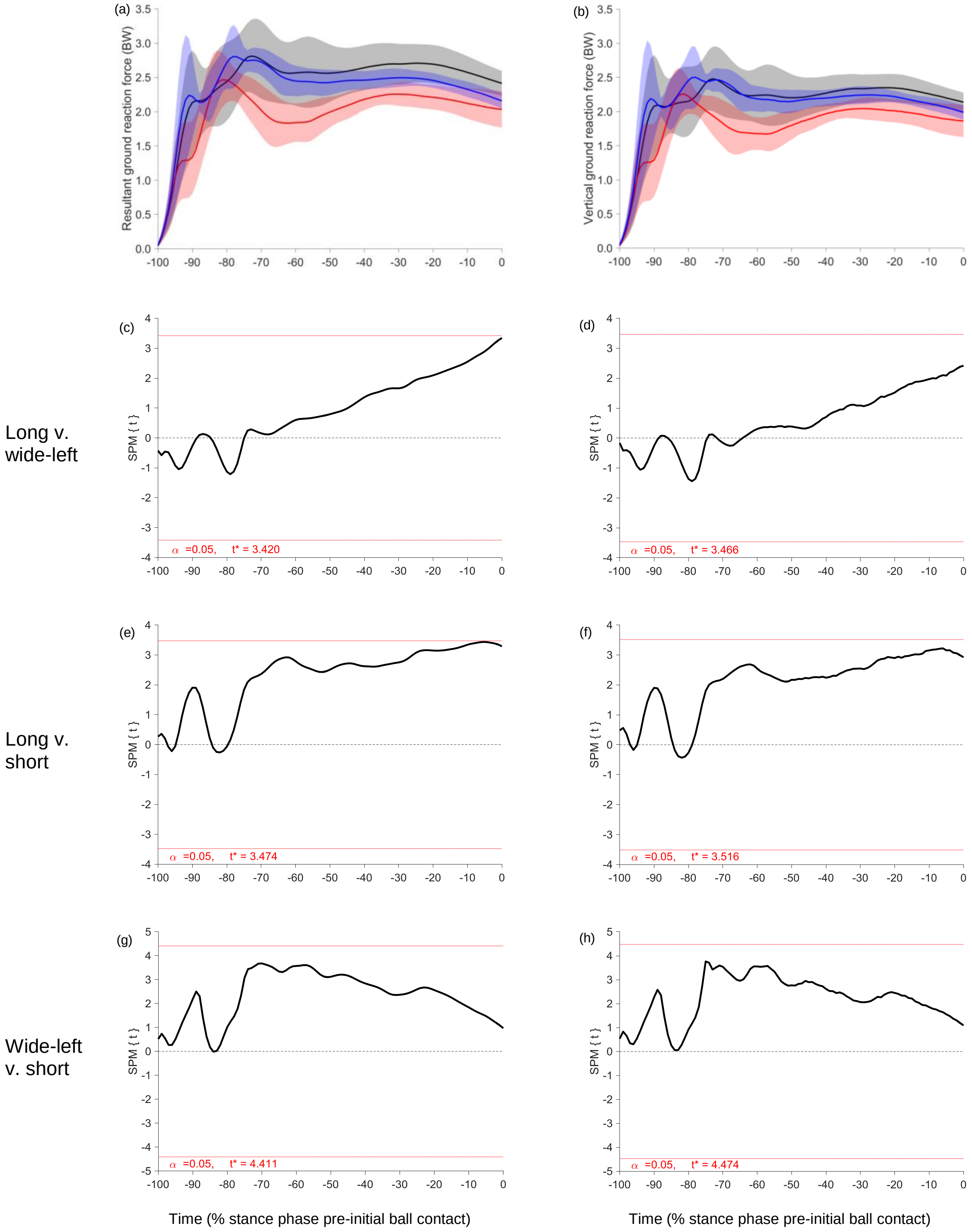


Figure 6.6. The time-normalised (a) resultant and (b) vertical ground reaction force time-histories from support foot contact (-100%) to initial ball contact (0%) for the long kickers (black), wide-left kickers (blue) and short kickers (blue; mean ± SD clouds) and below each time-history, the corresponding SPM{t} outputs for the comparisons between the groups. Shaded areas and p-value labels indicate SPM{t} critical-t threshold (t*, red dotted horizontal line) has been exceeded and there is a significant difference between conditions (α = 0.05).

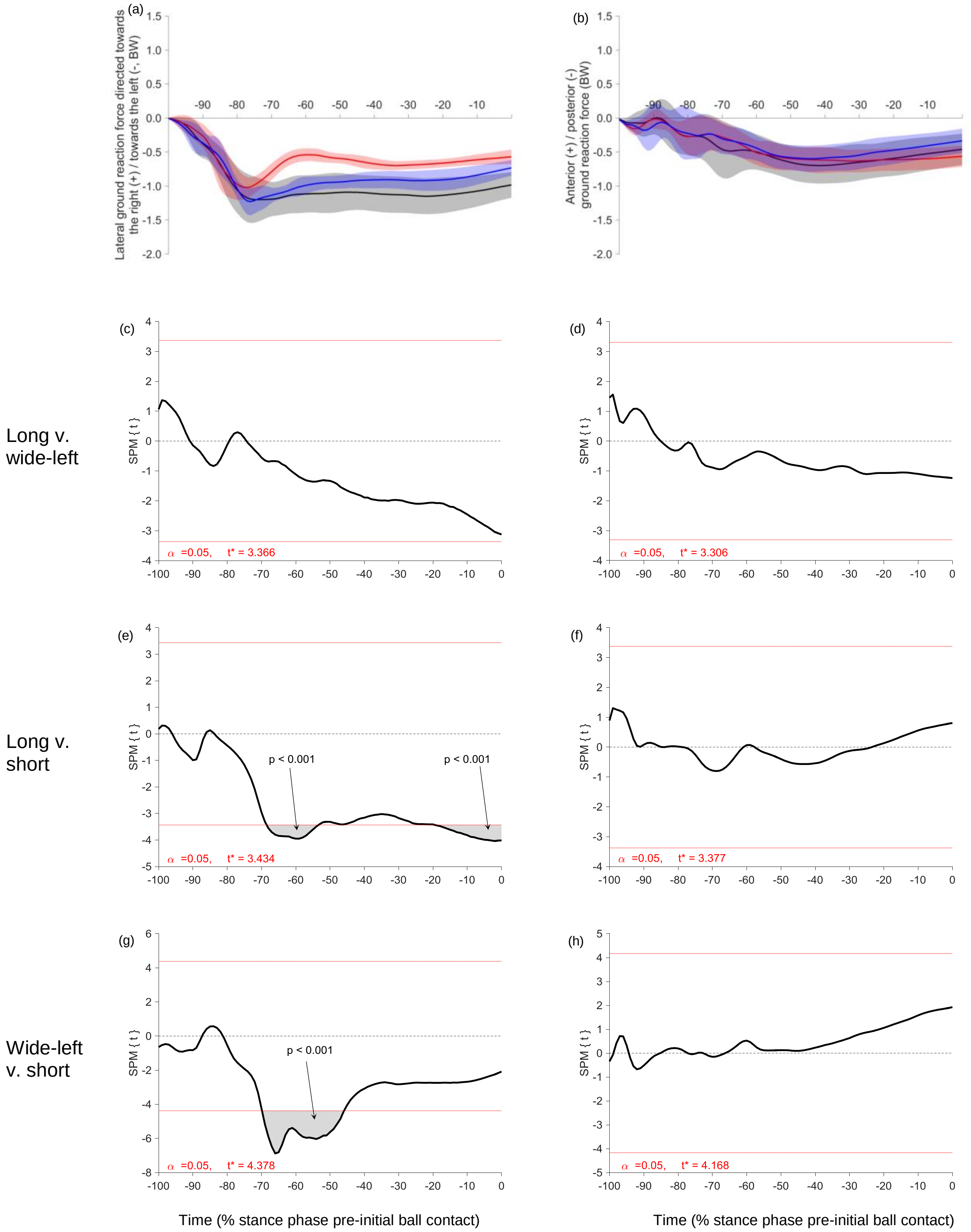


Figure 6.7. The time-normalised (a) medio-lateral and (b) antero-posterior ground reaction force time-histories from support foot contact (-100%) to initial ball contact (0%) for the long kickers (black), wide-left kickers (blue) and short kickers (blue; mean ± SD clouds) and below each time-history, the corresponding SPM{t} outputs for the comparisons between the groups. Shaded areas and p-value labels indicate SPM{t} critical-t threshold (t*, red dotted horizontal line) has been exceeded and there is a significant difference between conditions (α = 0.05).

The impulses due to these ground reaction forces reduced the kickers' lateral and forward whole-body CM velocities, and reversed their vertical velocity from a downwards to an upwards direction. There was no clear difference when comparing the reduction in lateral whole-body CM velocity between the long kickers and the wide-left kickers (Table 6.3) but the long and wide-left kickers reduced their lateral velocity by a substantially larger amount than the short kickers (by 0.3 and 0.2 m/s, respectively; Table 6.3). There were no clear differences when comparing the reduction in forward velocities between the three groups (Table 6.3) However, when the reduction in total horizontal velocity was compared between groups, the long kickers reduced their velocity by a substantially greater amount than the short kickers (by 0.3 m/s; Table 6.3). There were no clear differences between the wide-left kickers and either of the other two groups. There was no clear difference when comparing the increase in vertical velocity between the long and the wide-left kickers (Table 6.3), but both the long and wide-left kickers increased their vertical velocity by a substantially larger amount compared with the short kickers (by 0.3 m/s; Table 6.3).

Table 6.3. Change in the kickers' whole-body CM velocity during the kicking phase for each group (mean ± SD) and the magnitude-based inferences for the group comparisons.

	Change in whole-body CM velocity (m/s)	Compared with wide-left kickers Effect size ± 90% CI	(% Negative | Trivial | Positive)	Compared with short kickers Effect size ± 90% CI	(% Negative | Trivial | Positive)
Lateral					
Long	-1.1 ± 0.2*	-0.5 ± 0.8	(76 | 18 | 6)	-1.5 ± 0.9	(99 | 1 | 0)
Wide-left	-1.0 ± 0.2*			-1.0 ± 1.1	(90 | 7 | 3)
Short	-0.8 ± 0.2				
Forward					
Long	-0.5 ± 0.3	-0.2 ± 0.8	(50 | 32 | 18)	0.1 ± 0.9	(28 | 27 | 45)
Wide-left	-0.5 ± 0.2			0.4 ± 1.3	(22 | 18 | 60)
Short	-0.6 ± 0.1				
Vertical					
Long	1.3 ± 0.3*	-0.2 ± 0.8	(51 | 31 | 18)	1.8 ± 1.0	(0 | 0 | 100)
Wide-left	1.3 ± 0.2*			1.9 ± 0.9	(0 | 0 | 100)
Short	1.0 ± 0.2				
Total horizontal					
Long	-1.6 ± 0.3*	-0.5 ± 0.8	(76 | 18 | 6)	-1.0 ± 1.0	(91 | 7 | 2)
Wide-left	-1.5 ± 0.4			-0.4 ± 1.0	(63 | 21 | 16)
Short	-1.3 ± 0.3				

* Denotes a substantial effect compared with the short kickers † Denotes a substantial effect compared with the wide-left kickers

Whole-body CM kinematics at initial ball contact

At initial ball contact, the kickers' whole-body CM was to the left and behind the ball in all groups. There were no clear differences between the groups in the resultant distance between the whole-body CM and the ball CM at initial ball contact (Table 6.1). However, when resolving this distance in to each of the three principal directions, the whole-body CM was substantially further to the left of the ball at initial ball contact in the long kickers compared with both the wide-left and the short kickers (by 0.05 and 0.03 m, respectively; Table 6.1), but there was no clear difference between the wide-left and short kickers (Table 6.1). When comparing the position of the whole-body CM behind the ball at initial ball contact, there was no clear difference between the long and the wide-left kickers (Table 6.1). However, both of these groups positioned their whole-body CM substantially closer to the ball (i.e. further forward) compared with the short kickers (by 0.13 and 0.12 m, respectively; Table 6.1). Furthermore, the wide-left kickers' whole-body CM was substantially higher above the ball at initial ball contact compared with both the long and the short kickers (by 0.03 and 0.05 m, respectively; Table 6.1) but there was no clear difference between the long and short kickers (Table 6.1).

Regarding the resultant whole-body CM velocity at initial ball contact, the long kickers had a substantially faster velocity (2.5 ± 0.5 m/s) compared with both the wide-left (2.2 ± 0.5 m/s; Figure 6.8a) and short kickers (1.9 ± 0.2 m/s; Figure 6.8a) but there was no clear difference between the wide-left and short kickers (Figure 6.8a). When resolving the whole-body CM velocity in to its three principal components, the lateral whole-body CM velocity of the kickers at initial ball contact was directed towards the right-hand-side (when viewed from behind), away from the side they approached from. There was no clear difference in the lateral velocity of the long kickers (0.7 ± 0.3 m/s) compared with the wide-left kickers (0.7 ± 0.3 m/s; Figure 6.8b) but both of these groups exhibited a substantially faster lateral velocity compared with the short kickers (0.4 ± 0.3 m/s; Figure 6.8b). The long kickers exhibited a substantially faster forward whole-body CM velocity at initial ball contact (2.3 ± 0.5 m/s) compared with both the wide-left (2.1 ± 0.4 m/s; Figure 6.8c) and the short kickers (1.9 ± 0.2 m/s; Figure 6.8c) but there was no clear difference between the wide-left and short kickers. Finally, there was no clear difference in the vertical whole-body CM velocity of the long kickers (0.2 ± 0.1 m/s) compared with the wide-left kickers (0.2 ± 0.2 m/s; Figure 6.9d) but the vertical velocity of both of these groups was substantially faster than that of the short kickers (< 0.01 ± 0.2 m/s; Figure 6.9d).

6.3.2. Kicking foot motion

Position of the kicking foot at the top of the backswing

At the top of the backswing, there was no clear difference in the position of the kicking foot CM relative to the ball between the long and wide-left kickers (Table 6.4). However, both the long and wide-left kickers positioned their kicking foot substantially further away from the ball at the top of the backswing compared with the short kickers (by 0.19 and 0.16 m, respectively; Table 6.4). When this position was resolved in to the three principal directions, the long kickers positioned the kicking foot substantially further to the left of the ball at the top of the backswing (when viewed from behind) compared with both the wide-left and the short kickers (by 0.09 and 0.32 m, respectively; Table 6.4). The wide-left kickers also positioned their kicking foot substantially further to the left of the ball compared with the short kickers (by 0.23 m; Table 6.4). There were no clear differences when comparing the forward position of the kicking foot at the top of the backswing between the three groups (Table 6.4). There was also no clear difference in the vertical position of the kicking foot at the top of the backswing between the long and wide-left kickers (Table 6.4) but both of these groups positioned their kicking foot substantially higher above the ball at the top of the backswing compared with the short kickers (by 0.13 and 0.17 m, respectively; Table 6.4).

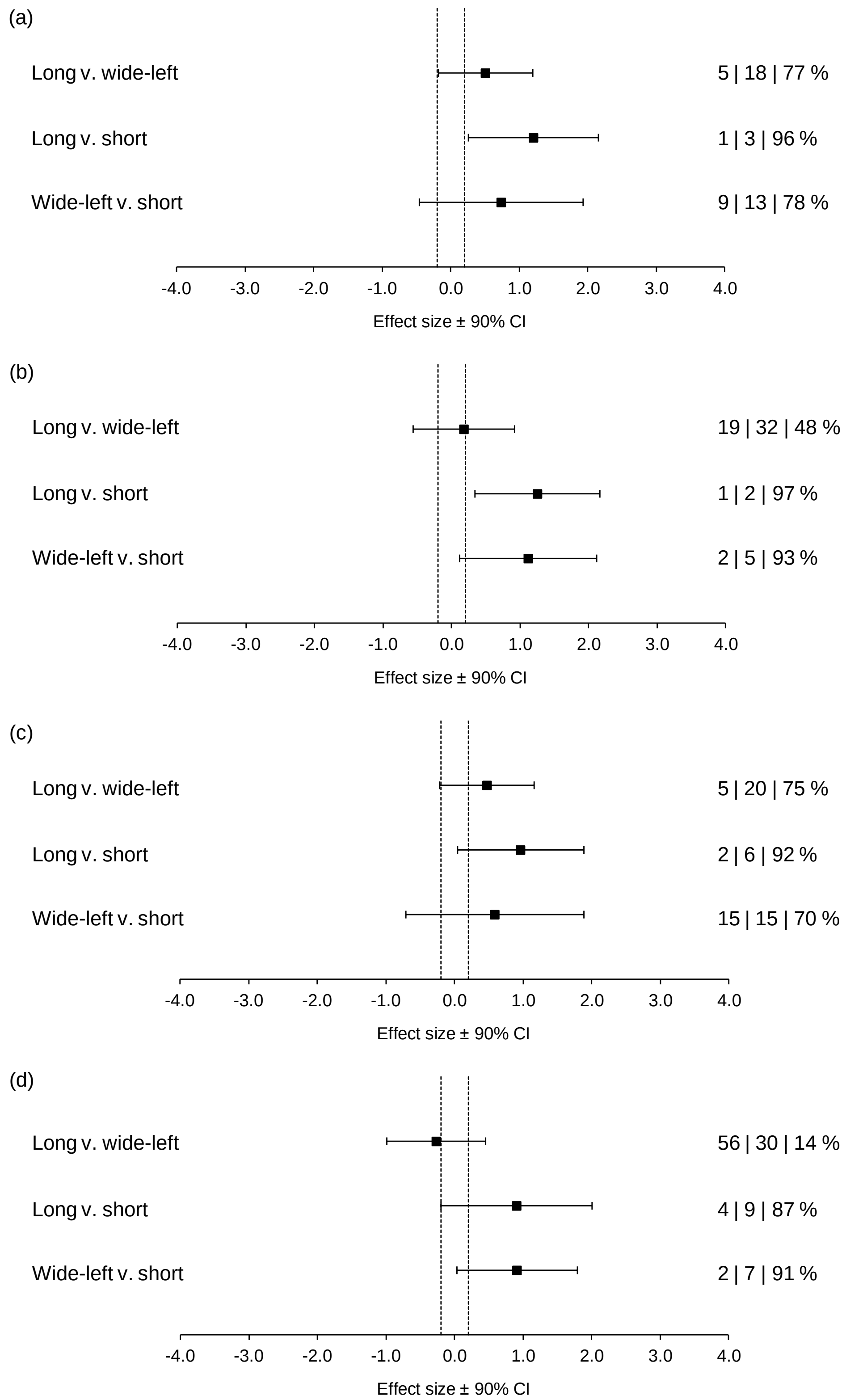


Figure 6.8. Effect sizes (± 90% CI) between the kickers' whole-body CM velocity magnitudes at initial ball contact: (a) resultant, (b) lateral, (c) forward and (d) vertical. The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each group comparison represent the likelihood that the effect is negative | trivial | positive.

Table 6.4. Kicking foot CM position relative to the ball at the top of the backswing for each group (mean ± SD) and the magnitude-based inferences for the group comparisons.

	Kicking foot CM position (m)	Compared with wide-left kickers Effect size ± 90% CI	(% Negative | Trivial | Positive)	Compared with short kickers Effect size ± 90% CI	(% Negative | Trivial | Positive)
Resultant					
Long	1.59 ± 0.14*	0.2 ± 0.7	(17 | 33 | 50)	1.4 ± 0.8	(0 | 1 | 99)
Wide-left	1.56 ± 0.05*			2.9 ± 2.0	(1 | 1 | 98)
Short	1.40 ± 0.07				
Lateral					
Long	-0.98 ± 0.17*†	-0.6 ± 0.8	(82 | 14 | 4)	-1.9 ± 0.8	(100 | 0 | 0)
Wide-left	-0.89 ± 0.07*			-2.0 ± 1.3	(98 | 1 | 1)
Short	-0.66 ± 0.18				
Forward					
Long	-1.09 ± 0.14	0.3 ± 0.7	(13| 30 | 57)	0.4 ± 0.9	(14 | 24 | 62)
Wide-left	-1.13 ± 0.09			0.2 ± 1.6	(34 | 18 | 48)
Short	-1.14 ± 0.07				
Vertical					
Long	0.57 ± 0.14*	-0.3 ± 0.7	(62 | 27 | 11)	1.0 ± 0.8	(1 | 4 | 95)
Wide-left	0.61 ± 0.06*			2.9 ± 2.0	(1 | 1 | 98)
Short	0.44 ± 0.11				

* Denotes a substantial effect compared with the short kickers † Denotes a substantial effect compared with the wide-left kickers

Kicking foot path during the downswing

The kicking foot path from the top of the backswing to initial ball contact is depicted from above (Figure 6.9a) and from the side (Figure 6.9b). There was no clear difference when comparing the length of the kicking foot paths during the downswing for the long and wide-left kickers (Table 6.5); however, the path was substantially longer for both the long and wide-left kickers compared with the short kickers (by 0.24 and 0.22 m, respectively; Table 6.5).

Table 6.5. Kicking foot CM path length from the top of the backswing to initial ball contact for each group (mean ± SD) and the magnitude-based inferences for the group comparisons.

	Kicking foot path length (m)	Compared with wide-left kickers Effect size ± 90% CI	(% Negative | Trivial | Positive)	Compared with short kickers Effect size ± 90% CI	(% Negative | Trivial | Positive)
Long	1.47 ± 0.17*	-0.1 ± 0.7	(44 | 35 | 21)	1.4 ± 0.8	(0 | 1 | 99)
Wide-left	1.45 ± 0.09*			2.1 ± 1.5	(1 | 1 | 98)
Short	1.23 ± 0.12				

* Denotes a substantial effect compared with the short kickers † Denotes a substantial effect compared with the wide-left kickers

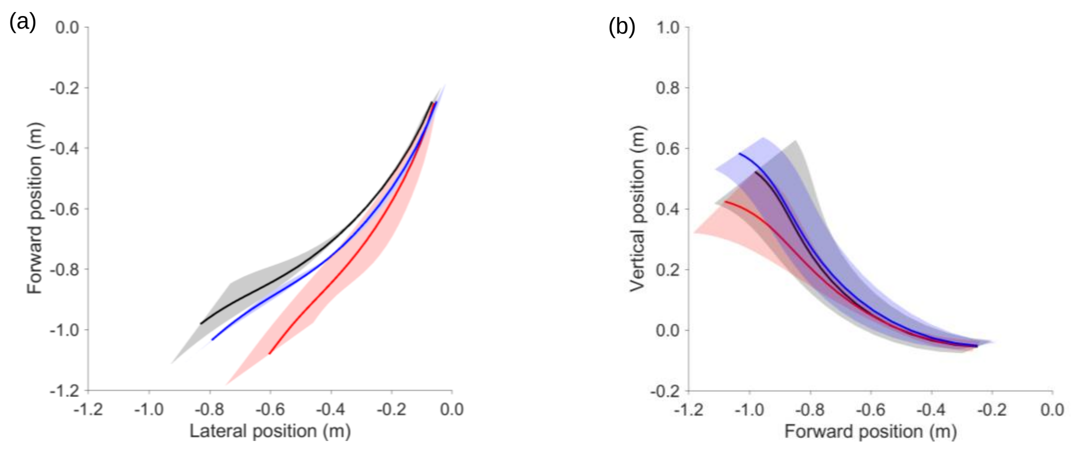


Figure 6.9. The mean ± SD path of the kicking foot CM (a) viewed in 2D from above and (b) from the side relative to the ball CM for the long kickers (black), wide-left kickers (blue) and short kickers (red).

Kicking foot CM kinematics at initial ball contact

The resultant kicking foot CM velocity at initial ball contact was substantially faster for the long kickers (20.3 ± 1.0 m/s) compared with both the wide-left (19.7 ± 0.9 m/s; Figure 6.10a) and the short kickers (17.0 ± 1.5 m/s; Figure 6.10a) and was substantially faster for the wide-left kickers compared with the short kickers (Figure 6.10a). When resolving this velocity in to its three principal directions, corresponding substantial differences were observed when comparing the medio-lateral kicking foot velocities at initial ball contact (directed towards the right-hand-side, when viewed from behind) between the groups (8.8 ± 1.5 m/s for the long kickers, 7.8 ± 1.6 m/s for the wide-left kickers and 5.4 ± 2.5 m/s for the short kickers; Figure 6.10b). When comparing the forward velocities of the kicking foot at initial ball contact, there was no clear difference between the long (18.1 ± 1.1 m/s) and wide-left kickers (17.8 ± 0.8 m/s; Figure 6.10c). However, the forward foot velocity of both of these groups was substantially faster than that of the short kickers (15.8 ± 0.9 m/s; Figure 6.10c). Finally, there were no clear differences when comparing the vertical velocities of the kicking foot at initial ball contact between the three groups (-2.5 ± 1.1 m/s for the long kickers, -3.0 ± 1.2 m/s for the wide-left kickers and -2.1 ± 0.6 m/s for the short kickers; Figure 6.10d).

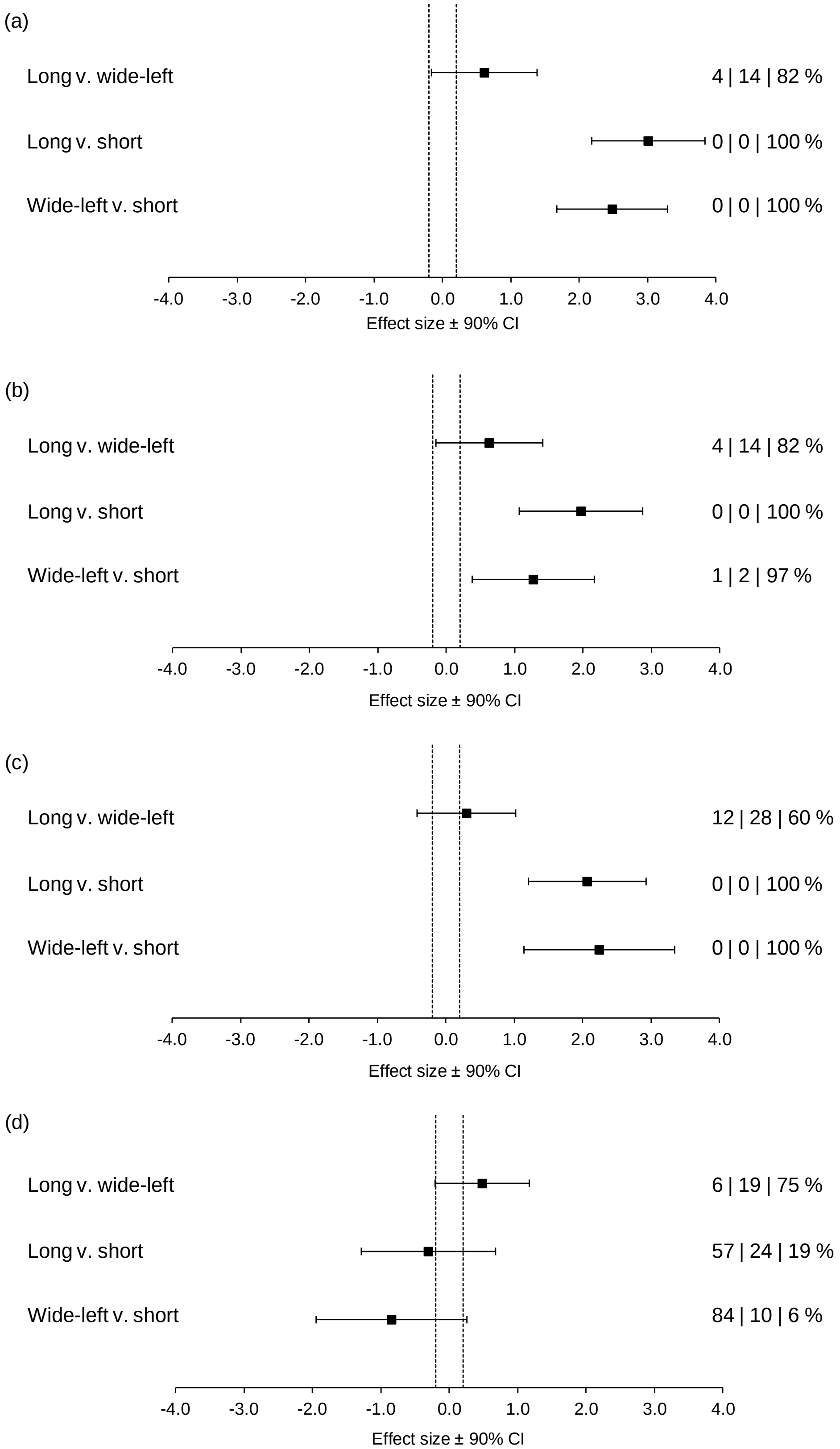


Figure 6.10. Effect sizes (± 90% CI) between the linear kicking foot CM velocities at initial ball contact: (a) resultant, (b) lateral, (c) forward and (d) vertical. The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each group comparison represent the likelihood that the effect is negative | trivial | positive.

6.4. Discussion

This chapter analysed the whole-body approach of the kickers towards the ball and the motion of the kicking foot during the kicking phase up to initial ball contact. In order to address research questions iii and iv, differences were identified between the techniques of the successful and less successful kickers to begin to explain the previously identified performance outcomes which occurred due to differences in the ball flight characteristics between the groups. This discussion will initially consider the whole-body and kicking foot motion of all of the groups of kickers in the context of previous literature. Specific comparisons between each pair of groups will then be discussed in turn.

6.4.1. General patterns across all groups

All kickers took an angled approach from a position to the left of the ball (when viewed from behind for right-footed kickers), the same as previously reported in a descriptive study of rugby place kicking (Cockcroft & van den Heever, 2016). The kickers within the current study took a final step towards the ball that was directed at an angle of approximately 15 - 26° (the range in mean angles of the three groups), straighter than that reported by Cockcroft and van den Heever (2016) of 36 ± 7°. The straighter final step recorded in the current study is likely due to differences in the methods used to measure this step, with the kicking foot and support foot CM positions used in the current study likely leading to a longer final step (particularly in the forward direction) compared with Cockcroft and van den Heever (2016) who compared the positions of the kicking foot toe and the support foot heel, thus affecting the calculated angle. The length of the final step in the current study ranged from 1.44 - 1.69 m (range in group means) which is similar to that reported by Cockcroft and van den Heever (2016; 1.52 ± 0.12 m) but again the different methods used make direct comparisons difficult. Following this final step, the kickers' support foot in the current study was positioned between 0.08 - 0.17 m behind the ball and 0.38 - 0.40 m to the left of the ball (group means). As with the final step, Cockcroft and van den Heever (2016) measured the support foot position using a different method to the current study, from the back of the kicking tee to the heel of the support foot as opposed to from the ball CM to the support foot CM (used in the current study). If both the length of the foot (assuming an average size 9 boot of 0.22 m from the position of the 5MTP to the heel) and the distance between the CM and posterior end of the ball when on the tee (up to 0.15 m, depending on the position of the ball) are considered, and assuming the posterior end of the ball is in-line with the rear of the tee, the support foot positions measured by Cockcroft and van den Heever (2016; 0.03 ± 0.07 m behind and 0.33 ± 0.03 m to the left of the ball) of professional players are comparable to those recorded in the current study, particularly for the long kickers (with an adjusted support foot position of 0.04 m behind and 0.40 m to the left of the ball, assuming the support foot was parallel to the direction of travel and the heel was in line with the support foot CM in the medio-lateral direction). The current support foot CM positions were similar to those used in the reference position (level with the ball CM in an anterior-posterior direction and 0.30 m to the left of the ball) by Baktash et al. (2009). Given the relatively small variation observed in the current study and that of Cockcroft and van den Heever (2016), the acute experimental manipulations used by Baktash et al. (2009) were clearly extreme (0.30 m in front of, behind and to the side of their reference position) and the direct application of their findings is likely limited.

The kickers approached the ball with a whole-body CM velocity of between 2.8 and 3.5 m/s (range in group means) and whilst this variable has not previously been reported in rugby place kicking it has in soccer instep kicking. Two studies have previously reported the kickers' approach velocity in tasks requiring them to perform maximum velocity soccer instep kicks. Andersen and Dörge (2011) reported that seven skilled kickers approached at speeds to 4.2 to 5.9 m/s and achieved ball velocities of 28.6 to 34.5 m/s when kicking for maximal velocity and with no prescribed accuracy demand. In contrast, Lees and Nolan (2002) reported approach velocities of two professional soccer players of 3.3 to 3.5 m/s when performing maximal velocity instep kicks, representative of penalty kicks towards the top-right corner of the goal, achieving ball velocities of 24.3 to 26.6 m/s. This approach velocity then reduced when the requirement of the kick was to hit a target in the top-right corner of the goal (2.4 to 2.5 m/s; Lees & Nolan, 2002) as did the ball velocities (18.1 to 20.4 m/s). Given the dual requirements of achieving both a fast and appropriately directed ball velocity vector in rugby place kicking, and the magnitude of the ball velocities recorded (20.8 to 27.6 m/s, range in group means), these approach velocities appear comparable to those in soccer instep kicking. From support foot contact onwards, the kickers exerted forces to alter their whole-body CM velocity. The ground reaction forces were directed predominantly posteriorly and wholly laterally throughout this phase (towards the left-hand-side and the direction the kickers had come from), decelerating the kickers' whole-body CM velocity in both the forward (by 0.5 - 0.6 m/s; range in group means) and lateral directions (towards the right-hand-side by between 0.8 and 1.1 m/s; range in group means), whilst reversing the direction of their initially downwards vertical velocity. These forces have not previously been investigated in rugby place kicking but broadly reflect those typically reported in soccer instep kicking (e.g. Lees et al., 2009; Orloff et al., 2008). Although there are similarities in the force time-histories, the normalised peak medio-lateral forces (1.08 - 1.38 BW, range in group means) were greater than those reported in the majority of studies investigating soccer instep kicking (the largest being 0.92 BW; Katis & Kellis, 2010; Kellis et al., 2004; Isokawa & Lees, 1988; Orloff et al., 2008) but similar to one of the few studies of professional players (1.24 BW; Rodano & Tavana, 1993). These differences in the peak forces may be due to the differences in the tasks performed in soccer instep kicking and rugby place kicking, differences in the experience and strength levels of the kickers or the angle from which they approached the ball. Katis and Kellis (2010), Lees et al. (2009) and Orloff et al. (2008) allowed the kickers to approach the ball at a self-selected angle, and although these angles were not reported, Scurr & Hall (2009) reported a self-selected approach angle of approximately 30 ± 15° for recreational soccer players performing instep kicks. This angle is smaller than that recorded for all groups in the current study (mean angle of 43° - 51° at kicking foot take-off across the groups), and a reduced angle has been shown to reduce the lateral ground reaction force but increase the force in the anterior-posterior direction (both peak forces and qualitatively across the time-history; Isokawa & Lees, 1988; Kellis et al., 2004). Whilst group comparisons will be discussed in more detail in later sections, the short kickers took a straighter approach to the ball than the other two groups and were also found to exert lower medio-lateral ground reaction forces during this phase, providing further support for this theory.

The deceleration in the kickers' whole-body CM velocity in the horizontal directions has previously been suggested as a mechanism to transfer the momentum of the kicker to their kicking leg and therefore achieve a faster kicking foot velocity in soccer instep kicking (Potthast et al., 2010). The kickers in the current study demonstrated greater deceleration of their whole-body CM velocity in the lateral direction than in the forward direction (range in group means of -0.8 to -1.1 m/s and -0.5 to -0.6 m/s, respectively) likely due to the angled approach taken to the ball. The total change in whole-body CM deceleration in these horizontal directions cannot be directly compared with the study by Potthast et al. (2010) as the masses of the soccer kickers were not presented in the previous study. However, the whole-body CM deceleration impulse of the long place kickers in the current study was similar to that reported for the soccer kickers (143.4 ± 30.0 kg.m/s compared with 144.5 ± 32.5 kg.m/s, respectively) and both groups of kickers achieved comparable ball velocities (27.6 ± 1.7 m/s and 27.8 ± 2.0 m/s). This deceleration in the horizontal whole-body CM velocities of the long kickers was substantially larger than the short kickers, and this difference will be discussed in more detail in Section 6.4.3.

The kinematics of the kicking foot at the top of the backswing and at initial ball contact were also investigated, as was the path of the kicking foot throughout the downswing between these two events. Kicking foot positions prior to initial ball contact have not been widely reported in literature investigating kicking skills in football codes. However, the importance of developing a stretch at the top of the backswing in rugby place kicking may be related to the 'tension arc' proposed by Shan and Westerhoff (2005) in soccer instep kicking, and has been recently suggested as important by an elite rugby kicking coach (Bezodis & Winter, 2014). The 'tension arc' (Shan & Westerhoff, 2005) involves a stretch-shortening cycle of the musculature of the torso being used to generate more forceful concentric muscular contractions and the pelvis being enabled to rotate through a greater range of motion, which may lead to a faster kicking foot velocity at initial ball contact. The elite rugby kicking coach termed this stretch the 'triangle', characterised as maximising the distances between the support foot, the kicking foot and the non-kicking-side shoulder at the top of the backswing (Bezodis & Winter, 2014). In the current study, the kicking foot was between 1.40 and 1.59 m from the ball when at the top of the backswing (group means). When this resultant displacement was resolved, the kicking foot was found to be between 1.09 and 1.14 m behind the ball, between 0.66 and 0.98 m to the left of the ball and between 0.44 and 0.61 m above the ball (all group means). The kicking foot then took a curved path down towards the ball of length 1.23 to 1.47 m (group means). The shape of these paths and the potential influence on the contact between the foot and the ball can be understood through analysis of the kicking foot velocity vector at initial ball contact. The resultant kicking foot velocity magnitude ranged from approximately 17.0 to 25.0 m/s (group means) which is faster than that recorded by Zhang et al. (2012) of 16.8 ± 1.6 m/s for rugby place kicks, likely due to the different playing levels of the kickers and also reflective of the differences in the recorded ball velocities between the two studies. The kicking foot velocities in the current study are comparable to the velocities recorded by Ball (2010; 21.8 ± 1.6 m/s) for elite Rugby League kickers. When the velocity vector was resolved, it was revealed that the kicking foot was still moving towards the right-hand-side of the goalposts (5.4 - 8.8 m/s, range in group means) and in a downward direction (-2.1 to -3.0 m/s, range in group means) at initial ball contact. The lateral component of the velocity vector indicates that the kicking foot was travelling across the ball towards the right-hand-side at an angle of between 20 and 30° relative to the direction of the centre of the post, suggesting that the path may have demonstrated more similarities to the 'C-shape'© rather than the 'J-shape'© that have been previously described in the coaching literature (Wilkinson, 2005). Furthermore, the differences in kicking foot paths between the groups of kickers (Figure 6.9a) suggest that the long kickers had the most 'C-shaped'© path and thus the 'J-shape'© may not be a necessary feature of successful place kicking, although this will be further discussed in the subsequent comparisons between the groups. Given the contrasting directions of the kicking foot velocity vectors of the three groups at initial ball contact and the ball velocities post-contact, further consideration of the foot-ball contact is required to fully understand how this kicking foot path affects the path of the ball.

This section has discussed the general whole-body motion of the kickers and the specific motion of the kicking foot in the context of previous rugby place kicking studies and relevant literature from other football codes. However, how these aspects of technique differ between successful and less successful kickers is of primary interest to address the research questions posed and meet the thesis aim. First, the technique of the long kickers will be compared with the wide-left kickers.

6.4.2. Comparison of long and wide-left kickers

Comparison of the techniques of the long and wide-left kickers will provide insight regarding how both groups were able to achieve fast resultant ball velocities, yet the long group were able to achieve a ball velocity vector direction and longitudinal spin which led to a superior performance outcome. Identification and understanding of these differences can ultimately be used to inform coaches and players as to how they may improve place kick performance.

Whilst the approach of these groups of kickers towards the ball was broadly similar, the long kickers exhibited a substantially faster resultant kicking foot velocity which was directed further towards the right-hand-side at initial ball contact than the wide-left kickers. The long kickers' whole-body CM was further to the left of the ball at kicking foot take-off, support foot contact and initial ball contact, but there were no differences in its anterior-posterior position. Maintaining a lateral whole-body CM position further away from the ball may have provided the long kickers with more space between their body and the ball to rotate their kicking leg towards the ball. This could potentially allow the kicking leg to be orientated away from the body and therefore enable a greater range of motion at the kicking leg joints, without the concern of the kicking foot clearing the ground. This kicking leg motion may then potentially lead to a faster foot velocity at initial ball contact (as observed for the long kickers, and previously proposed by De Witt, 2002) and/or a greater opportunity to ensure that the kicking foot velocity vector is more appropriately directed prior to initial ball contact. Furthermore, as the long kickers' whole-body CM was further to the left of the ball, their torso would also likely be orientated such that it was facing further towards the right-hand-side relative to the global antero-posterior axis during this approach. Such a torso orientation may facilitate greater longitudinal pelvic rotation and therefore retraction of the kicking leg, positioning the kicking foot further to the left of the ball at the top of the backswing (as was observed and will be discussed in more depth later in this section). The greater lateral kicking foot velocity (towards the right-hand-side) observed at initial ball contact for the long kickers compared with the wide-left kickers partly reflected the differences in the ball velocity vectors of the two groups reported in Chapter 5, whereby the long kickers' ball velocity was directed towards the right-hand-side and the wide-left kickers' was towards the left-hand-side. Furthermore, the long kickers achieved a substantially greater vertical ball velocity compared with the wide-left kickers (Chapter 5) and this could have been due to differences in the lateral lean of the body towards the left-hand-side which has previously been suggested to enable the kicking foot to make contact lower on the ball (Lees et al., 2009).

The final step taken by the long kickers was substantially longer than that taken by the wide-left kickers, resulting in support foot contact occurring substantially later for the long kickers. The timing of the technique has been suggested to be important by an elite rugby kicking coach, who identified that the *"the first thing to go"* was the speed of the final step, in that if kickers *"get quick... they don't give themselves time to get back to their full natural 'triangle'"* (Bezodis & Winter, 2014). This may be reflected by the above differences in this final step and is partly supported by soccer instep kicking research. A longer final step has previously been shown to enable greater longitudinal pelvis rotation and retraction of the kicking leg during the backswing and therefore a greater pelvis range of motion about the global longitudinal axis during the downswing, facilitating an increased kicking foot velocity at initial ball contact (Lees & Nolan, 2002). In Australian Rules punt kicking, Ball (2008) previously identified a moderate positive relationship between the final step length and kicking distance (r = 0.41, p = 0.03). Ball (2008) suggested that a longer final step length enabled greater extension at the kicking hip and consequent thigh range of motion and, therefore, the potential to generate a faster kicking foot velocity. However, in the current study, the resultant displacement of the kicking foot relative to the ball at the top of the backswing was comparable between the long and wide-left groups, as was the kicking foot path length during the downswing, both of which would likely be affected if the above theory held true for the current investigation. What did differ, however, was the lateral position of the kicking foot at the top of the backswing (the long kickers positioned it further to the left-hand-side of the ball), suggesting that both the more lateral whole-body CM adopted by the long kickers and the longer final step they took towards the ball may have affected the rotation of the pelvis about the global longitudinal axis and subsequent positioning of the kicking foot (which is one side of the 'triangle' described above) prior to the downswing.

The difference in this position of the kicking foot at the top of the backswing would likely influence the shape of the path of the kicking foot towards the ball and potentially the direction of the kicking foot velocity vector at initial ball contact. As the kicking foot started from a position further to the left-hand-side of the ball for the long kickers, it took a more lateral path towards the ball, and the greater lateral velocity of the kicking foot at initial ball contact for these kickers demonstrated that it was still travelling in a more lateral direction at this point. This appears to be more closely reminiscent of the ‘C-shape’© path as opposed to the ‘J-shape’© path which has been advocated as more favourable in the coaching literature due to the kicking foot travelling in a straighter direction (closer to the intended direction of ball travel) towards the ball for a longer part of the path (Wilkinson, 2005). Although the ball contact phase was not investigated in the current study, the long kickers were able to achieve a more desirable ball velocity vector post-contact compared with the wide-left kickers despite their kicking foot travelling faster in a lateral direction at initial ball contact. In contrast, the direction of the wide-left kickers' kicking foot velocity vector and the subsequently achieved ball velocity vector were in opposing directions and ultimately caused the ball to travel in a less favourable direction and with greater longitudinal spin, ultimately leading to a less successful performance outcome. It therefore appears that it is not the 'C-shape'© path *per se* that is less desirable, as the long kickers exhibited the most lateral kicking foot path towards the ball but were able to achieve the highest levels of performance outcome. As previously suggested, future consideration of the foot-ball contact is required to fully understand how this kicking foot path affects the path of the ball.

Following the final step, the long kickers' support foot landed less far behind the ball compared with that of the wide-left kickers. There is no consensus in the literature regarding the optimum support foot location for rugby place kicking; Baktash et al. (2009) previously concluded that support foot position did not affect ball velocity in place kicking but, as highlighted previously, their study was limited by the extreme and unrealistic manipulations to support foot position and did not consider any effects on kick accuracy. Theoretically, a support foot positioned substantially further ahead of the kickers' whole-body CM would result in the ground reaction force being directed more posteriorly and thus causing greater deceleration of the kickers' whole-body CM, the momentum of which can be transferred to the kicking foot (Potthast et al., 2010). However, despite there being no clear difference in the antero-posterior whole-body CM position of the two groups and thus the long kickers' whole-body CM was substantially further behind their support foot than the wide-left kickers, there were no significant differences in the antero-posterior ground reaction force time-histories throughout stance. Analysis of the ground reaction forces in the other principal directions also revealed no significant differences between these two groups which is consistent with a study of soccer instep kicking which found no significant differences in the peak ground reaction forces recorded during accurate and inaccurate kicks (Katis et al., 2013). Furthermore, there was no difference in the deceleration of the kickers' CM velocities from support foot contact to initial ball contact in the horizontal directions, suggesting the differences observed in kicking foot velocity at initial ball contact between the long and wide-left kickers in the current study do not appear to be due to greater deceleration in whole-body CM velocity (previously suggested as important in soccer instep kicking; Potthast et al., 2010). The differences observed in the whole-body approach of the kicker towards the ball and the kicking foot kinematics at the top of the backswing and at initial ball contact suggest that the motion of both the kicking leg and the torso from the top of the backswing to initial ball contact may provide a greater insight as to how the long and wide-left kickers achieved different performance outcomes, and should be the focus of the subsequent investigations (Chapter 7).

6.4.3. Comparison of long and short kickers

Analysis of the ball flight characteristics of the long and short kickers revealed that long kickers were more successful because they were able to achieve a faster ball velocity post-contact which was directed less far towards the right-hand-side and demonstrated less longitudinal ball spin. A comparison of the differences in the whole-body approach of the kickers and the motion of the kicking foot during the kicking phase will provide an initial indication as to why these differences in ball flight were observed.

The long kickers had a more lateral whole-body CM position at kicking foot take-off, support foot contact and initial ball contact as well as a greater resultant whole-body CM velocity at these events (a difference also seen when resolved in to all three principal directions) and a longer final step length which was directed further towards the right-hand-side. This clearly different approach resulted in the long kickers positioning their support foot substantially further forward and closer to the ball than the short kickers; however, unlike when compared with the wide-left kickers, the long kickers' whole-body CM was also substantially further forward compared with the short kickers. A significantly larger medio-lateral ground reaction force was evident for the long kickers during the mid-stance phase and just prior to initial ball contact compared with the short kickers, consistent with previous research in soccer instep kicking which revealed larger medio-lateral ground reaction forces when kickers approached the ball from a greater angle (Kellis et al., 2004). These larger medio-lateral forces meant that the long kickers reduced their lateral whole-body CM velocity by a greater amount between support foot contact and initial ball contact than the short kickers. Furthermore, although there was no significant difference between the antero-posterior ground reaction forces of the two groups at each time point or in the total antero-posterior ground reaction impulse, the total horizontal impulse decelerating the kickers' whole-body CM velocity in the horizontal plane was substantially greater for the long kickers compared with the short kickers. This supports the theory proposed by Potthast et al. (2010) that the long kickers were better able to decelerate their whole-body CM velocity and transfer this momentum to the kicking leg resulting in a faster kicking foot velocity. It is also important to note that this difference in whole-body CM deceleration was not observed when solely considered in the antero-posterior direction and the more angled approach of a rugby place kick and motion in the medio-lateral direction further emphasises the need to consider the movement in 3D.

Following the longer and more angled final step, support foot contact occurred substantially later for the long kickers compared with the short kickers. This appeared to enable the long kickers to adopt their *"full natural 'triangle'"* (Bezodis & Winter, 2014) as they positioned their kicking foot substantially further to the left and above the ball at the top of the backswing compared with the shorter kickers, potentially through greater rotation of the pelvis about the global longitudinal axis (as discussed above when comparing the long and wide-left kickers). The kicking foot of the long kickers subsequently travelled a longer path during the downswing and exhibited a faster resultant velocity at initial ball contact as would be expected given the differences in the ball velocity magnitude post-contact between the groups and the previously established relationship between the kicking foot velocity magnitude and ball velocity magnitude in other football codes (e.g. Ball, 2012; Kellis et al., 2004; Orloff et al., 2008; Potthast et al., 2010). This finding provides further support that the final step that the kickers take towards the ball is important in determining the position of the kicking leg at the top of the backswing and potentially the subsequent motion during the downswing towards initial ball contact. When the resultant kicking foot velocity was resolved in to the three principal directions, the long kickers' forward and lateral foot velocities were substantially faster than the short kickers'. Whilst both the kicking foot position at the top of the backswing and the greater deceleration of the kickers' whole-body CM velocity between support foot contact and initial ball contact for the long kickers may partially explain the differences in the kicking foot velocity magnitudes, the reasons for the differences in the direction of the velocity vector are initially less apparent. As previously mentioned, the long kickers positioned their kicking foot further above and to the left of the ball at the top of the backswing compared with the short kickers and the subsequent shape of the kicking foot path of the long kickers was also directed more laterally during the downswing. This more laterally directed path did not appear to be detrimental to the performance of the long kickers, as ultimately the ball velocity vector was directed appropriately. However, the longer path length may have provided the kicking leg joints more time to rotate and likely enable the kickers to achieve a faster kicking foot velocity (De Witt, 2002). As with the comparison between the long and wide-left kickers, a subsequent investigation into the motion of the torso and the kicking leg during the kicking phase may help to explain how some of these differences are achieved and will thus be the focus of the next chapter in this thesis.

6.4.4. Comparison of wide-left and short kickers

Comparisons were also made between the wide-left and short kickers' approaches to the ball and the motion of the kicking foot during the downswing to identify differences between the kicking techniques of those who achieved similar levels of overall performance but for different reasons because they either lacked accuracy (wide-left kickers) or distance (short kickers). However, as these comparisons do not directly address the research questions posed, the discussion will be brief and will only highlight factors which relate to the previously identified discussion points in the previous two sections.

The differences observed between the wide-left and short kickers were broadly similar to those identified between the long and short kickers (Section 6.4.3). Similar to the long kickers, the wide-left kickers approached from a wider angle compared with the short kickers and their whole-body CM remained further to the left of the ball at kicking foot take-off, support foot contact and initial ball contact. Unlike the long kickers, however, there was no substantial difference in the final step length taken by the wide-left kickers and the short kickers, and thus both groups' support foot landed a similar distance from the ball. This suggests that although the wide-left kickers final step length was comparable to the short kickers', they were still able to achieve greater kicking leg retraction, potentially due to the more angled approach meaning that their torso (and pelvis in particular) was orientated such that it was facing further towards the right-hand-side, resulting in their kicking foot being positioned substantially further from the ball at the top of the backswing. The kicking foot then took a substantially longer path down towards the ball, resulting in a faster kicking foot velocity at initial ball contact (potentially through greater range of motion at the kicking leg joints; De Witt, 2002). The faster kicking foot velocity at initial ball contact and subsequent ball velocity post-contact of the wide-left kickers compared with the short kickers also supports the previously identified relationship between these two variables in other football codes (e.g. Ball, 2012; Kellis et al., 2004; Orloff et al., 2008; Potthast et al., 2010).

Likely due to the more angled approach, the wide-left kickers exerted a significantly larger lateral force throughout the middle of the stance phase, and achieved a greater deceleration in their whole-body CM velocity in this direction compared with the short kickers. However, the total whole-body CM deceleration in the two horizontal directions was not different between the two groups and thus is unlikely to be the reason for the differences in the magnitudes of the kicking foot velocity vectors. Given the differences in the position of the kicking foot at the top of the backswing and the kicking foot velocities at initial ball contact, as with the other comparisons, an investigation into the motion of both the torso and the kicking leg is required to further understand how these differences in performance outcome are achieved.

6.5. Conclusion

The whole-body approach of the kicker towards the ball and the motion of the kicking foot from the top of the backswing to initial ball contact were compared between the successful and two groups of less successful kickers. The first research question that was addressed was:

iii. **How does whole-body motion prior to initial ball contact differ between successful and less successful kickers?**

The long kickers approached from a position further to the left-hand-side of the ball than both the wide-left and short kickers, with the wide-left kickers further to the left than the short kickers but as both the long and wide-left kickers took a more angled final step, they landed with their support foot in a comparable lateral position relative to the ball compared with the short kickers. Furthermore, the long kickers had a greater forward velocity and took a longer final step, landing with their support foot further forward relative to the ball, compared with both of the other groups. This longer final step meant the long kickers' support foot contact occurred later, giving these kickers more time to adopt *"their full natural 'triangle'"* at the top of the backswing (Bezodis & Winter, 2014) compared with the other groups of kickers. Throughout the stance phase, the long kickers also decelerated their whole-body CM velocity to a greater extent than the short kickers. Both the 'triangle' and the deceleration of the kickers' whole-body CM likely influenced the motion of the kicking foot during the downswing and at initial ball contact in particular. Thus, the next question to be addressed was:

iv. **How does kicking foot motion from the top of the backswing to initial ball contact differ between successful and less successful kickers?**

At the top of the backswing, the kicking foot of the long and wide-left kickers was substantially further away from the ball and subsequently took a longer path down towards the ball compared with the short kickers. At initial ball contact, both the long and wide-left kickers achieved a substantially faster forward kicking foot velocity than the short kickers which likely explains the differences in the magnitudes of the ball velocities between the three groups reported in Chapter 5. Furthermore, the long kickers also demonstrated a substantially faster lateral kicking foot velocity (directed towards the right-hand-side of the goalposts) at initial ball contact compared with both the wide-left and short kickers as did the wide-left kickers compared with the short kickers. When these lateral kicking foot velocity vectors were considered alongside the positions of the kicking feet at the top of the backswing, the path taken down towards the ball was more similar to the 'C-shape©' path (particularly by the long and wide-left kickers) as opposed to the 'J-shape©' path advocated by Wilkinson (2005). Thus, this assertion that a 'J-shape©' path is desirable for successful place kicking is not supported by the results of this study and future investigation into the foot-ball contact is required to fully understand how the path of the kicking foot may affect the ball flight.

Several fundamental differences in whole-body motion and kicking foot kinematics have been identified and discussed between the groups. However, in order to now understand how the observed differences in kicking foot kinematics were achieved, and to enable different kicking strategies to be identified with a view to informing coaching practice, a detailed investigation of the motion of the kicking leg joints and the torso is required.

Chapter 7: Understanding kicking leg and torso motion during the downswing to explain differences in place kick performance outcome

7.1. Introduction

The approach of the kicker was found to affect both the direction and magnitude of the incoming whole-body CM velocity as well as the subsequent motion of the kicking foot in Chapter 6. Whilst the kicking foot ultimately contacts the ball and determines the flight of the ball post-contact, the kicking foot is the distal end of a linked-segment system and its motion at initial ball contact is largely determined by rotations of the more proximal segments throughout the downswing. Analysis of the motion of the torso and kicking leg would therefore extend the understanding developed in Chapter 6, helping to explain how different kicking foot kinematics are achieved at initial ball contact, and the potential role of the approach of the kicker in influencing these.

The motion of the kicking leg throughout the downswing has been widely investigated in soccer instep kicking (e.g. Alcock et al., 2012; Lees & Nolan, 2002; Lees & Rahnama, 2013; Lees et al., 2009; Levanon & Dapena, 1998; Nunome et al., 2002), and aspects of it have been the focus of, or reported in, investigations of rugby place kicking technique (Aitchison & Lees, 1983; Baktash et al., 2009; Sinclair et al., 2014; Zhang et al., 2012). The downswing of the kicking leg from the top of the backswing to initial ball contact in kicking skills is initiated by longitudinal rotation of the pelvis and flexion of the kicking hip (Wickstrom, 1975). This is followed by extension of the kicking knee, the velocity of which at initial ball contact has previously been identified as a single significant kinematic predictor of ball velocity magnitude in rugby place kicking (Sinclair et al., 2014). However, this only explained 48% of the observed variance in ball velocity magnitude and there was no accuracy demand in the task or consideration of accuracy of the kick - as previously highlighted, kicking technique is known to differ when an accuracy constraint is imposed in soccer instep kicking (Lees & Nolan, 2002), as is the case in rugby place kicking. Furthermore, Sinclair et al. (2014) only investigated kinematic variables which may be one reason why they were not able to explain any further variance in ball velocity magnitude despite initially including 72 different discrete variables in their analysis. Whilst the kinematics describe the observed motion, it is important to understand the underlying causes of these motions by investigating the joint kinetics which may further help to explain differences in performance outcome. Given the angled approach towards the ball identified in Chapter 6, it is also likely that the motion of the pelvis and trunk may influence these kicking leg mechanics and further explain the identified differences in performance outcome. Finally, previous studies have only conducted statistical analyses on discrete data (e.g. peak values or values at specific events); analysis of the complete time-histories could identify differences throughout the movement and therefore provide further novel insight regarding the technical differences between kickers who achieve different performance outcomes. In-depth analyses of the kicking leg joint kinematics and kinetics (collectively termed 'mechanics' hereafter) and the torso kinematic time-histories will allow the following research questions to be addressed:

v. **What are the kicking leg joint mechanics during the downswing and how do these differ between successful and less successful kickers?**

vi. **How does the motion of the torso during the downswing differ between successful and less successful kickers?**

7.2. Methods

Thirty-three male place kickers (mean ± SD = age 22 ± 4 years, mass = 86.2 ± 8.8 kg, height = 1.82 ± 0.06 m) each performed five maximum range place kicks in a laboratory. Their segmental kinematics were tracked using 54 reflective markers (as described in Chapter 4).

The same raw data (trials and trial durations) were used as in Chapter 6. The kicking leg hip, knee and ankle joint angular displacements and velocities were calculated using an XYZ Cardan rotation sequence as described in Chapter 4 and the resultant joint moments and powers were calculated through an inverse dynamics analysis. These joint mechanical data about the flexion-extension axis were extracted for all joints, as were the hip abduction-adduction angular displacements. Absolute angular kinematics of the pelvis and trunk segments were calculated relative to the global coordinate system and the angular displacement of the trunk relative to the pelvis about the longitudinal axis was determined (described in Chapter 4). These absolute segment and relative joint angular data were time-normalised to 101 points between the top of the backswing and initial ball contact. The kicking leg segment orientations were also calculated relative to the global coordinate system, and their orientations about the medio-lateral and antero-posterior global axes at initial ball contact were extracted. The total positive and negative work done at the kicking leg hip and knee joints about the flexion-extension axis was also calculated using integration procedures as described in Chapter 4.

The hip joint abduction-adduction angular displacements and the segmental orientations about the global antero-posterior and longitudinal axes were inverted for left-footed kickers to allow comparisons with the right-foot kickers. The kinetic variables were normalised using the equations presented in Chapter 4 (Hof, 1996) to negate the effect of differences in the mass of the short kickers compared with the long and wide-left kickers. The kickers were grouped as determined in Chapter 5 to enable the variables of interest to be compared between kickers who achieved different performance outcomes ($n = 18$ long kickers, $n = 8$ wide-left kickers and $n = 4$ short kickers). Mean ± standard deviations were calculated for all variables for each of the three kick groups. Effect sizes were calculated to compare the kicking leg segment orientations at initial ball contact and the total positive and negative work done at the hip and knee joints between each group pairing (Cohen, 1988), before 90% CIs of these effect sizes and magnitude-based inferences were derived with a smallest important effect determined as an effect size of 0.2 (Batterham & Hopkins, 2006; detailed in Chapter 4). All time-normalised absolute segmental and relative joint mechanical time-histories were analysed using a statistical parametric mapping two-tailed independent samples t-test to assess differences between the groups (with an α-level of 5%, detailed in Chapter 4).

7.3. Results

7.3.1. Kicking leg joint mechanics

Hip joint kinematics, moment and power

In all three groups of kickers, the kicking hip was in an extended position of approximately -30° (relative to a vertical alignment) at the top of the backswing before flexing throughout the downswing until initial ball contact (Figures 7.1a,b). There was no significant difference in the kicking hip angle throughout the downswing between any of the groups ($p > 0.05$; Figure 7.1c,e,g). There was also no significant difference between the long kickers' kicking hip flexion velocity and that of either the wide-left or short kickers ($p > 0.05$; Figure 7.1d,f). However, the wide-left kickers had a faster hip flexion velocity throughout the middle part of the downswing compared with the short kickers ($p < 0.001$; Figure 7.1h).

The flexing of the kicking hip was accompanied by a resultant flexor moment throughout the downswing and thus positive hip flexor power was evident (Figure 7.2a,b). The flexor moment was greatest at the top of the backswing before gradually reducing until late in the downswing where a second smaller peak in the flexor moment was observed in all groups (Figure 7.2a). A rapid reduction in the moment was then observed immediately prior to initial ball contact for all groups of kickers (Figure 7.2a). The long kickers' hip flexor moment was briefly larger than the short kickers’ during the early downswing ($p = 0.022$; Figure 7.2e) but there were no significant differences in the flexor moment of the wide-left kickers and either the long or short kickers ($p > 0.05$; Figure 7.2c,g). No significant differences were observed when comparing the positive hip flexor power of the long kickers with either the wide-left or short kickers ($p > 0.05$; Figure 7.2d,f). However, the wide-left kickers demonstrated significantly greater positive hip flexor power compared with the short kickers for a brief period early in the downswing ($p = 0.033$; Figure 7.2h).

The kicking hip joint was in an abducted position throughout the downswing for all groups of kickers (Figure 7.3a). There was relatively little change in the long and wide-left kickers' hip abduction angle, but the short kickers' hip became more abducted throughout the downswing (Figure 7.3a). No significant differences were observed between the long kickers' hip abduction angle and either the wide-left or short kickers ($p > 0.05$; Figure 7.3b,c). However, the short kickers displayed a more abducted hip angle late in the downswing through to initial ball contact compared with the wide-left kickers ($p = 0.029$; Figure 7.3d).

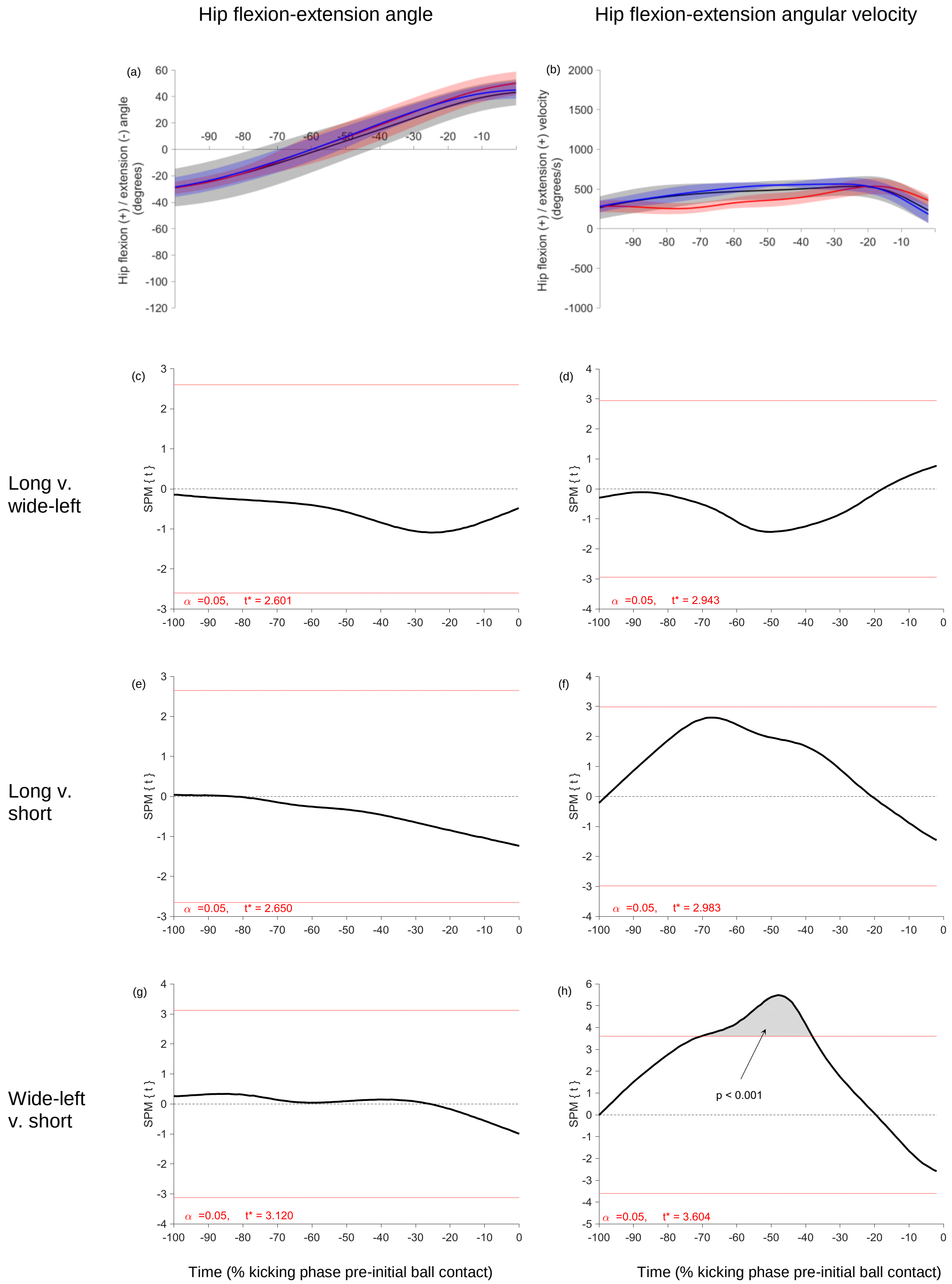


Figure 7.1. The hip flexion-extension (a) angle and (b) angular velocity (mean ± SD clouds) time-histories from the top of the backswing (-100%) to initial ball contact (0%) for the long (black), wide-left (blue) and short (red) kickers. Below the time-histories are the corresponding SPM{t} outputs comparing the long and wide-left kickers (c, d), the long and short kickers (e, f) and the wide-left and short kickers (g, h). Shaded areas and P-value labels indicate that the SPM{t} critical-t threshold (t*, dotted horizontal red line) was exceeded and there was a significant difference between conditions (α = 0.05).

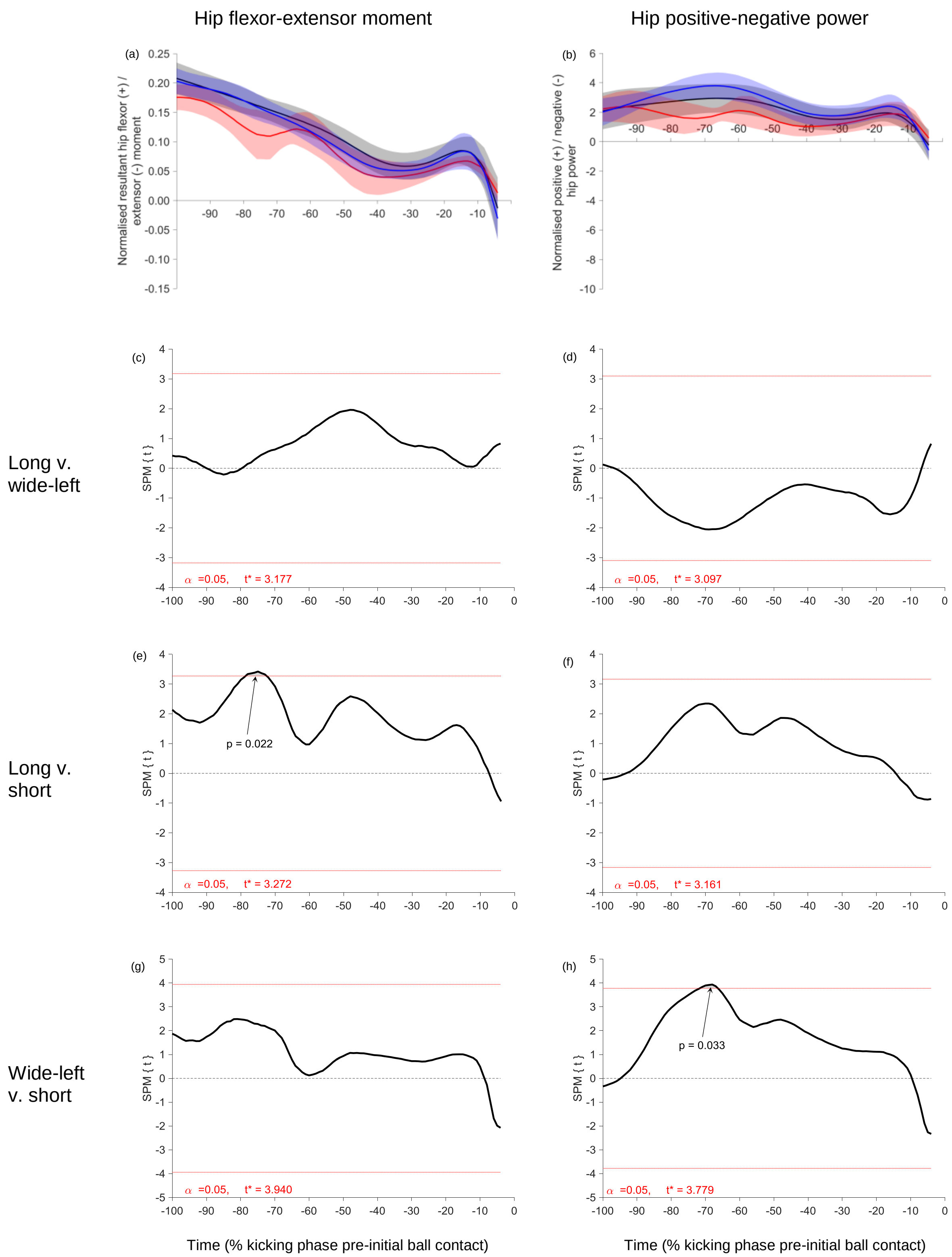


Figure 7.2. The hip flexion-extension (a) resultant joint moment and (b) joint power time-histories (mean ± SD cloud) from the top of the backswing (-100%) to initial ball contact (0%) for the long (black), wide-left (blue) and short (red) kickers. Below the time-histories are the corresponding SPM{t} outputs comparing the long and wide-left kickers (c, d), the long and short kickers (e, f) and the wide-left and short kickers (g, h). Shaded areas and P-value labels indicate that the SPM{t} critical-t threshold (t*, dotted horizontal red line) was exceeded and there was a significant difference between conditions (α = 0.05).

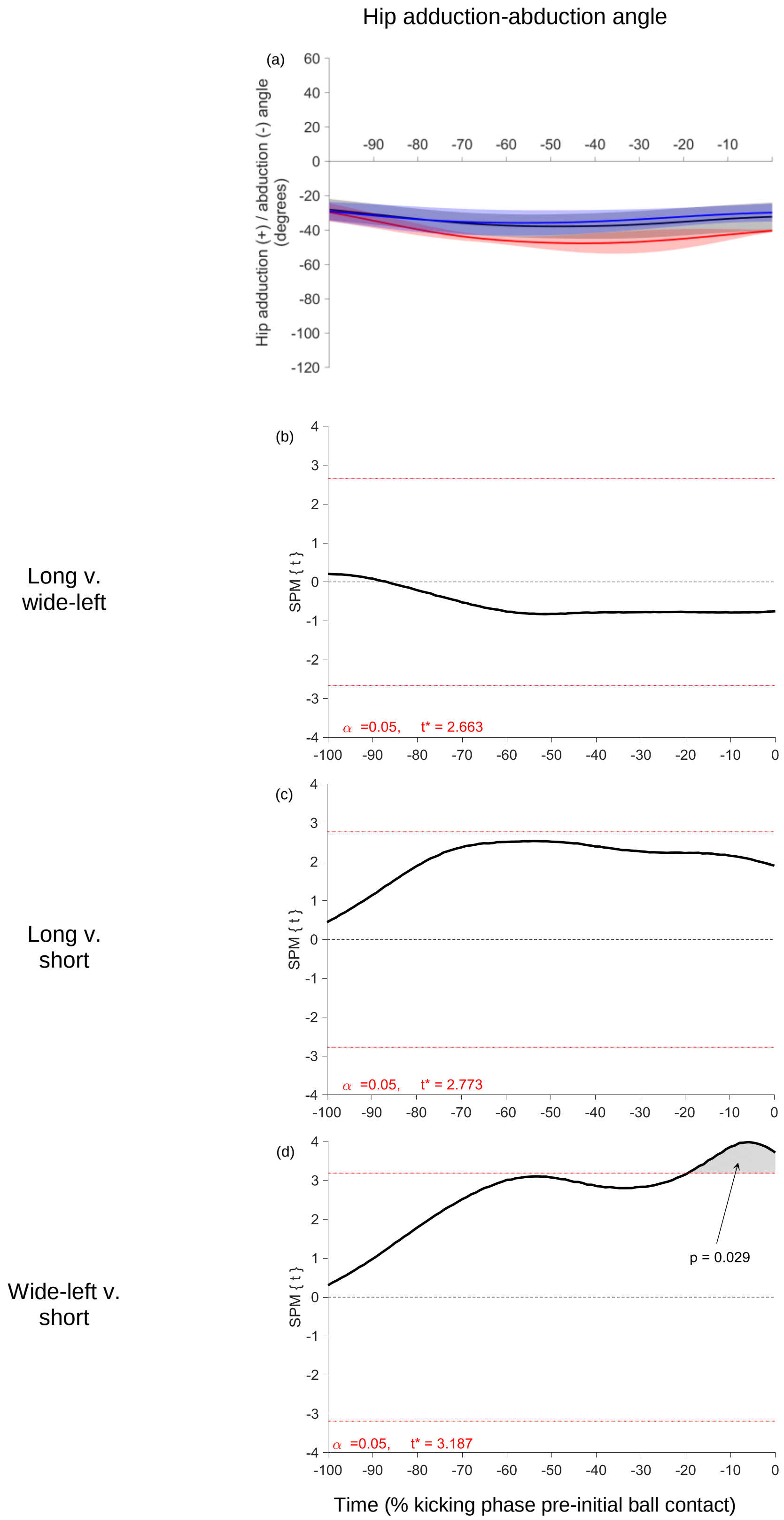


Figure 7.3. The (a) hip abduction-adduction angle time-histories (mean ± SD cloud) from the top of the backswing (-100%) to initial ball contact (0%) for the long (black), wide-left (blue) and short (red) kickers. Below the time-histories are the corresponding SPM{t} outputs comparing the (b) the long and wide-left kickers, (c) the long and short kickers and the (d) wide-left and short kickers. Shaded areas and P-value labels indicate that the SPM{t} critical-t threshold (t*, dotted horizontal red line) was exceeded and there was a significant difference between conditions (α = 0.05).

Knee joint kinematics, moment and power

The kicking knee was flexing at the top of the backswing and continued to flex until approximately 40% of the way through the downswing where it reached peak flexion before extending through to initial ball contact in all groups (Figure 7.4a,b). No significant differences were observed in the knee angles or angular velocities throughout the downswing between any of the groups of kickers ($p > 0.05$; Figure 7.4c-h). A knee extensor moment was observed for the majority of the downswing before it became flexor dominant during approximately the final 20% of the downswing (Figure 7.5a). This extensor moment was initially associated with knee flexion and thus a negative extensor power phase (Figure 7.5b). A positive extensor power phase then occurred as the knee began to extend, before a brief phase of negative flexor power occurred just prior to initial ball contact when a knee flexor moment became dominant (Figure 7.5b). No significant differences were found in the knee moment or power time-histories between the long and wide-left kickers ($p > 0.05$; Figure 7.5e,f). However, both the long and wide-left kickers produced a significantly larger knee flexor moment immediately prior to initial ball contact compared with the short kickers ($p < 0.05$; Figure 7.5c and $p = 0.012$; Figure 7.5g, respectively). Furthermore, the long kickers produced significantly greater negative knee flexor power immediately prior to initial ball contact compared with the short kickers ($p = 0.048$; Figure 7.5d) but there was no significant difference between the wide-left and short kickers ($p > 0.05$; Figure 7.5h).

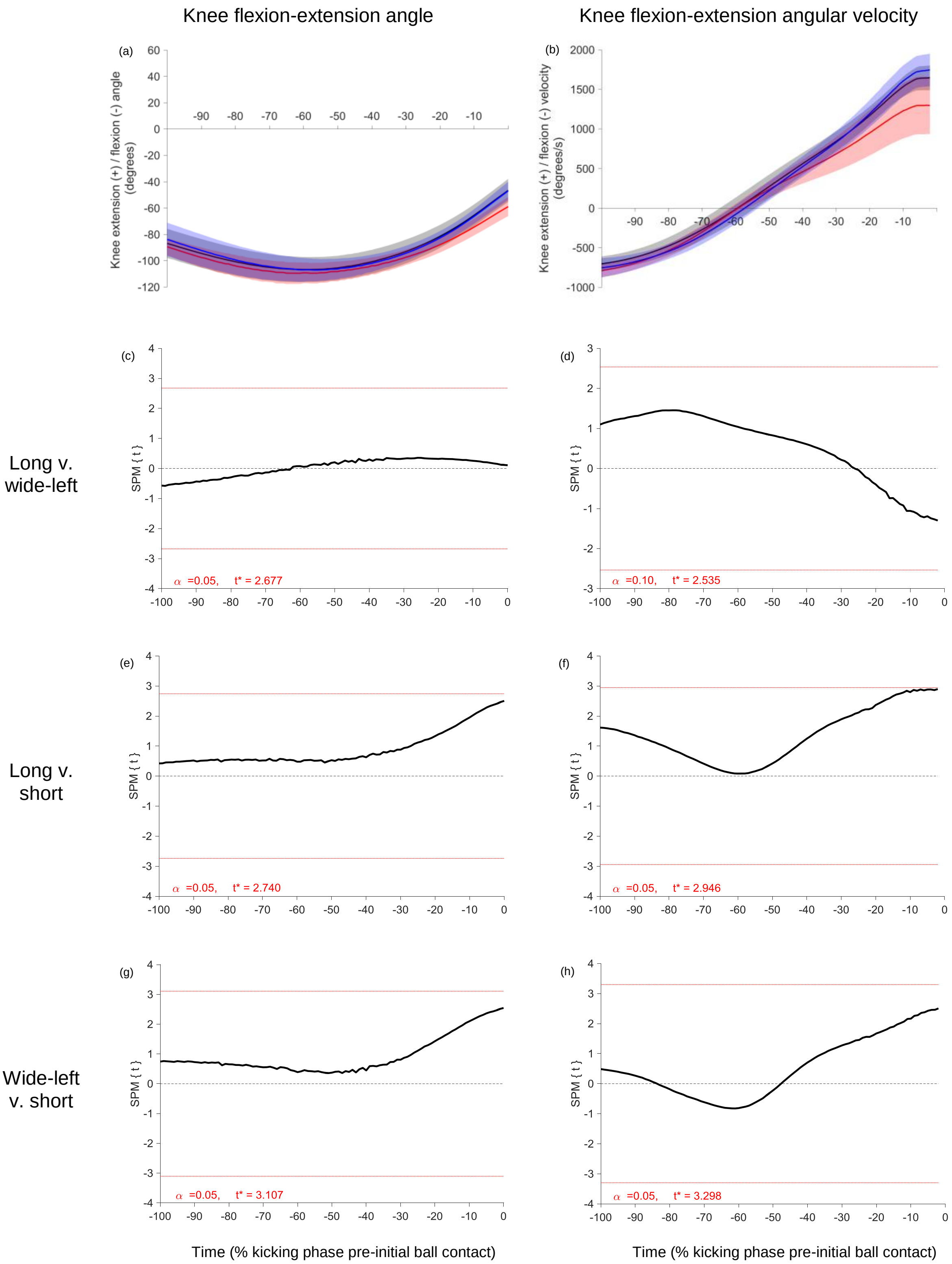


Figure 7.4. The knee flexion-extension (a) angle and (b) angular velocity time-histories from the top of the backswing (-100%) to initial ball contact (0%) for the long (black), wide-left (blue) and short (red) kickers. Below the time-histories are the corresponding SPM{t} outputs comparing the long and wide-left kickers (c, d), the long and short kickers (e, f) and the wide-left and short kickers (g, h). Shaded areas and P-value labels indicate that the SPM{t} critical-t threshold (t*, dotted horizontal red line) was exceeded and there was a significant difference between conditions (α = 0.05).

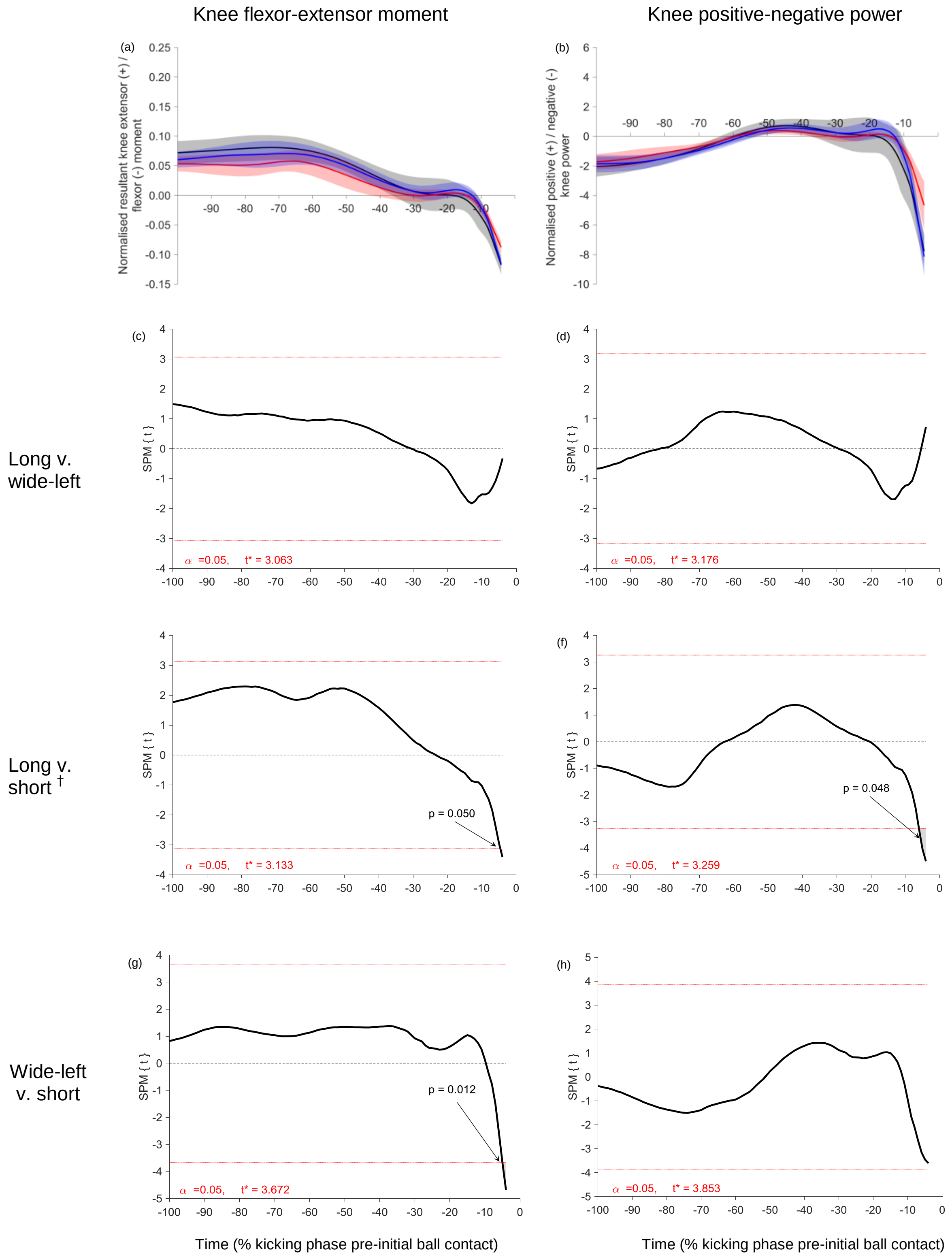


Figure 7.5. The knee flexion-extension (a) resultant joint moment and (b) joint power time-histories from the top of the backswing (-100%) to initial ball contact (0%) for the long (black), wide-left (blue) and short (red) kickers. Below the time-histories are the corresponding SPM{t} outputs comparing the long and wide-left kickers (c, d), the long and short kickers (e, f) and the wide-left and short kickers (g, h). Shaded areas and P-value labels indicate that the SPM{t} critical-t threshold (t*, dotted horizontal red line) was exceeded and there was a significant difference between conditions (α = 0.05).

† p = 0.0499 when the knee flexor-extensor moment was compared between the long and short kickers, reported as 0.050 to three decimal places.

Ankle joint kinematics, moment and power

The kicking ankle was in a plantar flexed position (relative to neutral standing) throughout the downswing with a slight dorsiflexion velocity generally present in all groups of kickers (Figure 7.6a,b). No significant differences were evident in the long and wide-left kickers' ankle angles throughout the downswing ($p > 0.05$; Figure 7.6c). However, the long kickers had a significantly more plantar flexed ankle than the short kickers during the middle part of the downswing ($p = 0.030$, Figure 7.6e) but there was no significant difference between the wide-left and short kickers ($p > 0.05$; Figure 7.6g). There were also no significant differences in ankle dorsiflexion velocity between the three groups (Figure 7.6d,f,h). An ankle dorsiflexor moment was observed throughout the downswing for all groups (Figure 7.7a) but negligible joint power was recorded (Figure 7.7b) and no significant differences were observed in the moment or power time-histories between the three groups ($p > 0.05$; Figure 7.7c-h).

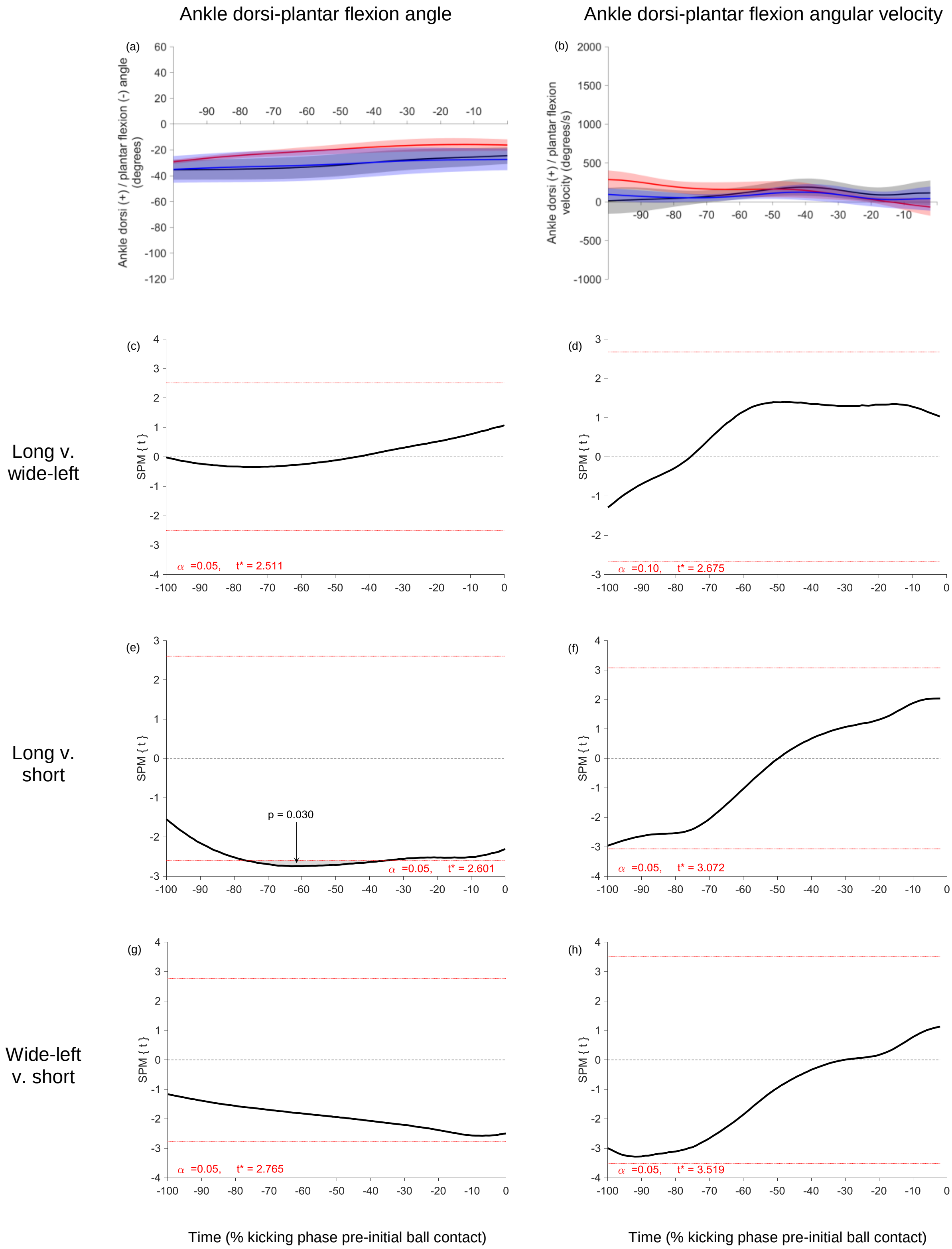


Figure 7.6. The ankle dorsi-plantar flexion (a) angle and (b) angular velocity time-histories from the top of the backswing (-100%) to initial ball contact (0%) for the long (black), wide-left (blue) and short (red) kickers. Below the time-histories are the corresponding SPM{t} outputs comparing the long and wide-left kickers (c, d), the long and short kickers (e, f) and the wide-left and short kickers (g, h). Shaded areas and P-value labels indicate that the SPM{t} critical-t threshold (t*, dotted horizontal red line) was exceeded and there was a significant difference between conditions (α = 0.05).

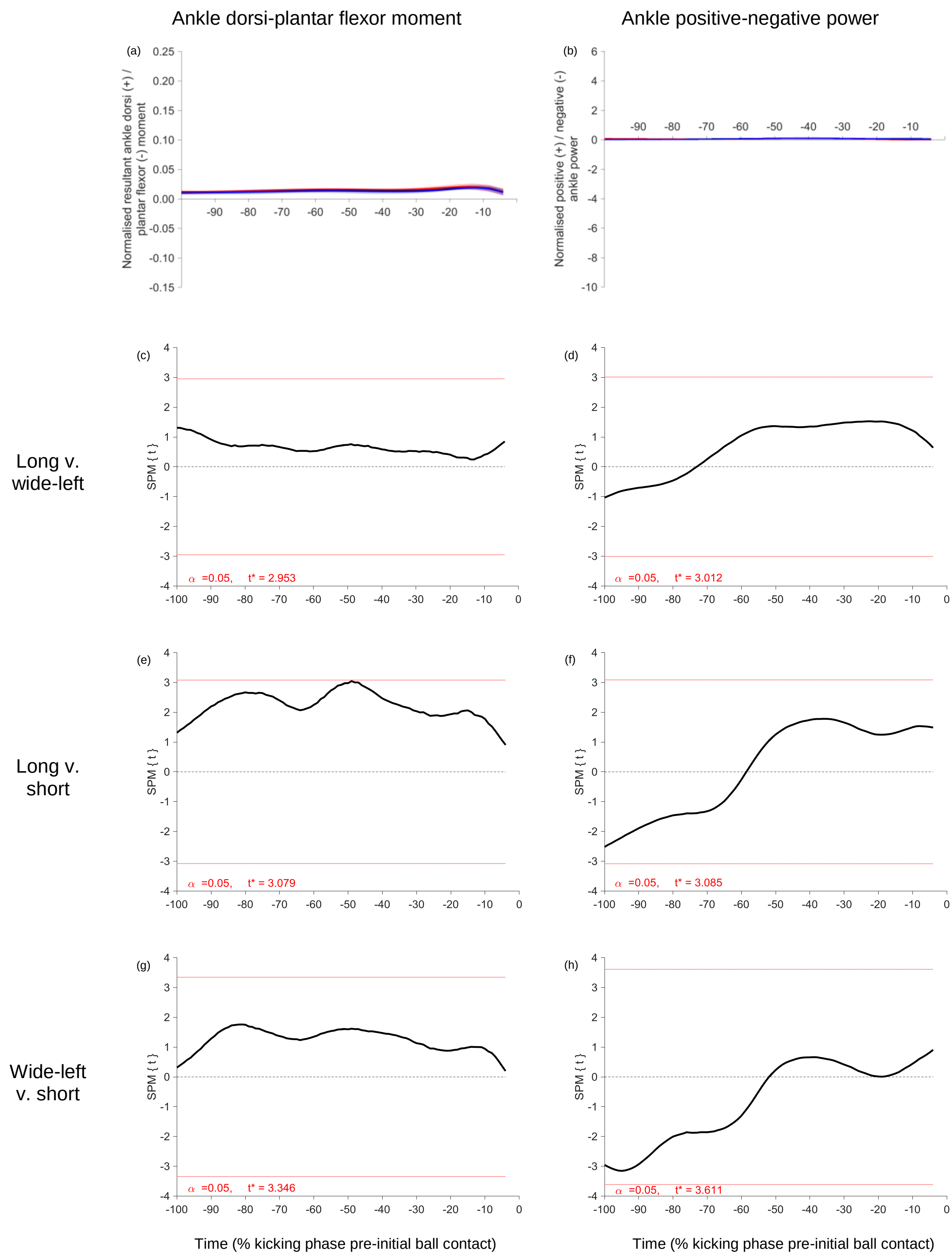


Figure 7.7. The ankle dorsi-plantar flexion (a) resultant joint moment and (b) joint power time-histories from the top of the backswing (-100%) to initial ball contact (0%) for the long (black), wide-left (blue) and short (red) kickers. Below the time-histories are the corresponding SPM{t} outputs comparing the long and wide-left kickers (c, d), the long and short kickers (e, f) and the wide-left and short kickers (g, h). Shaded areas and P-value labels indicate that the SPM{t} critical-t threshold (t*, dotted horizontal red line) was exceeded and there was a significant difference between conditions (α = 0.05).

Hip, knee and ankle joint work

Integration of the previously described joint power time-histories yielded the positive and negative work done at each of the kicking leg joints during the downswing. The long kickers did substantially less positive hip flexor work throughout the downswing than the wide-left kickers (mean difference in normalised work = -0.02; Table 7.1), but substantially more than the short kickers (mean difference = 0.02; Table 7.1). The wide-left kickers also did substantially more positive hip flexor work than the short kickers (mean difference = 0.04; Table 7.1). At the knee joint there were periods of both negative and positive work (Figure 7.5b). The knee extensors initially did negative work ($Knee_{extensor-}$; Figure 7.8), followed by positive work ($Knee_{extensor+}$; Figure 7.8) until just prior to initial ball contact when negative knee flexor work occurred ($Knee_{flexor-}$; Figure 7.8). There was no clear difference in the negative work done between the long and the wide-left kickers' knee extensors during $Knee_{extensor-}$. However, both of these groups of kickers did substantially more negative work during this phase than the short kickers (mean difference = -0.01 for both comparisons; Table 7.1). The long kickers did substantially more positive work at the knee during $Knee_{extensor+}$ than both the wide-left and short kickers (mean difference = 0.01 for both comparisons; Table 7.1) but there was no clear difference in the work done between the wide-left and short kickers during this period (Table 7.1). During $Knee_{flexor-}$, the long kickers' knee flexors did substantially more negative work compared with both the wide-left and short kickers' (mean difference = -0.01 for both comparisons; Table 7.1) but there was no clear difference when comparing the wide-left and short kickers' (Table 7.1).

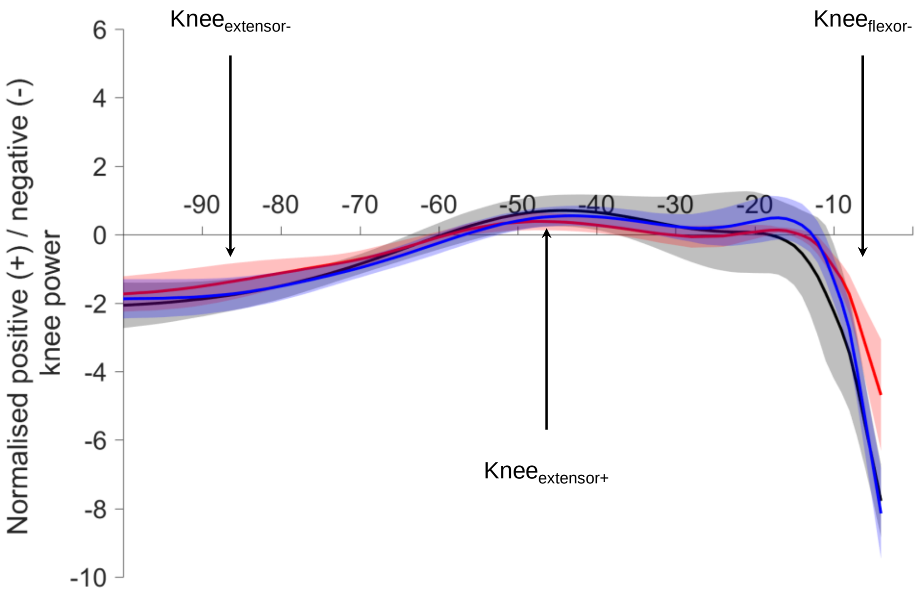


Figure 7.8. The identified periods of negative knee extensor ($Knee_{extensor-}$), positive knee extensor ($Knee_{extensor+}$) and negative knee flexor ($Knee_{flexor-}$) joint work throughout the downswing.

Table 7.1. Normalised kicking hip and knee joint work throughout the downswing (mean ± SD) and the magnitude-based inferences for the group comparisons.

	Normalised joint work	Compared with wide-left kickers Effect size ± 90% CI	(% Negative | Trivial | Positive)	Compared with short kickers Effect size ± 90% CI	(% Negative | Trivial | Positive)
$Hip_{flexor+}$					
Long	0.09 ± 0.02*†	-1.1 ± 0.8	(96 | 3 | 1)	1.0 ± 0.9	(2 | 6 | 92)
Wide-left	0.11 ± 0.02*			1.7 ± 0.8	(0 | 0 | 100)
Short	0.07 ± 0.03				
$Knee_{extensor-}$ ^					
Long	-0.03 ± 0.01*	< 0.1 ± 0.8	(29 | 34 | 37)	-1.0 ± 0.9	(92 | 6 | 2)
Wide-left	-0.03 ± 0.01*			-0.9 ± 1.0	(90 | 7 | 3)
Short	-0.02 ± 0.01				
$Knee_{extensor+}$					
Long	0.01 ± 0.01*†	0.6 ± 0.7	(2 | 12 | 86)	0.7 ± 1.0	(5 | 12 | 83)
Wide-left	< 0.01 ± 0.01			< 0.1 ± 1.2	(36 | 23 | 41)
Short	< 0.01 ± 0.00				
$Knee_{flexor-}$ ^					
Long	-0.02 ± 0.01*†	-0.7 ± 0.7	(90 | 9 | 1)	-1.0 ± 1.0	(90 | 7 | 3)
Wide-left	-0.01 ± 0.01			-0.1 ± 1.0	(46 | 25 | 29)
Short	-0.01 ± 0.00				

* Denotes a substantial effect compared with the short kickers † Denotes a substantial effect compared with the wide-left kickers
^ A negative effect size of the negative joint work values indicates more work was done during the phase

7.3.2. Motion of the torso

The pelvis segment

In all groups, the pelvis was anteriorly tilted about the global medio-lateral axis at the top of the backswing before rotating towards a more neutral position throughout the downswing until initial ball contact (Figure 7.9a). There was no significant difference between the long and wide-left kickers' anterior pelvic tilt ($p > 0.05$; Figure 7.9c). However, both the long and wide-left kickers exhibited a more anteriorly tilted pelvis compared with the short kickers throughout the first half of the downswing ($p = 0.027$ and $p = 0.016$, respectively; Figure 7.9e,g). About the global antero-posterior axis, minimal pelvic sideways tilt was observed at the top of the backswing in the three groups (Figure 7.9b). However, as the downswing progressed, sideways pelvic tilt occurred; the long kickers' pelvis was significantly more tilted down towards the left-hand-side (as viewed from behind) during the second half of the downswing compared with the short kickers ($p = 0.027$, Figure 7.9f) but there was no difference between the wide-left kickers and the other two groups (Figure 7.9d,h).

The pelvis was also orientated about the global longitudinal axis such that it was facing towards the right-hand-side throughout the downswing in all groups (Figure 7.10a). There was no significant difference between the long and wide-left kickers throughout the downswing ($p > 0.05$; Figure 7.10c), but the long kickers' pelvis was facing significantly further towards the right-hand-side compared with the short kickers throughout the entire downswing ($p = 0.002$; Figure 7.10e). The wide-left kickers' pelvis was also facing significantly further towards the right-hand-side than the short kickers' pelvis during the first half of the downswing ($p = 0.003$; Figure 7.10g) and then again just prior to initial ball contact ($p = 0.035$; Figure 7.10g). For all groups, the pelvis longitudinally rotated anti-clockwise (when viewed from above, right side moving forwards) during the downswing (Figure 7.10b) but there were no significant differences between the kickers' pelvis longitudinal rotation velocities ($p > 0.05$; Figure 7.10d,f,h).

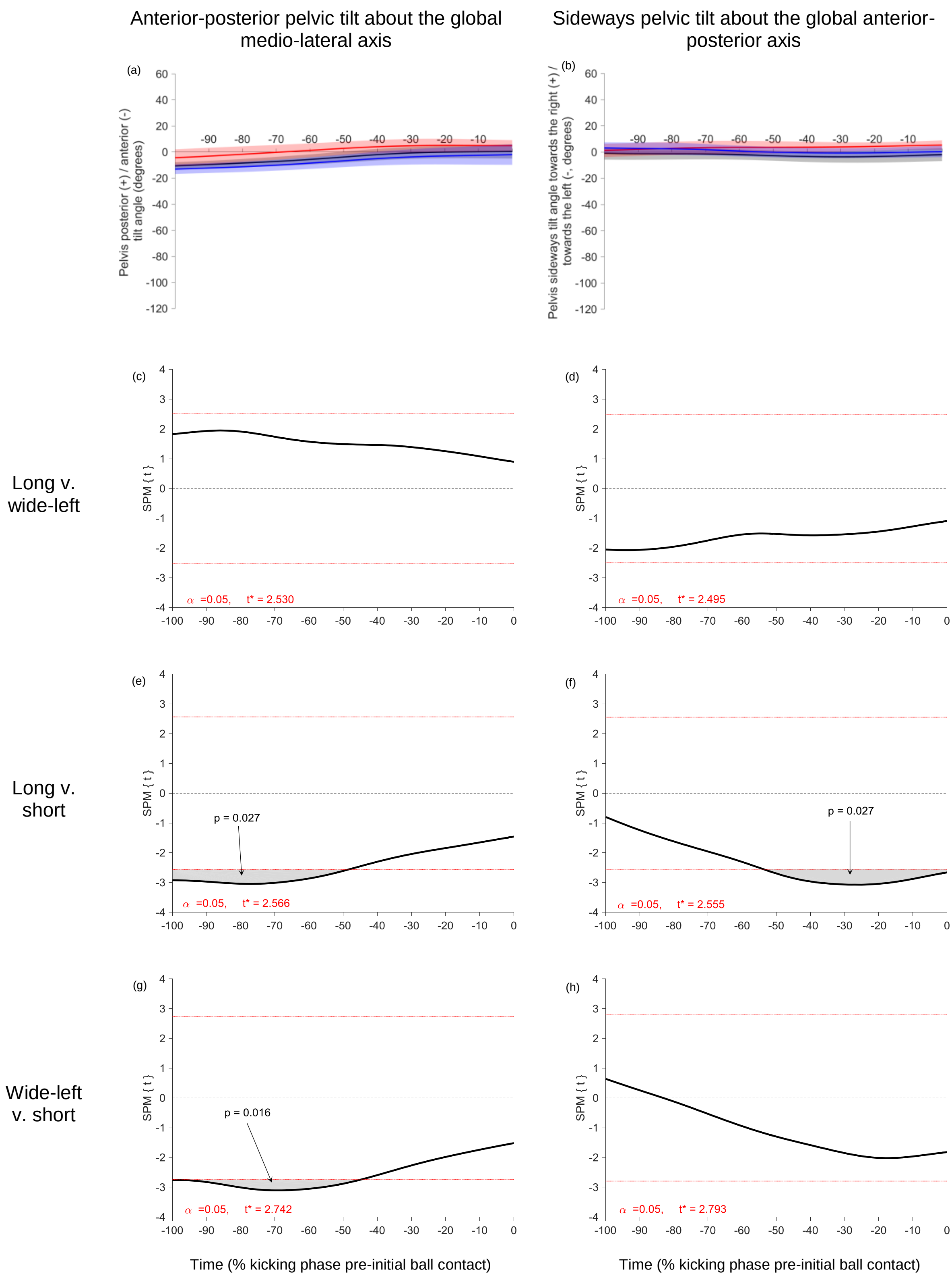


Figure 7.9. The pelvic (a) anterior-posterior and (b) sideways tilt angle time-histories (mean ± SD cloud) from the top of the backswing (-100%) to initial ball contact (0%) for the long (black), wide-left (blue) and short (red) kickers. Below the time-histories are the corresponding SPM{t} outputs comparing the long and wide-left kickers (c, d), the long and short kickers (e, f) and the wide-left and short kickers (g, h). Shaded areas and P-value labels indicate SPM{t} critical-t threshold (t*, dotted horizontal red line) was exceeded and there was a significant difference between conditions (α = 0.05).

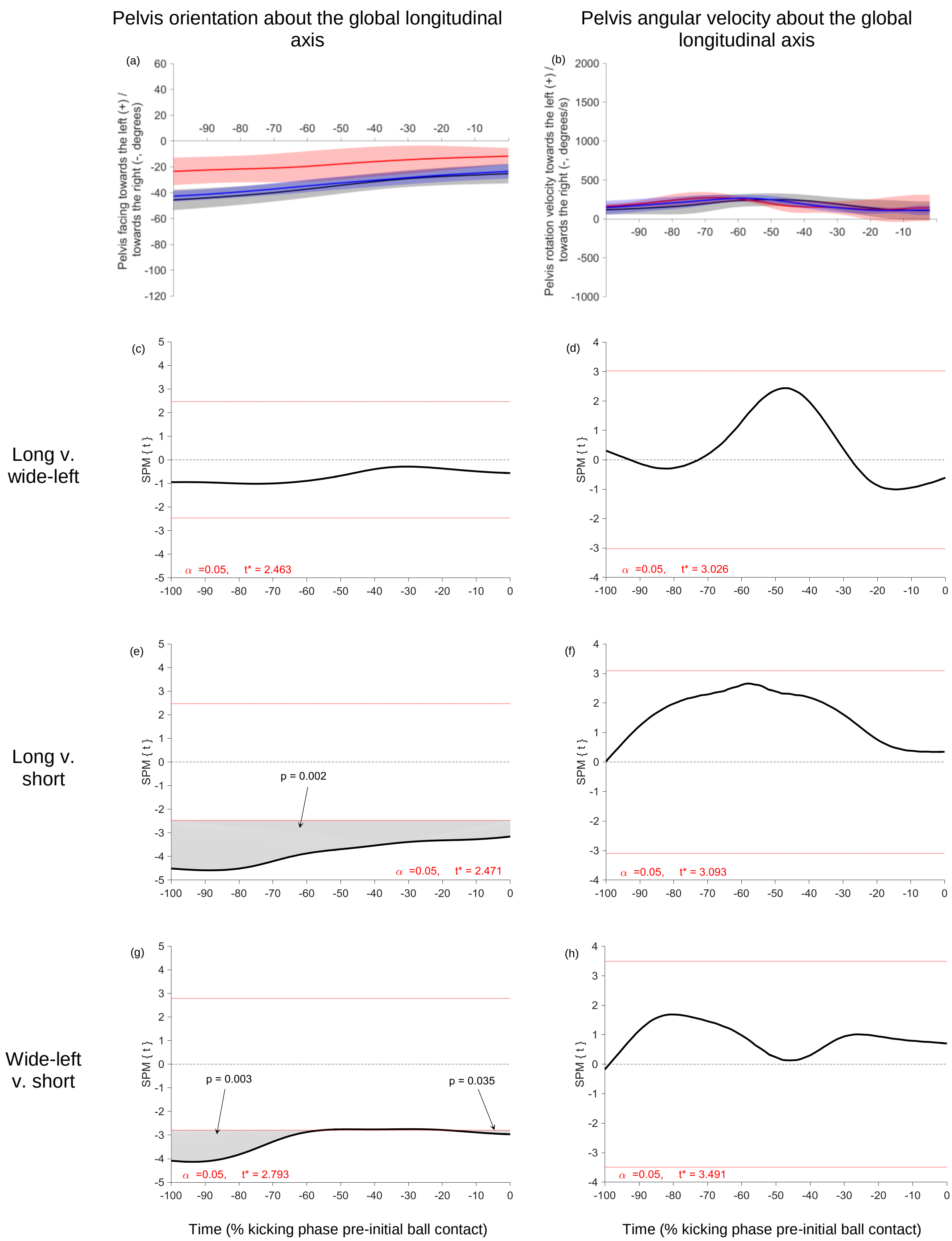


Figure 7.10. The pelvis (a) orientation about the global longitudinal axis and (b) longitudinal angular velocity time-histories (mean ± SD cloud) from the top of the backswing (-100%) to initial ball contact (0%) for the long (black), wide-left (blue) and short (red) kickers. Below the time-histories are the corresponding SPM{t} outputs comparing the long and wide-left kickers (c, d), the long and short kickers (e, f) and the wide-left and short kickers (g, h). Shaded areas and P-value labels indicate that the SPM{t} critical-t threshold (t*, dotted horizontal red line) was exceeded and there was a significant difference between conditions ($\alpha = 0.05$).

The trunk segment and relative pelvis-trunk motion

The trunk was orientated about the global longitudinal axis such that it was facing towards the right-hand-side in all groups of kickers from the top of the backswing to initial ball contact (Figure 7.11a). The long kickers' trunk was facing further towards the right-hand-side for the first 70% of the downswing compared with the wide-left kickers ($p = 0.022$; Figure 7.11c) and for the complete downswing compared with the short kickers ($p = 0.002$; Figure 7.11e). No significant differences were found between the orientation of the wide-left and short kickers' trunks throughout the downswing ($p > 0.050$; Figure 7.11g).

At the top of the backswing, all kickers' trunk segments were facing less far towards the right-hand-side than their pelvis. The relative angle between the wide-left kickers' trunk and pelvis was significantly greater than both the long kickers' and short kickers' (Figure 7.11b). Throughout the downswing, the short kickers' trunk remained approximately aligned with the pelvis (i.e. relative pelvis-trunk angle ≈ 0°; Figure 7.11b), however, the relative pelvis-trunk angle of both the long and wide-left kickers changed during the downswing (Figure 7.11b). The long kickers' trunk rotated slightly towards the right-hand-side during the downswing (Figure 7.11a) whilst the pelvis rotated towards the left-hand-side (Figure 7.10a). This initially reduced the relative pelvis-trunk angle until the two segments were aligned at approximately 40% into the downswing, before increasing again, in the opposite direction, as the pelvis rotated further towards the left-hand-side and the trunk towards the right-hand-side (Figure 7.11b). Whilst the orientation of the wide-left kickers' pelvis was comparable to the long kickers' throughout the downswing (Figure 7.10a,c), the trunk motion (and therefore relative pelvis-trunk angle) differed between these groups. The wide-left kickers' trunk was facing less far towards the right-hand-side (and thus more front-on) at the top of the backswing than the long kickers' (Figure 7.11c) but demonstrated a greater range of rotation towards the right-hand-side during the downswing (Figure 7.11a). This reduced the relative pelvis-trunk angle until the two segments were aligned after approximately 70% of the downswing (Figure 7.11b).

The wide-left kickers' trunk then continued to rotate towards the right-hand-side and there was no significant difference between the relative pelvis-trunk angles of the long and wide-left kickers during the final 20% of the downswing (Figure 7.11d). There were no significant differences in relative pelvis-trunk angles between the long and short kickers throughout the downswing (Figure 7.11f), or between the wide-left and short kickers following the initial 5% of the downswing (Figure 7.11h).

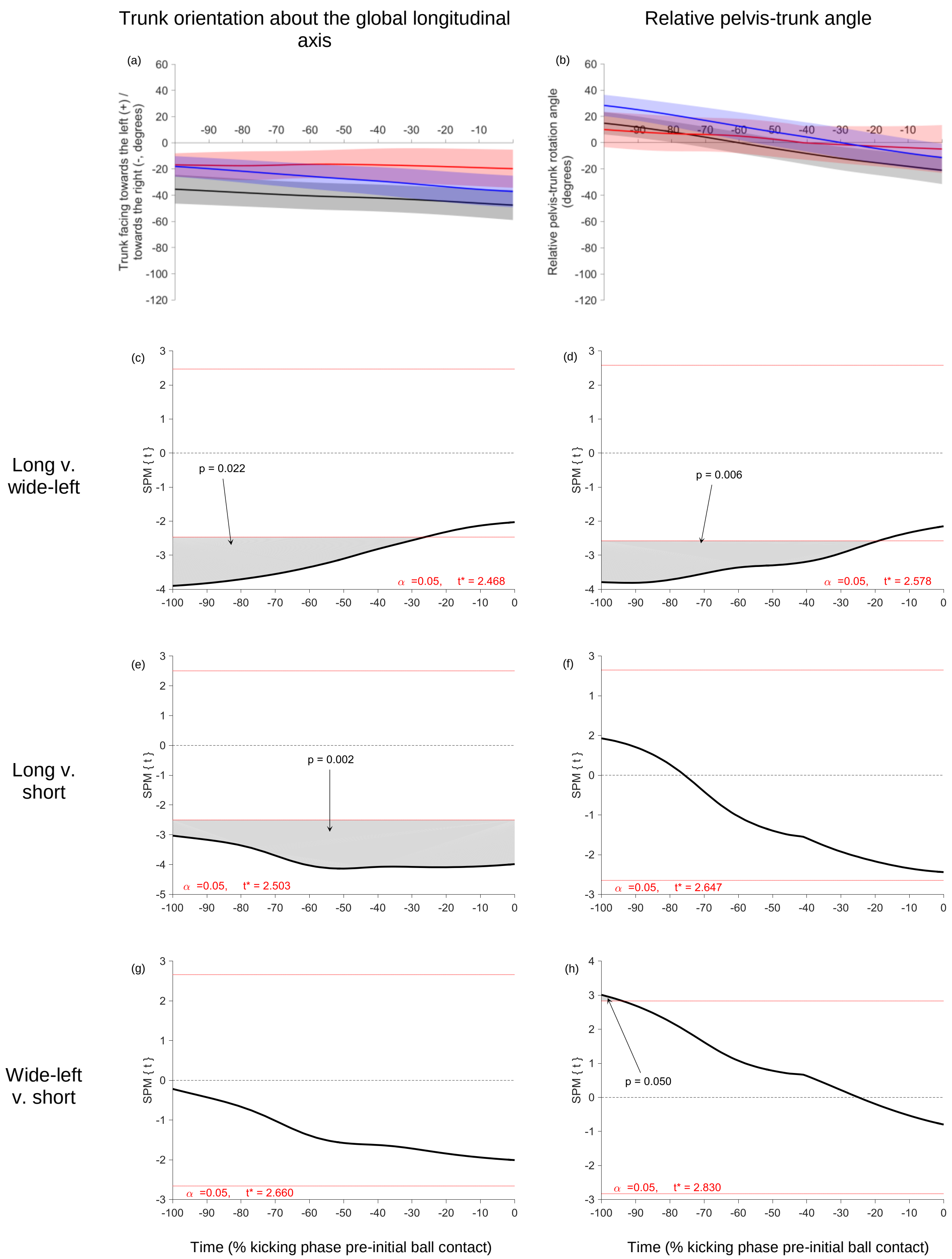


Figure 7.11. The (a) trunk rotation angle and (b) relative trunk-pelvis rotation angle about the longitudinal axis time-histories from the top of the backswing (-100%) to initial ball contact (0%) for the long (black), wide-left (blue) and short (red) kickers. Below the time-histories are the corresponding SPM{t} outputs comparing the long and wide-left kickers (c, d), the long and short kickers (e, f) and the wide-left and short kickers (g, h). Shaded areas and P-value labels indicate that the SPM{t} critical-t threshold (t*, dotted horizontal red line) was exceeded and there was a significant difference between conditions ($\alpha = 0.05$).

7.3.3. Orientation of the kicking leg segments at initial ball contact

The segmental orientations of the three groups of kickers at initial ball contact are depicted in Figure 7.12. The kicking knee was in front of the hip at initial ball contact in all three groups (Figure 7.12). There was no clear difference in thigh orientation between the long and wide-left kickers (Table 7.2) but the knee of the long and wide-left kickers was substantially less far in front of the hip compared with the short kickers (mean difference in absolute thigh angle = 16° and 14°, respectively; Table 7.2). The knee joint was also lateral to the hip joint (i.e. closer to the ball) in all three groups (Figure 7.12). The long kickers' knee was substantially more lateral relative to the hip than the wide-left kickers' (mean difference in absolute thigh angle= 4°; Table 7.2). However, there was no clear difference between either the long or wide-left and short kickers (Table 7.2).

The kicking knee was in front of the ankle in all three groups (Figure 7.12) but there were no clear differences when comparing the shank orientation between each group of kickers (Table 7.2). The ankle was also lateral to the knee (i.e. closer to the ball) in all of the kick groups (Figure 7.12). There was no clear difference in this frontal shank orientation between the long and wide-left kickers (Table 7.2). However, the ankle was substantially more lateral relative to the knee in both of these groups compared with the short kickers (mean difference in absolute shank angle = 7° and 6°, respectively; Table 7.2). When viewed from the side, the kicking foot was orientated such that the toes were below and lateral relative to the ankle joint (Figure 7.12). There were no clear differences when comparing this foot orientation between the three groups (Table 7.2).

Side view Frontal view

(a) Long kickers

(b) Wide-left kickers

(c) Short kickers

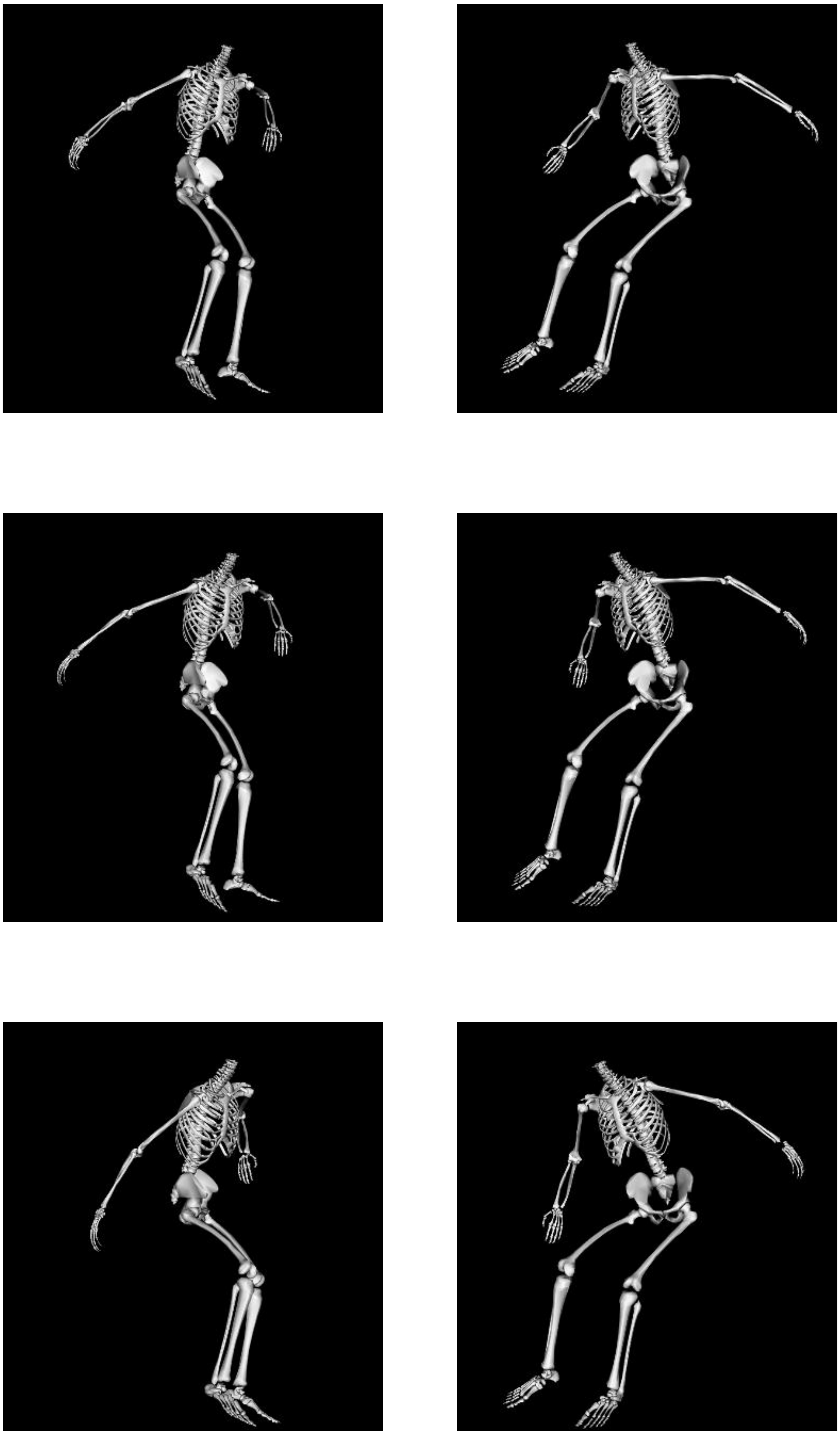


Figure 7.12. Side and frontal views of the mean positions of the kickers at initial ball contact for the (a) long kickers, (b) wide-left kickers and (c) short kickers.

Table 7.2. The orientation of the kicking leg segments at initial ball contact from the side and frontal views in the three groups (mean ± SD) and the magnitude-based inferences for the group comparisons.

	Segment orientation (°)	Compared with wide-left kickers Effect size ± 90% CI	(% Negative | Trivial | Positive)	Compared with short kickers Effect size ± 90% CI	(% Negative | Trivial | Positive)
Thigh					
Side view					
Long	26 ± 13*	-0.1 ± 0.7	(44 | 34 | 22)	-1.3 ± 0.9	(98 | 2 | 0)
Wide-left	28 ± 8*			-1.7 ± 1.3	(97 | 2 | 1)
Short	42 ± 11				
Frontal view					
Long	-48 ± 6†	-0.7 ± 0.7	(88 | 10 | 2)	-0.6 ± 0.9	(76 | 16 | 8)
Wide-left	-44 ± 5			0.1 ± 1.3	(32 | 21 | 47)
Short	-45 ± 2				
Shank					
Side view					
Long	-25 ± 5	-0.2 ± 0.7	(52 | 31 | 17)	-0.4 ± 1.0	(63 | 22 | 15)
Wide-left	-24 ± 5			-0.2 ± 1.1	(47 | 25 | 28)
Short	-23 ± 5				
Frontal view					
Long	-23 ± 4*	-0.3 ± 0.7	(62 | 27 | 11)	-1.6 ± 0.8	(100 | 0 | 0)
Wide-left	-22 ± 2*			-2.3 ± 1.7	(98 | 1 | 1)
Short	-16 ± 2				
Foot					
Side view ^					
Long	-47 ± 10	0.2 ± 0.7	(20 | 35 | 45)	-0.7 ± 0.7	(77 | 14 | 8)
Wide-left	-48 ± 12			-0.7 ± 1.0	(82 | 12 | 6)
Short	-41 ± 1				
Frontal view					
Long	-51 ± 7	-0.5 ± 0.7	(75 | 20 | 5)	-0.3 ± 1.0	(54 | 23 | 23)
Wide-left	-47 ± 10			0.2 ± 1.0	(22 | 26 | 52)
Short	-49 ± 8				

* Denotes a substantial effect compared with the short kickers † Denotes a substantial effect compared with the wide-left kickers

For all orientations an angle of 0° indicates the proximal and distal joints were aligned except ^ where the foot angle was relative to that recorded in a neutral standing position

7.4. Discussion

This chapter investigated the kicking leg joint mechanics and torso motion of rugby place kickers during the kicking phase from the top of the backswing to initial ball contact. As these variables have not previously been comprehensively presented for rugby place kicks, this section will commence with a general discussion of the observed patterns in the context of those previously reported, including for kicking skills in other football codes. In order to answer research questions v and vi, differences in these variables between groups of kickers who performed with different levels of success will then be identified to explain how the different performance outcomes were achieved.

7.4.1. General patterns across all groups

At the top of the backswing, the kicking hip was in an extended position before flexing throughout the downswing (with a peak velocity of between 543 - 622°/s, range in group means) to a flexion angle of approximately 40° at initial ball contact. For the majority of the downswing, this hip flexion was accompanied by a hip flexor moment and therefore positive hip flexor work was performed. The hip flexor moment reduced from a peak normalised value of approximately 0.20 at the top of the backswing, until late in the downswing after which it increased again towards a second smaller peak of between 0.05 and 0.10 just prior to initial ball contact. Following this second peak, a rapid reduction in the flexor moment was observed up to initial ball contact. The hip flexors did between 0.07 and 0.11 (range in group means) of normalised positive work during the downswing.

The broad patterns of the hip kinematics are similar to those reported by both Baktash et al. (2009) and Zhang et al. (2012) for amateur rugby kickers performing maximum effort place kicks. The peak flexion velocity in the current study is slightly faster than the peak velocities reported by Sinclair et al. (2014) of 499 ± 118°/s and Zhang et al. (2012) of approximately 400°/s which is likely due to less experienced kickers being analysed in the previous studies (a difference observed by Kawamoto et al., 2007 when comparing experienced and inexperienced soccer players performing side-foot kicks). The kinetics of the hip joint have yet to be reported for rugby place kicks, but these patterns and the magnitude of the first peak flexor moment are also comparable to those previously recorded in soccer instep kicking (e.g. Lees & Nolan, 2002; Lees & Rahnama, 2013; Lees et al., 2009; Nunome et al., 2002). The total positive work done by the hip flexors was also comparable to that recorded by Nunome et al. (2001) for side-foot and instep kicks in soccer. However, the second peak observed in the hip flexor moment for all groups in the current analysis has not been observed in previous studies of soccer instep kicking. One possible explanation for the initial reduction and then second peak in the hip flexor moment in the current study could be the additional requirement of a high ball launch angle in rugby place kicking. The majority of research in soccer instep kicking has not required the kickers to elevate the ball because a fast instep kick with a high launch angle (comparable to that in place kicking) is rarely necessary in a game of soccer. Thus, in such cases where a high launch angle is not required, the hip flexor moment has been found to reduce throughout the kick until becoming extensor dominant immediately prior to ball contact (Lees et al., 2009; Nunome et al., 2002). In contrast, the second peak found consistently across all three groups in the current study may enable place kickers to prepare to achieve greater hip flexion during the ball contact phase, kicking the ball in an upwards direction, as is encouraged by rugby coaches (Bezodis & Winter, 2014; Greenwood, 2003; Wilkinson, 2005). The joint kinetics of kicks with varying ball launch angles have not been investigated in any football codes, but future experimental studies could be conducted to confirm the role of this second peak in the hip flexor moment.

The kicking knee flexed before reaching a peak flexion angle of between 107 and 110° (range in group means) approximately 40% through the downswing, similar to the values previously reported for rugby place kicks (103 ± 7°) by Sinclair et al. (2014). This knee flexion has previously been described in soccer instep kicking literature as a 'cocking' phase, reducing the moment of inertia of the kicking leg and enabling more positive work to be done at the hip, thereby increasing the angular velocity of the thigh (Lees et al., 2009; Nunome et al., 2002). Furthermore, the 'cocking' of the kicking leg stretches the knee extensor muscles, which can subsequently contract more forcefully through the stretch-shortening mechanism (Komi, 1984), increasing the positive work done at the knee and subsequently the angular velocity of the shank and likely the linear kicking foot velocity (Dörge et al., 2002), resulting in a faster ball velocity post-contact.

Once the knee reached peak flexion, it rapidly extended up to initial ball contact, where a peak extension velocity of between 1296 and 1744°/s was achieved (range in group means), with the long and wide-left kickers achieving velocities similar to those recorded by Sinclair et al. (2014) of 1769 ± 207°/s. A knee extensor moment was dominant for the majority of the downswing, initially doing negative work and arresting the knee flexion, before doing positive work to initiate knee extension. This extensor moment reduced throughout the downswing until just prior to initial ball contact when a flexor moment became dominant and the knee extension velocity decreased. Similar to the hip mechanics, these broad patterns and the peak magnitudes are comparable with those previously recorded in soccer instep kicking (Lees & Rahnama, 2013; Lees et al., 2009; Nunome et al., 2002), although the timing of the peak knee extension velocity has been the subject of disagreement between studies. Early studies reported that the peak knee extension velocity occurred prior to initial ball contact (e.g. Barfield, 1995; Dörge et al., 2002, Teixeira, 1999). However, Nunome et al. (2006) demonstrated that this seemingly counter-intuitive reduction in knee extension velocity was due to the data processing methods used to smooth datasets with varying frequency content such as those containing impacts. When such a dataset was filtered using an algorithm which varied cut-off frequency over time, knee extension velocity was found to peak at initial ball contact (Nunome et al., 2006). The impact between the foot and the ball was not included in the current analysis and as appropriate filtering techniques were used (including data padding to alleviate end-point errors; Smith, 1989), the fact that knee extension velocity peaked at initial ball contact adds further weight to these being the true knee kinematics in rugby place kicking as well as in soccer instep kicking.

Previous rugby place kicking research has not reported the complete knee flexion-extension kinematics during the downswing. Representative knee angles of one kicker taking place kicks from different support foot positions were presented by Baktash et al. (2009) but no indication of the timing of events prior to initial ball contact was provided on these figures. Zhang et al. (2012) also presented an individual representative trial of the knee angles and angular velocities prior to initial ball contact, but this representative trial did not feature flexion of the knee during the initial part of the downswing as was evident for all groups of kickers in the current study. This disparity may be due to the differences in the performance levels of the kickers that participated in the two studies (as evident from the slower ball velocities reported by Zhang et al., 2012, of between 16.2 and 18.4 m/s). The 'cocking' of the kicking leg which was apparent in the current study may therefore be a factor which differentiates kickers capable of achieving higher ball velocities than their lower-performing counterparts, although given the ball velocities reported by Zhang et al. (2012) and the fact that there were no differences in the ‘cocking’ between the three groups in the current study, this difference may only be apparent at a relatively low performance level.

Baktash et al. (2009) also presented the resultant knee moment time-histories of an individual rugby place kicker from four different support foot positions, and whilst the pattern of the resultant knee moment was broadly comparable to the current study with a resultant knee flexor moment prior to initial ball contact, the previously identified limitations of the study of Baktash et al. (2009) restrict further direct comparison. Two potential reasons for the resultant knee flexor moment prior to initial ball contact have been proposed for soccer instep kicking (Lees et al., 2009). Firstly, it has been suggested to be a protective mechanism, whereby the angular velocity at a joint must decelerate to zero as the joint reaches full extension in order to protect the anatomical structures around the joint (van Ingen Schenau et al., 1987). Secondly, a more flexed knee could allow greater external rotation of the shank relative to the thigh (albeit relatively small due to the joint constraints) and therefore a more desirable orientation of the foot at initial ball contact. However, no further increase in tibial external rotation has been observed at knee flexion angles beyond 20° of flexion (Blankevort et al., 1988), meaning the knee flexion angle of 47 - 59° (range in group means) at initial ball contact in the current study would allow no additional external rotation than a more extended knee angle. As a knee angle closer to 20° of flexion at initial ball contact would allow a potentially greater prior range of motion and thus kicking foot velocity, it therefore appears unlikely that greater external shank rotation is the primary reason for the flexed knee angle of rugby place kickers at initial ball contact. The reason for this resultant flexor moment requires further investigation, potentially through computer simulation which would allow the effect of systematic alterations to kicking knee mechanics on joint and individual muscle forces to be investigated without the possible risks of injury associated with the aforementioned anatomical constraint (van Ingen Schenau et al., 1987).

The total positive work done by the knee extensors was comparable to that recorded for side-foot soccer kicking (Nunome et al., 2001). As this is the first time that the negative work done by the knee extensors during the early part of the downswing and the knee flexors during the latter part of the downswing has been quantified in any form of kicking, comparisons cannot be drawn for these variables with previous research. These periods of negative work indicate times when, if active, the monoarticular knee extensor and hip flexor muscle-tendon units are generating force whilst lengthening. Such an action may have potential injury implications if the muscles themselves are acting eccentrically at this time (Garrett, 1990), particularly at fast velocities (Chapman, Newton, Sacco & Noaska, 2006) such as when the knee flexors are doing negative work immediately prior to initial ball contact when the knee extension velocity is greatest. Although addressing potential injury implications is beyond the scope of this thesis, the negative work done at the knee is an important consideration when considering the initial 'cocking' phase of the kicking leg prior to knee extension and for the deceleration in knee extension velocity prior to initial ball contact.

As in soccer instep kicking, minimal motion was observed at the ankle throughout the downswing (Kawamoto et al., 2007; Lees & Rahnama, 2013; Lees et al., 2009; Nunome et al., 2002). At the top of the backswing, the ankle was in a plantar flexed position before dorsiflexing slightly throughout the downswing due to a dorsiflexor moment, but it remained in a plantar flexed position (relative to a neutral standing position) at initial ball contact. The energy generated at the ankle was negligible throughout. Simple collision mechanics would suggest that a rigid foot segment during the ball contact phase allows the kicker to achieve a high coefficient of restitution between the foot and the ball and thus a faster ball velocity magnitude post-contact for a given foot velocity. Research in soccer instep kicking has indicated that the ankle is plantar flexed at initial ball contact (Levanon & Dapena, 1998), as was observed in the current study, ensuring the less deformable aspect of the foot contacts the ball. However, during the ball contact phase of a soccer instep kick, the ankle has been found to be forced into further plantar flexion and as the range of ankle plantar flexion during the ball contact phase increased, the magnitude of the ball velocity post-contact was found to decrease (Asami & Nolte, 1983). The resultant dorsiflexor moment observed prior to initial ball contact in the current study may therefore have been a mechanism through which the place kickers prepared to resist this forced plantar flexion and therefore achieve a faster ball velocity post-contact.

The motion of the torso has received considerably less attention than the kicking leg in previous analyses of kicking skills. In the current study, the pelvis tilted posteriorly from an anterior position at the top of the backswing to a relatively neutral orientation at initial ball contact. To date, no studies have reported the motion of the pelvis during rugby place kicking despite the clearly angled approach adopted by rugby place kickers, and the role the pelvis has been shown to play in soccer instep kicking by retracting the kicking leg during the backswing before initiating forward motion of the hip during the downswing (Lees et al., 2009). The anterior tilt angle of the pelvis at the top of the backswing was similar to that previously reported in soccer instep kicking, however, a greater range of motion during the downswing was observed in the instep kicks than in the current study resulting in a posteriorly tilted pelvis at initial ball contact (Lees et al., 2009). This difference in pelvic motion about the medio-lateral axis between the two skills may also be due to the aforementioned higher ball launch angles required in rugby place kicks compared with soccer instep kicks and therefore the need for the kicking foot to contact the ball lower which may have been achieved by a more anteriorly tilted pelvis at initial ball contact. There was minimal sideways tilt throughout the downswing for the rugby place kickers in the current study, with the long kickers' tilted down towards the left-hand-side by approximately 5° (with the kicking side elevated), the wide-left kickers' neutral and the short kickers' tilted down towards the right-hand-side by approximately 5°. Lees et al. (2009) reported a relatively stable sideways pelvis tilt angle of 10° down towards the left-hand-side for soccer instep kickers throughout the kicking phase. It was suggested that the stable sideways tilt angle may have been beneficial to the kicker in controlling the direction of the kicking foot velocity vector during the downswing (Lees et al., 2009), a factor which is an important consideration for rugby place kicking and which may therefore explain the minimal motion observed within each group. In the place kicks in the current study, the pelvis was rotated about the longitudinal axis such that it was facing towards the right-hand-side at the top of the backswing. During the downswing, the pelvis then rotated in an anti-clockwise direction (when viewed from above) towards the left-hand-side with a velocity of less than 300°/s and was still facing towards the right-hand-side at initial ball contact. In comparison, a greater range of longitudinal pelvis rotation was observed in soccer instep kicks (approximately 30° in soccer instep kicks compared with 12-20° in the current study, range in group means) which resulted in the pelvis facing the left-hand-side at initial ball contact (Lees & Nolan, 2002; Lees et al., 2009). This greater range of rotation may enable the soccer instep kickers to achieve a greater kicking foot velocity at initial ball contact (Lees & Nolan, 2002; Lees et al., 2009) but could result in the kicking foot travelling in an undesirable direction, across the ball (from right-to-left) at initial ball contact and throughout the ball contact phase, a factor which has been deemed undesirable in the rugby coaching literature owing to its proposed likelihood to affect the accuracy of the kick (Bezodis & Winter, 2014; Greenwood, 2003).

Similar to the pelvis, the trunk was orientated about the longitudinal axis such that it was facing the right-hand-side at the top of the backswing by between 24 and 47° from the centre of the target (range in group means). The longitudinal rotation of the trunk during the downswing was relatively limited for two groups of kickers in the present study (long and short kickers), however, the wide-left kickers rotated their trunk in a clockwise direction so that it was facing further towards the right-hand-side up to initial ball contact. This longitudinal trunk rotation is a characteristic of the release of the 'tension arc' identified in soccer instep kicking (Shan & Westerhoff, 2005) and will be discussed in detail when comparing the groups of kickers. When the relative angle between the pelvis and trunk segments about the longitudinal axes was considered, the pelvis was facing further towards the right-hand-side than the trunk at the top of the backswing for all of the groups of kickers. The relative motion of these two segments during the downswing, however, varied between the groups; the long and wide-left kickers rotated their pelvis towards the left-hand-side and the trunk towards the right-hand-side, thus reducing this relative angle until the segments were aligned (approximately 40% and 70% through the downswing, respectively) before continuing to rotate both segments so that the trunk was ultimately facing further towards the right-hand-side than the pelvis at initial ball contact. In contrast, the short kickers maintained a near neutral relative pelvis-trunk angle throughout the downswing. In the only study which has investigated the relative motion of these two segments in any football code, a larger relative angle between the two segments at the top of the backswing was the key characteristic of the 'tension arc' identified in soccer instep kicking (Shan & Westerhoff, 2005), the subsequent release of which was related to a faster ball velocity post-contact. The greater relative longitudinal pelvis-trunk rotation demonstrated by the wide-left kickers compared with the short kickers in the current study and the faster ball velocities achieved by the wide-left kickers would provide partial support of this assertion. However, the same difference was not observed between the long and short kickers, suggesting that the long kickers employed a different strategy to the wide kickers in achieving an equally fast, yet more accurate ball velocity post-contact, and this will be discussed in detail in Section 7.4.2. Furthermore, the effect of the torso rotation on the accuracy of the kick has not previously been investigated and will also be discussed when comparing between the groups.

The general motion of the kicking leg joints recorded for place kicks in the current study are broadly comparable to those previously reported in studies investigating both rugby place kicking and soccer instep kicking. An additional peak in the resultant hip flexor moment was observed late in the downswing which has not previously been observed in soccer instep kicking, and may increase hip flexion throughout the ball contact phase to assist a higher ball launch angle post-contact. Analysis of the motion of the torso suggested that longitudinal rotation of the pelvis was important in determining the position of the kicking foot at the top of the backswing and the subsequent forward rotation of the kicking leg down to initial ball contact. The wide-left kickers also demonstrated a trunk orientation that was facing away from the pelvis, representative of the 'tension arc' previously observed in soccer instep kicking. In order to fully address the research questions posed, the techniques of the successful and less successful kickers will now be discussed in turn.

7.4.2. Comparison of long and wide-left kickers

Comparison of the techniques between the long and wide-left kickers will provide insight regarding how both groups were able to achieve high resultant ball velocity magnitudes, yet the long group were able to achieve ball velocity vector directions and longitudinal spin which ultimately led to a superior performance outcome. At initial ball contact, both groups achieved a comparably fast forward kicking foot velocity (Chapter 6), however, they appeared to employ different strategies to do this. The long kickers demonstrated a knee extensor strategy, performing more positive knee extensor work throughout the downswing, whereas the wide-left kickers demonstrated a hip flexor strategy and performed more positive hip flexor work. These kicking leg joint rotations are two of the three actions identified by Wickstrom (1975) that characterise the downswing of the kicking leg in soccer instep kicking (the other being the longitudinal rotation of the pelvis), suggesting that the two groups tend to utilise these fundamental movements in a different fashion. The positive work done by the various joints of the kicking leg of accurate and inaccurate kickers has not previously been quantified in any football code. However, two different strategies in kicking leg motion have been identified in maximum distance Australian Rules football punt kicking (Ball, 2008) where a large negative relationship was observed between knee angular velocity and thigh angular velocity at initial ball contact ($r = -0.90$, $p < 0.001$). The kickers were separated into two groups ('thigh' and 'knee' strategy) based on the ratio of knee angular velocity to thigh angular velocity. These two groups were able to achieve comparable kicking foot velocity magnitudes and maximum punt distances but were deemed to use two different strategies to do so, similar to the findings in the current study. Given the small range of posterior pelvic tilt in the current study (9 - 11°, range in group means), it may be assumed that the thigh was the more dynamic segment about the hip and thus, the 'thigh' strategy identified by Ball (2008) appears similar to the hip flexor strategy of the wide-left kickers in the current study. However, Ball (2008) did not consider the accuracy of the kicks and the effects of the two strategies he identified on kick accuracy is thus unknown. Further to the findings of Ball (2008), Alcock et al. (2012) identified a significantly larger knee extension velocity at initial ball contact for female players performing curve kicks compared with instep kicks. This difference was attributed to the need for greater control of the kicking foot in the curve kick, enabling the kickers to adjust the path of their kicking foot early in the downswing before then extending the knee faster, later in the downswing to increase the foot velocity. No difference was observed in the hip angular velocities at initial ball contact between the two kick types (Alcock et al., 2012) and as the study was limited to the analysis of the joint kinematics it is not known whether there were also differences in the joint kinetics which may support the results in the current study. However, it does suggest that the knee extensor strategy used by the long kickers in the current study may have enabled the long kickers to control the motion of the kicking foot by doing less positive hip flexor work and instead relying on the positive knee extensor work to achieve a fast kicking foot velocity at initial ball contact. In contrast, the hip flexor strategy enabled the wide-left kickers to also achieve a fast kicking foot velocity at initial ball contact, but the muscles crossing the hip joint may not have been as able to assist the control of motion of the kicking foot and therefore, the direction of the kicking foot velocity vector was compromised. One further study conducted by Nunome et al. (2002) provides additional support for existence of the two strategies identified from the current results. Although Nunome et al. (2002) did not find a significant difference in the peak hip flexor moments of instep and side-foot soccer kicks, their figures depicting the complete time-histories show that the peak flexor moment occurred earlier in the side-foot kicks than the instep kicks (approximately 40% and 60% through the kicking motion, respectively). As side-foot kicks require a more controlled foot-ball contact, this earlier peak and subsequent reduction in hip flexor moment may also reflect a greater use of the muscles crossing the hip joint to control the position of their kicking foot during the downswing and ensure it was travelling along a desirable path prior to initial ball contact rather than mainly contributing towards its velocity. Work done at the hip joint was not presented by Nunome et al. (2002) and so a direct comparison cannot be made, but combined with the above findings of Ball (2010) and Alcock et al. (2012), there is previous evidence in support of the current findings which suggest the existence of hip flexor and knee extensor strategies for achieving fast ball velocities in rugby place kicking. The current results therefore suggest that whilst both groups are able to do sufficient positive work at the kicking leg joints to achieve a fast kicking foot velocity at initial ball contact, the long kickers' knee extensor strategy enables them to achieve a more accurate kick by doing less of this work at the hip joint and instead rely on more positive work at the knee, potentially allowing the muscles crossing the ball-and-socket hip joint to control the path of the kicking foot.

Analysis of the motion of the trunk and pelvis segments of the two groups provides an explanation for why the wide-left kickers adopt the hip flexor strategy, and a further potential explanation for how this could negatively affect their kick accuracy. At the top of the backswing, the wide-left kickers' trunk was facing substantially further towards the left-hand-side relative to their pelvis compared with the long kickers, representative of a greater 'tension arc' as previously identified in soccer instep kicking (Shan & Westerhoff, 2005). This creates a stretch across their torso and has also been qualitatively suggested as being important in rugby place kicking (Bezodis & Winter, 2014). The subsequent release of this stretch enables the muscles previously stretched, including the hip flexors, to contract more forcefully through the stretch-shortening cycle (Shan & Westerhoff, 2005), which was likely reflected in the greater positive work done at the hip joint by the wide-left kickers. The release of this stretch also appeared to cause the trunk of the wide-left kickers to longitudinally rotate towards the right-hand-side during the downswing (through approximately 20°), whereas the long kickers' displayed less rotation (less than 10°). Bezodis et al. (2007) reported a minimal amount of trunk angular momentum about the global longitudinal axis at initial ball contact for more accurate place kickers compared with their less accurate counterparts. The minimal trunk longitudinal rotation of the long kickers in the current study indicates that they may have opposed the angular momentum of the kicking leg more effectively than the wide-left kickers. In contrast, the wide-left kickers' use of the 'tension arc' appeared to negatively affect their accuracy through a combination of greater positive hip flexor work and over-rotation of the trunk potentially affecting the direction of the kicking foot path prior to and during the ball contact phase.

7.4.3. Comparison of long and short kickers

Comparison of the long and short kickers' techniques will help to explain how the long kickers were able to achieve faster resultant ball velocities, a straighter ball velocity vector and a reduced longitudinal ball spin, and subsequently a substantially greater maximum distance. As identified in Chapter 6, the short kickers took a straighter approach to the ball and this seemingly resulted in the pelvis being more front-on at the top of the backswing compared with the long kickers, confirming suggestions previously made in rugby coaching literature (Greenwood, 2003) and in research in soccer instep kicking (Scurr & Hall, 2009) which suggested that an angled approach enables greater longitudinal pelvic rotation prior to the kicking phase. Early in the downswing the short kickers demonstrated significantly less anterior pelvic tilt compared with the long kickers and as there was no significant difference in the hip extension angles of the two groups; this indicates that the short kickers' thigh was in a less retracted, and more vertical, position. As there was also no significant difference in the knee flexion angle at the top of the backswing between the long and short kickers, this more front-on pelvis and vertical kicking leg thigh position explains why the kicking foot of the short kickers was closer to the ball at the start of the kicking phase. This resulted in the shorter kicking foot path observed throughout the downswing to initial ball contact (Chapter 6), indicative of a more 'compact' technique compared with the long kickers.

In addition to a more front-on pelvis orientation throughout the kicking phase, the short kickers also adopted a more front-on trunk orientation and thus a small pelvis-trunk separation about the longitudinal axis. There was no significant difference in the relative pelvis-trunk angle between the long and short kickers and neither appeared to create a greater stretch across the torso to utilise the 'tension arc', but the short kickers' hip flexors did substantially less positive work during the downswing than the long kickers. The short kickers also did less positive knee extensor work, and therefore appeared to use neither the knee extensor nor hip flexor strategies employed by the long and wide-left kickers, respectively, for generating a fast kicking foot velocity. As the kicking foot velocity magnitude is directly determined by the linear velocity of the kicking hip and rotations of the kicking leg joints, it is therefore unsurprising that the short kickers' kicking foot velocity at initial ball contact was slower than the long kickers'. The reduction in the positive work done at the kicking leg joints by the short kickers' may have been due to strength differences between them and the long kickers or a deliberately more controlled kicking leg motion. Future research may seek to investigate the leg strength of long and short kickers and, if differences are found, the effects of relevant experimental strength training interventions on the place kick performance of short kickers would clearly be of interest.

During the final 50% of the downswing the short kickers' pelvis was tilted down towards the right-hand-side (when viewed from behind) which was significantly different from the long kickers' which was tilted down towards the left-hand-side. The long kickers' sideways pelvic tilt towards the left-hand-side would raise the kicking leg hip, a movement previously thought to allow soccer instep kickers to achieve greater kicking hip flexion and knee extension (without hitting the floor), and potentially a faster kicking foot velocity at initial ball contact (Lees et al., 2009). This suggestion is partially supported by the longer path taken by the long kickers' kicking foot in the current study and the subsequent faster kicking foot velocity that they were able to achieve at initial ball contact, but no specific differences were found in the hip or knee angular displacement time-histories between the two groups of kickers. A sideways pelvic tilt towards the left-hand-side (as seen for the long kickers) may also enable the kicking leg to swing along a more lateral path, away from the body which may have been necessary for the long kickers as their whole-body CM was further to the left of the ball at both support foot contact and initial ball contact (Chapter 6). This meant that the long kickers had to position their kicking foot more laterally relative to their body in order to achieve an appropriate foot-ball contact, a feature reflected by the long kickers' ankle being more lateral to their knee and in the more laterally directed kicking foot path observed for the long kickers compared with the short kickers (Chapter 6). The reduced work done by the muscles crossing the kicking leg joints of the short kickers may have allowed these kickers to control the motion of the kicking foot during the downswing, using the muscles crossing the joints to facilitate an accurate ball trajectory but to the detriment of the ball velocity magnitude, resulting in a less successful performance outcome compared with the long kickers.

7.4.4. Comparison of wide-left and short kickers

The technique differences between the wide-left and short kickers will only be briefly discussed as this comparison does not directly address the research questions posed. The wide-left kickers' hip flexors did substantially more positive work than the short kickers and they demonstrated a significantly faster hip flexion velocity from -70 to -40% of the downswing. There was no clear difference in the positive work done by the knee extensors between the two groups, and the wide-left kickers were able to achieve a faster kicking foot velocity at initial ball contact.

The wide-left kickers orientated their pelvis at the top of the backswing such that it was facing further towards the right-hand-side of the goalposts than the short kickers' pelvis. As their trunk segments were facing in a comparable direction at the top of the backswing, the relative angle between the trunk and the pelvis segments was significantly greater for the wide-left kickers, stretching the muscles of the torso as the 'tension arc' was formed which enabled them to subsequently perform greater positive hip flexor work during the downswing as the stretch was released. As discussed in Section 7.4.2, however, this strategy of generating a fast kicking foot velocity through the formation of a 'tension arc' before rotating their torso and doing more positive work with the hip flexors appeared to negatively influence the direction of the ball velocity vector post-contact. Although the short kickers' technique did not enable them to obtain a fast kicking foot velocity at ball contact, the mis-directed ball velocity vector of the wide-left kickers meant that ultimately their overall level of place kick performance was comparable.

7.5. Conclusion

The joint mechanics of the kicking leg and the motion of the torso were presented and analysed throughout the downswing of rugby place kicks for the first time in order to understand and explain how differences in performance outcomes are achieved, allowing the following research questions to be addressed:

v. **What are the kicking leg joint mechanics during the downswing and how do these differ between successful and less successful kickers?**

vi. **How does the motion of the torso during the downswing differ between successful and less successful kickers?**

Whilst the motion of the kicking leg of the successful (long) kickers was broadly similar to that of the less successful (wide-left and short) kickers throughout the downswing, some important differences were identified. The wide-left kickers appeared to adopt a hip flexor strategy whereby they developed a 'tension arc' at the top of the backswing, stretching the muscles across their torso including the hip flexors. This 'tension arc' was then released enabling them to do more positive work at the hip joint during the downswing. In contrast, the long kickers adopted a knee extensor strategy, doing less positive hip flexor work and instead relied on greater positive knee extensor work. Both groups achieved comparable foot velocities at initial ball contact but the long kickers were better able to apply this to direct the subsequent ball flight, likely through adjustments to the path of the kicking foot from the hip joint and potentially by maintaining a more stable trunk orientation. The short kickers did substantially less positive hip flexor and knee extensor work than the long and wide-left kickers and were unable to achieve as fast a kicking foot velocity at initial ball contact. The short kickers did not develop the 'tension arc' observed for the wide-left kickers, nor did they produce the positive knee joint work of the long kickers – instead they orientated both their trunk and pelvis segments in a more front-on position, and this more ‘compact’ technique reduced the length of the path of the kicking foot towards the ball. These short kickers therefore adopted neither of the strategies used by the long or wide-left kickers, but when overall performance was considered, this technique was no less effective than that of the wide-left kickers.

Chapter 8: General discussion

8.1. Context

The importance of successful place kick performance in determining the result of Rugby Union matches has been demonstrated (Quarrie & Hopkins, 2015). However, relatively few biomechanical research studies have investigated the technical characteristics of place kicking in order to understand how different levels of performance are achieved. The overall aim of this thesis was therefore to investigate rugby place kicking technique and performance, and understand how these differ between successful and less successful place kickers, with a view to helping to direct coaching practice. Six research questions were developed in Chapter 1 to focus the subsequent investigations and address this thesis aim. Based on a review of relevant literature, a conceptual model was proposed which summarised the key technical factors during the approach and kicking phases that appeared to be potentially important for successful performance. In this discussion chapter, each of the research questions will be addressed in turn, with the main findings related to each question summarised. The methodological approaches adopted to address these questions will then be critiqued. The technique differences between the successful (long) and less successful (wide-left and short) kickers will then be discussed in detail and two revised versions of the conceptual model will be presented to highlight specific aspects of technique that differ between these groups (long versus wide-left and long versus short). These differences will then be used as a framework for discussing the practical implications arising from this thesis before the potential directions for future research are proposed.

8.2. Addressing the research questions

The biomechanical studies that have previously investigated rugby place kicking have typically quantified successful performance as a high ball velocity magnitude. Whilst this may have primarily been due to space constraints not allowing the full flight path of the ball to be tracked, and whilst ball velocity magnitude is one determinant of place kick performance, the direction of this velocity vector is also crucial due to the inherent accuracy demands of the skill. In order to determine whether a more complete and meaningful single performance measure could be accurately determined within typical laboratory constraints, the first research question was therefore:

i. **How accurately can overall place kick performance outcome be estimated from initial ball flight data?**

A mathematical model was developed in Chapter 3 which applied equations of motion to initial ball flight data and determined the maximum distance that any given place kick could be taken from and be successful (i.e. pass between the goalposts and above the crossbar, assuming that it was taken from directly in front of the posts). Aerodynamic force coefficients were selected from previous wind-tunnel experiments (Seo et al., 2006a; 2007) based on the match between the model outputs and new experimental data collected in a large indoor volume. The model code was systematically verified before the model was validated using additional independent data to assess the consistency of its accuracy. The model predicted final ball position with a mean error of 4.0% of the forward ball displacement, a considerable improvement over that achieved in a previous model of ball flight during screw and high punt kicks in rugby (25.8%; Tanino & Suito, 2009). The model could therefore be subsequently applied with confidence to provide an accurate and objective measure of the maximum distance from which any kick would be successful given the initial ball flight kinematics. As this measure incorporates the magnitude and direction of any kick's velocity into a single composite value, it provides a highly meaningful assessment of performance that is understandable for coaches and kickers.

Using the evaluated model, it was then possible to understand the effects of differences in initial ball flight characteristics on performance success. Thirty-three experienced rugby place kickers (from senior international to amateur levels) performed five maximum range place kicks aiming at a suspended target in a laboratory. The mathematical model was applied to the initial ball flight kinematics to determine the maximum distance of each place kick and identify the best kick for each kicker. These initial ball flight kinematics were then considered in greater detail to address the second research question:

ii. **How do the initial ball flight characteristics differ between place kicks with different performance outcomes?**

Three distinct groups of kickers were identified based on the outcomes of their best kicks: long kickers (successful from more than 32 m), short kickers (successful from less than 32 m because the ball would have dropped below the height of the crossbar) and wide-left kickers (successful from less than 32 m because the ball would have missed the left-hand goalpost). The long kickers were subsequently considered to represent the successful kickers, whilst the short and wide-left kickers were less successful, but for different performance-based reasons. Despite the long kicks being successful from a substantially greater maximum distance compared with the wide-left kicks, there was no difference in their resultant ball velocity magnitudes. However, the long kicks did have a substantially faster vertical velocity, less longitudinal spin and a velocity vector directed towards the right-hand-side of the goalposts compared with the wide-left kicks (in which the velocity vector was directed towards the left-hand-side). For the wide-left kicks, these latter two differences combined to cause the flight of the ball to start, and curve, towards the left-hand-side. The substantially shorter maximum distance of the short kicks compared with the long kicks was primarily due to a slower resultant ball velocity, although the short kicks also had a higher launch angle, a ball velocity vector directed further towards the right-hand-side of the goalposts and more longitudinal spin. These latter two differences meant that in the short kicks the ball curved away from the original right-hand trajectory before dropping short of the crossbar as opposed to continuing to curve so much that it missed the goalpost, as observed in the wide-left kicks. These differences in the initial ball flight characteristics between the kicks highlight the effect of not just the magnitude of the resultant ball velocity on place kick performance, but also its direction and longitudinal spin.

To further unpick these differences in ball flight characteristics, the techniques of the kickers during the approach and kicking phases were analysed based on full-body kinematic data and ground reaction forces from under the support foot which were collected using the methods described in Chapter 4. The main findings relating to the final four research questions will now be briefly described in turn, but they will be critically discussed in Section 8.4 where the key differences between the groups of kickers are considered in detail. The whole-body motion of the kickers was first considered, to investigate the extent to which the approach of the kicker could explain differences in the ball flight characteristics. The third research question that was addressed was therefore:

iii. **How does whole-body motion prior to initial ball contact differ between successful and less successful kickers?**

The long kickers approached the ball from a position further to the left and with a greater velocity, taking a longer final step and positioning their support foot closer to the ball in the antero-posterior direction, than both the wide-left and short kickers. The long and wide-left kickers exerted greater medio-lateral forces compared with the short kickers, decelerating their whole-body CM velocity prior to initial ball contact. The long kickers' also remained further to the left of the ball at initial ball contact compared with both of the other groups. As the whole-body motion towards the ball is intended to influence the motion of the kicking foot (which ultimately contacts the ball and therefore directly affects the flight of the ball post-contact), the following research question was subsequently addressed:

iv. **How does kicking foot motion from the top of the backswing to initial ball contact differ between successful and less successful kickers?**

At the top of the backswing, the kicking foot was further away from the ball for the long and wide-left kickers compared with the short kickers, and it therefore travelled a longer path down to initial ball contact. The long kickers' kicking foot was also further to the left at the top of the backswing compared with the wide-left kickers but there was no difference in the lengths of their kicking foot paths. The long kickers achieved a faster kicking foot velocity at initial ball contact compared with both the wide-left and short kickers. This was primarily reflected in a greater lateral kicking foot velocity, directed towards the right-hand-side of the goalposts compared with both the wide-left and short kickers. The long kickers also exhibited a greater forward velocity of the kicking foot compared with the short kickers. Having identified these differences in kicking foot kinematics, the motion of the more proximal segments of the kicking leg were then investigated to understand how they were achieved by addressing the following research question:

v. What are the kicking leg joint mechanics during the downswing and how do these differ between successful and less successful kickers?

The kicking hip flexed from the top of the backswing, accompanied by knee flexion for the first 40% of the kicking phase before the knee extended and the hip continued to flex up to initial ball contact. Ankle motion was minimal throughout the kicking phase. The long kickers' hip flexors and knee extensors did more work throughout the kicking phase compared with those of the short kickers. Comparison of joint work profiles between the long and the wide-left kickers' revealed two different strategies - knee extensor and hip flexor - the long kickers performed more positive knee extensor work whereas the wide-left kickers performed more positive hip flexor work. The formation of a 'tension arc' (Shan & Westerhoff, 2005) was identified as a possible explanation for these differences, and this led to the final research question that was addressed:

vi. How does the motion of the torso during the downswing differ between successful and less successful kickers?

The long and wide-left kickers orientated their pelvis such that it was facing less front-on to the goalposts compared with the short kickers throughout the kicking phase. Whilst the long kickers' trunk was facing in a similar direction to their pelvis at the top of the backswing, the wide-left kickers' trunk was more front-on meaning there was a larger relative angle between the trunk and the pelvis segments at the top of the backswing, thereby creating a greater 'tension arc' across the torso which was subsequently released during the downswing. The release of this ‘tension arc’ by the wide-left kickers was characterised by a greater range of longitudinal trunk rotation (towards the right-hand-side) up to initial ball contact. This hip flexor strategy appeared to allow the wide-left kickers to do greater positive hip flexor work and achieve comparable ball velocity magnitudes to the long kickers (who used a knee extensor strategy more reliant on positive knee extensor work), but which may have influenced their ability to appropriately direct this velocity vector, thus reducing their accuracy (as will be discussed in detail in Section 8.4.1).

8.3. Methodological considerations

The key findings outlined in the previous section were obtained from laboratory-based data collections. A novel measure of rugby place kick performance was developed and used to categorise kickers in to groups so that statistical comparisons could be made to identify distinguishing features of their techniques. This section will now discuss the key methodological considerations related to this process.

8.3.1. Laboratory-based data collection

Although competitive rugby place kicks are performed outside on a rugby pitch, the laboratory environment enabled integrated motion capture and ground reaction force data to be collected whilst controlling for external factors such as wind and degrading ground conditions that may influence a kicker's technique and therefore the reliability of the collected data. Ground reaction forces are difficult to record in a field environment, but were identified in the literature review as being an important consideration owing to their clear role in determining the performance of other kicking skills (e.g. Ball, 2013; Inoue et al., 2014; Katis et al., 2013; Orloff et al., 2008), and the current results confirmed this importance in rugby place kicking. However, the ecological validity of the protocol must also be considered. All kickers wore their own moulded rugby boots (that they would wear on a firm natural pitch or on an artificial surface), used their own kicking tee, set the ball up on the tee as they preferred and took their usual approach to the ball which was a standard Gilbert Virtuo Matchball (Size 5) maintained at a pressure of between 9.5 and

10.0 psi as required in the Laws of the Game (World Rugby, 2015). The kickers all performed multiple practise trials until they confirmed that they were familiar and comfortable with the environment.

The automatic motion capture system used to record the motion of the kicker tracked markers placed on the skin to estimate the movement of the underlying skeleton. These markers are subject to movement artefact, particularly in dynamic movements (Leardini et al., 2005) such as rugby place kicks. A set of marker clusters were therefore developed and mounted on a rigid, conformable material to reduce this artefact. The effects of movement artefact were also minimised through the use of a global optimisation (Inverse Kinematics) approach to compute segmental pose data (Lu & O'Connor, 1999). This approach allowed joint constraints to be imposed on the linked segment model, restricting the relative segmental motion to what is physically realistic; 3D joint rotations but no translations of adjacent segments relative to one another.

Finally, whilst most studies performing biomechanical analyses of kicking skills have instructed the kickers to kick the ball as fast as possible, this is not representative of true place kick performance where accuracy is also paramount. Therefore, whilst the kickers were instructed to perform maximal range place kicks they were also instructed to aim for a suspended target representative of the centre of the goalposts. The ball velocities recorded in this study were comparable to those recorded for professional rugby players on an outdoor pitch (Holmes et al., 2006) and demonstrate that ecologically valid performance levels were maintained. A laboratory data collection rarely, however, allows the full flight path of the ball to be tracked meaning a measure of overall place kick performance must be estimated from the recorded initial ball flight data.

8.3.2. Determination of performance levels

A novel method of determining overall place kick performance from initial ball flight data that can be collected in an indoor laboratory was proposed, formulated and evaluated in Chapter 3. This measure enabled the identification of a group of successful kickers and two distinct groups of less successful kickers. A 4.0% error in estimating this applied performance measure was determined, and two kickers were removed from all subsequent analysis to accommodate this error and ensure that all kickers were confidently placed in appropriate groups. The identified groups of kickers then formed the basis for the comparisons of technique in the subsequent chapters in order to address research questions ii - vi. Whilst a substantially positive relationship existed in the rank order of kickers between their estimated maximum kick distance and their resultant ball velocity ($\rho = 0.52$), the rank order of the kickers changed considerably depending on the performance measure used, highlighting the importance of considering overall place kick performance. This was further evident when comparing the long and wide-left kickers; if resultant ball velocity magnitude was the performance criterion (as has been the case in previous rugby place kicking research, e.g. Baktash et al., 2009; Sinclair et al., 2014; Zhang et al., 2012), the success of the kickers in these two groups would have been considered to be comparable. Consequently, the differences in technique between these two groups would not have been identified and the important understanding of why some kickers miss to the left of the target would have been overlooked.

8.3.3. Statistical analysis

Two different statistical analysis methods were used to compare variables between the three groups. For the analysis of discrete variables, magnitude-based inferences were calculated to assess the effects between each group pair as opposed to the more traditional method of null-hypothesis significance testing. As described in the review of literature, magnitude-based inferences provide an indication of the likely practical importance of an effect, something that is of more interest in the analysis of sports performance than whether or not an effect is zero (Batterham & Hopkins, 2006). Furthermore, magnitude-based inferences are a less conservative approach than null-hypothesis significance testing, particularly when the sample sizes being analysed are small as is often the case when investigating sports performance. Whilst magnitude-based inferences were used to compare discrete data points (e.g. peak values or values at specific events), Statistical Parametric Mapping was adopted to compare the time-histories of data such as the joint mechanics and ground reaction forces. Whilst this method uses null-hypothesis significance testing and is thus more conservative in nature as identified above, the ability to consider the complete time-histories and make comparisons between multiple groups whilst maintaining a Type I error rate of 5% rendered this an appropriate approach for analysing the time-histories investigated in Chapters 6 and 7. It is important to consider, however, that the Type II error rate may likely be higher in these analyses and as such not all true differences may have been identified between the time-histories. This combination of magnitude-based inferences for analysing discrete data and Statistical Parametric Mapping for analysing time-histories ultimately enabled a comprehensive investigation of the technique differences between the three groups of kickers. This therefore allowed technique-related reasons for why different performance outcomes were achieved to be objectively identified.

8.4. Consideration of the key differences between groups

A number of differences in whole-body, kicking leg and torso motion were identified between the groups of kickers as research questions iii - vi were sequentially addressed. These differences were identified in Section 8.2 and will now be discussed in greater detail to understand the key differences between the techniques of the successful and each of the groups of less successful kickers (wide-left and then short) in turn.

8.4.1. Technique differences between long and wide-left kickers

The wide-left kickers achieved a comparable resultant ball velocity magnitude to the long kickers. However, when the velocity vector was resolved, the lateral velocity of the wide-left kicks was directed towards the left-hand-side of the goalposts as opposed to the right-hand-side for the long kicks. Furthermore, the wide-left kicks had substantially more longitudinal spin causing the ball to curve further towards the left-hand-side of the goalposts. Positive relationships have previously been observed between the magnitude of the kicking foot velocity vector at initial ball contact and the velocity magnitude of the ball post-contact (Ball, 2008; Levanon & Dapena, 1998; De Witt & Hinrichs, 2012; Nunome et al., 2006). Initially, these findings did not appear to extend to the current between-group comparison as although the resultant ball velocity magnitude was not different between the long and wide-left kickers, the resultant velocity magnitude of the long kickers' kicking foot was substantially faster at initial ball contact than the wide-left kickers'. However, when this foot velocity was resolved, it was apparent that the magnitudes of the forward and vertical velocities were comparable between the groups, as would be expected given the previous findings, but the long kickers' foot had a higher velocity component towards the right-hand-side of the goalposts at initial ball contact. As the ball velocity vector was also directed towards the right-hand-side of the goalposts post-contact in the long kicks and directed towards the left-hand-side in the wide-left kicks, this provides an initial indication as to why the different performance outcomes were observed. There were no differences in the orientation of the kicking foot at initial ball contact between the two groups; it was therefore important to consider how more proximal aspects of the techniques of the kickers may have influenced the direction of the kicking foot velocity vector at initial ball contact.

Both the long and wide-left kickers took an angled approach to the ball. However, the long kickers' whole-body CM was substantially further to the left of the ball at kicking foot take-off, support foot contact and initial ball contact compared with that of the wide-left kickers. The long kickers also took a substantially longer final step towards the ball, resulting in support foot contact occurring temporally closer to initial ball contact. The timing of the final step taken by the kicker towards the ball has been suggested by an elite rugby kicking coach as being important, with a more rushed approach not allowing the kicker time to reach *"their full natural 'triangle'"* (Bezodis & Winter, 2014). The 'triangle' referred to the positioning of the kicking foot, the non-kicking-side shoulder and the support foot at the time of top of the backswing (Bezodis & Winter, 2014). Whilst the kicking foot was a comparable distance away from the ball at the top of the backswing in the two groups, the long kickers' foot was substantially further to the left of the ball compared with that of the wide-left kickers, indicating that the long kickers adopted a more lateral kicking foot position as part of their 'triangle' compared with the wide-left kickers. This may be a potentially more appropriate kicking foot position from which to initiate the downswing in order to achieve an accurate, high velocity kick. Previous research in other football codes suggested that a longer final step enabled greater kicking leg retraction (Ball, 2008), and therefore a kicking foot position further away from the ball at the top of the backswing, through greater longitudinal pelvis rotation (Lees & Nolan, 2002), although there were no differences in the pelvis orientation between the two groups in the current study. Therefore the long kickers likely achieved this more lateral kicking foot position through differences in the orientations of either the kicking leg or support leg segments achieved during the longer final step. Furthermore, the long kickers positioned their support foot substantially less far behind the ball than the wide-left kickers, which is the third point of the 'triangle', providing further support for the assertion that the long kickers obtained their natural 'triangle' but the wide-left kickers did *"not give themselves time to get back to their full natural 'triangle'"* (Bezodis & Winter, 2014).

The adoption of the 'triangle' by place kickers is intended to create a stretch across the torso, similar to the 'tension arc' described by Shan and Westerhoff (2005) in soccer instep kicking. The 'tension arc' enables kickers to stretch the muscles across the torso through longitudinal rotation of the trunk away from the pelvis, directing the non-kicking-side shoulder away from the kicking-side hip. Shan and Westerhoff (2005) proposed that the kickers could then benefit from a stretch-shortening mechanism in order to generate greater concentric muscle forces using the muscles that were previously stretched, primarily the hip flexors. Shan and Westerhoff (2005) reported that as experienced kickers released the 'tension arc' during the downswing, the trunk flexed and longitudinally rotated, facing towards the right-hand-side, movements that were not evident for inexperienced kickers. Comparison of the orientation of the trunk about the longitudinal axis between the long and wide-left kickers at the top of the backswing revealed that whilst the trunk was facing the right-hand-side (the same direction as the pelvis) in both groups, the trunk was more front-on compared with the pelvis for the wide-left kickers than for the long kickers whose trunk was facing in a similar direction to the pelvis. The wide-left kickers' relative trunk-pelvis angle was therefore significantly greater at the top of the backswing compared with the long kickers', indicative of a greater stretch across their torso.

During the downswing, the motion of the pelvis about the global longitudinal axis was similar in both groups, rotating so that it was facing more front-on at initial ball contact. However, whilst the long kickers' trunk demonstrated a small amount of longitudinal rotation towards the right-hand-side during the downswing in opposition to their pelvis so that it was facing further towards the right-hand-side at initial ball contact compared with at the top of the backswing, the wide-left kickers demonstrated a greater range of longitudinal trunk rotation over this time (and by initial ball contact it had reached an orientation similar to that of the long kickers). This longitudinal trunk rotation during the downswing by the wide-left kickers may be symptomatic of the release of the stretch across the torso, resulting in more forceful contractions of the stretched hip flexor muscles compared with the long kickers. This more forceful contraction of the wide-left kickers' hip flexors was supported by the substantially greater positive hip flexor work done during the downswing (hip flexor strategy) compared with the long kickers' greater positive knee extensor work (knee extensor strategy). These different strategies in torso and kicking leg motion employed by the long and wide-left kickers both facilitated the generation of a fast foot velocity at initial ball contact, and consequently a fast ball velocity post-contact. However, the differences between the strategies may be an important factor which influenced the direction of the foot velocity vector at initial ball contact and therefore the ball kinematics post-contact and ultimately the accuracy of the kick. As the long kickers did less positive work at the hip, it is possible that they were able to better control the motion using the muscles crossing this ball-and-socket joint, helping to ensure that the kicking foot took a more desirable path towards the ball.

A similar strategy has been observed in a previous investigation of kicking leg kinematics in curve and instep kicking in soccer (Alcock et al., 2012). A significantly faster knee extension velocity at initial ball contact was reported when kickers performed curve kicks which required a more precise foot-ball contact compared with when they took an instep kick (yet comparable peak kicking toe velocities were achieved). The current results extend these findings through investigating the joint kinetics that are ultimately causing these differences in the observed motion. Furthermore, in a study by Nunome et al. (2002) which investigated soccer instep and side-foot kicks, the peak resultant hip flexor moment occurred earlier in the side-foot kicks - although this was not a finding discussed by the authors, it appears to align with the current results and those of Alcock et al. (2012) as achieving a peak hip flexor moment earlier in the downswing may enable greater use of the muscles crossing the hip to control the motion of the kicking leg during the latter part of the downswing. Finally, when kicking for maximum distance Australian Rules football punt kickers have been found to employ either a 'thigh dominant' or a 'knee dominant' strategy (likely similar to the hip flexor and knee extensor strategies observed in the place kickers), based on the ratio of thigh angular velocity to knee angular velocity at initial ball contact (Ball, 2008). Comparable maximum distances were achieved regardless of the strategy used by the Australian Rules kickers, however, the accuracy of the kicks was not considered and given the results of the current thesis this is an area worthy of further investigation. It therefore appears that whilst the greater stretch across the torso of the wide-left kickers, caused by the trunk facing further away from the pelvis at the top of the backswing, enabled greater positive work to be done by the hip flexors, this may not have provided the kickers with the opportunity to maintain as desirable a kicking foot motion at initial ball contact. The release of this stretch also appeared to cause the wide-left kickers' trunk to longitudinally rotate throughout the downswing. This movement may have further reduced the control of the kicking foot motion compared with the long kickers who demonstrated less trunk rotation during the downswing as more accurate place kickers have previously been found to demonstrate less longitudinal trunk angular momentum at initial ball contact (Bezodis et al., 2007). These key differences found between the kicking techniques of the long and wide-left kickers can provide guidance to coaches and players as to why, even when a high ball velocity can be achieved, some kicks may miss the left-hand goalpost from greater distances. The practical implications of these identified differences will be discussed in Section 8.5.

8.4.2. Technique differences between long and short kickers

The technique of the long kickers was also compared with the short kickers to understand why kickers may exhibit lower performance levels due to a lack of distance. The resultant ball velocity of the short kicks was substantially slower compared with the long kicks. When this velocity vector was resolved, the short kicks were slower in the forward and vertical directions and substantially faster in the lateral direction (towards the right-hand-side) compared with the long kicks. These differences in ball flight characteristics suggested that there would be differences in both the magnitude of the kicking foot velocity and either the direction of this velocity vector or the orientation of the kicking foot at initial ball contact between the two groups.

The long kickers achieved a substantially faster kicking foot velocity at initial ball contact compared with the short kickers in all three principal directions. Although this difference may be expected given the previously identified relationship between kicking foot velocity magnitude at initial ball contact and ball velocity magnitude post-contact (Ball, 2008; Levanon & Dapena, 1998; De Witt & Hinrichs, 2012; Nunome et al., 2006), it was important to identify how the techniques of the kickers contributed to these differences. Both the long and short kickers took an angled approach to the ball, but the long kickers' whole-body CM was substantially further away from the ball at kicking foot take-off due to them being both further behind and further to the side of the ball. The long kickers' whole-body CM velocity was also substantially faster than the short kickers' and they subsequently took a substantially longer and more angled final step towards the ball. As mentioned previously, a longer final step is thought to enable greater kicking leg retraction and longitudinal rotation of the pelvis in soccer instep kicking (Lees & Nolan, 2002), and a similar effect has been experimentally shown when kickers took a more angled approach towards the ball (Scurr & Hall, 2009). In the current study, the long kickers displayed a pelvis orientation about the global longitudinal axis that was facing significantly further towards the right-hand-side of the goalposts compared with the short kickers at the top of the backswing, which likely enabled the kicking foot to be positioned substantially further away from the ball, supporting the above soccer research. The shorter final step taken by the short kickers appeared to stop them achieving *"their full natural 'triangle'"* (Bezodis & Winter, 2014) at the top of the backswing, and this more 'compact' technique limited the subsequent kicking leg motion during the downswing. The shorter path taken by the short kickers' kicking foot from the top of the backswing to initial ball contact provided an initial global indication of this reduced kicking leg motion.

The ground reaction forces recorded underneath the support foot from support foot contact to initial ball contact reduced the velocity of all kickers' whole-body CMs in both the lateral and forwards directions, whilst increasing their vertical velocity. The long kickers exerted a significantly larger lateral force during this phase, likely due to the more angled approach they took towards the ball (Isokawa & Lees, 1988), thereby reducing their lateral whole-body CM velocity more than the short kickers. Although no significant differences were observed at each time-point of the ground reaction force time-histories between these groups in the other principal directions, the long kickers increased their vertical velocity by a substantially greater amount when the total impulse across the entire phase was considered. At initial ball contact, the long kickers' vertical whole-body CM velocity was substantially faster than the short kickers' which may have raised the kicking foot during the ball contact phase and therefore helped to cause the greater vertical velocity of the ball post-contact observed in Chapter 5. Furthermore, the total reduction in whole-body CM velocity in the two horizontal directions from support foot contact to initial ball contact was substantially greater for the long kickers compared with the short kickers. Greater deceleration of the kickers' whole-body CM has previously been suggested as a mechanism for generating faster kicking foot and ball velocities in soccer instep kicking through the transfer of whole-body momentum to the kicking leg (Potthast et al., 2010). This therefore provides a further partial explanation for why the long kickers were able to generate faster kicking foot velocities at initial ball contact than the short kickers.

Similar to the orientation of the pelvis, the short kickers' trunk was more front-on throughout the kicking phase, resulting in a relatively neutral pelvis-trunk angle and therefore a minimal stretch across the torso. The short kickers did substantially less positive work at both the kicking hip and knee throughout the downswing compared with the long kickers. It would appear therefore that the short kickers used neither the knee extensor nor the hip flexor strategy adopted by the long or wide-left kickers to achieve a fast kicking foot velocity, further explaining the slower velocity observed at initial ball contact.

When these technical differences are considered together, it appears that the differences in performance between the long and short kickers arose from their original approach towards the ball. As the long kickers took a more angled approach towards the ball they were able to orientate their body so that the torso was facing further towards the right-hand-side than the short kickers, with their kicking foot further away from the ball at the top of the backswing. The long kickers also approached the ball with a substantially faster whole-body CM velocity compared with the short kickers, which they were then able to reduce substantially more between support foot contact and initial ball contact and transfer to the kicking leg. This is reflected in the fact that the long kickers performed substantially more positive work at both the kicking hip and knee joints than the short kickers, accelerating their kicking foot over a greater distance and ultimately achieving a faster kicking foot velocity at initial ball contact. These differences in kicking technique help to explain some of the observed differences in the ball flight and provide guidance to coaches and players as to the key factors that differentiate the more successful kickers from those who are less successful because the ball would drop short of the crossbar from greater distances.

8.5. Practical implications

Firstly, the finding that successful performance cannot solely be determined as a fast ball velocity is an important consideration when aiming to improve place kick performance, and therefore achieving a fast kicking foot velocity at initial ball contact should not be the sole focus in place kicking coaching or research. Place kicks may be less successful because they lack either accuracy or distance, and this thesis identified differences in the techniques of two groups of kickers that represent these respective limitations compared with successful kickers (depicted in the revised conceptual models, Figures 8.1 and 8.2). Thus, the practical implications are specific to each group of less successful kickers and will be discussed in turn.

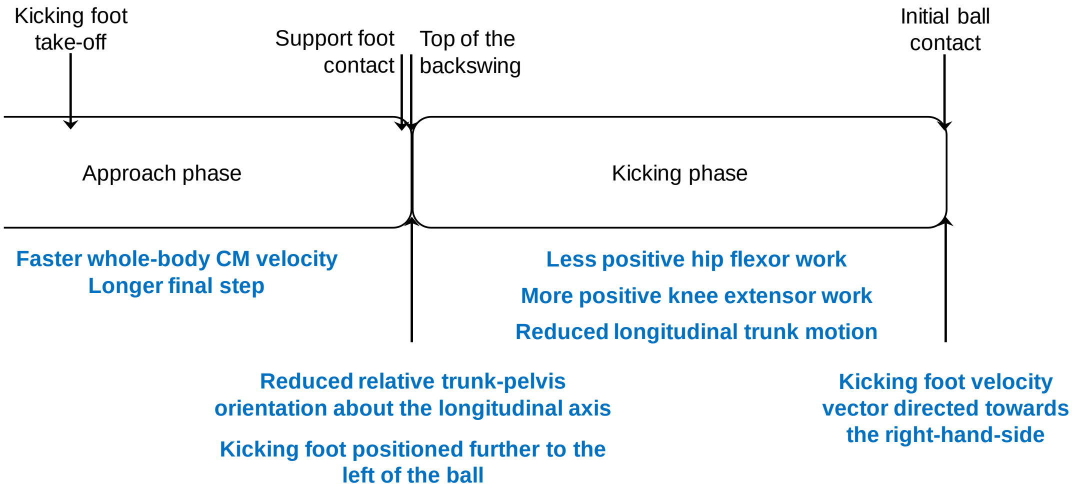


Figure 8.1. The revised conceptual model identifying the key differences in the techniques of the long and wide-left kickers during the approach and kicking phases of a rugby place kick (the expressed differences correspond to the observed motion of the long kickers compared with the wide-left kickers).

Based on the observed differences in the technique of the long and wide-left kickers, there are specific technical aspects relating to the approach of the kicker towards the ball that a coach or player may try to alter to improve the performance of kickers who are less successful because they miss the left-hand goalpost from greater distances. Simply taking a longer final step towards the ball, from an initial position further to the left, may help these kickers to adopt their *"full natural 'triangle'"* and thus a kicking foot position further to the left of the ball at the top of the backswing and a support foot position less far behind the ball. Furthermore, adopting a trunk orientation facing further towards the right-hand-side at the top of the backswing (which may be initiated in the preceding approach towards the ball) and then subsequently minimising the motion of this segment throughout the kicking phase, may help the kicker to control the motion of the kicking foot during both the kicking and ball contact phases. Acute interventions could be used by a coach to investigate the effect of alterations to these aspects of technique on the place kick performance of kickers who typically miss to the left of the posts.

The long kickers adopted a knee extensor strategy, doing more positive work at the kicking knee joint as opposed to the hip, which appeared beneficial in terms of generating the necessary kicking foot velocity whilst potentially allowing the kicker to control the motion of the kicking leg to ensure a more desirable kicking foot path and therefore an appropriately directed ball velocity vector post-contact. Adjustments to the orientation of the trunk at the top of the backswing (as suggested above) may help to encourage a change in the joint work strategies as there will be less stretch across the torso and therefore less contribution from the stretch-shortening cycle to the positive work done by the hip flexors. However, as the desired technique is for the kickers to do more positive work with the knee extensors, if differences in the strength of the long and wide-left kickers' knee extensors is identified, an intervention seeking to increase the strength of the knee extensors through both the knee range of motion and at the knee extension velocities observed in a place kick may also be beneficial to these kickers.

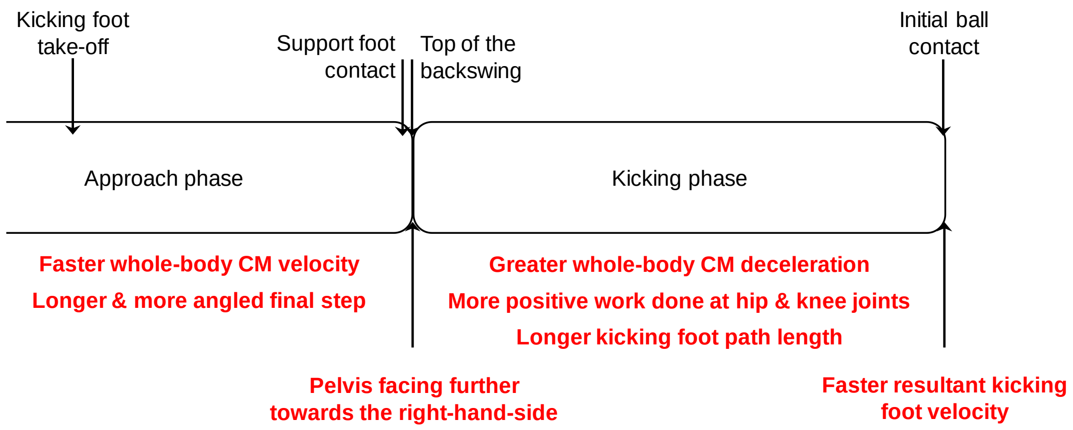


Figure 8.2. The revised conceptual model identifying the key differences in the techniques of the long and short kickers during the approach and kicking phases of a rugby place kick (the expressed differences correspond to the motion of the long kickers compared with the short kickers).

For short kickers to be successful from greater distances, the current results suggest that an increase in both their approach velocity and the angle of approach towards the ball may be important. These differences in the kickers' approach may also enable them to take a longer final step and orientate their torso such that it is facing further towards the right-hand-side, thereby adopting their *"full natural 'triangle'"* at the top of the backswing. The angle from which the kickers approach the ball can be directly manipulated and the effect on the kicking technique and performance outcome can be observed. Training drills that require the kickers to approach the ball with a greater velocity (often termed 'run through' drills by coaches) may be used to encourage a transfer of this increased approach velocity to their conventional place kicks.

The positive work done by both the long kickers' hip flexors and knee extensors was greater than that done by the short kickers. Whilst this may have been due to the transfer of momentum from greater deceleration of their faster approach, strength training may also be important for the short kickers if they are found to have lower levels of leg strength (particularly given their substantially lower body mass compared with the long kickers; Table F.1, Appendix F). Such programmes could focus on developing the strength of the kicking leg hip flexors and knee extensors in exercises which correspond to, and gradually overload, the demands of place kicking through the corresponding ranges of motion and joint velocities experienced in the skill. If the short kickers are also encouraged to approach with a faster velocity, in order to decelerate their whole-body CM velocity during the stance phase they will likely require a greater reactive strength in the support leg and therefore plyometric drills designed to enhance this ability may be beneficial to ensure they are able to exert sufficient force and control their whole-body motion.

The practical implications of the results of this thesis have been discussed and potential suggestions of how they may be applied are proposed. However, not all of the differences in the flight of the ball can be explained by the results of these investigations and so potential suggestions for future research must also be considered.

8.6. Future directions for research

Whilst a number of important technical differences were identified between the successful and less successful groups of kickers, these did not explain all of the identified differences in the ball flight characteristics. It is suggested that an analysis of the ball contact phase may provide additional insight into why these differences occur. However, the ball contact phase has been shown to last approximately 10 ms in soccer instep kicking and contains high frequency movements of the foot which can only be truly recorded by sampling at very high frequencies. Furthermore, previous analyses of the ball contact phase in soccer instep kicking have revealed deformation of the foot segment during contact (Shinkai et al., 2009) which suggests that the foot cannot be considered as a single rigid segment during this time and would need to be defined using a more complex model. Nunome et al. (2006) also demonstrated that the inclusion of the initial ball contact in analyses affects the data both preceding and following the ball contact phase if the varying frequency components within the data are not treated appropriately. Therefore, a specifically-designed, focussed and controlled analysis of the ball contact phase of rugby place kicking is required to obtain appropriate insight into this phase of rugby place kicking.

The previous section highlighted practical implications arising from the findings of this thesis, and comprised both technical and strength training interventions. Whilst both of these types of intervention appear potentially beneficial based on the results of this thesis, their potential effectiveness is unknown and future investigations should also seek to focus on these aspects. Previous research investigating the effect of strength training interventions on the performance of soccer instep kicks revealed that although leg strength was improved, there was no change in ball velocity (Aagaard et al., 1996; Trolle et al., 1993). However, the leg strength and ball velocity achieved by the kickers included within these studies had not previously been identified as a limiting factor to their performance (they achieved maximum ball velocities of between 24 and 32 m/s, compared with the short place kickers in the current study of 20.8 ± 2.2 m/s) and the strength training conducted was not specific to the kicking action. It is therefore suggested that any strength training intervention should correspond to the kicking movement as opposed to isolating specific muscles and not replicating the relevant movement patterns of the skill; loaded kicks where the kicking leg is resisted by a band or pulley-system, as suggested by Young and Rath (2010) for soccer instep kicking, may be one such option. Although the strength of the kickers was not directly assessed in this thesis, and should also be considered, an investigation into the effect of a strength training intervention for the less successful kickers (focussing on knee extensor strength for those kickers who miss the left-hand goalpost and on both hip flexor and knee extensor strength for those whose kicks drop below the height of the crossbar from longer distances) would be of interest given the current findings. Furthermore, the differences observed in the body mass of the long and short kickers could be a consideration for future research to investigate. The approach of the short kickers was also identified as an area that could be improved. In order to investigate the potential effectiveness of such a change in technique, both acute and long-term technique intervention studies could be conducted to experimentally assess how the approach angle and velocity of these kickers who initially demonstrated a slow and straight approach could affect their performance.

Finally, all of the investigations within this thesis were empirical studies which compared the techniques of the kickers in order to understand how differences in performance outcomes were achieved. Computer simulation studies have previously been used to theoretically further the understanding of sporting skills through the manipulation of individual or combinations of variables that may not be possible in experimental studies. Such a forward dynamics approach could enable investigation of alterations to specific aspects of place kicking technique, and how they affect the motion of the kicking foot and therefore the nature of the foot-ball contact. These investigations could provide direction for, and a deeper understanding of, the potential effectiveness of both technical (if an angle-driven model) and strength (if a muscle/torque-driven model) interventions on place kick performance.

8.7. Thesis conclusion

This thesis investigated rugby place kicking technique and how movement execution differs between successful and less successful place kickers. Six research questions were sequentially addressed and a conceptual framework was proposed and revised to help inform coaching practice. Through the development of a novel method of measuring place kick performance, the importance of considering overall performance was demonstrated to ensure that kick accuracy was inherently considered when investigating technique. This enabled three distinct groups of kickers to be identified; successful kickers (long kickers) and two groups of less successful kickers (those who lacked accuracy - wide-left kickers, and those who lacked distance - short kickers). The long kickers adopted a trunk orientation that was facing further towards the right-hand-side of the goalposts at the top of the backswing and then demonstrated less longitudinal trunk rotation throughout the kicking phase compared with the wide-left kickers. Furthermore, the long kickers also adopted a different joint work strategy in that they did more positive work at the kicking knee as opposed to the hip which may have enabled them to have more control over the motion of the kicking leg at the hip joint, thereby ensuring a more desirable kicking foot path prior to initial ball contact. These factors likely ensured the long kickers were able to achieve a more appropriately directed ball flight post-contact compared with the wide-left kickers. When compared with the short kickers, the long kickers approached the ball from a greater angle, positioning their kicking foot further away from the ball at the top of the backswing and with a faster whole-body velocity which they subsequently decelerated prior to initial ball contact through exerting larger horizontal forces against the ground. The long kickers also did more positive work at both the kicking leg hip and knee throughout the downswing compared with the short kickers. These combined factors appeared to result in the long kickers achieving a faster kicking foot velocity at initial ball contact and subsequently a faster ball velocity post-contact. These specific differences in kicking technique were used to provide evidence-informed recommendations for how players and coaches may specifically seek to improve their place kick performance if they are lacking either distance or accuracy.

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Appendix A: Matlab script of ball flight model

```
clear all clc

% DEFINE CONSTANTS FOR THE MODEL
p = 1.225;          % The density of the air in kg/m^3 at sea level at 15 degrees (SMU officially 14 m above sea
                    level which would equate to 1.223 but has less than 1 cm difference on result)
m = 0.435;          % Average mass of the ball in kg from World Rugby laws
Vb = 0.0048;        % Volume of the ball m3 (from Seo et al. 2006a)
Ix = 0.0033;        % Moment of inertia about transverse axis kg.m^2 (from Seo et al. 2006a)
Iz = 0.0026;        % Moment of inertia about longitudinal axis kg.m^2 (from Seo et al. 2006a)
g = -9.81;          % Acceleration due to gravity m/s^2
max_dx = 2.65; % Maximum dx in the positive direction in m
min_dx = -2.65; % Maximum dx in the negative direction in m

% DEFINE TIME STEP FOR ITERATIONS (in seconds)
t = (1/10000);

% DEFINE INITIAL CONDITIONS
i = 1;

θ_deg(i) = 21;          % Input initial absolute pitch angle in degrees (absolute value)
γ_deg(i) = 1;           % Input initial yaw angle in degrees (of the ball relative to the global A-P axis)
ωx_deg(i) = 3093;       % Input initial end-over-end spin rate in degrees/s (absolute value)
ωy_deg(i) = 664;        % Input yaw spin rate in degrees/s
ωz_deg(i) = 23;         % Input initial longitudinal spin rate in degrees/s
dx(i) = 0.02;           % Input initial ball position in lateral direction in m
dy(i) = 0.33;           % Input initial ball position in forward direction in m
dz(i) = 0.39;           % Input initial ball position in vertical direction in m
vx(i) = 0.5;            % Input initial ball velocity in lateral direction in m/s
vy(i) = 25.1;           % Input initial ball velocity in forward direction in m/s
vz(i) = 15.4;           % Input initial ball velocity in vertical direction in m/s
ax(i) = 0;              % Initial linear accelerations zero
ay(i) = 0;              % Initial linear accelerations zero
az(i) = 0;              % Initial linear accelerations zero
v⃗(i) = sqrt((vx(i)^2)+(vy(i)^2)+(vz(i)^2));
pitch_direction = 1;    % Input pitch direction - nose in front of Ball CM = 1, nose behind Ball CM = 2;

ωz = ωz_deg(i)/360;              % Calculate longitudinal spin rate in rev/s
revs = abs(ωz);                  % Calculate absolute longitudinal spin rate

if pitch_direction(i) == 2;      % Convert end-over-end spin rate based on pitch direction
  ωx_deg(i) = ωx_deg(i)*-1
else
end

flight_angy(i) = atan(vx(i)/vy(i));             % Calculation of ball flight direction
flight_ang_degy(i) = flight_angy(i)*180/pi; % Convert ball flight direction to degrees

relative_flight_yaw_ang_degy(i) = yaw_deg(i) - flight_ang_degy(i); % Calculation of relative angle yaw
                                                                    angle from flight direction

if relative_flight_yaw_ang_degy(i) > 90;          % Adjust relative angle if > 90°
   yaw_deg(i) = -90 + (yaw_deg(i)-90);
   relative_flight_yaw_ang_degy(i) = yaw_deg(i) - flight_ang_degy(i);
elseif relative_flight_yaw_ang_degy(i) < -90;
   yaw_deg(i) = yaw_deg(i) + 180;
   relative_flight_yaw_ang_degy(i) = yaw_deg(i) - flight_ang_degy(i);
end

ball_yaw_angle(i) = abs(relative_flight_yaw_ang_degy(i)); % Absolute angle for coefficients

revs = abs(ang_velz);                       % Convert longitudinal spin rate to revs
```

```
ωx _rev(i) = (ωx _deg(i)/360); % Convert end-over-end spin rate to revs

S(i) = (pi*(abs(ωx_rev(i)))*(Vb^(1/3)))/ v⃗(i); % Calculate spin coefficient
```

% BALL FLIGHT SIMULATION

```
while dx(i)<max_dx && dx(i)>min_dx; % Run the simulation until the ball passes wide of the goalposts

    i = i + 1;

    if revs <=1; % Calculate spin coefficient if longitudinal spin rate > 1 rev/s (Seo et al., 2006a)
        Cx(i) = 0;
    else
        Cx(i) = ((-0.00150+(0.000649*revs) - (0.0000835*(revs^2)))*θ_deg(i-1)) + ((-0.0000411-
         (0.0000382*revs) + (0.00000264*(revs^2))) * (θ_deg(i-1)^2)) +
         ((0.000000494+(0.000000274*revs) - (0.0000000177*(revs^2))) * (θ_deg(i-1)^3));
    end

    Cy(i) = 0.859 - (0.209*S(i-1)) - ((0.00409 + (0.00257*S(i-1)))*ball_yaw_angle(i-1));
                                      % Calculation of drag coefficient (Seo et al., 2007)

    Cz(i) = (0.00148 + (0.00664*S(i-1)))*ball_yaw_angle(i-1);
                                      % Calculation of lift coefficient (Seo et al., 2007)

    if ωz > 0;         % Calculation of side force if longitudinal spin is anti-clockwise (Seo et al., 2006a)
        Fx(i) = Cx(i)*p*(Vb^(2/3))*0.5*(v⃗(i-1)^2);
    elseif ωz < 0      % Calculation of side force if longitudinal spin is clockwise direction
        Fx(i) = -Cx(i)*p*(Vb^(2/3))*0.5*(v⃗(i-1)^2);
    end

    Fy(i) = Cy(i)*p*(Vb^(2/3))*0.5*(v⃗(i-1)^2); % Calculation of drag force (Seo et al., 2007)
    Fz(i) = Cz(i)*p*(Vb^(2/3))*0.5*(v⃗(i-1)^2); % Calculation of lift force (Seo et al., 2007)

    ax(i) = (Fx(i)/m);     % Calculation of linear acceleration of the ball in the medio-lateral axis
    ay(i) = - (Fy(i)/m);   % Calculation of linear acceleration of the ball in the anetro-posterior axis
    az(i) = (Fz(i)/m)+g;   % Calculation of linear acceleration of the ball in the vertical axis

    vx(i) = vx(i-1)+((ax(i-1)+ax(i))*0.5*t);   % Update of linear ball velocity in the medio-lateral axis
    vy(i) = vy(i-1)+((ay(i-1)+ay(i))*0.5*t);   % Update of linear ball velocity in the anetro-posterior axis
    vz(i) = vz(i-1)+((az(i-1)+az(i))*0.5*t);   % Update of linear ball velocity in the vertical axis
    v⃗(i) = sqrt((vx(i)^2)+(vy(i)^2)+(vz(i)^2));  % Calculation of resultant linear ball velocity

    dx(i) = dx(i-1)+((vx(i)+vx(i-1))*0.5*t);   % Calculation of position of the ball in the medio-lateral axis
    dy(i) = dy(i-1)+((vy(i)+vy(i-1))*0.5*t);   % Calculation of position of the ball in the anetro-posterior axis
    dz(i) = dz(i-1)+((vz(i)+vz(i-1))*0.5*t);   % Calculation of position of the ball in the vertical axis

    θ_deg(i) = (θ_deg(i-1)+(ωx_deg(1)*t)); % Update of pitch angle

    S(i) = (pi*(abs(ωx_rev(1)))*(vb^(1/3)))/res_vel(i); % Calculation of spin coefficient

    γ_deg(i) = (γ_deg(i-1)+(ωy_deg(1)*t));       % Update of yaw angle in degrees
    ωy_deg(i) = ωy_deg(i-1); % Update of yaw angular velocity in degrees

    relative_flight_yaw_ang_degy(i) = yaw_deg(i) - flight_ang_degy(i); % Calculation of relative angle
                                                                  yaw angle from flight direction

    if relative_flight_yaw_ang_degy(i) > 90;          % Adjust relative angle if > 90°
         yaw_deg(i) = -90 + (yaw_deg(i)-90);
         relative_flight_yaw_ang_degy(i) = yaw_deg(i) - flight_ang_degy(i);
    elseif relative_flight_yaw_ang_degy(i) < -90;
```

```
        yaw_deg(i) = yaw_deg(i) + 180;
        relative_flight_yaw_ang_degy(i) = yaw_deg(i) - flight_ang_degy(i);
    end

    ball_yaw_angle(i) = abs(relative_flight_yaw_ang_degy(i)); % Absolute angle for coefficients


    if θ_deg(i)<0 && pitch_direction == 1;          % Recalculation of ball pitch angle and angular velocity
                                                      if calculated angle in degrees is less than 0 degrees
        θ_deg(i) = 0-θ_deg(i);
        ωx_deg(i) = ωx_deg(i)*-1;
        pitch_direction = 2;
    elseif θ_deg(i)<0 && pitch_direction == 2;
        θ_deg(i) = 0-θ_deg(i);
        ωx_deg(i) = ωx_deg(i)*-1;
        pitch_direction = 1;
    elseif θ_deg(i)>90 && pitch_direction == 1; % Recalculation of ball pitch angle and angular velocity
                                                  if calculated angle in degrees is more than 90 degrees
        θ_deg(i) = 90-(θ_deg(i)-90);
        ωx_deg(i) = ωx_deg(i)*-1;
        pitch_direction = 2;
    elseif θ(i)>90 && pitch_direction == 2;
        θ_deg(i) = 90-(θ(i)-90);
        ωx_deg(i) = ωx_deg(i)*-1;
        pitch_direction = 1;
    else
        θ_deg(i) = θ_deg(i);
        ωx_deg(i) = ωx_deg(i);
    end


    if dy(i)>10 && dz(i)<3.15     % Check to see if ball has dropped below the height of the crossbar
        break
    else
        continue
    end
end

% MODEL OUTPUT

final_dx = dx(i-1)
final_dy = dy(i-1)
final_dz = dz(i-1)
flight_time = t(i-1)
```

Appendix B: Determination of number of ball flight frames needed to reliably calculate ball velocity

Table B.1. Ball velocity calculated over an increasing number of ball flight frames.

	Ball velocity (m/s)					
	2 frames	3 frames	4 frames	5 frames	6 frames	7 frames
Kicker 1						
Kick 1	25.4	26.2	25.7	25.6	25.5	25.4
Kick 2	31.9	25.6	24.8	24.8	24.8	24.9
Kick 3	25.6	25.5	25.5	25.4	25.3	25.3
Kick 4	24.8	25.1	25.1	25.1	25.1	25.1
Kick 5	26.8	25.8	25.8	25.7	25.7	25.6
SD	*2.9*	*0.4*	*0.4*	*0.4*	*0.3*	*0.3*
Kicker 2						
Kick 1	25.3	27.4	27.3	27.1	26.8	26.7
Kick 2	25.5	25.2	24.8	24.5	24.3	24.1
Kick 3	28.8	29.8	28.7	28.4	28.3	28.1
Kick 4	28.6	28.3	28.4	28.2	28.1	28.0
Kick 5	27.1	26.8	26.8	26.6	26.4	26.3
SD	*1.6*	*1.7*	*1.5*	*1.6*	*1.6*	*1.6*
Kicker 3						
Kick 1	29.7	29.1	28.9	28.8	28.6	28.6
Kick 2	28.7	28.9	28.9	28.9	28.9	29.0
Kick 3	29.4	31.0	29.5	29.3	29.2	29.1
Kick 4	27.6	27.6	27.6	27.4	27.5	27.6
Kick 5	27.4	27.9	28.2	28.1	28.0	28.0
SD	*1.0*	*1.3*	*0.7*	*0.8*	*0.7*	*0.7*
Kicker 4						
Kick 1	23.9	23.9	23.8	23.7	23.6	23.6
Kick 2	23.2	23.0	23.0	22.9	22.8	22.8
Kick 3	23.6	23.5	23.5	23.4	23.3	23.3
Kick 4	25.0	25.0	24.8	24.8	24.7	24.7
Kick 5	24.2	24.2	24.1	24.0	23.9	23.9
SD	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*
Kicker 5						
Kick 1	30.1	29.4	29.2	29.0	29.0	28.9
Kick 2	28.5	29.1	29.2	29.1	29.0	29.0
Kick 3	30.9	30.4	29.9	29.7	29.5	29.3
Kick 4	29.1	29.0	28.9	28.8	28.7	28.6
Kick 5	29.7	31.0	30.6	30.3	30.1	29.9
SD	*0.9*	*0.9*	*0.7*	*0.6*	*0.5*	*0.5*

Appendix C: Aerodynamic force coefficient equations presented by Seo et al. (2007) and Seo et al. (2006a)

Aerodynamic force coefficient equations - Seo et al. (2007)

$$S_{(i)} = (\pi_{(i-1)} \cdot \gamma_{(i-1)} \cdot \omega_{y(i-1)} \cdot V_b^{1/3}) / \vec{v}_{(i-1)} \tag{C.1}$$

$$C_{x(i)} = (-0.0174 - 0.0321 \cdot S_{(i)}) \cdot \gamma_{(i-1)} + (0.0000862 + 0.00171 \cdot S_{(i)}) \cdot \gamma_{(i-1)}^{2} + (0.0000012 - 0.0000151 \cdot S_{(i)}) \cdot \gamma_{(i-1)}^{3} \tag{C.2}$$

$$C_{y(i)} = (0.859 - 0.209 \cdot S_{(i)}) - (0.00409 + (0.00257 \cdot S_{(i)}) \cdot \gamma_{(i-1)} \tag{C.3}$$

$$C_{z(i)} = (0.00148 + 0.00664 \cdot S_{(i)}) \cdot \gamma_{(i-1)} \tag{C.4}$$

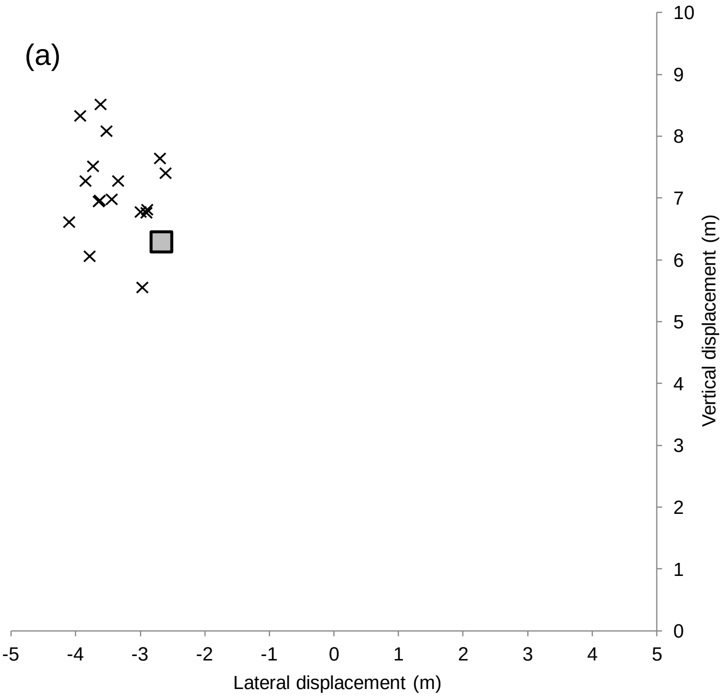
$$Cm_{y(i)} = (-0.00489 - 0.00432 \cdot S_{(i)}) \cdot \gamma_{(i-1)} + (0.0000544 + 0.000048 \cdot S_{(i)}) \cdot \gamma_{(i-1)}^{2} \tag{C.5}$$

Aerodynamic force coefficient equations - Seo et al. (2006a)

$$C_{x(i)} = (-0.0015 + 0.000649 \cdot \omega_{z(i-1)} - 0.0000835 \cdot \omega_{z(i-1)}^{2}) \cdot \theta_{(i-1)} + (-0.0000411 - 0.0000382 \cdot \omega_{z(i-1)} + 0.00000264 \cdot \omega_{z(i-1)}^{2}) \cdot \theta_{(i-1)}^{2} + 0.0000000494 + 0.000000274 \cdot \omega_{z(i-1)} - 0.0000000177 \cdot \omega_{z(i-1)}^{2}) \cdot \theta_{(i-1)}^{3} \tag{C.6}$$

$$Cm_{x(i)} = (0.0151 \cdot \theta_{(i-1)}) - (0.000169 \cdot \theta_{(i-1)}^{2}) \tag{C.7}$$

Appendix D: Repeated digitisations of an individual trial with more than 360°/s longitudinal spin



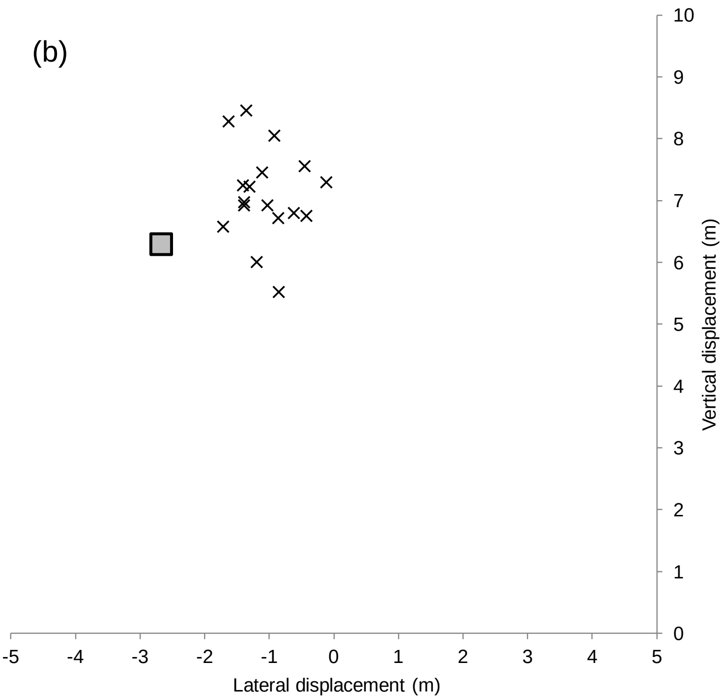


Figure D.1. The estimated positions of the 17 repeated digitisations (**×**) of a kick with more than 360°/s of longitudinal spin compared with the measured position (filled square); (a) using model v.8 including the side force, (b) using model v.2 without any side forces.

Appendix E: Definition of 14 segment full-body model

The definition of the body and ball segments modelled throughout the data collection for this research are detailed below alongside the definition of the Local Coordiate Systems (LCSs) of all segments and the markers used to track the segments throughout the dynamic trials. The marker locations are detailed in Chapter 3. To define a segment, both a proximal and distal joint must be identified. This definition uses either a landmark or marker as a lateral or medial location or a joint centre location and a corresponding joint radius. The definition of some segments required the calculation of virtual landmarks from the anatomical marker locations (detailed in Table E.1) which was performed within Visual3D. The origin of each segment's right-handed orthogonal LCS was at the proximal joint centre and the orientation is individual to each segment.

Table E.1. The definition of the virtual landmarks created to construct the 14 segment model.

Landmark	Definition
MidFrontHead	50% distance between RFHD and LFHD
MidBackHead	50% distance between RBHD and LBHD
MidRightHead	50% distance between RFHD and RBHD
MidClavC7	50% distance between CLAV and C7
MidSternT10	50% distance between STRN and T10
Torso_Y	50% distance between MidSternT10 and STRN
Shoulder Joint Centre (SJC)[†]	Point where the line between the AGH and PGH intersects with the perpendicular line projected from the ACR marker
Elbow Joint Centre (EJC)	50% distance between MELB and LELB
Adjusted_RGT	Translation of RGT in negative direction in x-axis by 50% marker diameter
Adjusted_LGT	Translation of LGT in positive direction x-axis by 50% marker diameter
Adjusted_R/LAGH	Translation of AGH in negative direction in y-axis by 50% marker diameter
Adjusted_R/LPGH	Translation of PGH in positive direction in y-axis by 50% marker diameter
Adjusted_RMELB	Translation of RMELB in positive direction in x-axis by 50% marker diameter
Adjusted_LMELB	Translation of LMELB in negative direction in x-axis by 50% marker diameter

[†] Definition presented by Chin et al. (2009).
Anatomical landmarks used in the definitions refer to those detailed in Table 4.2.

E.1. Head

The RFHD, LFHD, RBHD and LBHD markers were used to define the segment and to track the segment during the dynamic trials. The proximal end of the segment was defined with the MidFrontHead landmark as the joint centre and the distance between the MidFrontHead landmark and the RFHD marker as the joint radius. Similarly, the distal end of the segment was defined using the MidBackHead landmark as the joint centre, with the distance between the MidBackHead landmark and the RBHD marker as the joint radius. RightMidHead was identified as an additional lateral landmark in order to determine the orientation of the segment.

The line from the origin of the coordinate system to the MidRightHead landmark was defined as the positive x-axis of the LCS. The line from the distal to the proximal joint centre was identified as the positive y-axis and the cross-product of the two was the z-axis.

E.2. Upper trunk (termed 'Trunk' throughout the thesis)

The upper trunk segment is termed 'trunk' throughout the thesis and is the segment analysed in Chapter 7. The C7, T10, STRN and CLAV markers were used to define the upper trunk segment, and all but T10 tracked the segment during the dynamic trials. The proximal joint centre of the segment was identified as landmark MidClavC7, with the radius of the joint being defined as 50% distance between the right and left shoulder joint centre (SJC) landmarks. The distal joint centre was identified as the MidSternT10 landmark, with the radius being equal to 50% distance between RILC and LILC.

Landmark Torso_Y was identified as anterior to the LCS origin and the line between the two was the positive y-axis. The positive z-axis represented the line from the distal to the proximal joint centre. The x-axis was calculated as the cross-product of the two other axes, using the right-hand rule.

E.3. Lower trunk

This segment was used to determined the kickers' whole-body CM location, but its motion was not analysed in the thesis. The lower trunk segment was defined using the STRN, T10, RILC and LILC markers, and all but the STRN markers were also used to track the segment during dynamic trials. The proximal joint centre of the segment was identified as the location of the MidSternT10 landmark, with the joint radius defined as 50% distance between the RILC and LILC markers. The distal joint was defined using the RILC and LILC markers, with the RILC identified as the lateral joint marker and the LILC, the medial joint marker. The distal joint centre was identified as 50% the distance betwen the RILC and LILC markers.

The positive z-axis of the segment's LCS was the line from the distal to the proximal joint centre. The xz (frontal) plane was established between the MidSternT10 landmark and the RILC and LILC markers. The y-axis was calculated perpendicular to both the Z axis and the x-z plane. The x-axis was determined as the cross product of the two, using the right-hand rule.

E.4. Pelvis

The pelvis segment was defined using the RILC, LILC, RGT and LGT markers, and tracked using the RASIS, LASIS, RPSIS and LPSIS markers. The proximal joint of the segment was defined using the RILC and LILC markers, with the RILC identified as the lateral joint marker and the LILC the medial joint marker. The proximal joint centre was identified as 50% the distance betwen the RILC and LILC markers.The distal joint was defined using the RGT and LGT markers, with the RGT identified as the lateral joint marker and the LGT the medial marker.

The positive z-axis of the segment's LCS was the line from the distal to the proximal joint centre. The x-z (frontal) plane was established using a leastsquares fit to the four joint definition markers. The y-axis was calculated perpendicular to both the Z axis and the x-z plane. The x-axis was determined as the cross product of the two, using the right-hand rule.

E.5. Upper arm

The upper arm segment was defined using the ACR, AGH, PGH, LELB and MELB markers and tracked using a three-marker cluster. The proximal joint centre was identified as the location of the SJC landmark. The radius of the proximal joint was defined as 50% diameter of the humerus (calculated as the distance between the Adjusted_AGH and Adjusted_PGH landmarks). The distal joint was defined using the LELB marker as the lateral marker and the MELB as the medial marker. The joint centre was located at 50% distance between the LELB and MELB markers.

The positive z-axis of the segment’s LCS was the line from the distal to the proximal joint centre. The x-z (frontal) plane was established between the SJC landmark and the LELB and MELB markers. The y-axis was calculated perpendicular to both the Z axis and the xz plane. The x-axis was determined as the cross product of the two, using the right-hand rule.

E.6. Lower arm

The lower arm segment was defined using the LELB, MELB, LWRI and MWRI markers and tracked using a three-marker cluster. The proximal joint centre of the segment was defined as the EJC landmark and the radius as the distance between the EJC and the Adjusted_MELB marker. This landmark was used due to errors associated with the measurement of forearm rotations when MELB and LELB markers are used (Wu et al., 2005). The distal joint was defined using LWRI marker as the lateral marker and MWRI as the medial marker. The distal joint centre was located at 50% the distance between the MWRI and LWRI markers.

The positive z-axis of the segment’s LCS was the line from the distal to the proximal joint centre. The x-z (frontal) plane was established between the EJC landmark and the LWRI and MWRI markers. The y-axis was calculated perpendicular to both the Z axis and the x-z plane. The x-axis was determined as the cross product of the two, using the right-hand rule.

E.7. Upper leg

The upper leg segment was defined using the GT, LKNE and MKNE markers and tracked using a four-marker cluster. The proximal joint was defined using Adjusted_GT as the lateral marker and 25% distance between the Adjusted_RGT and Adjusted_LGT markers as the joint radius. The distal joint was defined using LKNE as the lateral marker and MKNE as the medial marker. The joint centre was located a distance of 50% between the MKNE and LKNE markers.

The positive z-axis of the segment's LCS was the line from the distal to the proximal joint centre. The x-z (frontal) plane was established between the Adjusted_GT and the LKNE and MKNE markers. The y-axis was calculated perpendicular to both the Z axis and the x-z plane. The x-axis was determined as the cross product of the two, using the right-hand rule.

E.8. Lower leg

The lower leg segment was defined using the LKNE, MKNE, LANK and MANK markers and tracked using a four-marker cluster. The proximal joint was defined using LKNE as a lateral marker and MKNE as a medial marker, with the joint centre located 50% between the two markers. The distal joint was defined using LANK as a lateral marker and MANK as a medial marker, with the joint centre located 50% between the two markers.

The positive z-axis of the segment's LCS was the line from the distal to the proximal joint centre. The x-z (frontal) plane was established using a leastsquares fit to the four joint definition markers. The y-axis was calculated perpendicular to both the Z axis and the x-z plane. The x-axis was determined as the cross product of the two, using the right-hand rule.

E.9. Foot

The foot segment was defined using the LANK, MANK, 5MTP and 1MTP markers. The proximal joint was defined with LANK as the lateral marker and MANK as the medial marker, with the joint centre located at 50% distance between the two markers. The distal joint was defined such that 5MTP was the lateral marker and 1MTP was the medial marker, with the joint centre at a distance of 50% between the two markers. The HEE, LANK, MIDFOOT and 5MTP markers were then used to track the segment during the dynamic trials.

The positive z-axis of the segment’s LCS was the line from the distal to the proximal joint centre. The x-z (frontal) plane was established using a leastsquares fit to the four joint definition markers. The y-axis was calculated perpendicular to both the z-axis and the x-z plane. The x-axis was determined as the cross product of the two, using the right-hand rule.

E.10. Ball

The ball segment was defined using the four MIDBALL markers (MIDBALL1, MIDBALL2, MIDBALL3, MIDBALL4). The proximal joint was defined with MIDBALL1 as the lateral marker and MIDBALL2 as the medial marker, with the joint centre located at a distance of 50% between the two markers. The distal joint was defined such that MIDBALL4 was the lateral marker and MIDBALL3 was the medial marker, with the joint centre at a distance of 50% between the two markers. The MIDBALL1, MIDBALL2, MIDBALL3, MIDBALL4 and TOPBALL1, TOPBALL2 markers were then used to track the segment during the dynamic trials.

The positive y-axis as the segment's LCS was the line from the distal to the proximal joint centre. The x-y (transverse) plane was established using a leastsquares fit to the four joint definition markers. The z-axis was calculated perpendicular to both the y-axis and the x-y plane. The x-axis was determined as the cross-product of the two, using the right-hand rule.

Appendix F: Descriptive statistics of the three groups of kickers

Table F.1. Descriptive statistics of the three groups and the magnitude-based inferences for the group comparisons.

	Group mean ± SD	Compared with wide-left kickers Effect size ± 90% CI	(% Negative | Trivial | Positive)	Compared with short kickers Effect size ± 90% CI	(% Negative | Trivial | Positive)
Age (years)					
Long	21 ± 3	-0.2 ± 0.8	(49 | 31 | 20)	-0.6 ± 1.1	(75 | 15 | 10)
Wide-left	22 ± 5			-0.3 ± 0.9	(58 | 26 | 16)
Short	23 ± 5				
Height (m)					
Long	1.82 ± 0.05	<0.1 ± 0.7	(29 | 36 | 35)	0.3 ± 1.2	(25 | 21 | 54)
Wide-left	1.82 ± 0.09			0.2 ± 0.9	(25 | 29 | 46)
Short	1.81 ± 0.03				
Leg length (m)					
Long	0.96 ± 0.03	0.1 ± 0.7	(21 | 35 | 44)	0.6 ± 1.2	(13 | 16 | 71)
Wide-left	0.95 ± 0.06			0.3 ± 0.9	(18 | 26 | 56)
Short	0.94 ± 0.11				
Mass (kg)					
Long	87.0 ± 6.8*	-0.2 ± 0.7	(51 | 33 | 16)	1.3 ± 1.0	(1 | 4 | 95)
Wide-left	88.9 ± 12.7*			1.0 ± 0.7	(1 | 3 | 96)
Short	77.3 ± 5.9				

* Denotes a substantial effect compared with the short kickers [†] Denotes a substantial effect compared with the wide-left kickers