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Investigating the Influence of Ball Orientation on the Foot–Ball Interaction in Rugby Union Place Kicking

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Abstract

Rugby Union place kicking contributes 45% of all points scored and 5.7% of matches are decided by a single kick (Quarrie and Hopkins, 2015). Biomechanical investigations of the place kick have often focused on the movements of the kicker without consideration of how the ball is orientated on the tee and whether that might interact with the kicker's technique. Therefore, the overall aim of this thesis was to investigate how ball orientation interacts with kick technique and performance to inform the ball setup preferences of kickers. An initial study identified the ball orientation preferences of international kickers at the 2019 Rugby World Cup and assessed kick performance when kicks were categorised by ball orientation. Binomial logistic regression analysis, which also accounted for additional situational factors, revealed that kicks taken with a slanted orientation (approximately 45°) had a greater predicted kick success (90.0%) than with a forward orientation (approximately 15°; 84.4%) and a horizontal orientation (approximately 75°; 86.8%). The second study experimentally altered ball orientation to investigate the effects on kickers' technique, impact characteristics and resulting kick performance. There were few clear effects of ball orientation on the kicking foot swing plane characteristics or the kicking leg shank and foot segment orientations at initial foot–ball impact, suggesting that each kicker maintained relatively consistent 'end-point' characteristics of technique. However, impact location on the ball generally varied significantly ($p < 0.05$) with ball orientation and when kickers struck the ball closer to the belly, impact efficiency was typically improved. This thesis provides information which could help to inform the ball orientation preferences of place kickers and coaches. There does not appear to be one ball orientation that results in the best performance for all kickers, but exploration of a ball orientation which encourages impact nearer the belly may improve impact efficiency.

Declarations and Statements

DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed ..[redacted]...................................... (candidate)

Date ......21/03/2021..

STATEMENT 1

This thesis is the result of my own investigations, except where otherwise stated.
Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

Signed ..[redacted].. (candidate)

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STATEMENT 2

I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

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Statements on Candidate Contributions

Chapter Three

All data collection and analysis in Chapter 3 was conducted by the candidate and are original.

Chapter Four

The raw data presented in Chapter 4 were collected as part of an earlier project at which the candidate was not involved. The candidate conducted all analysis of the data presented in this chapter.

Signed ....[redacted].. (candidate)

Date ....21/03/2021..

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Conference Papers

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CHAPTER 1: INTRODUCTION

1.1 Context

Place kicking can have a large impact on Rugby Union matches. From 2002 to 2011, 6769 place kicks were attempted during 582 international matches and these kicks resulted in 45% of all points scored (Quarrie & Hopkins, 2015). A single kick can affect the outcome of a match: during this period, 5.7% of games were decided by a single place kick, and if the kicking success percentages were swapped between competing teams then the match result would have reversed on 14% of occasions.

Although the importance of place kicking success is clearly illustrated, there are many different ways in which the place kicking movement is executed. Several aspects of the place kick are clearly subject to personal preference, such as the approach length (Padulo et al., 2013) and the approach angle (Cockcroft & Van Den Heever, 2016). The movements employed by kickers from the start of their approach towards the ball to the end of the follow through (hereafter place kick ‘technique’) have been relatively widely investigated, generally with a focus placed on the approach phase (Figure 1.1). These include biomechanical explorations of joint kinetics (Atack et al., 2019a), contributions of the non-kicking-side arm (Bezodis et al., 2007), kicking foot swing planes (Bezodis et al., 2019), and lower limb kinematics (Sinclair et al., 2014, 2017), including the variability of the movements (Ford & Sayers, 2015).

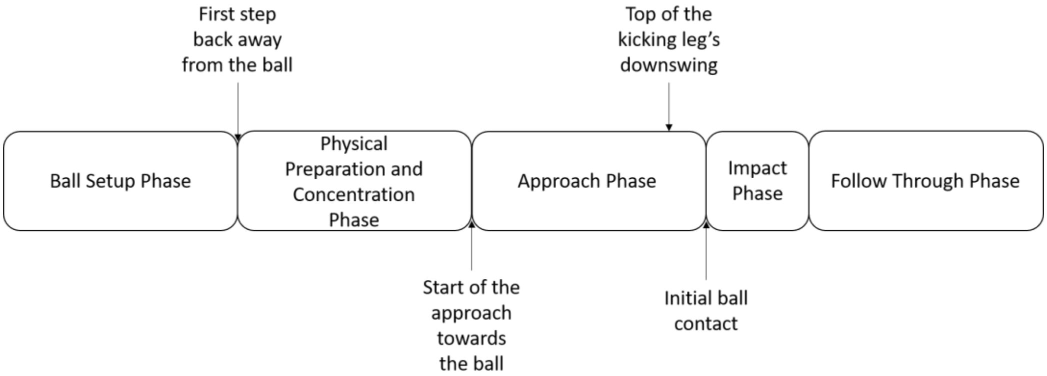

Figure 1.1. The five phases of a place kick as defined in this thesis and some of the key events during a kick. Physical preparation and concentration phase adapted from Jackson and Baker (2001); approach phase adapted from Atack (2016); and impact and follow through phases consistent with Atack (2016). Widths of the phases are not scaled to their respective durations, but the impact phase is illustrated as narrower due to its considerably shorter duration than the other phases.

However, differences between kickers are visible even prior to the start of the approach phase as kickers choose to set up the ball in different ways. The kicking tee used and orientation at which the ball is placed on the tee often differs between kickers and is generally reported to be a matter of personal preference (Bezodis & Winter, 2014). In the only study to have quantified the ball orientations used by Rugby Union place kickers it was identified that the kickers used orientations ranging from 2° (long axis of the ball nearly vertical) to 56° (top of the ball leaning towards the target; Bezodis et al., 2018). Given the non-uniform, prolate spheroid shape of the ball used in Rugby Union it is possible that altering the ball orientation may lead to different outcomes for a given kick technique, or could lead to a kicker adjusting their technique in order to achieve the desired impact locations on the foot and the ball. The combination of the kicker’s technique and the position and orientation of the ball would likely interact and have consequences for the impact characteristics, and as a result, for the ball flight characteristics and outcome of the kick.

The effects of the orientation of prolate spheroid shaped balls has been investigated during drop tests (Holmes, 2008) and through the use of a mechanical kicking limb (Peacock & Ball, 2017). Holmes (2008) observed that impacts involving the ends of a Rugby Union ball’s long axis (hereafter ‘point’ of the ball) resulted in a ~15% reduction in the coefficient of restitution in comparison to impacts halfway up the surface of the ball’s panels (hereafter ‘belly’ of the ball). This finding was consistent across all prolate spheroid balls from the codes of Rugby Union, Rugby League, American Football, and Australian Football (Holmes, 2008). In contrast, the employment of a mechanical kicking limb with fixed but more ecologically valid kinematics led to a greater ball velocity (24 m/s) when the impact occurred on the point of the ball, rather than when the impact occurred on the belly of the ball (20 m/s). Whilst these contradicting findings may be of some relevance to Rugby Union place kicking, neither use nor consider the influence of human kickers who are inherently variable and possess numerous degrees of freedom with which to execute a movement. Initial ball flight velocity is also not the sole variable that indicates kick success; sufficient launch characteristics, which determine kick accuracy, are also required to ensure that the ball passes above a crossbar located 3.0 m above the ground and between two upright posts set 5.6 m apart (World Rugby Laws, 2020).

To date, there has been very little focus on the impact phase (Figure 1.1) of Rugby Union place kicking, likely due to its short duration and therefore the difficulties associated with collecting sufficient amounts of accurate data. The impact phase is the phase in which the preceding motion of the kicker, which has been relatively well investigated, ultimately affects the subsequent flight characteristics of the ball. Targeted research is therefore required to investigate this phase of the place kick and provide a greater understanding of the relative merits of different ball setups for practitioners and players. Particular attention should be given to the interactions between different ball orientations, the kicker's technique, and resulting kick performance (defined as the flight characteristics of the ball, and where applicable also the kick distance, accuracy, or a combination of these to determine kick outcome).

1.2 Aim

This thesis aims to *investigate the influence of ball orientation on Rugby Union place kicking technique, impact efficiency, and resulting kick performance, in order to further the understanding of why kickers use different ball orientations*. Quantification of the effects of altering ball orientation through descriptive performance analysis and experimental analysis of the interaction between the foot and the ball will help to understand whether one ball orientation leads to the greatest kick performance regardless of the kicker, or various factors interact to influence the ball orientation preferences of kickers.

1.3 Research Questions

To adequately address the aim of this thesis, research questions were developed to ensure that ball orientation effects were sufficiently explored and that relationships and interactions with kick technique and performance were considered.

1.3.1 Research Question 1

The first research question explored the different ball orientations used by elite Rugby Union place kickers and any potential associations these may have had with kick performance.

What are the ball setup preferences of elite international Rugby Union players, and how do these associate with kick performance?

1.3.2 Research Question 2

The second research question investigated any potential changes in kick technique when the orientation of the ball is altered.

How do individuals change their kick technique when different ball orientations are used?

1.3.3 Research Question 3

The third research question evaluated the effects of ball orientation on kick outcome by assessing impact efficiency measures and using the ball flight characteristics to model ball flight and assess kick performance.

How does ball orientation affect impact efficiency and resulting ball flight characteristics and kick performance?

1.4 Thesis Structure

This thesis will be divided into five chapters which will present context to the research area and provide a rationale for the research, review previous literature, analyse place kicks taken during the 2019 Rugby World Cup, investigate the alteration of ball orientation during place kicks, and then discuss all of these in the context of the thesis aim and implications for applied practice.

1.4.1 CHAPTER 1: INTRODUCTION

The introduction will provide an overview of the importance of place kicking within Rugby Union and a rationale for why the interaction between the foot and the ball is an important area for consideration. The thesis aim will be stated, and subsequent research questions listed. Additionally, the structure of the thesis will be summarised.

1.4.2 CHAPTER 2: LITERATURE REVIEW

The start of this chapter will introduce and outline previous kicking research. Biomechanical research surrounding Rugby Union place kicking will then be reviewed in the order that the phases progress through the movement (Figure 1.1) and, where required, kicking research from other Football codes will be discussed. Relevant data processing methods will also be reviewed.

1.4.3 CHAPTER 3: THE BALL SETUPS USED BY KICKERS AT THE 2019 RUGBY WORLD CUP AND THEIR ASSOCIATIONS WITH KICK SUCCESS

This chapter will investigate the different ball setups, primarily focussing on the ball orientations, used by elite international place kickers at the 2019 Rugby World Cup. It will quantify the success of the place kicks and explore potential associations between kick performance and the ball orientations used whilst accounting for other situational factors.

1.4.4 CHAPTER 4: INVESTIGATION INTO THE EFFECTS OF CHANGING BALL ORIENTATION ON PLACE KICK TECHNIQUE AND PERFORMANCE.

This chapter will be an experimental study in which the orientation of the ball will be systematically manipulated. The effects of ball orientation on the place kick technique of eight kickers, the impact efficiency and the resulting performance will be assessed using empirical methods.

1.4.5 CHAPTER 5: GENERAL DISCUSSION

In the final chapter, the findings from Chapters Three and Four will be synthesised in the context of the overriding aim of the thesis and each research question will be addressed. The adopted protocols and methodological decisions will be critiqued, and the practical applications for the future practice of place kicking will be discussed.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview of Previous Research

The importance of place kicking in Rugby Union (Quarrie & Hopkins, 2015), along with the need for further investigations into the foot–ball interaction, was briefly highlighted in Chapter One. Previous studies that have researched kicking movement biomechanics have been conducted in multiple sports and date back to the mid-1900s (American Football – Marshall, 1958). Whilst Rugby Union place kicking technique during the phases surrounding the impact phase have been of particular interest (Atack et al., 2019a; Baktash et al., 2009; Bezodis et al., 2007, 2014, 2018, 2019; Bezodis & Winter, 2014; Cockcroft & Van Den Heever, 2016; Ford & Sayers, 2015; Green et al., 2016; Padulo et al., 2013; Sinclair et al., 2014, 2016, 2017; Zhang et al., 2012), the impact phase and foot–ball interaction has generally not been considered. However, given the non-uniform, prolate spheroid shape of the ball used, and therefore the ability for the ball to be placed at varying orientations on the kicking tee (Figure 2.1), it is possible that the ball orientation used could interact with a kicker's technique and the resulting kick performance.

The impact phase has been researched to a greater extent during kicking in other sports. There are many investigations surrounding the foot–ball interaction in Soccer (Bull Andersen et al., 1999, 2008; Ishii & Maruyama, 2007; Nunome et al., 2006, 2013; Sakamoto et al., 2010; Shinkai et al., 2006, 2007, 2009; Tsaousidis & Zatsiorsky, 1996) and whilst these are partly relevant due to similarities in the general movement patterns between Soccer and Rugby Union, the use of a uniform, spherical ball and no kicking tee in Soccer means that many of the findings may have limited application to Rugby Union. Potentially more relevant investigations into the impact dynamics of a prolate spheroid ball have been carried out in Australian Football (Peacock et al., 2017; Peacock & Ball, 2017, 2018a, 2018b, 2019a, 2019b) and Rugby League (Ball, 2010; Ball et al., 2010, 2013a, 2013b). The balls used in these codes are similar in shape to that used within Rugby Union and therefore impact characteristics identified in these studies may also partly apply to Rugby Union. However, slight differences in the size, shape, structure and materials of the balls do exist. As such, exploration into the foot–ball interaction using a Rugby Union ball placed at varying ball orientations is necessary.

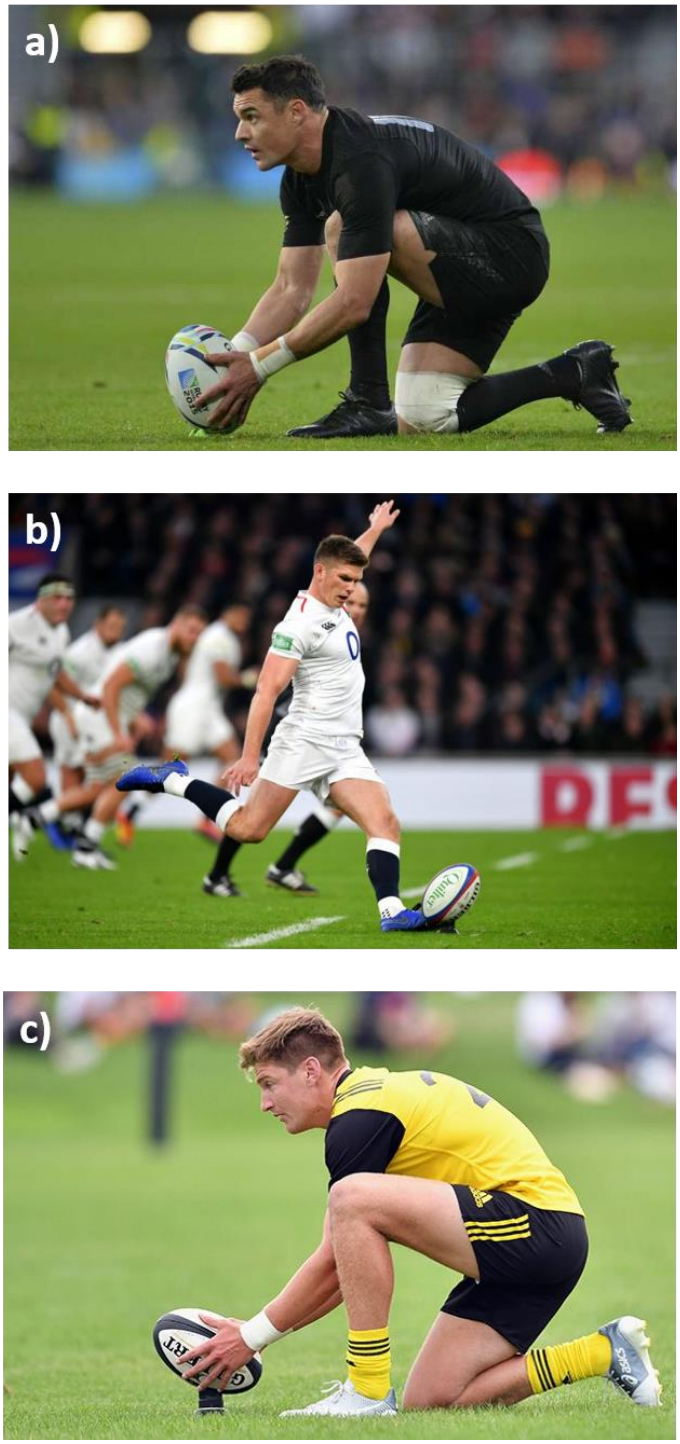

Figure 2.1. Images of three international Rugby Union place kickers depicting a range of different ball orientations. a) Ball setup with a more vertical orientation; b) ball setup with a slanted orientation; c) ball setup with a more horizontal orientation.

This chapter will critically review the previous research that has been conducted surrounding the biomechanics of kicking in various sports, but in particular the place kick in Rugby Union. It will discuss place kicking in Rugby Union by progressing through each of the phases in the order in which the movement is executed (i.e. the ball setup, physical preparation and concentration, the approach, the impact, and the follow through; Figure 1.1). Where there is a lack of available evidence in the Rugby Union literature, particularly around the impact phase, kicking during other sports (such as instep kicking in Soccer and punt kicking in Australian Football) will be discussed.

2.2 The Ball Setup Phase

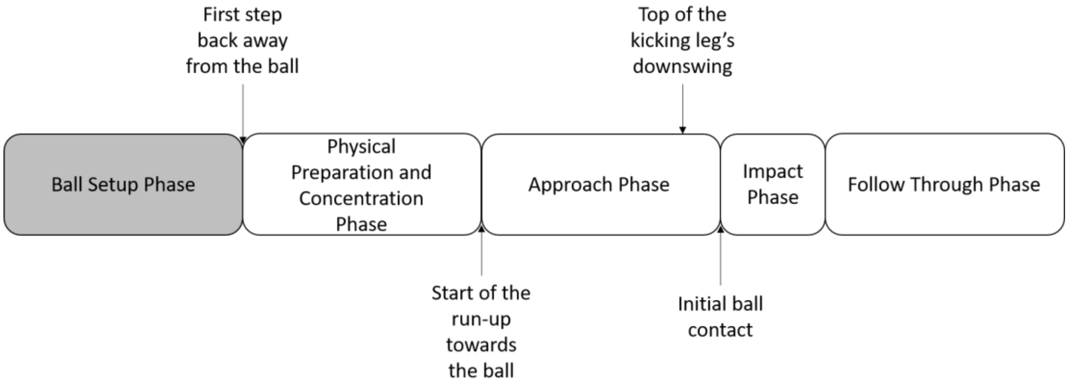

Figure 2.2. The phases of a place kick (i.e. Figure 1.1) with the ball setup phase highlighted.

The first procedure involved during place kicking is the placement of the ball. The ball setup, which comprises the kicking tee and ball orientation on the tee, has the capability to allow for the use of different variations in each component and therefore combinations of the two. Tees can be manufactured to various heights and range from being lower-set (e.g. Figure 2.1a) to higher-set (e.g. Figure 2.1b and 2.1c), with no current laws or regulations surrounding their height or shape (World Rugby Laws, 2020). Kicking tees may be designed with the intention of a specific ball orientation to be used but are not limited to such an orientation. The long axis of the ball can be placed with any degree of angular displacement about the global axes as desired by the kicker providing it sits on the tee. This notion has been previously identified by a professional kicking coach who stated that the ball setup is largely individual since kickers typically use a setup of their personal preference (Bezodis & Winter, 2014). The coach also stated, "*there's an advance for people leaning the ball slightly to open a sweet spot...some like [to kick] on the point...others [prefer to position the ball] upright*" (Bezodis & Winter, 2014). This suggests that a range of ball orientations are likely used by place kickers on the premise that personal preference is the underlying reasoning. Despite the possibility of intra- and inter-individual variation, there has been little research into the distinct ball setup styles used by kickers and, in particular, the ball orientations used in place kicking.

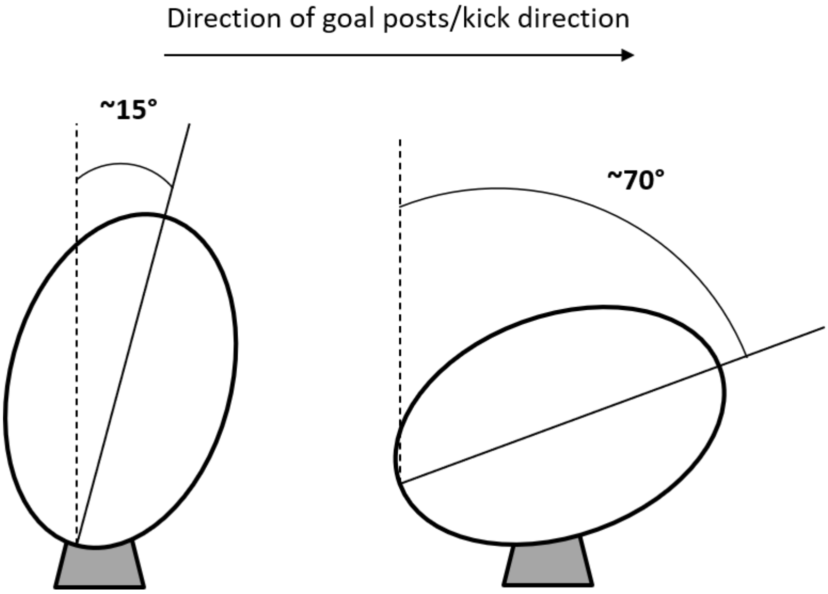

Figure 2.3. Examples of the ball orientation convention used throughout this thesis. In any studies that did not use this convention, the angles that were reported have been changed to match this convention. Zero degrees represents the long axis of the ball being orientated vertically and a positive value indicates the top of the ball leaning towards the goal posts.

To date only one study has quantified the ball orientation used by place kickers in Rugby Union. Bezodis et al. (2018) analysed the place kicking techniques of 14 male place kickers, all of whom were Under 20 age-grade international players and contracted to a professional Rugby Union club. A range of 2° to 56° was identified across the group of kickers, based on the convention that 0° represented the long axis of the ball being orientated vertically and a positive value indicated the top of the ball leaning towards the goal posts (see Figure 2.3 for illustration of this convention). Upon further analysis it was found that five of the kickers placed the ball with an orientation between 53° and 56° and eight placed the ball between 2° and 26° (leaning the ball slightly forward), with the remaining participant using an intermediate angle of 34°. Whilst the study of Bezodis et al. (2018) has strengths that kinematics were recorded based on the suggestions from the professional coach’s interview and ball orientation was quantitatively measured, performance outcomes were only briefly examined as a group mean and the potential associations between ball orientation and resulting ball flight characteristics were not discussed. Although this was not the main focus of the study, the potential associations between ball orientation and the proceeding kick technique and performance remain unknown.

The 54° range in ball orientation used by 14 Rugby Union place kickers (Bezodis et al., 2018) is larger than that used by four kickers during place kicking in Rugby League (Ball, 2010; Ball et al., 2013b). Using the same angle convention, four place kickers, all of whom were contracted to an Australian National Rugby League team, were reported to tilt the top of the ball forward towards the posts, resulting in a mean ± *SD* ball orientation of 54 ± 4° (Ball, 2010). Similarly, values in the range of 50-60° were identified in another group of four elite Rugby League place kickers (Ball et al., 2013b) and therefore it could be implied that there is less variation in the ball orientations used in Rugby League place kicking (10°). A consideration to be made is the possibility that all the kickers included in the trials (Ball et al., 2013b; Ball, 2010) were coached by the same coach. This may result in the observed small range since the coach might prefer to teach the use of a certain ball orientation, of which all the kickers continued to employ. Nonetheless, both studies had relatively small sample sizes and may have been biased by coaches' input, so these data may not be representative of the wider population of kickers in Rugby codes (defined as both the codes of Rugby Union and Rugby League). Therefore, further analyses identifying the ball orientations used by a greater number of highly skilled place kickers could prove valuable in directing future research.

Although the ball orientations used by place kickers have previously been quantified (Ball et al., 2013b; Ball, 2010; Bezodis et al., 2018), the kickers participating in biomechanical studies have generally used their chosen setup and therefore this is a factor not controlled when investigating kick performance. This is likely due to the fact that it allows for the kicker to use a ball setup they are accustomed to and have practised with extensively. One study that did control ball setup for human kickers was conducted by Padulo et al. (2013) when looking into the effects of different kick approach distances. Six kickers who were playing at national level partook in the study, all of whom took 16 kicks with the ball setup kept constant (ball placed vertically, 0°, on the same tee) for all trials. However, this may have had negative implications on their performance. Although longer approach distances led to greater ball velocities, the forced and predetermined approach distances and setup might have been unfamiliar to the kickers, and as such, they may have had to employ lower body kinematics that are not the norm for their individual preferences. This may explain the observed variations in kick success percentage, but these acute changes in the approach distances may mean the findings of Padulo et al. (2013) possess limited ecological validity and should be considered with caution.

Controlling the ball setup may eliminate any effects of ball orientation since the ball used in both Rugby codes is a prolate spheroid shape. Thus, the use of various ball orientations could potentially influence the kicker's technique and impact locations on the foot and ball. It is possible that a kicker may alter the orientations and locations of their kicking limb segments relative to the ball so to impact the ball in their desired location – which may change as a consequence of altering the ball orientation. For example, a more horizontal ball orientation of approximately 80° may lead to the kicker aiming to impact the ball on the point, whereas a more upright orientation of approximately 10° may lead to a desired impact location being more towards the belly of the ball. This in turn could lead to possible implications for the foot–ball interaction (specifically ball deformation and impact efficiency; see section 2.4), and therefore the initial ball flight characteristics which ultimately determine performance.

The effects of changing the orientation of a prolate spheroid ball has been investigated in Australian Rules Football through the use of a mechanical kicking limb (Peacock & Ball, 2017). The mechanical leg removed any human variation or error and enabled systematic exploration of precise changes in ball orientation. This was achieved by controlling and keeping other variables constant, but also realistic to the true motion of a kicker's lower leg during a punt kick (a further appraisal of this methodological approach will be discussed in section 2.4). Over the span of 28 trials ball orientation was adjusted to values in the range of -11.6° and 85.3°, leading to varying impact locations on the ball due to the consistent nature of the swing path and mechanical kinematics of the leg. Foot velocity and impact location on the foot were constant throughout, enhancing analysis into the effects of ball orientation on the recorded dependent variables. For a given foot velocity of 16.7 m/s, the orientation of a stationary Australian Football ball was found to influence ball velocity. Ball velocity increased as ball orientation increased until a maximum ball velocity of 24.4 m/s was achieved when the ball was orientated at approximately 43°, before velocity began to decrease at greater orientations. A further important finding was that ball velocity was greater when impact occurred on the point (ball velocity of 24 m/s when ball orientation was 65°), compared to impact being on the belly of the ball (ball velocity of 20 m/s when ball orientation was -25°). Although the non-uniform shape of an Australian Football ball is similar to that of a Rugby Union ball, and so it is possible that similar outcomes may apply, they cannot be directly transferred to Rugby Union place kicking due to the different materials, constructions, and slight differences in shape between the two balls.

The influence of ball orientation on coefficient of restitution (CoR) has been investigated by Michelini et al. (2019) using the same mechanical kicking limb. The results obtained by Michelini et al. (2019) are more relevant to this thesis than the findings of Peacock and Ball (2017) because a Rugby Union ball was used in the former. Michelini et al. (2019) used the mechanical limb to perform a total of 22 kicks; one kick with each of the possible combinations of 11 different ball orientations (ranging from -17° to 59°) and two foot velocity conditions (high = 17.7 ± 0.4 m/s; moderate = 12.3 ± 1.2 m/s) were tested. Although the two foot velocity conditions were not completely consistent (based on the reported standard deviations, likely due to some inherent variability in the machine), it was identified that irrespective of the foot velocity condition, the coefficient of restitution varied in a non-linear fashion as ball orientation was altered. When the impacts occurred on the point of the ball (ball orientation = approximately 59°) coefficients of restitution of 0.55 and 0.47 were achieved for the high and moderate foot velocities, respectively. Rotating the ball such that the impacts occurred between the point and the belly of the ball resulted in a drop in values to 0.41 (high foot velocity) and 0.39 (moderate foot velocity). The largest values of coefficient of restitution were then achieved for the high (0.65) and moderate (0.77) foot velocities when the impact occurred near the belly of the ball (ball orientation = approximately -8°). This parabolic relationship between ball orientation and coefficient of restitution suggests that changing the orientation of the ball does result in changes in the impact efficiency in a non-uniform manner. However, caution should be applied when making conclusions from this data since there was some variation in the employed foot velocities and each condition was only tested with a single kick.

Further use of the mechanical kicking limb (Ball & Peacock, 2020) and drop tests (Holmes, 2008) have produced similar results to that observed by Michelini et al. (2019) when comparing the effects of impact location on impact efficiency and characteristics (impact characteristics are discussed further in section 2.4). When comparing impacts on the point (‘point’) of a Rugby Union ball against impacts approximately a third (‘third’) of the way up a ball (representing two of the common impact locations in Rugby codes, as determined by the authors), Ball and Peacock (2020) observed that foot–ball velocity ratio (calculated as v_b/u_f; where v_b = resultant velocity of the ball at the end of impact; u_f = resultant velocity of the foot at the start of impact; third = 1.25, point = 1.32), contact time (third = 10.9 ms, point = 11.8 ms), contact distance (third = 0.15 m, point = 0.17 m), and work done on the ball (third = 132 J, point = 151 J) were all greater with impacts involving the point of the ball. When drop tests have been performed using prolate spheroid balls it has been found that impacts on the balls’ points resulted in significant drops in coefficient of restitution and increases in contact time, compared to when the impacts occurred on the bellies of the balls (Holmes, 2008). Although methods have varied between studies, these results of Michelini et al. (2019), Ball and Peacock (2020), and Holmes (2008) indicate that impacting near the belly of the ball appears to result in the greatest impact efficiency measures, followed by impacting near the point of the ball, and finally impacting between the point and the belly of the ball results in the smallest measures of impact efficiency.

Peacock and Ball (2018b) have additionally included effective mass as a measure of impact efficiency, along with coefficient of restitution and foot–ball velocity ratio. Effective mass is calculated using the same input velocity data as coefficient of restitution and foot–ball velocity ratio thus it is a similar way of describing the impact efficiency, but the mass of the ball is also required in the equation. Therefore, it can be deemed that both coefficient of restitution and foot–ball velocity ratio are more relevant measures of impact efficiency since they are both direct ratios comparing the velocities of the colliding bodies before and after impact. The only difference is that coefficient of restitution also accounts for the change in foot velocity during the impact phase. For this reason, and the fact that the majority of previous studies have reported one or a combination of these two variables, the current thesis will only consider coefficient of restitution and foot–ball velocity ratio and will define these as impact efficiency measures.

The use of the mechanical kicking limb or drop tests enable controlled and systematic investigations, however it must be considered that the human element is overlooked. This is not only because the effects of soft tissue are ignored but it is possible that variations in the ball orientation, and so the task constraint, may lead to a kicker altering their technique, as is consistent with the constraints-led approach developed by Newell (1986). Different techniques could potentially interact differently with changes in ball orientation. This includes changes in the impact location on the foot and ball and therefore possible implications for the impact characteristics (discussed further in section 2.4), and as such, for the magnitude and direction of ball velocity.

It is clear that ball orientation and impact location influence ball velocity and impact characteristics such as coefficient of restitution (Ball & Peacock, 2020; Holmes, 2008; Michelini et al., 2019; Peacock & Ball, 2017), but that the effects are not always consistent. However, it is also expected that the prolate spheroid shape of a Rugby Union ball will mean that ball orientation and impact location will influence ball spin. In Australian Football, ball flight elevation angle and spin rate were found to be influenced by ball orientation and these were best represented by partial sinusoidal curves (Peacock & Ball, 2017). They followed a similar trend to the previously mentioned ball velocity data, although elevation angle and pitch spin (spin about the global x-axis when the ball's horizontal axis is perpendicular to the direction of the kick) rate were found to be largest at a ball orientation of approximately 25°. Azimuth angle of the initial ball flight was also measured but the small magnitude of gradient of the linear line fitted to the data suggested a low dependence on ball orientation. Many Rugby Union place kicking studies have simply used ball velocity as the primary performance measure (Baktash et al., 2009; Linthorne & Stokes, 2014; Padulo et al., 2013; Sinclair et al., 2014, 2016), and whilst azimuth angle does give some measurement with regards to accuracy, ball velocity, spin rate, spin direction, and ball flight trajectory all combine to determine the overall success of a kick (Atack et al., 2019b). The influence of ball orientation on kick accuracy was therefore not fully considered by Peacock and Ball (2017), partly due to the lack of ball spin measurements in more than one axis of rotation. Only pitch spin was recorded but it has previously been identified in a wind tunnel experiment that spin about the longitudinal axis of the ball (roll spin) causes the ball flight path to deviate laterally (Seo et al., 2006). Subsequently, future research should aim to measure ball flight characteristics in three dimensions to provide a more in-depth understanding of the effects of ball orientation on place kick accuracy, and therefore on the more complete performance effects.

Ball setup phase summary

No clear conclusions can be made from the previous research that has investigated the influence of ball orientation on impact efficiency or flight characteristics when kicking a prolate spheroid ball since it appears that the findings are equivocal. Kicking on the point of the ball has been observed to be preferable for achieving larger ball velocities in one study (Peacock & Ball, 2017). However, there are also data relating to the coefficient of restitution of impacts and varying ball orientations which appear to contradict this (Holmes, 2008; Michelini et al., 2019). These findings, along with the shortage of kick accuracy measurements and fact that a range of ball orientations have been identified as being used by Rugby Union place kickers, demonstrate the need for further investigations to better understand the effects of different ball orientations. Research should aim to better understand the underlying reasons that may influence a kicker's choice in ball orientation and whether it is that case that; one specific ball orientation is always preferential regardless of the kicker, different ball orientations are better suited to individual kickers based on their kick technique, or there are no overriding effects and ball orientation is purely a matter of personal preference.

2.3 The Physical Preparation and Concentration Phase

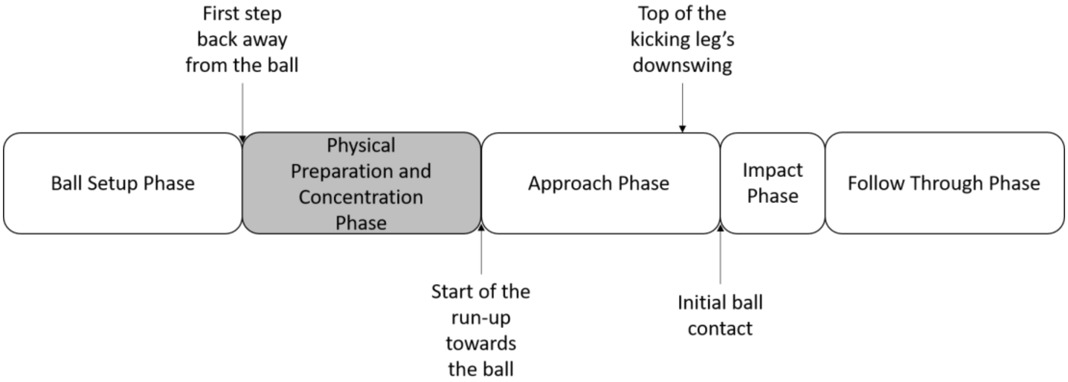

Figure 2.4. The phases of a place kick (i.e. Figure 1.1) with the physical preparation and concentration phase highlighted.

The physical preparation and concentration phase begins once the kicker has finished setting up the ball on the tee and ends when the kicker begins their approach towards the ball. During this phase, kickers may take a chosen number of steps away from the ball. In Rugby League place kicking the number of steps taken by four elite kickers have been observed to vary between three steps back and two across, to five steps back and four across (Ball et al., 2013b). The time taken to perform this part of the phase has been defined as the physical preparation time (Jackson & Baker, 2001). Following this, the concentration time is the period when the kicker is stationary between the end of the physical preparation time and the initiation of the approach to the ball (Jackson & Baker, 2001). The physical preparation and concentration time measures during this phase are known to vary on both intra-individual and inter-individual levels, and generally the time taken for each period increases as kick difficulty increases (Jackson, 2003; Jackson & Baker, 2001). Padulo et al. (2013) investigated the effects of varying the number of steps away from the ball on ball flight velocity and kick success (discussed further in the next section). However, the steps taken away from the ball during the physical preparation and concentration phase are not as important to consider as the approach towards the ball because, whilst the latter is essentially determined by the former, it is the approach to the ball that generates whole body approach velocity. This in turn increases the momentum and kinetic energy that can be transferred to the ball during the impact phase, when the subsequent ball flight characteristics are imparted onto the ball. Therefore, although the physical preparation and concentration phase is an important part of the place kicking action, particularly from a psychological perspective (Jackson, 2003; Jackson & Baker, 2001), the movements undertaken during this phase are beyond the scope of this thesis.

2.4 The Approach Phase

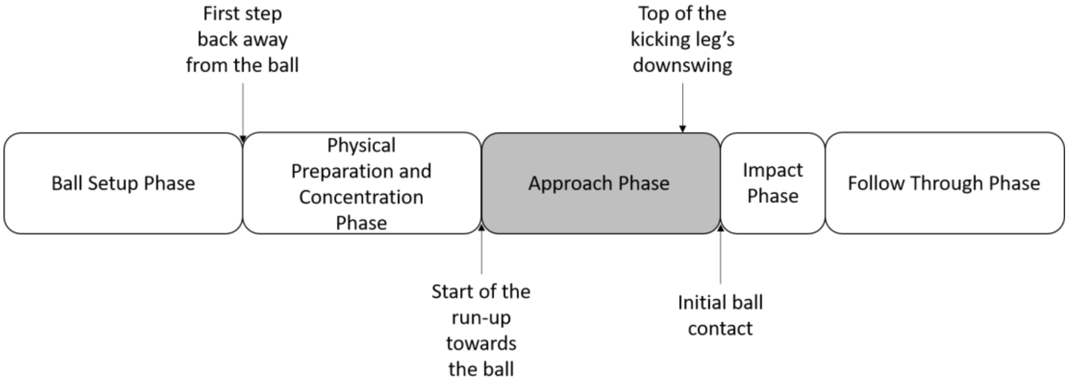

Figure 2.5. The phases of a place kick (i.e. Figure 1.1) with the approach phase highlighted.

Most of the previous biomechanical research into Rugby Union place kicking has investigated the approach phase, with a focus on movement kinematics. These studies include analyses of kinematics of the whole body (Atack et al., 2019; Bezodis et al., 2007, 2018; Cockcroft & Van Den Heever, 2016; Green et al., 2016; Padulo et al., 2013) and many that have solely analysed the kicking leg motion from the moment of final support foot ground contact to initial ball contact (Baktash et al., 2009; Bezodis et al., 2014; Ford & Sayers, 2015; Minnaar & van den Heever, 2015; Sinclair et al., 2014, 2017; Zhang et al., 2012). The reasoning behind more focused analyses of the kicking leg is that this is the limb that ultimately impacts the ball. However, these analyses of the impact phase stop at the instant of initial ball contact and therefore ignore the foot–ball interaction during the impact phase – the phase over which energy and flight characteristics are transferred to the ball. Whilst the kick approach is not the focal point of this thesis, the approach phase is important because of its overarching purpose to contribute to the resultant velocity of the kicking foot and its position and orientation relative to the ball at the start of the impact phase. This in turn will determine the characteristics of the foot at the start of the impact phase which combine with the position and orientation of the ball to ultimately determine the flight characteristics of the ball.

Being the first part of the approach phase (Figure 2.5) and accounting for the greatest amount of time during the phase, whole-body translation towards the ball has been an area of consideration. Padulo et al. (2013) explored the use of four different approach distances and the resulting effects on place kick characteristics. It was found that increasing the approach distance led to greater ball velocities (mean ± *SD* = 23.7 ± 2.3 m/s for P1, one step back and one to the side; 25.4 ± 2.4 m/s for P4, four steps back and one to the side) but also reduced kick success (P1 = 71.5%; P4 = 67.5%). Although there was an increase in ball velocity when the approach was lengthened, this was not significant between the approach conditions. Lower body kinematics were also analysed but this was limited to angular kinematics of the kicking knee, and it was found that the different approaches had no effect on this variable. The use of these predetermined approach distances may have had negative implications on the kickers' kick performance since the distances may have been unfamiliar to the kicker. As such, this may have forced the kickers to adopt unpractised lower body kinematics (as discussed in section 2.2). Additionally, changing the approach distance in this manner also altered the angle of approach to the ball – a factor which could have further influenced the kickers' performance and which cannot be separated from the approach distance effects in this study. Despite this, some of the experimental approach distances used are likely to be ecologically valid since similar kick approaches have been identified within Rugby League place kicking (Ball et al., 2013b).

Although a variety of place kick approach distances have been observed and used experimentally with greater approach distances linked to increased whole body approach velocity (Ball et al., 2013b), there is likely a need for kickers to ultimately maintain a consistent final support foot placement. This is because support foot placement may in turn enable a more consistent delivery of the kicking foot to the ball due to the overall positioning of the whole body and lower limbs in space, and as such greater consistency in the foot–ball interaction when determining the ball flight characteristics. Cockcroft and van den Heever (2016) examined the variability of the final two steps leading into ball contact. Average distances and angles of the final two approach steps and their associations with support foot placement relative to the kicking tee were reported, along with the inter- and intra-participant variability (Cockcroft & van den Heever, 2016). Within a group of 15 professional Rugby Union place kickers, the variability in foot distance to the tee and step approach angle decreased with each subsequent step towards ball contact. This was the case both within and between kickers. The implications of a reduced variation in the latter steps of the approach are that each kicker aimed to ultimately place the support foot a relatively consistent distance from the tee at the last ground contact for each trial. Support foot contact distances to the tee were found to be 0.330 ± 0.031 m in the medio-lateral direction and -0.031 ± 0.074 m in the antero-posterior direction (whole group mean ± *SD*). Similar values (medio-lateral = 0.32 ± 0.04 m and antero-posterior = 0.09 ± 0.07 m) have also been reported by Bezodis et al. (2018). The findings from both studies show that there is nearly twice the between-kicker variation (based on the reported standard deviations) in the antero-posterior direction than the medio-lateral direction. Ball orientation may be an underlying factor that influenced the differences in support foot placement variation. Kickers may display differences in the position of their support foot in the antero-posterior direction due to the implementation of different ball orientations, but changing the orientation of the ball about the global x-axis would not result in changes to the position of the middle of the ball in the medio-lateral direction. Thus, if kickers aimed to kick through the middle of the ball then the use of different ball orientations may result in smaller differences in support foot placement in the medio-lateral direction. Cockcroft and van den Heever (2016) additionally discovered that group standard deviation was reduced with each subsequent step leading into ball contact. This illustrates that of all steps taken during the approach phase, the 15 kickers were most consistent with their final support foot placement. Nonetheless, there is a need to first fully understand place kick technique at the instant of ball contact and the effects of ball orientation on this portion of technique since this will likely have direct implications for the impact phase and subsequent ball flight characteristics.

When experimenting with manipulations in the final support foot placement, no clear effects were observed between support foot distance from the ball and ball flight velocity (Baktash et al., 2009). However, the placements used by Baktash et al. (2009) appear highly limited from a practical sense since the maximum medio-lateral distance of 0.6 m that they prescribed between the support foot and the ball was approximately double that of previously observed mean values (Ball et al., 2013b; Bezodis et al., 2018; Cockcroft & Van Den Heever, 2016). Furthermore, the antero-posterior distance of 0.3 m is up to, approximately, ten times those same means (Ball et al., 2013b; Bezodis et al., 2018; Cockcroft & Van Den Heever, 2016). Therefore, the range used for the independent variable by Baktash et al. (2009) may lack ecological validity. The work of Baktash et al. (2009) is further limited since the extent to which the kickers achieved the prescribed support foot placements was not reported and no accuracy constraints were placed on the small number of kickers. The only focus was on generating ball velocity and so any potential effects of support foot placement on the accuracy component of kick performance were not considered or quantified. Additionally, any kinematic differences observed in kick technique may have arisen due to that fact that the kickers were forced to try and use extreme support foot placements (Baktash et al., 2009), and hence there was a considerable, and unrealistic, change in the task constraints (Newell, 1986).

Even though it is the support foot placement which positions the kicker in space and therefore may have consequences for the path of the kicking foot leading into impact, it does not have any direct effects on the foot–ball interaction. For this reason, the translation and orientation of the kicking foot with respect to the ball at the instant of, and potentially through the duration of, ball impact remains the primary concern given the lack of knowledge in this area. However, researchers should remain cognisant of the underlying factors which occur earlier in the movement and may influence this, such as the placement of the support foot.

2.3.3 Upper Body

The first study to primarily analyse the upper body during Rugby Union place kicking (Bezodis et al., 2007) examined the effects on kick accuracy to a greater extent than the literature which has solely investigated lower body kinematics and has tended to focus on ball velocity magnitudes. Bezodis et al. (2007) observed the non-kicking-side arm during place kicks and its associations with kick technique and resulting kick performance were investigated. It was concluded that more accurate kickers utilised rotations of the non-kicking-side arm to a greater extent than less accurate kickers, and that increased non-kicking-side arm motion about the vertical axis appeared to assist in the conservation of accuracy when kicking for maximal distance. Further discussions were made surrounding the reasons for such arm rotations. These included that the rotations of the non-kicking-side arm about the vertical axis may counteract the rotations of the kicking leg during the downswing and into the follow through, acting as a result of an action-reaction convention and, in doing so, aiding in the prevention of over-rotation of the whole body. Although this may contribute to the motion of the kicking foot, it is the impact phase that ultimately determines the ball flight characteristics and so the foot–ball interaction should be the initial focal point for future research. However, interventions surrounding the impact may not be as simple as altering kicking foot mechanics, and coaches and kickers could also have to consider other factors such as motion of the upper body which may help to facilitate the desired impact kinematics.

Additional analyses of the upper body have been performed on both the kinematics (Green et al., 2016) and kinetics (Atack et al., 2019a) of place kicking. Relationships between kick distance and accuracy, and upper body kinematics were assessed by Green et al. (2016). At initial ball contact, torso (45.4 ± 12.6°) and pelvis (28.2 ± 9.9°) orientations were reported in the transverse plane, where positive values indicate that the support side (left side for a right-footed kicker) was closer to the goal posts. It was found that there was an ‘excellent’ relationship between kick distance and torso orientation in the transverse plane (r = 0.76) and a ‘moderate to good’ relationship between kick distance and orientation of the pelvis in the transverse plane (*r* = 0.66), both at initial ball contact (Green et al., 2016). On the other hand, a 'moderate to good' negative relationship was identified between kick accuracy and torso orientation in the transverse plane (*r* = -0.66; Green et al., 2016). This suggests that producing a less front-on torso (support side closer to the goal posts) at initial ball contact is beneficial for the generation of kick distance but that the converse is true for kick accuracy. The work by Green et al. (2016) was also the first to test for accuracy and distance independently in an outdoors environment. This adds to the ecological validity of the study and provides valuable information relating to place kick accuracy – something which has generally been ignored in previous literature.

Atack et al. (2019a) used a previously developed ball flight model (Atack et al., 2019b) to group 33 place kickers based on their kick performance. The kickers were defined as either 'long', 'short', or 'wide-left' kickers depending on whether their kicks would have been successful from a distance of 33.3 m straight in front of the goal posts ('long'), or would have missed short ('short'), or missed left ('wide-left') from a distance of more than 30.7 m based on the modelled ball flight. The 'short' (thorax = approximately 20°, pelvis = approximately 10°) and 'wide-left' (thorax = approximately 35°, pelvis = approximately 25°) kickers demonstrated a thorax and pelvis orientation that was more front-on to the target than 'long' kickers (thorax = approximately 45°, pelvis = approximately 25°) at the instant of ball contact (Atack et al., 2019a). Therefore, it could be implied that having the thorax and pelvis more front on to the goal posts at the point of ball contact can hinder place kick performance. Comparable observations have been made in Rugby League place kickers with group mean values of 28° and 21° for shoulder and pelvis orientations in the transverse plane at ball contact, respectively, implying that the trunk was not facing directly towards the target and hence was not front on (Ball et al., 2013b). Based on the discussed literature, it appears that upper body motion does have implications for place kick performance. This role that the upper body plays during a place kick likely includes influences on the kicking foot motion towards the ball before impact and again coaches and kickers should be cognisant of this if attempting to make any alterations to the kicking limb mechanics during the approach or impact phases.

One issue from the methods used by Bezodis et al. (2007), which is of direct relevance when seeking to better understand the foot–ball interaction, was the definition of the point of ball contact. Although not a key consideration for that study given its aims, foot–ball contact was determined to have occurred at the instance of initial displacement of a marker at one end of the longitudinal axis of the ball. Assuming foot contact on the ball happened near to one end of the longitudinal axis of the ball, and therefore the marker was at the other, this marker would not have been displaced immediately. This has been discovered in Soccer instep kicking where the opposite edge of the ball to that at which the impact occurred remained stationary for approximately the first 20% of impact duration until the ball moved forward as a whole (Shinkai et al., 2009; the impact phase is discussed in section 2.4). As a result, there may be some degree of error and loss of accuracy of the values recorded at ball contact compared to the true values. Future research should therefore strongly consider the definition used for initial foot–ball contact, whether that be through visual identification or the instant of peak kicking foot velocity (Atack et al., 2019a; Shinkai et al., 2009).

2.3.4 Lower Body

Previous Rugby Union place kicking literature has predominantly investigated lower body motion (Atack et al., 2019a; Baktash et al., 2009; Bezodis et al., 2007, 2014, 2017, 2018; Cockcroft & Van Den Heever, 2016; Ford & Sayers, 2015; Green et al., 2016; Minnaar & van den Heever, 2015; Padulo et al., 2013 Sinclair et al., 2014, 2017; Zhang et al., 2012) with a focus often placed on the kicking leg. Velocities of both the kicking foot and ball have predominantly been the variables used to quantify performance. Zhang et al. (2012) identified the movement sequencing of the kicking leg segments and examined the relative contributions of these to the generation of kicking foot velocity. Since velocities were the main performance measure, no accuracy constraint was placed upon the 84 maximal effort kicking trials undertaken by seven participants. Percentage contributions to foot velocity for each segment were then calculated and it was found that knee extension was the greatest contributor, accounting for 75 ± 8% of the final foot velocity. Hip flexion provided the second largest contribution with 13 ± 2%. Proximal to distal sequences of movement were identified, implying a potential interaction of adjoining segments which may explain the findings that contributions increased distally up to the knee joint. Similar findings were also reported by Sinclair et al. (2014) who analysed the maximal place kicks of 20 participants (20 trials each) using their individual choice of kicking tee and their preferred kick approach. This would likely have allowed the participants to have performed near to, or at, their best ability and so enhanced the ecological validity of the study. However, performing this number of kicks may lead to other complications such as fatigue. The study of Sinclair et al. (2014) was the first to use a multiple regression analysis to identify the effects of kicking leg kinematics on ball velocity and it was established that peak knee extension velocity was the only significant predictor of ball velocity ($R^2 = 0.481$, $p < 0.01$). As well as being similar to the aforementioned finding of Zhang et al. (2012), it is also consistent with that of Ball (2008). When investigating Australian Football punt kicks, Ball (2008) identified a significant relationship ($r = 0.63$, $p < 0.05$) between knee angular velocity at ball contact and kick distance in 10 professional players – likely related through $v = r\omega$ (where v = linear velocity, r = radius, ω = angular velocity) and larger kicking foot velocities being associated with greater kick distances ($r = 0.68$, $p < 0.001$).

The relationships between knee angular velocity, kicking foot velocity and kick distance have been further supported by the results of Hébert-Losier et al. (2020). The use of Cohen's standardised effect sizes and self-organised map analyses revealed that increasing knee flexion at the top of the downswing, and so allowing for a greater range of motion of the knee joint during the downswing, appeared to improve place kicking performance (in this study performance was defined based on whether the ball passed through the goal posts and qualitative feedback from the coach and kicker). This may occur because a greater knee flexion at the top of the downswing would in turn provide a longer duration for knee angular velocity to increase, and therefore for foot linear velocity to be greater by the time impact with the ball occurs. The distance over which the body's muscles can apply force to the foot would be increased with greater knee flexion and hip extension, allowing more work to be done and in turn producing a greater foot velocity. This is a feature further observed by Roger-Lund et al. (2020); the Rugby Union kickers displayed greater knee flexion and hip extension angles at the top of the downswing when kicking from a distance of 40 m, compared to kicking from 32 m and 22 m.

Ankle orientation angles and angular velocities in all three planes at the point of defined ball contact have also been reported by Sinclair et al. (2014) but these were not found to be a significant predictor of ball velocity. However, ankle orientations and angular velocities did deviate throughout the trials on an inter-individual level. These observed differences between individuals suggest that there were variations in technique between the kickers, and it is possible that this could be due to them using their individual preferred ball setup (kicking tee and ball orientation). This may have led to the differing ankle orientations and motion at ball contact, although further work is required to establish any potential link between ball orientation and the kinematics of the foot and ankle.

Further work has been undertaken to investigate the differences in lower body kinematics between two place kick conditions: kicking for maximum ball velocity and kicking towards a target for maximum accuracy (Sinclair et al., 2017). Although an accuracy constraint was placed upon the participants, no measurement of accuracy outcome was recorded. Accuracy is an important consideration because of the notion of a distance-accuracy trade-off (Green et al., 2016) and because a place kick requires both sufficient distance and accuracy to be successful (Atack et al., 2019b). Accuracy is therefore something that should be considered in addition to just distance (or ball flight velocity magnitude) in future research. However, Sinclair et al. (2017) did identify kinematic differences in technique at ball contact between the kick conditions with knee extension angular velocity (difference in means = 217°/s), kicking foot linear velocity (3.2 m/s) and ball velocity (3.6 m/s) all being significantly greater when kicking for maximum distance compared with kicking for accuracy. However, similarly to the previously discussed results of Sinclair et al. (2014), a finding more relevant to this current thesis was that of the kicking foot ankle orientation and angular velocity at impact. The kicking foot ankle was significantly more plantar-flexed (difference in means = 9°) when kicking for maximum velocity and in the accuracy condition kicks the ankle was significantly more externally rotated (9°) in the transverse plane (Sinclair et al., 2017). Although it appears likely that these differences emerged as a result of the different kick conditions placed upon the kickers, ball orientation was a variable that was not considered. It was not discussed whether the kickers could use their preferred ball setup or if it was determined for them. The ball setup, in particular the orientation of the ball on the tee, may have implications for the ankle angle and foot orientation at ball contact since the kicker might manipulate their foot in such a way to achieve their desired impact locations on both the foot and ball, and these could differ depending on the ball's orientation.

Differences in lower body mechanics during place kicking have additionally been identified by Atack et al. (2019a) when examining kickers who achieved varying levels of success. Those categorised as 'short' kickers performed less positive work at both the hip and knee joints during the downswing than the 'long' kickers. This led to lower kicking foot and ball velocities, and as such a shorter distance over which the place kick was modelled to have been successful. When comparing the ‘wide-left’ kickers to the ‘long’ kickers, similar foot and ball velocities were observed since kick distance was not the reason for kick failure in the ‘wide-left’ group. However, the ‘wide-left’ kickers produced greater positive work at the hip and reduced work at the knee which resulted in a misdirected ball velocity vector, and as such an inaccurate kick (Atack et al., 2019a).

Investigations into the kicking foot swing planes (Bezodis et al., 2019) have further illustrated the mechanical differences between kickers who achieved varying performance outcomes. Bezodis et al. (2019) established that the ‘long’ kickers (using the same definitions as Atack et al., 2019a) displayed a moderately shallower kicking leg plane inclination (50.6 ± 4.8° when viewed from behind) and a swing plane directed moderately further to the right of the target (20.2 ± 5.4° when viewed from above) than the ‘wide-left’ kickers (inclination = 54.3 ± 2.1°; direction = 16.7 ± 4.1°). Although the differences reported by Atack et al. (2019a) and Bezodis et al. (2019) may in part explain the observations in place kick accuracy and overall performance, the ball setup was not controlled as all kickers could set the ball up to their individual preference. This could have had implications on the findings since the use of different height kicking tees and ball orientations may have caused the kickers to employ varying kick kinematics. Differing kicking foot swing planes may have arisen to allow for varying deliveries of the kicking foot to the ball, dependent on the ball setup. The interaction between ball setup and the techniques used by the kickers, ultimately starting with the delivery of the kicking foot towards the ball at impact, is therefore an important consideration for future research.

The position and orientation of the kicking foot relative to the ball is the final product of the kicking foot’s path during the downswing. The effects of variability in support foot placement on the motion of the kicking leg during the downswing and the variability in the position of the kicking foot at ball contact have been investigated by Ford and Sayers (2015). The results suggested that a relationship does exist between support foot placement, kicking leg swing variability (measured using knee-hip and hip-pelvis angular displacements) and kicking foot position relative to the ball. Although the vertical aspect of the kicking foot position was ignored and impact location was not a variable that was directly recorded, the kicking foot centre of mass position did vary relative to the ball centre of mass position and this would suggest that impact location of the foot on the ball also varied. Ford and Sayers (2015) observed differing patterns between support foot placement, kicking leg swing variability and kicking foot position relative to the ball within the kickers. One kicker produced the lowest variability in support foot placement (*SD* = ± 0.01 m), in turn displaying the most consistent kicking leg swing motion and, as such, a low variability in kicking foot position on the ball (*SD* = ± 0.01 m). However, a contradictory pattern was identified in another kicker who demonstrated a larger variation in support foot placement (*SD* = ± 0.04 m) but also a low variation in kicking foot position relative to the ball (*SD* = ± 0.01 m). The implications for this are that Rugby Union place kickers likely aim to be consistent with their impact locations on the foot and ball and can adapt their kick technique during the approach phase in order to achieve this. Consistent impact locations have also been observed by Peacock and Ball (2019a) where a normal distribution was identified for impact location on the foot in both the medio-lateral and antero-posterior directions in kicking of a prolate spheroid ball in Australian Football punt kicking (discussed further in section 2.4).

Although kickers may attempt to be consistent with their kicking foot placement relative to the ball (Ford & Sayers, 2015), the actual orientation of the foot at the point of contact was not analysed and there has been no previous research investigating precise impact locations during Rugby Union place kicking. One Rugby Union study that did report values of kicking foot orientations was that of Bezodis et al. (2018). It was observed that the kickers' kicking foot had a mean orientation of 46 ± 8° relative to global x-axis (medio-lateral direction) at ball contact and that this came about in part as a by-product of 25 ± 6° more plantar flexion than a neutral anatomical position. Despite recording these values, any potential associations between foot orientation and performance were not assessed. Given the fact that a range of ball orientations on the tee were identified by Bezodis et al. (2018), investigations into the potential interactions between ball orientation and foot position and orientation at ball contact could prove valuable. It may be the case that; kickers always produce a specific foot orientation as a result of their overall kick technique, kickers produce a varying foot orientation dependent on the ball orientation, that one foot orientation produces the best kick performance regardless of other factors such as ball orientation, or that foot orientation has no effect, and further research is required to investigate this.

Controlled analyses using a mechanical kicking simulator have been undertaken to explore the effects of kicking foot position and orientation at the instant of ball contact (Minnaar & van den Heever, 2015). When controlling ball orientation on the tee at 24° (see Figure 2.3 for convention) and keeping the impact location on the foot constant, it was found that changes in kicking foot position and orientation did affect the ball flight characteristics (Minnaar & van den Heever, 2015). Ball velocity and work done on the ball during the impact phase were greatest when ankle plantar flexion at ball contact was reduced to 67° (ball velocity = 16.7 ± 3.7 m/s; work done = 44.6 ± 15.7 J) from the baseline setting of 82° (ball velocity = 14.6 ± 3.9 m/s; work done = 24.7 ± 5.0 J). Increasing foot abduction at ball contact from 12.5° to 27.5° was the only other change that resulted in a greater ball velocity (15.9 ± 5.8 m/s; work done = 33.3 ± 14.3 J) than the baseline setting. These results from a mechanical kicking simulator demonstrate that, when all else remains constant, foot orientation is a factor which will interact with ball orientation. As a result, the combination of these variables will likely play a considerable role in determining the mechanics and characteristics of the impact.

The use of a single ball orientation, as implemented by Minnaar and van den Heever (2015), aids in investigating the influence of the kicking foot kinematics since it reduces the number of dynamic variables. However, it may be that case that different foot orientations are more suited and beneficial for certain ball orientations. Additionally, the study undertaken by Minnaar and van den Heever (2015) used a mechanical kicking simulator and therefore gives a repeatable representation of the foot–ball interaction. This also allowed for systematic changes in individual place kick variables, but the limb mass and shape did not accurately represent that of human kickers and rotation at the ankle was fixed. As a result, the simulator was not able to replicate forced plantar flexion during the impact – a feature which has previously been observed in human kickers (Peacock et al., 2017; Shinkai et al., 2007, 2009). The velocity of the end foot segment (10 m/s) was also approximately half that observed in human kicking trials (Atack et al., 2019a; Baktash et al., 2009; Zhang et al., 2012). Future research should therefore investigate the potential interactions between ball orientation and foot orientation when considering the effects on kick performance outcomes. This should be done in human kickers given the complexity of ankle joint motion and the interaction between the foot and the ball during the impact phase.

Approach phase summary

In summary, there has been a wide range of research conducted which focusses on the kick approach phase. The approach phase starts with more gross movements during the whole-body translation towards the ball, before proximal-to-distal sequencing is employed during the kicking leg downswing, finishing with the kicking foot striking the ball. Although the foot and ball are not interacting during this phase, the resulting outcomes of the approach include the resultant velocity, location, and orientation of the kicking foot at the point of impact. These will clearly have implications for the subsequent impact characteristics and therefore the transfer of flight characteristics to the ball. However, these elements all need to be considered relative to the ball since changing the position and orientation of the ball may have additional effects due to its prolate spheroid shape. An encompassing weakness of all the aforementioned Rugby Union studies (bar that of Green et al., 2016) is that they were undertaken in a laboratory environment. Whilst this does allow for more control and standardisation of testing conditions, ecological validity is compromised compared to those conducted outdoors in a more applied field setting. Future research should aim to explore how the kicker's kinematics, particularly those of the more distal segments such as the kicking shank and foot, change at the instant of ball contact when ball orientation is varied and any potential associations these factors may have with ball flight characteristics and overall place kick performance.

2.5 The Impact Phase

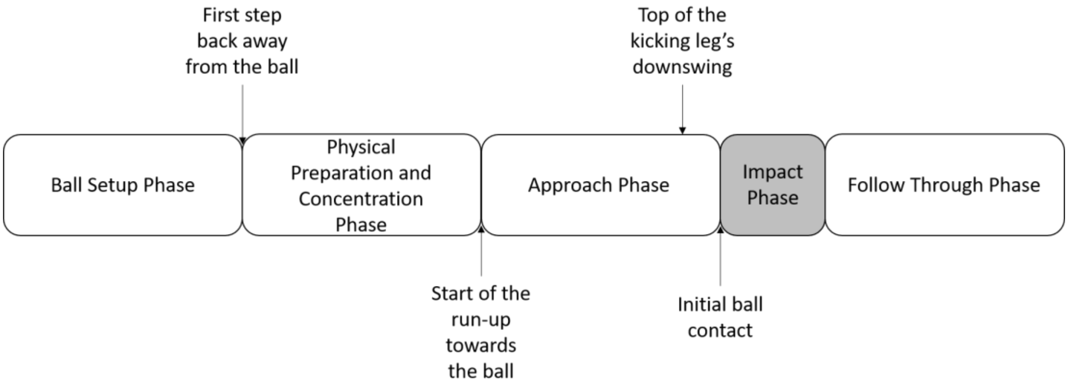

Figure 2.6. The phases of a place kick (i.e. Figure 1.1) with the impact phase highlighted.

The impact phase is the only part of place kicking where the kicker's movements have a direct influence on the outcome of the kick. It is the span of time over which all preceding factors combine in order to impart the flight characteristics to the ball, and therefore determine the ball's flight path and the resulting performance outcome (in combination with the external environmental factors). However, due to the short duration of impacts (mean ± *SD*; 7.4 ± 0.3 ms for Rugby League place kick, Ball, 2010; 12.1 ± 1.3 ms for Australian Football drop punt, Peacock et al., 2017; 9.0 ± 0.4 ms for Soccer instep kick, Shinkai et al., 2009), and therefore the difficulty in acquiring sufficient data for analysis using the majority of widely available measurement equipment, there has been limited research into this potentially key phase. To the best of the author's knowledge, the durations of Rugby Union place kicking impacts have yet to be reported in research and are therefore unknown. Further to this, studies have often only been able to calculate means of variables across the whole impact phase as opposed to analysing the foot and ball throughout impact duration when investigating kicking. This is largely due to the short durations of impacts and thus the high sampling rates required to capture sufficient data. The problem of filtering through impacts is also a factor because motion generally transitions from being low frequency before impact to high frequency during impact, and back to low frequency again afterwards (Nunome et al., 2006; filtering methods are discussed further in section 2.6). Most previous work that has investigated the impact phase of kicking across all Football codes (defined as both Rugby codes with the inclusion of Soccer, Australian Football and American Football) has been conducted in Soccer, primarily on the commonly used instep kick (Bull Andersen et al., 2008; Ishii & Maruyama, 2007; Nunome et al., 2013; Shinkai et al., 2007, 2009; Tsaousidis & Zatsiorsky, 1996). However, the non-uniform, prolate spheroid shape of the ball used in Rugby codes, Australian Football and American Football introduces an additional problem to be considered since, unlike a spherical Soccer ball, its orientation at contact will likely interact with that of the foot to further influence the impact characteristics and resulting outcome measures.

Although variables such as ball and foot orientations and locations relative to one another likely play a key part in determining the properties of the impact (section 2.3), the culminating impact locations on the ball have not been quantitatively analysed within Rugby Union place kicking. This is despite the fact that empirical testing of place kicking in American Football, including investigations into the effects of impact location through the use of an early mechanical kicking machine, dates back to the 1950s (Marshall, 1958). Marshall (1958) recorded the impact location on the ball by first chalking the end-effector (constructed kicking foot) of the machine so that a chalked mark was transferred to the ball in the position that the point of impact occurred. A potentially key finding of this investigation was that the greatest ball flight distance was achieved when the ball was placed with an orientation of -15° (i.e. top of the ball posterior to the bottom of the ball), and when the impact between the end-effector and the ball occurred 0.14 m up the ball (approximately on the belly of the ball). Ball orientation and impact location were also visually observed to have effects on ball flight elevation angle and spin rate. Whilst Marshall's (1958) study is limited by its inability to use accurate modern-day equipment to record variables of interest, it demonstrates that the investigation of impact factors on place kicking is an age-old problem, and one that still has not been considered to a great extent to this day.

Many of the more recent analyses into kicking impacts have been undertaken on Soccer kicking (Bull Andersen et al., 2008; Ishii & Maruyama, 2007; Shinkai et al., 2006), although there have also been several conducted using a prolate spheroid Australian Football ball (Peacock & Ball, 2017, 2018a, 2018b, 2019a, 2019b; Peacock et al., 2017). In many of these Australian Football studies the foot and ball were computationally modelled in either two or three dimensions so that impact locations could be determined. By using their previously mentioned mechanical kicking limb, Peacock and Ball (2017) were able to systematically explore the effects of varying impact locations on the foot in both the medio-lateral and proximal-distal directions. As impact location on the foot was moved distally to 7.5 cm from the foot centre of mass, ball back-spin rate increased linearly to a maximum of approximately 1800°/s, as did ball velocity to approximately 25 m/s. This came about as a result of increased linear velocity of the impacting part of the foot which can be derived from the equation $v = r\omega$ given the fixed angular velocity about the simulated knee joint and the increased radius as impact location moved distally. Altering the impact location on the foot led to analogous effects on ball elevation angle, while azimuth angle was not influenced.

Peacock and Ball (2017) also found that when altering the medio-lateral impact location, both ball velocity and back-spin rate were greatest when impact occurred 0.5 cm medially to the foot centre of mass. However, ball velocity had a low dependence on medio-lateral impact location. Ball elevation angle also appeared to display a low dependence on the medio-lateral impact location, but a steeper linear gradient was fitted to the azimuth angle data. Minimum and maximum values of approximately -8° and 4° were observed when the impact occurred -3.6 cm and 0.8 cm from the foot centre, respectively. Through post hoc analysis it was further identified that angular velocity about the y-axis of the ball was also linearly dependent on the medio-lateral impact location on the foot.

The effects of medio-lateral impact location on ball launch kinematics (Peacock & Ball, 2017) can be described by the oblique impact theory. Ball flight trajectory and spin characteristics are determined by the line of the foot's force vector with respect to the ball's centre of mass. Since the trajectory of the kicking foot was not altered in this study then these changes must come about as a result of the non-uniform impacting surfaces and relative angle between the foot and ball. However, the swing of the mechanical kicking leg followed a perfectly vertical swing plane, a feature more relevant to Australian Football punt kicking. This vertical action differs from the kicking motion of Rugby Union place kicks where analyses of swing planes in human kickers have observed inclination angles of 50.6 ± 4.8° above the horizontal (viewed in the frontal plane) in accurate kickers (Bezodis et al., 2019). As a result, the swing plane of the mechanical leg may not accurately replicate that of a human Rugby Union place kicker. The importance of the impact location on the foot for kick accuracy has nonetheless been identified and although Peacock and Ball (2017) did measure ball flight in the medio-lateral direction, the resultant kick performance (whether the ball would have passed between goal posts and from what distance) was not quantified. This is something that should be explored in future research since it is necessary to measure or simulate the three-dimensional ball flight trajectory and spin rate to determine the true outcome of place kicks (Atack et al., 2019).

The mechanical leg can be deemed to accurately represent the leg of a human kicker. It was produced to have the same shank length and mass as that of a typical Australian Football player and the foot segment was printed as a three-dimensional object based on a scan of a human's plantar-flexed foot and fitted with a Football boot. However, the use of this mechanical limb also leads to associated weaknesses. The potential effects of soft tissue are left unknown and in this study the ankle joint was kept fixed. This disabled the capacity for forced plantar flexion – a feature that has previously been observed during the impact phase in human kicking (Peacock et al., 2017; Shinkai et al., 2006, 2007, 2009). The ability to apply the findings from the mechanical limb when the ankle is fixed to kicking in humans would be limited to a greater extent when investigating the proximal-distal impact location on the foot

(Peacock and Ball, 2017). A more distal impact location on the foot would increase the moment arm about the ankle and thus create a greater external moment due to the reaction force of the ball on the foot. A greater torque would therefore be required at the ankle to fix the joint in the mechanical limb, when in human kickers it could be assumed that a greater moment as a result of a more distal impact location would result in greater forced plantar flexion effects (Peacock & Ball, 2019a).

When investigating drop punt kicks, also on a prolate spheroid Australian Football ball, the influence of impact location on the foot was reported for a group of ten human kickers when kicking for accuracy over a distance of 30 m (Peacock & Ball, 2019a). The anterior surface of the kicking foot and the ball were both modelled as three-dimensional rigid bodies for each trial (a semi-elliptical cylinder and a prolate spheroid, respectively) so that the relative foot–ball orientation and translation could be accounted for and impact location on the foot could be identified. It was found that azimuth ball flight angle was again influenced by the impact location on the foot in the medio-lateral direction and that ankle plantar flexion during impact was influenced by the proximal-distal impact location. Foot–ball velocity ratio, a measure previously used to describe impact efficiency (Ball et al., 2010; Peacock et al., 2017; Peacock & Ball, 2018b; Smith et al., 2009), was also influenced by impact location in most of the kickers, with a peak ratio of approximately 1.3 arising when impact occurred 4 mm distally from the foot centre (Peacock & Ball, 2019a).

As impact location moved distally, the observed increase in forced plantar flexion (Peacock & Ball, 2019a) could partly explain the findings of Peacock and Ball (2019a) that foot–ball velocity ratio decreased with increasing distal impact locations. An additional factor associated with greater forced plantar flexion is that more energy may have been stored in the soft tissue around the ankle instead of being transferred to the ball. Nonetheless, an overarching finding was that all players appeared to target a specific impact location on the foot since they each produced a normal distribution of impact locations in both the medio-lateral and proximal-distal directions. Based on this fact and that the impact location influenced kick outcome measures, the authors concluded that a ‘sweet spot’ (impact location resulting in optimal task-related kick outcomes) exists on the foot. However, due to the nature of a drop punt kick, relative foot–ball orientation and resulting impact locations on the foot and ball could not be systematically controlled. For this reason and the lack of impact-based research in Rugby Union kicking, similar analyses should be conducted on the place kick where the ball is stationary and therefore ball orientation can be adjusted in a controlled manner. Whilst determining if place kickers aim to impact a specific location on the foot would prove valuable, impact locations on the ball should first be explored. This should include whether impact location on the ball changes when the orientation of the ball on the tee is altered, and potential effects these factors may have on place kick performance measures.

Ankle joint motion through impact is another variable that has been analysed using the mechanical kicking limb by allowing the joint to rotate (Peacock & Ball, 2018b, 2019b). When simply comparing differences in impact efficiency between two conditions (rigid ankle and non-rigid ankle) and employing a consistent initial foot velocity it was found that foot–ball velocity ratio (rigid = 1.16 ± 0.01, non-rigid = 1.11 ± 0.01), ball velocity (rigid = 19.0 ± 0.3 m/s, non-rigid = 18.3 ± 0.2 m/s) and translational kinetic energy of the ball (rigid = 82.3 J, non-rigid = 76.7 J) were significantly greater when the rigid ankle setting was employed. Additionally, the non-rigid ankle led to a significantly reduced coefficient of restitution (rigid = 0.42 ± 0.01, non-rigid = 0.40 ± 0.02; Peacock & Ball, 2018b). These results imply that, for a given foot velocity, measures of impact efficiency and ball flight velocity are improved when a rigid ankle is implemented in the mechanical limb. It could then be expected that maintaining as rigid an ankle as possible during the impact phase would also be beneficial for impact efficiency in human kickers and the findings of Peacock & Ball (2019b) appear to support this.

Foot velocity, ankle joint stiffness and proximal-distal impact location on the foot have all been found to influence impact efficiency (Peacock & Ball, 2019b). The non-rigid setting of the mechanical limb was determined to validly replicate that of a human ankle during impact, and it was identified that moving the impact location distally meant that the change in ankle plantar flexion angles between the start and end of the impact phase increased (R^2 = 0.9682). A similar finding has been observed in human kickers (Peacock & Ball, 2019a). Through the use of the mechanical kicking limb, Peacock and Ball (2019b) identified that increasing the joint stiffness was found to reduce forced ankle plantar flexion (R^2 = 0.7961) and increase ball flight velocity (R^2 = 0.5755; Peacock & Ball, 2019b). When Peacock and Ball (2019b) progressed to systematically altering foot velocity, analysis of the effects of foot velocity revealed that whilst ball velocity increased with foot velocity, the change in ankle plantar flexion during impact decreased and there was an initial period of dorsiflexion for high foot velocity (21.9 m/s) which did not occur for low foot velocity (17.7 m/s). This is also a common feature in experienced kickers who have also been observed to dorsiflex at the beginning of the impact phase in Soccer instep kicks and Australian Football drop punt kicks (Peacock et al., 2017; Shinkai et al., 2009). Peacock and Ball (2019b) modelled the anterior aspect of the foot surface and the ball in two dimensions to allow for identification of the onset of the foot–ball impact phase and the impact location on the mechanical foot, based on ball deformation. Despite this, no values of ball deformation were calculated by Peacock and Ball (2019b).

Ball deformation and impact characteristics have been analysed to a greater extent in Soccer (Bull Andersen et al., 2008; Ishii & Maruyama, 2007; Nunome et al., 2013; Shinkai et al., 2007, 2009; Tsaousidis & Zatsiorsky, 1996). However, the relationships between foot velocity, ball deformation, impact duration and ball flight velocity are complicated and have not been systematically explored. In Soccer, ball deformation has most commonly been computed throughout the impact phase using the distance between the ball's geometric centre and a point on the foot – a marker on the fifth metatarsal (Nunome et al., 2013; Shinkai et al., 2007, 2009) or the identified point of contact with the ball (Ishii & Maruyama, 2007). As a result of such calculations, it was revealed that trials with greater ball deformation (approximately 3 cm compared to 4 cm) also produced greater ball velocities (13.1 m/s compared to 16.3 m/s; Ishii & Maruyama, 2007). However, this finding did not appear to account for the potential different foot velocities at the point of impact even though foot–ball velocity ratio was considered for other analyses. This greater ball deformation, and subsequent greater ball velocity, may therefore simply have been a function of greater initial foot velocity. The pattern that greater ball deformation appears to lead to greater ball flight velocity can be extended further using the findings of Shinkai et al. (2009) where approximate peak ball deformation and ball velocity values were 6 cm and 30 m/s, respectively (Figure 2.7). Analysis of the ball motion has also led to the conclusion that decompression of the ball is the most important factor for increasing ball velocity in the second half of the impact phase (Nunome et al., 2013). This is likely the case since during the second half of the impact phase the velocity of the ball is greater than that of the foot and is still increasing, whereas the velocity of the foot is decreasing further (Figure 2.7).

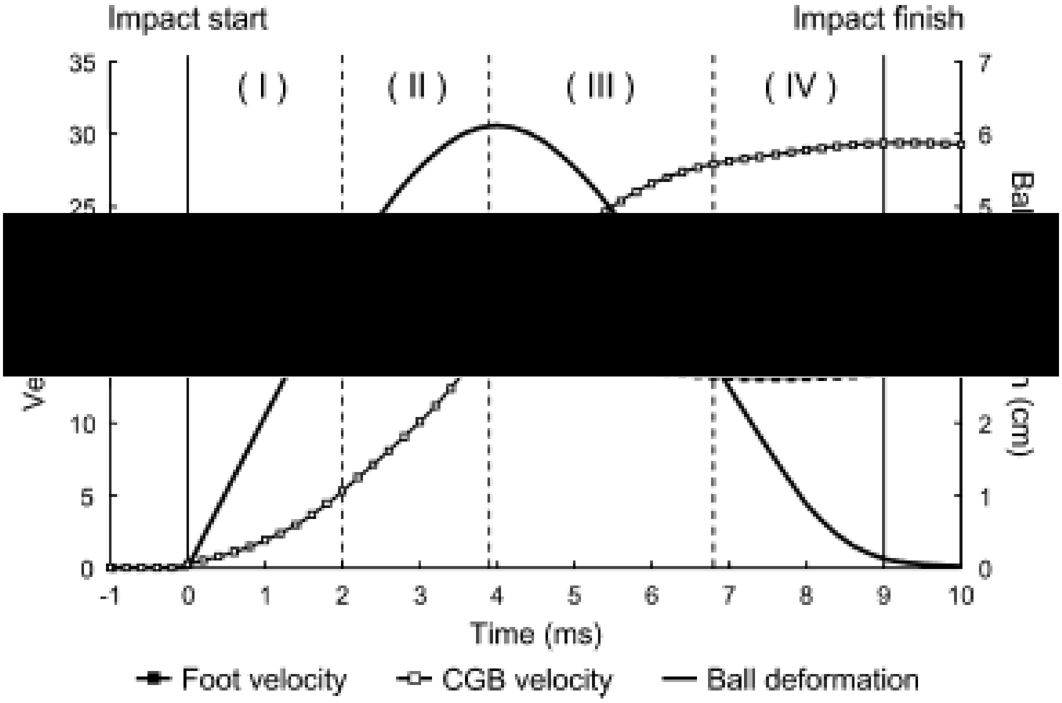

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Figure 2.7. Foot–ball interaction during ball impact of an instep kick in Soccer, including the four sub-phases of foot–ball impact (discussed on page 36). CGB = centre of gravity of the ball (from Shinkai et al., 2009).

It appears that achieving a greater ball deformation during the impact phase will lead to more subsequent decompression of the ball, and therefore an increased ball flight velocity (Iga et al., 2018; Ishii & Maruyama, 2007; Nunome et al., 2013; Shinkai et al., 2007, 2009). However, these studies were conducted using a Soccer ball of uniform, spherical shape and not a Rugby Union ball of prolate spheroid shape. Given this fact and the results of Holmes (2008) and Peacock and Ball (2017) surrounding ball orientation/impact location and resulting changes in ball deformation, coefficient of restitution and ball flight characteristics, it is likely that findings relating to non-uniform impact dynamics will be seen in Rugby Union place kicking. These would be influenced by ball orientation and impact locations also, with the possibility that specific combinations of these factors would interact to result in faster ball flight velocities. This would result in greater ball flight distances that could translate to the potential of more point scoring opportunities in a competitive, match environment. For this reason, future place kicking research should consider the effects of ball orientation on ball flight characteristics and kick performance.

Impact duration is a variable that may also interact with ball deformation and ball flight velocity. Although it appears that a greater ball deformation leads to a greater ball velocity (Iga et al., 2018; Ishii & Maruyama, 2007; Nunome et al., 2013;

Shinkai et al., 2007, 2009), it could be assumed that a greater deformation will result in an impact of longer duration. This may contradict the findings discussed above since Nunome et al. (2013) concluded that a longer impact duration appeared to hinder resultant ball velocity, based on the findings of a weak, negative relationship (*r* = -0.438) between the two variables. A negative linear relationship between impact duration and ball flight velocity was similarly reported by Shinkai et al. (2009) and Iga et al. (2018). Iga et al. (2018) fired a Soccer ball at a stationary, flat force plate using various initial impact velocities. It was discovered that increasing the initial ball velocity before impact resulted in a decrease in impact duration (r = -0.96, p < 0.01) but an increase in subsequent ball velocity after the impact. These findings contradict the suggestions that a greater ball velocity can be achieved as a product of a longer contact time between the foot and the ball (discussed further in section 2.5) – potentially emanating from and revolving around the impulse-momentum relationship ($J = F\Delta t = \Delta p$; where J = impulse, F = force, t = time, p = momentum), where a greater impact duration would mean that the foot applies a force to the ball for longer, producing a greater change in the ball's momentum. Though again, these results generally fail to take into account other potentially influential variables. It is likely that slower foot velocities result in longer impact durations and consequently reduced ball flight velocities. Whilst ball orientation was not controlled due to the nature of Australian Football drop punt kicks in humans, when kicking for accuracy a significantly slower foot velocity before impact (17.7 ± 0.9 m/s, *d* = 1.69) resulted in a significantly longer impact duration (13.2 ± 1.4 ms, *d* = 0.81) and significantly reduced ball flight velocity (22.1 ± 1.1 m/s, *d* = 1.67) than when kicking for maximal distance (foot velocity = 22.1 ± 1.6 m/s; impact duration = 12.1 ± 1.3 ms; ball velocity = 28.1 ± 2.5 m/s, Peacock et al., 2017). Unless analyses control for these variables of foot velocity, ball deformation, impact duration and outgoing ball velocity then it may not be possible to truly determine the underlying relationships between them.

Detailed investigations of the foot–ball interaction have also led to the determination of four sub-phases within the impact phase; first achieved during instep Soccer kicking (Shinkai et al., 2009; Figure 2.7). The first sub-phase is defined as starting from the identified moment of initial foot–ball contact and lasts for approximately 2.0 ms (approximately 20% of the total impact duration). During this sub-phase there is a minimal decrease in foot velocity, and whilst the ball begins to deform and its centre of gravity begins to accelerate, the edge of the ball opposite to the impact location remains stationary. In the second sub-phase the whole of the ball begins to move as it continues to deform, and the ball centre of gravity continues to accelerate until its velocity is equal to that of the decelerating foot. This has previously been noted to occur 4.0 ± 0.3 ms (approximately 45% of the total impact duration) after impact onset and is also the moment when maximum ball deformation arises (6.2 ± 0.6 cm in the case of Shinkai et al., 2009). Sub-phase three is characterised by a continued increase in the velocity of the ball as it starts to decompress and the foot continues to decelerate, before sub-phase four begins when the ball and foot velocities start to plateau (ball velocity reaching approximately 95% of its final launch velocity). During this final sub-phase, the ball continues to decompress yet there is little interaction between the foot and the ball as their velocities have reached near to their final values (Shinkai et al., 2009; Figure 2.7). These sub-phases and all values were based on an initial foot velocity of 20.5 ± 1.0 m/s.

Similar sub-phases and characteristics to that of Shinkai et al. (2009) have also been determined in punt kicking of prolate spheroid balls in Rugby League (Ball et al., 2013a) and Australian Football (Peacock et al., 2017). However, due to the nature of drop punt kicks the ball was not initially stationary and the ball orientation at the start of the impact could not completely be controlled. Based on the evidence that the deformation of Rugby balls is affected by ball orientation, and so impact location on the ball given the nature of the drop test performed (Holmes, 2008), it is possible that the relative durations of these sub-phases may be altered depending on the impact location on the ball during Rugby Union place kicking. There is also the likelihood that alterations in ball orientation may lead to changes in the impact location on the ball during kicking and so these could be areas of consideration for future work.

It has previously been assumed that the reaction force exerted by the ball onto the foot reaches a peak when ball deformation is at its greatest at the end of sub-phase two (Shinkai et al., 2009), and the Rugby Union-specific results of Holmes (2008) appear to support this. When investigating the amount of force required to compress a Soccer and Rugby Union ball, and hence the reaction force produced by the balls (based on Newton’s third law of motion), Holmes (2008) observed that to increase the compression of the balls a greater applied force was necessary. A further interesting discovery of current relevance was that when the force was applied to the belly of the Rugby Union ball (1046 N), a greater force was required to compress the ball by the same amount (30 mm) as opposed to when the force was applied to the point of the ball (approximately 800 N). Using computer-aided design, the surface area of the force-applying plate was calculated at the time of 30 mm of linear deformation. The surface area for the belly of the ball was 0.026 m^2 and the surface area for the point of the ball was 0.017 m^2 (Holmes, 2008). Whilst the surface area during deformation may be an improved measure over linear deformation, it is likely that volumetric deformation would give greater insights for comparison given the non-uniform shape of a Rugby Union ball. Nonetheless, the results of Holmes (2008) relating to force and deformation also support the likelihood that differing impact characteristics would be observed when varying the ball orientation.

Impact phase summary

Although the impact phase is short in duration, its function of imparting the flight characteristics onto the ball arguably make it the most important phase within kicking. Despite this, there has been very little research conducted on the impact phase of Rugby Union place kicking. Previous research has investigated the foot–ball interaction to determine sub-phases within the impact phase during the instep kick of spherical balls in Soccer (Nunome et al., 2013; Shinkai et al., 2007, 2009) and the motion of the kicking foot has been reported through the impact of kicking prolate spheroid balls in Australian Football (Peacock & Ball, 2018b, 2019a, 2019b). It has also been identified that kickers aim for a specific impact location on the foot during punt kicks and that this factor has further implications for the flight of the ball (Peacock & Ball, 2019a). However, it is not currently known whether Rugby Union place kickers aim to impact the ball in a certain location or whether this may be influenced by the ball's orientation, given its non-uniform shape. Additionally, considering that deformation, coefficient of restitution (Holmes, 2008, Michelini et al., 2019), and resulting ball flight characteristics (including ball velocity and spin rates; Peacock & Ball, 2017) can vary depending on ball orientation, and that Rugby Union place kickers are known to use a range of orientations (section 2.2), quantitative analysis of the potential effects of ball orientation and impact locations on both impact characteristics and ball flight characteristics should be considered in future place kicking research.

2.6 The Follow Through Phase

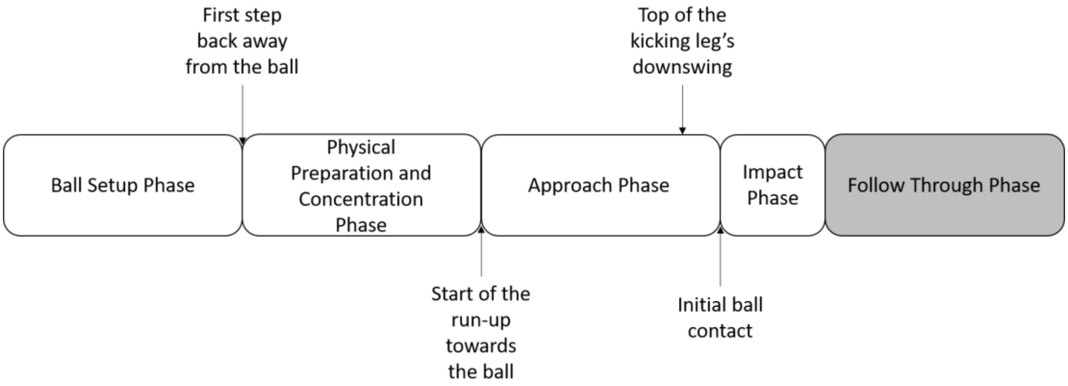

Figure 2.8. The phases of a place kick (i.e. Figure 1.1) with the follow through phase highlighted.

The follow through phase of a kick begins once the impact phase has finished; hence when the ball has left the foot and the ball flight characteristics have been imparted. For this reason and the fact that most previous research has been conducted with performance as the primary focus, there have been no direct investigations into the follow through phase of Rugby Union place kicking. Despite this, the follow through has still been identified as an important phase of kicking by a professional coach (Bezodis & Winter, 2014). The coach suggested that a follow through is necessary as a release mechanism to allow for the dissipation of energy. It was proposed that "*there needs to be a...release mechanism...at the end...to dissipate the energy build up...[due to] the braking forces they're putting on themselves*". The coach also stated that the follow through can be carried out however the kicker wishes, whether that be "*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"*, and this raises the idea that it potentially aids in reducing the risk of injury. Although it is believed that the style of follow through is chosen based on the kicker's personal preference, there is also the possibility that the style exhibited is produced as a consequence of prior variables in the place kick.

Whole body and segmental angular momentum data have been presented during the follow through phase of Rugby Union place kicking (Bezodis et al., 2007) and some styles of follow through have also been identified (Bezodis et al., 2018). Out of the 14 kickers in the study by Bezodis et al. (2018), nine 'hopped' forward onto their support leg post foot–ball impact and five 'stepped' forward with their kicking leg making the next ground contact after the impact phase. Those who ‘hopped’ forward displayed a greater peak kicking hip flexion (range = 100 to 121°) during the follow through than those who were identified with a ‘stepping’ style (range = 88 to 93°; Bezodis et al., 2018). A similar pattern was consequently observed for peak kicking foot centre of mass height. The kickers with the ‘hopping’ style reached values in the range of 42 to 62% of standing height whereas those who ‘stepped’ forward reached a lower relative peak foot height (range = 28 to 38%; Bezodis et al., 2018). This highlights that different strategies are employed by place kickers and that they can lead to variations in kicking leg kinematics, but the potential causes and relative merits of each strategy were not investigated.

In literature researching the biomechanics of kicking in Soccer, the follow through has been described has having two purposes (Barfield, 1998). The first is so that the kicker can maintain foot contact with the ball for as long as possible, leading to the possibility of greater momentum being transferred onto the ball. This is reinforced by the finding that the follow through may increase the resultant ball velocity through the prior ability of the body’s muscles to do increased mechanical work on the ball (Tsaousidis & Zatsiorsky, 1996). The second purpose discussed by Barfield (1998) is for the follow through to act as a mechanism of protection for the body – supporting the previously discussed statements of the professional Rugby Union coach (Bezodis & Winter, 2014). The follow through phase may provide time for any generated forces and transformed energy during the approach and through impact to be dissipated (Hay, 1993). Both of the discussed purposes have a time increase as the overarching theme because it influences the impulse-momentum relationship. Force can be applied to the ball over a longer duration, increasing the impulse imparted to the ball. The subsequent reduction in kicking leg momentum would also occur over an increased time period, reducing the magnitude of the forces experienced in slowing the movement once the ball has left the foot and therefore potentially reducing the possibility of injury. Although as discussed in Section 2.5, a longer impact duration appears to hinder ball flight velocity. Since the general kicking action of both the in-step kick in Soccer and place kick in Rugby Union are similar in nature (Zhang et al., 2012), with the follow through being a common feature, the importance of the follow through phase on injury mechanisms and performance outcomes will likely apply to both kicking movements.

Follow through summary

Although the follow through has been identified as a likely important phase of place kicking with regards to injury prevention and player longevity (Barfield, 1998; Bezodis & Winter, 2014), it occurs post foot–ball impact; the period of time that the ball flight characteristics, and resultant performance outcomes, are transferred to the ball. Therefore, any performance effects must be identified before the beginning of the follow through phase. As this thesis is focused on place kick performance, the follow through phase is beyond the scope of this thesis.

2.7 Data Processing Methods

Processing raw data surrounding and during the impact phase of ball kicking movements is a process that requires sufficient consideration. Biomechanical data obtained during such movements typically consists of transitions from low frequency data, both before and after impact, to data consisting of higher frequencies during impact. Using conventional methods to filter through the entire movement, including through the impact phase, can therefore distort and reduce the accuracy of kinematic variables of interest (Knudson & Bahamonde, 2001; Nunome et al., 2006). Despite this being a recognised problem, advanced filtering methods have generally been overlooked in biomechanics and instead past investigations of impacts have opted for more conventional filters; for example, low-pass Butterworth filters (Ball et al., 2013a; Peacock et al., 2017; Peacock & Ball, 2017, 2018a, 2018b, 2019a, 2019b; Shinkai et al., 2009). Previous research has consequently only investigated the approach (Atack et al., 2019a; Bezodis et al., 2007, 2014, 2019; Green et al., 2016; Sinclair et al., 2014, 2016, 2017; Zhang et al., 2012) or impact (Nunome et al., 2006; Peacock et al., 2017; Peacock & Ball, 2017, 2018a, 2018b, 2019a, 2019b; Shinkai et al., 2006, 2007, 2009) phases separately. There has also only been a small number of studies that have aimed to elucidate this topic and compare data processing procedures over the whole duration of biomechanical movements that involve impacts (Augustus et al., 2020a, 2020b; Georgakis & Subramaniam, 2009; Nunome et al., 2006).

Nunome et al. (2006) used four different filtering conditions to subsequently determine impact phase kinematics during Soccer instep kicking. The resulting variables were then compared to determine the viability of each filtering method. Raw, three-dimensional movement data of the kicking shank and foot were collected at

1000 Hz and the applied filter processes included: a modified time-frequency filtering algorithm (Georgakis et al., 2002a, 2002b); a conventional Butterworth filter with a cut-off frequency of 200 Hz; data resampled at 250 Hz and left unfiltered; and data resampled at 250 Hz and filtered with a conventional Butterworth filter with a cut-off frequency of 10 Hz. When investigating the resulting ankle angular velocity and angular acceleration during the kicks it was seen that both the modified time-frequency filter and the conventional Butterworth filter with cut-off at 200 Hz matched the peaks in the raw data during the impact phase to the greatest extent. However, filtering with the Butterworth filter with cut-off at 200 Hz led to the data being under-smoothed during the low-frequency movement of the swing phase (defined as the approach phase and the follow through phase, i.e. when the foot and ball were not in contact). Thus, considerable noise remained in the filtered data which would affect the interpretation of the movement. The resampled and non-filtered data did not display the sudden change in angular velocity during the impact which likely indicates the need for a sufficiently high sampling frequency. This was further pronounced in the angular acceleration data, whilst the resampled and filtered (10 Hz) data completely distorted both sets of data. Similar trends were visible in the shank angular velocity data and in the linear velocity and linear acceleration data of the knee, ankle, and toe (Figure 2.9). Although these trends were observed, the differences in the data between the filtering conditions appeared to lessen for the more proximal landmarks. This may have originated from the fact that the more proximal landmarks are further from the impact, potentially meaning that the frequency of the motion that they experience during the impact phase is attenuated. During gait trials Angeloni et al. (1994) determined that the optimal cut-off frequency for various segments generally decreased for the more proximal segments that were furthest away from the impact of the foot on the ground. This decrease was also more prominent for the horizontal coordinate data and it could be assumed that the horizontal data would experience the largest changes in frequency content during place kicking.

In summary, Nunome et al. (2006) demonstrated that the use of high sampling rates (to capture sufficient data during the short duration of the impact phase) and a time-frequency filter achieved superior results during kicking, compared with those methods conventionally used. This was accomplished through the filter adequately removing noisy data and yet still capturing the transition in the frequency content of the data from the swing phase to the impact phase, thus maintaining the peak values of derivatives of kinematic data during the impact. The evidence therefore suggests that a combination of the aforementioned high sampling rates and advanced time-frequency filtering methods should be employed in the future research of movements that involve impacts, such as place kicking in Rugby Union.

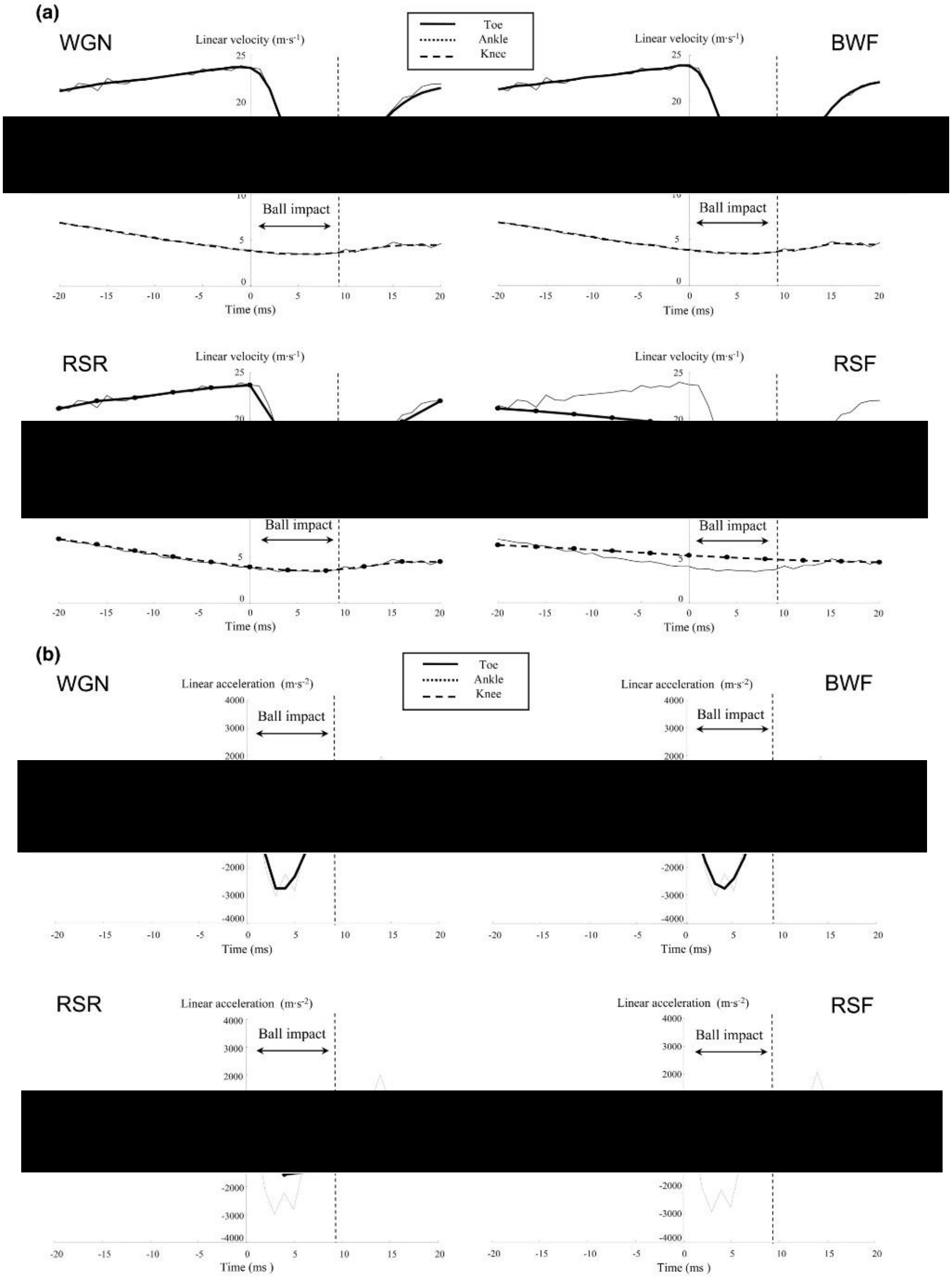

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Figure 2.9. Raw data plotted against the filtered data, comparing four different filtering methods (WGN = Wigner representation/time-frequency filter; BWF = Butterworth filter with cut-off at 200 Hz; RSR = raw data resampled at 250 Hz and left unfiltered; RSF = raw data resampled at 250 Hz and filtered with a Butterworth filter with cut-off frequency at 10 Hz), for toe, ankle and knee landmarks. **(a)** Comparison of linear velocities. **(b)** Comparison of linear accelerations (from Nunome et al., 2006).

A further time-frequency filter was developed by Georgakis and Subramaniam (2009) using a Fourier transform. This filter used a lower cut-off frequency during the swing phase and a triangular shaped filter boundary during the impact, centred about the point of peak acceleration, that enabled the cut-off frequency to increase and accommodate for the higher frequency data content. It was found to have improved performance over both conventional filters and other advanced filtering methods – including a similar implementation of the time-frequency filter tested by Nunome et al. (2006) – when aiming to effectively remove noise from biomechanical impact data from markers attached to the middle of the tibia during a landing task (Georgakis & Subramaniam, 2009).

Augustus et al. (2020b) modified the fractional Fourier filter of Georgakis and Subramaniam (2009) for implementation on ball kicking data in Soccer, collected at 1000 Hz. The modified fractional Fourier filter was tested against the conventional filters that had most commonly been employed in prior kicking-based literature, as well as a reference accelerometer (Augustus et al., 2020b). The modified fractional Fourier filter produced a significantly lower percent peak error (%PE) in resultant acceleration than any of the conventional filters, when compared to the reference accelerometer (mean ± *SD*; modified fractional Fourier filter %PE = -5.0 ± 11.4%; the next lowest method was a fourth order, dual pass Butterworth filter with cut-off at 250 Hz %PE = -25.4 ± 18.3%). The modified fractional Fourier filter also outperformed all bar one of the conventional filters when looking at the root mean square error (RMSE) of the resultant acceleration between the final approach step to the end of the follow through (modified fractional Fourier filter RMSE = 37.3 ± 7.6 m/s^2; data truncated one frame before impact and a fourth order, dual pass Butterworth filter with cut-off at 20 Hz RMSE = 25.4 ± 10.8 m/s^2). This demonstrates the modified fractional Fourier filter's ability to effectively remove noisy data from the phases surrounding impact and the impact phase itself. Although a conventional filter (Butterworth filter with cut-off at 20 Hz) did perform better than the modified fractional Fourier filter with respect to the previously presented RMSE values (Augustus et al., 2020b), the conventional filter was not assessed through the impact phase. This means that the RMSE value for the conventional filter did not account for any error that may have emanated if the filter was applied during and after the impact phase. Therefore, it is not valid to compare the ability of this filtering method to effectively remove noisy data from kicking impacts with that of the modified fractional Fourier filter.

The performance of the modified fractional Fourier filter from Augustus et al. (2020b) has also been compared against further conventional filters and on data collected from a greater number of Soccer players (Augustus et al., 2020a). Augustus et al. (2020a) compared filter performance using data collected from 23 semi-professional players. It was concluded that the modified fractional Fourier filter and conventional Butterworth filters with high cut-off frequencies (70 Hz and greater) performed comparably when comparing kicking leg impact kinematics. These included angular velocities of the knee, changes in angular displacement of the ankle, and foot velocities. Although, for higher order kinematics such as angular and linear accelerations the modified fractional Fourier filter produced more accurate results through the maintenance of peak accelerations during impact and removal of noise before and after the impact phase. The modified fractional Fourier filter should thus be preferred if second order derivatives or kinetics are the focus variables. In contrast, the conventional filter with a 70 Hz cut-off frequency removed noise during the approach and follow through but did not preserve the peak accelerations during impact, and the conventional filter with greater cut-off frequency (150 Hz) better matched the peak values during impact but produced noisier acceleration data during the approach and follow through.

A consideration to be made is that previous time-frequency filters have only been tested using data sampled at maximum rates of 1000 Hz. Given the short duration of impacts (discussed in Section 2.4), and as such the need to collect sufficient data for subsequent analyses, sampling rates greater than 1000 Hz would prove valuable and have been used in previous research focused around the impact phase (4000 Hz: Ball et al., 2013a; Peacock et al., 2017; Peacock & Ball, 2017, 2018a, 2018b, 2019a, 2019b; 5000 Hz: Nunome et al., 2013; Shinkai et al., 2006, 2007, 2009; 6000 Hz: Ball, 2010; Ball et al., 2010; Smith et al., 2009). Whilst it is the case that time-frequency filters such as the modified fractional Fourier filter require data sampled at adequate rates, it is not known whether these same filtering methods would be equally effective with data sets collected at frequencies greater than 1000 Hz. The modified fractional Fourier filter has also only been tested on data from Soccer instep kicking and so its performance on Rugby Union place kicking data is unknown. For these reasons it is possible that some adjustment and altering of the filtering methods may be necessary to ensure that these filters are suitably implemented on high frequency data and in Rugby Union place kicking.

Data processing summary

Previous research investigating the effects of various data processing methods on kinematic data has demonstrated that time-frequency filters produce superior performance over conventional filters when filtering over the entire duration of kicking in Soccer. Consequently, future explorations of ball kicking impacts likely do not need to analyse the swing phase and impact phase separately but can filter throughout the entire duration and still achieve accurate results. This would be of particular benefit when investigating Rugby Union place kicking since no such filtering methods have previously been used when investigating place kicking. Time-frequency filters have, however, only been tested on biomechanical kicking impact data when sampled at 1000 Hz during Soccer kicking. Consequently, due to this fact and that a single filtering method (including the employed cut-off frequency) cannot be readily applied to all investigations, caution should be taken when investigating kicking within other sports and when sampling at greater rates to ensure satisfactory results are obtained. Nonetheless, previous analyses of time-frequency filters have demonstrated their effectiveness in removing noise whilst maintaining peak values (Augustus et al., 2020a, 2020b; Georgakis et al., 2002a; Georgakis & Subramaniam, 2009; Nunome et al., 2006) and they should therefore be more widely implemented in biomechanical movements that contain impacts – in particular the place kick in Rugby Union where the impact phase has largely been ignored.

2.8 Chapter Summary

This chapter began by outlining the first phase of a place kick – the setting up of the ball on the kicking tee and the orientations at which it can be placed. It was identified that only one study has previously quantified the ball orientations used by kickers in Rugby Union. However, no further conclusions were made relating to the ball orientations. The effects of the orientation of a prolate spheroid ball on ball flight characteristics were discussed in the context of Australian Football and the results suggested that ball orientation does influence impact efficiency and ball flight velocity.

The time between setting up the ball and the impact, consisting of the physical preparation and concentration phase and the approach phase, was discussed. The approach phase has been the focus of the majority of prior research into Rugby Union place kicking. The kinematics and kinetics of the approach phase, including the whole-body translation towards the ball and the swing of the kicking leg, were described. The implications of this phase on kick performance (distance and accuracy) were explored, and it was concluded that whilst the foot and ball are not in contact during this phase, the result of the approach includes the delivery of the kicking foot to the ball.

The next section of this literature review outlined the importance of the impact phase and its role in transferring the flight characteristics to the ball. However, there have been no previous investigations into the impact phase during Rugby Union place kicking. For this reason, the impact phase was explored in the context of kicking in Soccer and Australian Football and the influence of ball orientation on impact characteristics was highlighted.

Finally, the follow through was briefly discussed and data processing methods were compared and appraised. The filtering of raw trajectory data is an area of important consideration for place kicking due to the transition of data with low frequency content surrounding the impact phase to data with high frequency content during the impact phase. It was determined that the implementation of a time-frequency filter can generally produce the most accurate results during movements that contain impacts. This would help to enable the previously unexplored place kicking impact phase, including the instants of ball contact and release, to be examined whilst not under-smoothing the data around the impact.

CHAPTER 3: THE BALL SETUPS USED BY KICKERS AT THE 2019 RUGBY WORLD CUP AND THEIR ASSOCIATIONS WITH KICK SUCCESS

3.1 Introduction

The importance of successful place kicking in Rugby Union and the impact it can have upon results is clear (Quarrie & Hopkins, 2015), as described in Chapter One. Despite this, there is not one technique used by all kickers. Differences between players are also evident right from the ball setup phase when the ball is placed on the tee. Different kicking tees are used and the long axis of the ball is often orientated differently between kickers. A range of orientations from 2° to 56° have previously been observed in 14 professional Rugby Union place kickers (Bezodis et al., 2018). Due to the prolate spheroid shape of the ball used in Rugby Union, the use of various ball orientations could potentially influence the kicker's technique so that they can impact the desired location on the ball. This in turn may have implications for the foot–ball collision, consequent ball flight characteristics, and ultimately the performance outcome.

The effects of differing impact variables on the kicking of prolate spheroid balls have previously been investigated in some detail, as discussed in Chapter Two (Ball & Peacock, 2020; Holmes, 2008; Michelini et al., 2019; Peacock & Ball, 2017). It has been identified that ball orientation influenced ball velocity, elevation angle and spin rate when a mechanical kicking limb enabled systematic exploration of various impact variables – ball orientation, foot velocity, and impact location on the foot in both the medio-lateral and proximal-distal directions (Peacock & Ball, 2017). A ball orientation of 43° was found to produce the greatest Australian Football ball velocity when foot velocity (16.7 m/s) and impact location on the foot in both the medio-lateral and proximal-distal directions were controlled (Peacock & Ball, 2017). Additionally, controlled investigations into the effects of the orientation of Rugby Union balls have found that orientations leading to impacts between the ball belly and the point of the ball resulted in the lowest coefficient of restitution (Michelini et al., 2019) and foot–ball velocity ratio (Ball & Peacock, 2020) – two variables commonly used to measure impact efficiency. Altering the ball orientation such that the impact occurred on the point led to an increase in coefficient of restitution (Michelini et al., 2019), but the largest values were seen when the impact occurred on the belly of the ball (Holmes, 2008; Michelini et al., 2019). These findings would likely have implications on scoring opportunities within a match since a greater ball velocity would result in a greater flight distance, increasing the range at which points could be scored from (providing the velocity vector is directed appropriately). However, accuracy is a constraint that was not considered, and it is not known exactly how this would translate to place kicking in human kickers.

Before further experimental studies with human participants are conducted into the effects of ball orientation on kick technique, impact and ball flight characteristics, and resulting kick performance measures, it is first beneficial to explore what ball orientations are used by elite kickers and how these might associate with kick success. The aim of this chapter was to therefore investigate the different ball setups used by international Rugby Union place kickers competing in the 2019 Rugby World Cup and to quantify the success of place kicks from different ball orientations after accounting for other situational factors (kick position on the field, time in game the kick was taken, current match score, and outcome of the kicker's previous kick). This Chapter will address research question 1: *"What are the ball setup preferences of elite international Rugby Union players, and how do these associate with kick performance?*" and inform future research to investigate the mechanics of kick technique and the foot–ball impact.

3.2 Methods

3.2.1 Participant Information

The place kicks of 51 international Rugby Union kickers (mean ± *SD*: age = 27 ± 4 years; mass = 88.8 ± 6.6 kg; height = 1.83 ± 0.05 m; descriptive statistics collected from the Rugby World Cup 2019 website, www.rugbyworldcup.com/2019; descriptive statistics of each individual kicker are presented in Appendix A) were analysed. Consistent with the methods of Pocock et al. (2018), each of the included kickers attempted at least one place kick during the tournament. It was also deemed important to include all kicks such that subsequent analyses were representative of the whole tournament. Removing kickers who took less than an arbitrary threshold number of kicks would lead to a greater bias towards those kickers who took more kicks than would be the case if all kickers were retained. This criteria for including kicks will be appraised further in section 5.3.

3.2.2 Data Collection

Data were collected visually from televised footage of the 45 matches played at the 2019 Rugby World Cup, hosted in Japan. The type of tee used and ball (size 5 Gilbert Sirius match ball) orientation were observed for each kicker, at each kick. These were qualitatively categorised by a single observer as either *high* or *low* (for tee type), and ball orientation was defined as either *forward*, *slanted* or *horizontal* depending on whether it visually appeared to be closest to 15° (e.g. Figure 2.1a), 45° (e.g. Figure 2.1b) or 75° (e.g. Figure 2.1c), respectively.

Distances and angles to the goal posts (kick angle was 0° if the kick was straight in front of the goal posts and increased as the kick position moved towards either the left or right touchline) were collected from www.goalkickers.co.za for all kicks (consistent with Pocock et al., 2018), where they had been manually plotted and calculated (to the nearest integer) based on the television footage.

The following variables were also recorded for each kick based on the procedures of Pocock et al. (2018): time in game the kick was taken (categorised into 10-minute intervals, where kicks taken after 40 minutes but during the first half were included in the 31-40 interval, and kicks taken after 80 minutes were included in the 71-80 interval), the current score (categorised into score margin intervals relative to the current kicker’s team: winning by 8+, 4-7, 1-3; scores tied; or losing by 1-3, 4-7, 8+), kick type (conversion or penalty), outcome (success or miss), and the outcome of the kicker’s previous kick (success, miss or first kick).

3.2.3 Statistical Analysis

Mean distance and angle were calculated for the kicks taken in each category of ball orientation. A one-way ANOVA was used to identify any significant ($p < 0.05$) main effects of kick distance and angle, and pairwise comparisons were made with Fisher’s LSD.

Binomial logistic regression analysis was performed to estimate the probability of kick success based on the recorded variables (SPSS Statistics version 26, IBM, USA). A logistic regression model was used for comparisons between the orientation categories since the outcome was dichotomous and the model can account for the interacting constraints that can influence kick outcome. Categorised time of kick and score margin, kick distance, kick angle, success of previous kick and ball orientation category were therefore all used in the regression model as independent variables. The model was trained on all kicks using a forced entry method since the variables that were desired in the model were already known based on the methods and results of Pocock et al. (2018), with the additional inclusion of ball orientation. The performance of the model was evaluated based on the proportion of kicks that it was able to correctly classify as success or miss.

One unit was regarded as 1 m and 1° for kick distance and kick angle, respectively. Predicted odds of success were calculated from the output of the regression model at each independently increasing metre and degree, for each of the three ball orientations. In all calculations the other situational variables were kept constant by using the reference category and hence were accounted for in this manner. Distance and angle thresholds were then identified (separately for each category of ball orientation) as the first values where predicted percentage of success dropped below the mean success percentage for the tournament (Pocock et al., 2018).

3.3 Results

A total of 416 place kicks were taken by 51 different kickers; 314 were successful, giving a mean tournament success percentage of 75.5%. Of the 416 kicks, 116 (27.9%) were setup with a forward ball orientation, 152 (36.5%) with a slanted orientation, and 148 (35.6%) with a horizontal orientation. Each kicker used a consistent ball orientation for all of their kicks throughout the tournament; 13 (25.5%) of the kickers used a forward ball orientation, 14 (27.5%) used a slanted orientation, and 24 (47.1%) of the kickers used a horizontal orientation. Raw success rate varied between the categories of kicks with the slanted category being the most successful and the forward category being the least successful (Table 3.1). Overall mean kick success percentage for all kicks was greatest when taken during the 21-30-minute time interval (84.9%) and lowest when taken during the 71-80-minute time interval (67.7%; Figure 3.1a). Match score at the time of the kick also influenced kick success. Overall mean kick success percentage was greatest when scores were level (80.8%) and lowest when the kicker’s team were winning by 1-3 points (68.2%; Figure 3.1b).

Table 3.1. Success percentages and mean distances and angles for all kicks taken in each category (mean ± *SD*).

Ball Orientation Category	Success (%)	Distance (m)	Angle (°)
Forward	73.3	28.0 ± 12.1	31 ± 15
Slanted	78.9	29.8 ± 11.4	31 ± 16
Horizontal	73.6	31.0 ± 11.3*	29 ± 16
All	75.5	29.7 ± 11.6	30 ± 16

* Significantly ($p < 0.05$) different from the forward ball orientation category.

Kicks in the horizontal category were taken from the greatest mean distance to the posts (31.0 ± 11.3 m), whilst the forward (31 ± 15°) and slanted kicks (31 ± 16°; Table 3.1) were taken from the largest mean kick angle. There was no significant main effect of ball orientation category on kick distance ($p = 0.12$) or angle ($p = 0.59$), although pairwise comparisons revealed kicks set up with a horizontal orientation were taken from significantly ($p < 0.05$) further away than those with a forward orientation. Over the course of the tournament, six kicks were attempted from more than 50 m and all used ball orientations classified into the horizontal category.

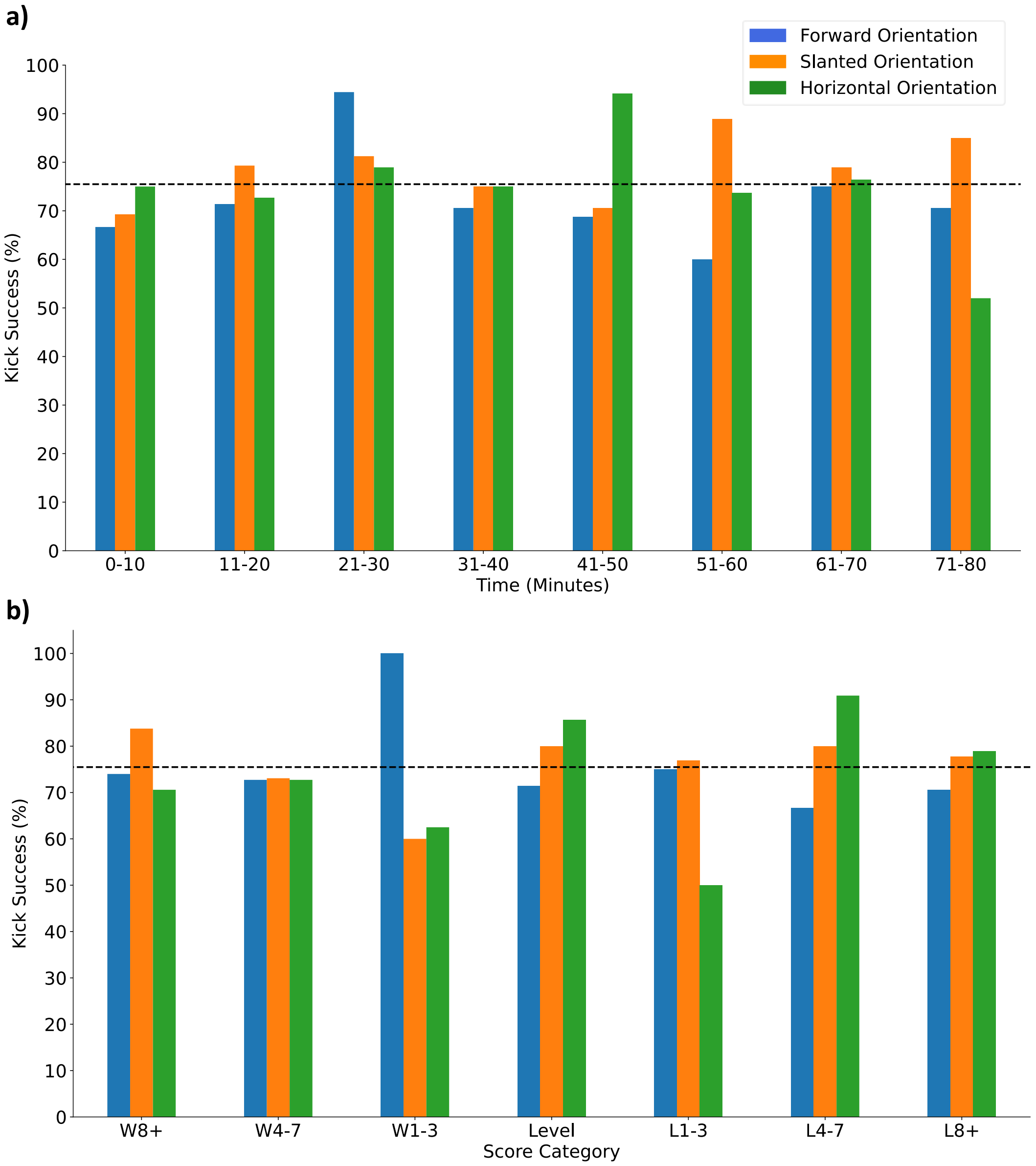


Figure 3.1. Success percentages for kicks taken in a) each 10-minute time interval, and b) each score category, presented for each ball orientation category. The black, horizontal dashed line illustrates the mean tournament success percentage.

In comparison to a model with no independent variables, the binary logistic regression was statistically significant in predicting the outcome of kicks at goal ($\chi^2 = 93.1$, $df = 19$, $p < 0.001$). The model correctly predicted 79.1% of cases; 37.3% of misses were classified correctly, whilst 92.7% of successful kicks were classified correctly. Kick distance ($p < 0.001$) and kick angle ($p < 0.05$) were the only two independent variables statistically significant in predicting kick outcome (Table 3.2). When setting the forward ball orientation as the reference category, the slanted category had an odds ratio for success of 1.7 (95% CI = 0.9 – 3.2) and the odds ratio for the horizontal orientation was 1.2 (95% CI = 0.6 – 2.3).

Table 3.2. Results of the binomial logistic regression.

	Coefficient	SE	*p*	OR	95% CI for OR	
					Lower	Upper
Time Period (0-10)^			0.826			
Time Period (11-20)	0.092	0.558	0.870	1.096	0.367	3.273
Time Period (21-30)	0.862	0.597	0.149	2.367	0.735	7.630
Time Period (31-40)	0.304	0.544	0.576	1.356	0.466	3.940
Time Period (41-50)	0.463	0.588	0.431	1.589	0.502	5.034
Time Period (51-60)	0.454	0.589	0.441	1.575	0.496	5.000
Time Period (61-70)	0.278	0.585	0.635	1.320	0.420	4.155
Time Period (71-80)	0.033	0.545	0.951	1.034	0.355	3.008
Score Categories (W8+)^			0.877			
Score Categories (W4-7	-0.055	0.399	0.891	0.947	0.433	2.071
Score Categories (W1-3)	-0.019	0.556	0.972	0.981	0.330	2.914
Score Categories (Level)	0.667	0.668	0.318	1.948	0.526	7.210
Score Categories (L1-3)	-0.233	0.577	0.686	0.792	0.256	2.453
Score Categories (L4-7)	-0.307	0.512	0.548	0.735	0.270	2.005
Score Categories (L8+)	-0.342	0.467	0.464	0.710	0.285	1.774
Kick Distance (m)	-0.106	0.017	<0.001*	0.899	0.870	0.929
Kick Angle (°)	-0.021	0.010	0.029*	0.979	0.961	0.998
Previous Kick (Successful)^			0.691			
Previous Kick (Missed)	0.289	0.345	0.402	1.335	0.679	2.622
Previous Kick (First Kick)	-0.017	0.413	0.968	0.984	0.438	2.208
Ball Orientation (Forward)^			0.307			
Ball Orientation (Slanted)	0.512	0.338	0.130	1.669	0.860	3.239
Ball Orientation (Horizontal)	0.196	0.328	0.550	1.216	0.640	2.313
Constant	4.835	0.846	<0.001	125.870		

SE = standard error of the coefficient; OR = odds ratio; CI = confidence interval for the OR.
* Significant ($p < 0.05$) in predicting kick outcome.
^ Category used as the reference category.

From the tournament mean distance (29.7 m) and an angle of 0° (i.e. directly in front of the goal posts), the model indicated that a place kick had an expected success of 84.4%, 90.0%, or 86.8% when taken using a forward ball orientation, slanted orientation, or horizontal orientation, respectively. Using the mean tournament success percentage of 75.5% as a threshold, distance thresholds were identified (using kick angle = 0°) from the results of the logistic regression for the forward ball orientation (35 m), slanted orientation (40 m) and horizontal orientation (37 m; Figure 3.2a). The angle thresholds (when keeping distance constant at the tournament average of 29.7 m) were 27° (forward orientation), 52° (slanted orientation), and 37° (horizontal orientation; Figure 3.2b).

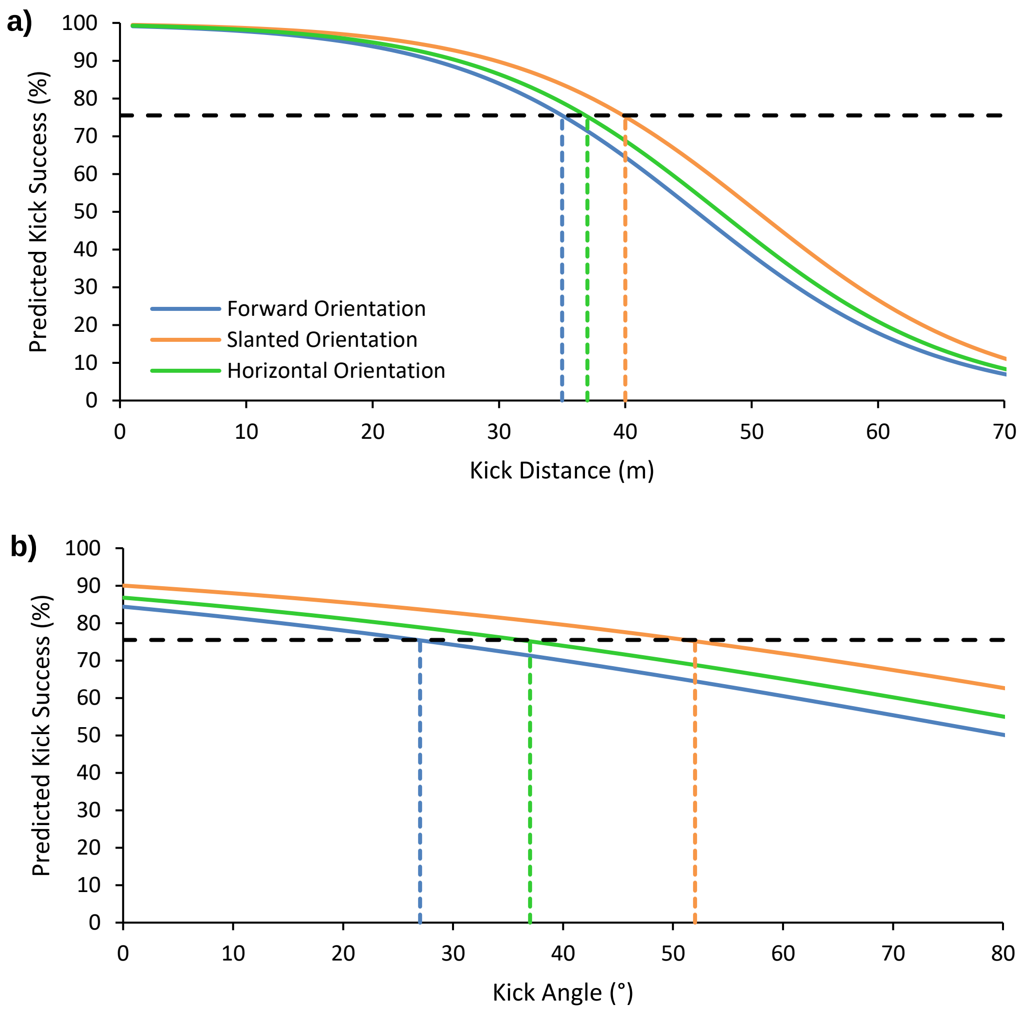


Figure 3.2. Predicted percentages of kick success at a) each independent metre, and b) each independent angle when distance is kept constant at 29.7 m, presented for each ball orientation category. Threshold distances (vertical dashed lines) are calculated from the results of the logistic regression as the distance or angle at which success dropped below the mean tournament success percentage (black, horizontal dashed line).

3.4 Discussion

This chapter investigated the use of different place kicking ball orientations at the 2019 Rugby World Cup and the association these had with success. In doing so, it aimed to address research question 1: "*What are the ball setup preferences of elite international Rugby Union players, and how do these associate with kick performance?*". It was identified that of the 51 different kickers analysed, 13 used a forward ball orientation, 14 used a slanted orientation, and 24 used a horizontal orientation. This indicates that the ball orientation preferences of the kickers were reasonably well distributed between the three orientation categories. The logistic regression revealed that, when controlling for all other considered variables, kicks taken with a slanted ball orientation had greater predicted success (90.0% for a kick taken from 29.7 m and 0°) than the forward (84.4%) and horizontal (86.8%) orientation categories (Figure 3.2a). Whilst it cannot be concluded from these differences in predicted success that one orientation is better than the others, it does demonstrate that kicks taken with a slanted ball orientation had the greatest predicted success levels even when other factors were taken into consideration.

The sigmoidal curve indicating predicted success, at progressively increasing distances, is shifted furthest to the right for the slanted orientation. Therefore, this orientation has the greatest chance of success at any given distance when potentially influential factors such as time period of match, current match score, and previous kick success are accounted for. A similar pattern was observed when investigating kick angle. These differences in predicted kick success are due to the odds ratios of the ball orientation categories. An odds ratio of 1.7 was calculated from the logistic regression for the slanted category and an odds ratio of 1.2 for the horizontal orientation category (relative to the forward orientation as the reference category). This means that when all other factors remain constant, the increase in odds of success is greater for the slanted category of kicks than the horizontal category, in relation to the forward ball orientation category. Therefore, when accounting for the effects of other potentially influential factors, at the 2019 Rugby World Cup, the use of a slanted ball orientation led to the highest rate of predicted success, whilst the forward orientation led to the poorest predicted kick success. No statistical analyses were performed on the raw success percentages (Table 3.1) between the three orientation categories, as a direct comparison between them is limited due to that fact that they do not account for other interacting constraints. These include those input into the logistic regression as independent variables, as have previously been used in analyses of the previous (2015) Rugby World Cup (Pocock et al., 2018).

The inclusion of ball orientation as an independent variable in the binomial logistic regression analysis increased the accuracy of the model compared to a model from the previous Rugby world Cup that did not take ball orientation into consideration (Pocock et al., 2018). The model in this chapter, which took into account the ball orientation used by the kickers, correctly predicted 79.1% of all cases. Of all the misses, 37.3% were classified correctly, and 92.7% of successful kicks were classified correctly. The model implemented by Pocock et al. (2018), on which the current analysis was based, correctly classified 76% of all cases (54% of missed kicks classified correctly and 79% of successful kicks classified correctly) at the 2015 Rugby World Cup. This shows good consistency in the accuracy with which place kick performance outcome can be predicted from the assessed variables at the highest level of competition. However, caution should be applied when making direct comparisons between the performance of these two models since the input data differed between the two studies. When comparing the model that includes ball orientation as an independent variable to one that does not, similar findings are still seen when using a consistent data set (i.e. that of this chapter). A model without ball orientation had slightly reduced performance and correctly classified 77.4% of all kicks; 31.4% of all misses and 92.4% of all successful kicks were classified correctly. Therefore, considering the ball orientation employed during place kicking is useful in enabling a slightly more accurate prediction of kick outcome, but ball orientation itself is not a statistically significant variable in the model as a whole.

Kicks categorised as using a horizontal ball orientation were attempted from the greatest mean distance (31.0 m) and contained the only kicks taken from greater than 50 m (n = 6), with the furthest attempted kick being 57 m. Two of the kicks attempted from greater than 50 m were by kickers classified as non-first choice kickers. In these cases, the previous and regular kicker paused their kicking duties to allow the non-first choice kicker to attempt the current kick, before the regular kicker resumed the role for subsequent kicks. On these two occasions both kicks were unsuccessful but failed due to a lack in accuracy as opposed to ball flight distance. These types of scenarios and kicks give support to the anecdotal observations of specialist long distance kickers who are deemed to be more competent at kicking over longer distances than the other more regular kickers in their team. This would enhance the team's point scoring opportunities and therefore positively affect their likelihood of winning a match, if all else remained unchanged. It is probable that other factors such as the technique of the kicker influence this long-distance capability, but these may also interact with the orientation of the ball to enable greater ball flight distances. Although it is currently a very limited sample size, based on the two reported cases the use of a horizontal ball orientation does appear to be a preference of specialist long distance kickers.

The results of Peacock and Ball (2017), Ball and Peacock (2020) and Michelini et al. (2019) may all aid in understanding the results observed in this chapter. Peacock and Ball (2017) found that Australian Football ball velocity is greater when impact occurs on the point (ball orientation of 65°, comparable to the horizontal category of this chapter = ball velocity of 24 m/s) compared to the belly (ball orientation of -25° = ball velocity of 20 m/s). However, the greatest ball velocity (24.4 m/s) was achieved when using an orientation of 43°, comparable to the slanted category of this chapter (Peacock & Ball, 2017). Ball and Peacock (2020) found that foot–ball velocity ratio was greater when the ball was orientated such that the impact occurred on the point of the ball (foot–ball velocity ratio = 1.32) compared to impacting between the point and the belly of the ball (foot–ball velocity ratio = 1.25). It has additionally been observed that coefficient of restitution is greater when impact occurred on the point (0.55; ball orientation = approximately 59°) than when impact occurred between the point and the belly of a Rugby Union ball (0.41; ball orientation = approximately 45°, comparable to the slanted category of this chapter; Michelini et al., 2019). However, a coefficient of restitution value of 0.65 was achieved when the ball was orientated such that the impact occurred on the ball's belly (ball orientation = approximately -8°). The results of Michelini et al. (2019) suggest that impacting on the belly of the ball would lead to greater ball flight velocities than other impact locations for a given foot velocity. Ball flight elevation angle and angular velocity must also be considered. Peacock and Ball (2017) found that the elevation angle of ball flight and the rate of backspin are affected by changes in ball orientation. Since these are factors known to influence kick performance measures (Atack et al., 2019b; Linthorne & Stokes, 2014; Seo et al., 2007) and ball flight parameters combine to determine whether a given kick is successful, further work is needed to quantify the overall performance (i.e. incorporating distance and accuracy) of a kick when the effects of ball orientation are explored.

Although ball orientations were visually categorised into one of three categories, the current results revealed the existence of different ball orientation preferences between kickers at the very highest level of competition. It was identified that individual kickers used a consistent ball orientation and that these preferences appear to have an effect on kick success. However, the developed logistic regression model incorrectly classified 20.9% of all kicks which indicates there are parameters not included in the model that influence kick outcome. This is further illustrated by the fact that the model incorrectly classified 62.7% of misses, and so these were not predictable using the currently implemented independent variables. Since these results were obtained from television footage, it was not possible to quantify the differences in the kickers’ technique or impact mechanics between the different orientations used, and clearly these factors are likely to explain at least some of the model’s inability to correctly classify all kicks. Additionally, the criteria used for the inclusion of kickers in the regression model is a potential limitation. Kickers were included if they attempted at least one place kick (Pocock et al., 2018). Some kickers attempted up to 34 kicks, however several kickers attempted a single kick across tournament. This, combined with the fact that the distribution of kicks was not spread evenly between matches across the tournament, will likely have acted as a random factor and potentially resulted in the model being biased towards those kickers who attempted a greater number of kicks (limitation discussed further in section 5.3). Nonetheless, these results identify that different ball orientation preferences exist and are distributed somewhat evenly across a large group of elite international kickers. Whilst the mean odds ratios suggest that using a slanted ball orientation may lead to the greatest odds of kick success, this finding was non-significant in the model and further research with larger samples sizes is warranted to confirm the direction and magnitude of this finding. However, different ball orientation preferences clearly exist and it is possible that these may have some influence on performance. More detailed experimental analyses of the foot–ball interaction in Rugby Union place kicking from different ball orientations would therefore likely prove valuable. These could enable an understanding of whether one orientation is simply preferable to the others for all performance considerations (i.e. distance and accuracy) irrespective of the technique of the kicker striking the ball, or whether a range of factors interact to influence and inform the selection of a preferred ball orientation for a given kicker.

3.5 Chapter Summary

This chapter investigated the ball orientations used by international place kickers at the 2019 Rugby World Cup and explored the associations of these orientations with kick performance. The ball orientations were grouped into three categories and performance between these categories was assessed using the raw success percentages and a binomial logistic regression model was also developed to compare performance, whilst accounting for other situational factors. Ball orientation was not a significant factor in the model used to predict kick success. However, differences between the ball orientation categories were observed in both the raw and the predicted kick success percentages, with the slanted ball orientation (approximately 45°) seemingly resulting in the highest levels of performance based on the mean odds ratios. More detailed experimental analyses of the foot–ball interaction using a variety of different ball orientations would likely be beneficial in order to further understand why these differences may occur and whether certain orientations might be preferable for a given kicker based on their place kicking technique.

CHAPTER 4: INVESTIGATION INTO THE EFFECTS OF CHANGING BALL ORIENTATION ON PLACE KICK TECHNIQUE AND PERFORMANCE

4.1 Introduction

As identified in Chapter 3, different ball orientation preferences have been observed between international-level place kickers and performance was found to vary when kicks were categorised based on the ball orientation used. Aspects of place kick technique were not considered, however. Differences in the swing planes of the kicking foot have been observed between kickers and these were associated with different performance outcomes (Bezodis et al., 2019). The final product of the kicking foot's path during the downswing is the position and orientation of the foot relative to the ball at initial foot–ball contact, and it appears that individual kickers are relatively consistent at controlling these foot kinematics at initial foot–ball contact when using their preferred ball orientation (Ford and Sayers, 2015).

Whilst variations in place kick kinematics have been observed during the downswing and at the instant of initial foot–ball contact when comparing technique across groups of kickers (Bezodis et al., 2018, 2019; Ford & Sayers, 2015; Sinclair et al., 2014, 2017), the orientation of the ball is a variable that has not been controlled or considered. As a result of practising with a consistent ball orientation a place kicker is likely to have developed predetermined movement patterns that are more specific to that ball orientation. However, the orientation of the ball on the tee is a task constraint that may influence various aspects of a place kicker's technique (Newell, 1986). Therefore, this chapter aims to investigate the potential changes in place kick technique when the orientation of the ball is systematically altered and to evaluate the effects of these alterations to ball orientation on resulting impact efficiency and kick performance measures. As such, the current chapter will aim to answer research questions 2 and 3: *"How do individuals change their kick technique when different ball orientations are used?"* and *"How does ball orientation affect impact efficiency and resulting ball flight characteristics and kick performance?"*.

4.2 Methods

4.2.1 Participants

Eight male kickers (mean ± *SD*: age = 23 ± 4 years; mass = 73.0 ± 2.9 kg; height 1.75 ± 0.04 m), consisting of four university-level Rugby Union players and four Soccer players (two university-level, two semi-professional) volunteered to participate and were free from injury at the time of the study (Table 4.1). The inclusion of Soccer kickers was such that they did not have a preferred ball orientation but were chosen over novice kickers since the Soccer kickers were still highly experienced with a general kicking technique. All procedures were approved by an institutional ethics committee for human research.

Table 4.1. Descriptive characteristics of all kickers.

Kicker	Height (m)	Mass (kg)	Age (Years)	Rugby Experience (Years)	Kicking Experience (Years)
Rugby Kickers					
1	1.73	73	22	14	5
2	1.71	75	21	13	8
3	1.71	75	20	14	4
4	1.71	73	22	13	11
Mean ± *SD*	1.72 ± 0.01	74.0 ± 1.2	21 ± 1	14 ± 1	7 ± 3
Soccer Kickers					
5	1.79	73	22	0	14
6	1.77	70	21	0	15
7	1.82	77	34	0	25
8	1.74	68	24	0	12
Mean ± *SD*	1.78 ± 0.03	72.0 ± 3.9	25 ± 6	0	17 ± 6
Overall Mean ± *SD*	1.75 ± 0.04	73.0 ± 2.9	23 ± 4	14 ± 1	12 ± 7

Kicking experience = number of years playing Soccer (for the Soccer kickers), or number of years that place kicking was part of a training routine (for the Rugby kickers).

4.2.2 Data Collection

Data were collected outdoors on rubber infill 3G artificial turf using three high-speed cameras (Photron Fastcam MiniAX50) sampling at 4000 Hz. One camera was placed perpendicular to the ball setup, 4 m away viewing the sagittal plane, and the other two were placed approximately 30° either side of the perpendicular (each approximately 4.6 m away from the ball setup; Figure 4.1). Calibration markers were used to calibrate a volume of 0.80 m × 1.30 m × 0.60 m, and the volume of the capture area was approximately 1.20 m × 1.50 m × 0.75 m. The global coordinate system was set such that the y-axis was in the direction of the target, the z-axis was the vertical direction, and the x-axis was the cross product of the two.

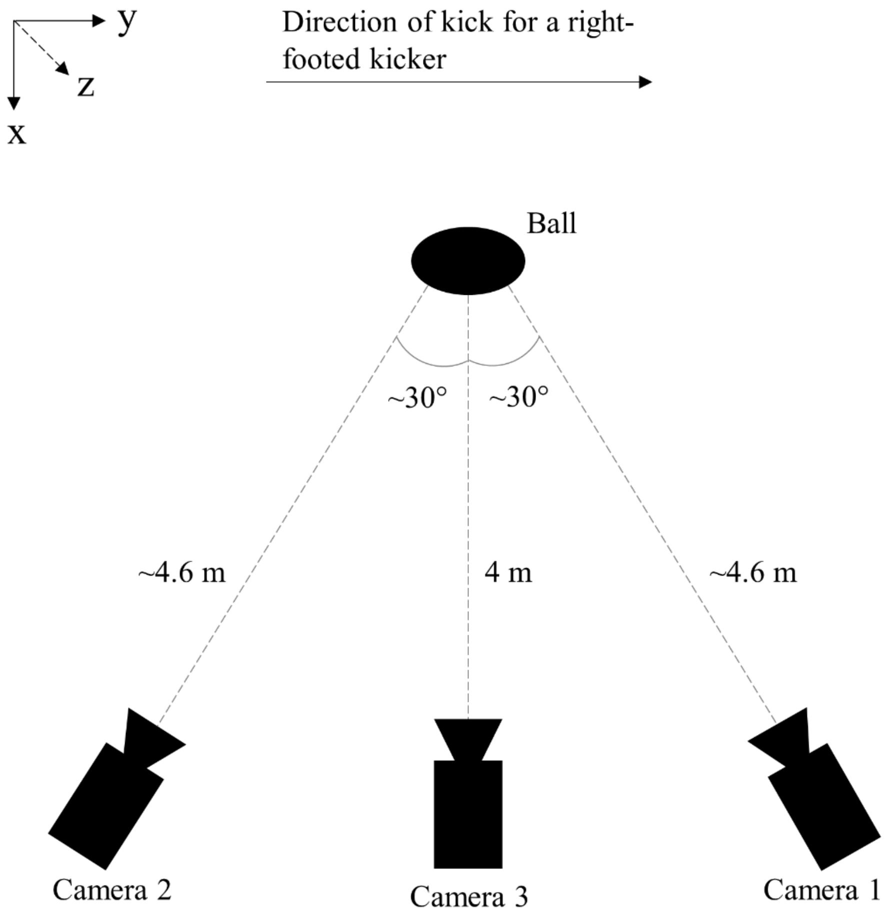


Figure 4.1. Plan view of the camera setup. For the left-footed kickers the setup was the same, but they kicked in the opposite direction.

All kickers wore their own moulded boots and used a size 5 Gilbert Virtuo Match Ball. Six hemispherical markers were placed on the kicker's kicking leg and three points on the ball's surface were identified to allow for tracking of the segmental and ball displacements (locations of markers and ball tracking points are illustrated in Figure 4.2).

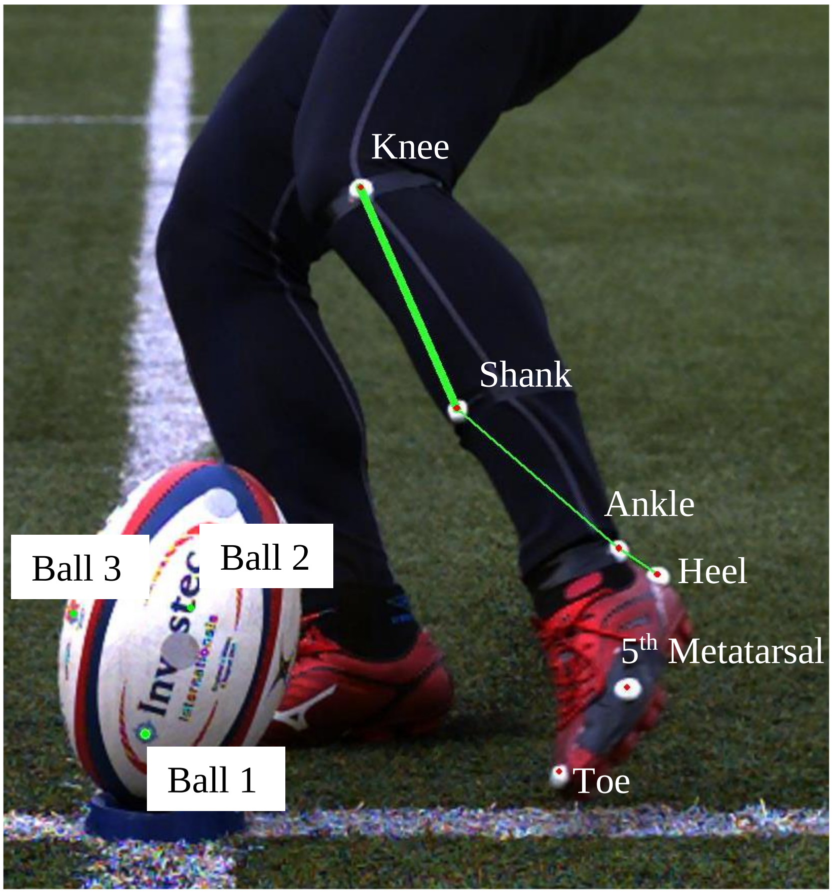


Figure 4.2. The six markers placed on the kicker's kicking leg (overlaid with red dots) and the three tracking points on the ball (overlaid with green dots). Knee = lateral epicondyle; shank = approximately midway down the shank, non collinear with the knee and ankle markers; ankle = lateral malleolus; heel = lateral side of the calcaneus; 5th metatarsal = head of the fifth metatarsal; toe = most distal point of the foot.

4.2.3 Procedures

Following their usual self-directed kicking warm-up, each kicker performed nine maximal effort place kicks. Right-footed kickers kicked in the positive y direction and the left-footed kickers kicked in the negative y direction. For the Rugby kickers, these comprised three kicks where the ball was placed leaning forward slightly (*forward* orientation), three with the long axis of the ball orientated just above the horizontal (*horizontal* orientation), and three taken with the kicker's personal preference of ball orientation (*normal* orientation). The Soccer kickers took three using a forward orientation, three with a horizontal orientation, and three where the ball was placed leaning backwards slightly (*backward* orientation). For all kicks, except those taken with the Rugby kicker's normal orientation, one experienced investigator placed the ball on the tee by visually determining the ball's orientation. The actual resting ball orientations were subsequently quantified three separate times for each kick from the camera 3 footage using 2D video analysis software (Quintic Biomechanics v31, Quintic Consultancy Ltd, UK). The mean value across the three digitisations was taken for each kick. Ball orientations for each condition are presented in Table 4.2, where an angle of 0° represents the long axis of the ball being vertical and a positive value indicates the top of the ball leaning forward in the direction of the kick. An Optimum Adjustable Kicking Tee was used for kicks taken with a horizontal ball orientation, a Gilbert Quicker Kicker II Kicking Tee was used for all forward and backward kicks, and the Rugby kickers used their own preferred tee for kicks taken with their normal ball orientation.

Table 4.2. Orientation of the ball when stationary on the kicking tee, viewed in the sagittal plane. An angle of 0° represents the long axis of the ball being vertically upright, and a positive angle indicates the top of the ball being anterior to the bottom of the ball (mean ± *SD*).

		Ball Orientation Condition			
		Forward	Horizontal	Normal*	Backward
All Kickers ($n = 8$)	Ball Orientation (°)	15.1 ± 0.9 ^{H}	69.3 ± 1.0 ^{F}		
Rugby Kickers ($n = 4$)	Ball Orientation (°)	14.4 ± 0.6 ^{H,N}	69.6 ± 1.5 ^{F,N}	4.6 ± 4.2 ^{F,H}	
Soccer Kickers ($n = 4$)	Ball Orientation (°)	15.8 ± 0.6 ^{H,B}	69.0 ± 0.3 ^{F,B}		-15.8 ± 0.4 ^{F,H}

F = significantly ($p < 0.05$) different to kicks taken with a forward ball orientation.
H = significantly ($p < 0.05$) different to kicks taken with a horizontal ball orientation.
N = significantly ($p < 0.05$) different to kicks taken with a normal ball orientation.
B = significantly ($p < 0.05$) different to kicks taken with a backward ball orientation.
* The orientation of the ball was not controlled when the Rugby kickers placed the ball at their normal, preferred orientation, and as a result this has the largest overall standard deviation. The ball orientation (mean ± *SD*) for each of Rugby kickers' three kicks taken using their normal setup are as follows: 9.0 ± 1.7°; -1.0 ± 3.5°; 6.0 ± 2.6°; 4.3 ± 1.5°.

4.2.4 Data Processing

The markers were each digitised (Frame Dias V, DKH/Q'sfix, Japan) over every frame spanning from a minimum of 88 frames before the start of the impact phase to at least 24 frames after the end of the impact phase. This was undertaken for all three camera views by a single investigator and three-dimensional marker coordinate data were reconstructed using Direct Linear transformation (Abdel-Aziz &

Karara, 1971). Impact start and end frames were visually identified as the frames in which the foot and ball first appeared to make contact and when they first separated again, respectively. Three-dimensional marker coordinate data were exported to MATLAB R2018b (v9.5., MathWorks, USA) for all subsequent processing and analysis using custom-written scripts. Three trials were removed from all analyses due to errors in recording and in any trials where a marker was obscured, or a digitisation/reconstruction error occurred, the affected variable of interest was removed for that trial (Appendix B). Displacement data in the y-axis were inverted for the left-footed kickers to align them with the convention used for the right-footed kickers.

Kicking foot swing plane

The swing plane of the kicking foot was analysed based on the methods of Bezodis et al. (2019). Briefly, the approximate kicking foot centre of mass location was determined using the heel marker on the lateral calcaneus and the marker on the toe tip (based on the method of de Leva (1996) where the foot centre of mass was defined as 44.15% of the distance from the pternion to the toe tip), and its raw trajectory was resampled at 0.01 m intervals (Willmott & Dapena, 2012), ending at visually identified impact start. The trajectory start point was determined at a total path distance equal to 24% of the kicker’s height since this was the greatest relative distance that could be analysed for all kickers. The kicking foot swing plane has previously been found to be planar up to 1.25 m before foot–ball contact in place kicking (Bezodis et al., 2014) and thus this shorter distance would still yield correct swing plane orientations for the downswing. A least-squares plane was subsequently fitted to the kicking foot centre of mass trajectory using orthogonal distance regression (Willmott & Dapena, 2012). The direction of each kicker’s kicking foot swing plane was defined as the angle between the global y-axis and the line of intersection between the swing plane and the global x-y plane. Inclination of the swing plane was defined as the angle between the global x-axis and the line of intersection between the swing plane and the global x-z plane.

Marker data filtering

Raw displacement data from the kicking leg markers were filtered using an adapted fractional Fourier filter based on the procedures of Augustus et al. (2020b). The visually identified impact start and impact end times were first used to define the width of the impact phase (i.e. the duration of the impact phase), and the temporal midpoint of impact was found. All marker displacement data were filtered using a fourth order zero-lag Butterworth filter. During the swing phase, both prior to and after impact, a cut-off frequency of 80 Hz was used. From the start of the impact phase this cut-off frequency linearly increased from 80 Hz, up to a peak cut-off frequency at the temporal midpoint of impact, before linearly decreasing back down to 80 Hz at the visually identified end of impact. A visual representation of the employed filter is presented in Figure 4.3. The peak cut-off frequency values during impact varied from 100-265 Hz depending on the marker being filtered. Cut-off frequencies for each marker were chosen based on visual inspection of their respective filtered displacement and velocity data against their raw displacement and velocity data. Judgement was made based on how well the filtered data visually matched the raw low frequency data around the impact phase and then the filter's ability to filter at a higher frequency during the impact phase whilst still removing clearly noisy data (see Figure 4.4 for an example).

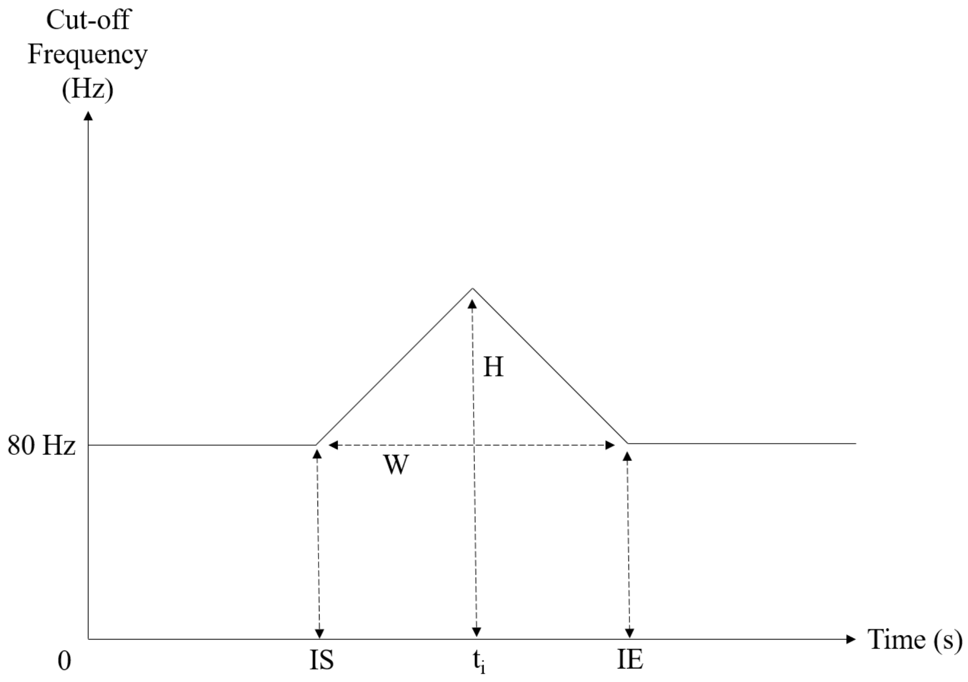


Figure 4.3. Visual representation of the implemented fractional Fourier filter. IS = visually identified start of impact; IE = visually identified end of impact; W = width of impact; H = height of impact; t_i = temporal midpoint of impact.

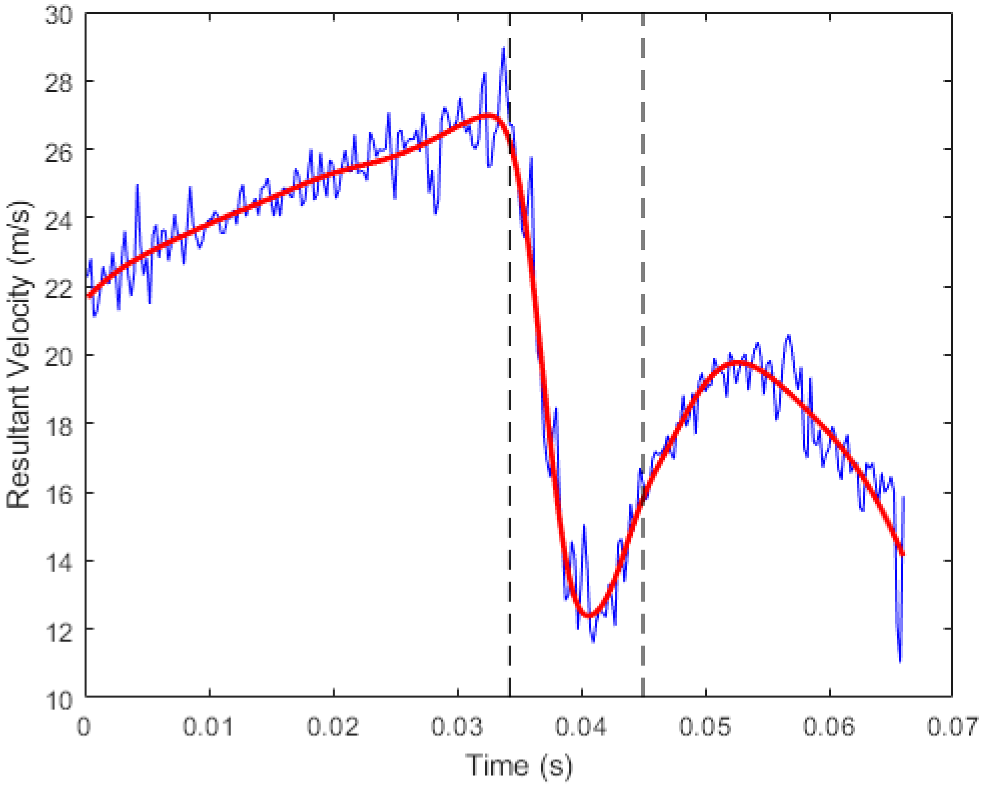


Figure 4.4. Example of raw resultant velocity (blue) plotted against filtered resultant velocity (red) for a fifth metatarsal marker. Data were filtered at 80 Hz during the non-impact phases and up to a peak cut-off frequency of, in this example, 247 Hz during the impact phase. Impact phase start and end times are represented by the vertical dashed lines.

Segment reconstructions

Shank and foot segments were then reconstructed from the filtered marker data as three-dimensional vectors originating from the ankle and heel markers, respectively, and finishing at the knee and fifth metatarsal markers, respectively. Using these vectors, global orientations of the segments and plantar flexion angles were calculated. The azimuth angle for each segment was defined as the angle between a vector in the positive x direction (originating from the segment's origin) and the segment vector projected in the x-y plane. The elevation angle for each segment was defined as the elevation of the three-dimensional segment vector from the x-y plane (Figure 4.5). Plantar flexion of the foot was defined as the angle between the shank and foot segments, calculated using the vector product. An angle of 0° was defined as when the segment vectors were perpendicular, with a positive value indicating plantar flexion.

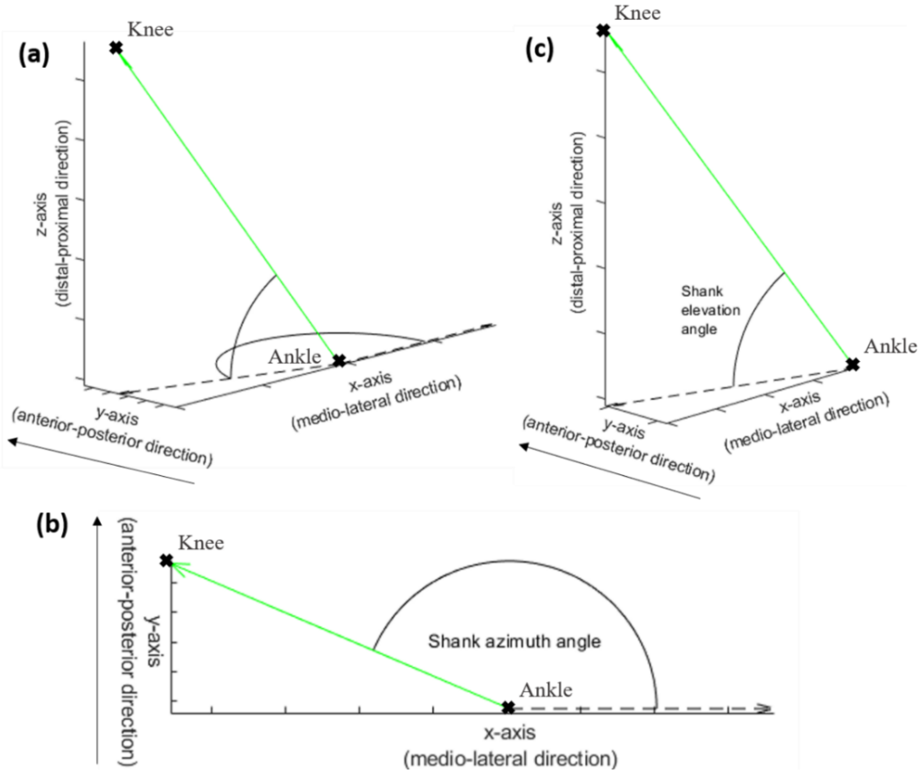


Figure 4.5. Segment angle conventions for the shank (green arrow), with the origin of the arrow representing the ankle and the arrowhead representing the knee. The solid black arrow indicates the direction of kick (positive y direction). **(a)** Both the shank segment azimuth and elevation angles. **(b)** Shank segment azimuth angle (angle between a vector in the positive x direction, originating from the ankle, to the segment vector projected in the x-y plane), viewed from above. **(c)** Shank segment elevation angle (angle between the 3D segment vector and the x-y plane).

Ball impact location

The impact location on the ball was obtained through analysis of the kicks in the sagittal plane using footage from camera 3. The top and bottom of the ball and the visually identified point of impact on the ball shell were digitised three times for each kick (Quintic Biomechanics v31, Quintic Consultancy Ltd, UK). This provided two-dimensional coordinate data for each point, allowing for impact location angle to be calculated and defined locally as the angle from the vector joining the centre (midpoint between the top and bottom of the ball) and top of the ball to the impact location in the clockwise direction about the ball centre (Figure 4.6). A mean value was then found for each kick using the three sets of digitised coordinates. Impact location was also represented globally by adding the ball orientation angle, resulting in an angle between a vector in the positive z direction, originating from the ball centre, and the impact location in the clockwise direction.

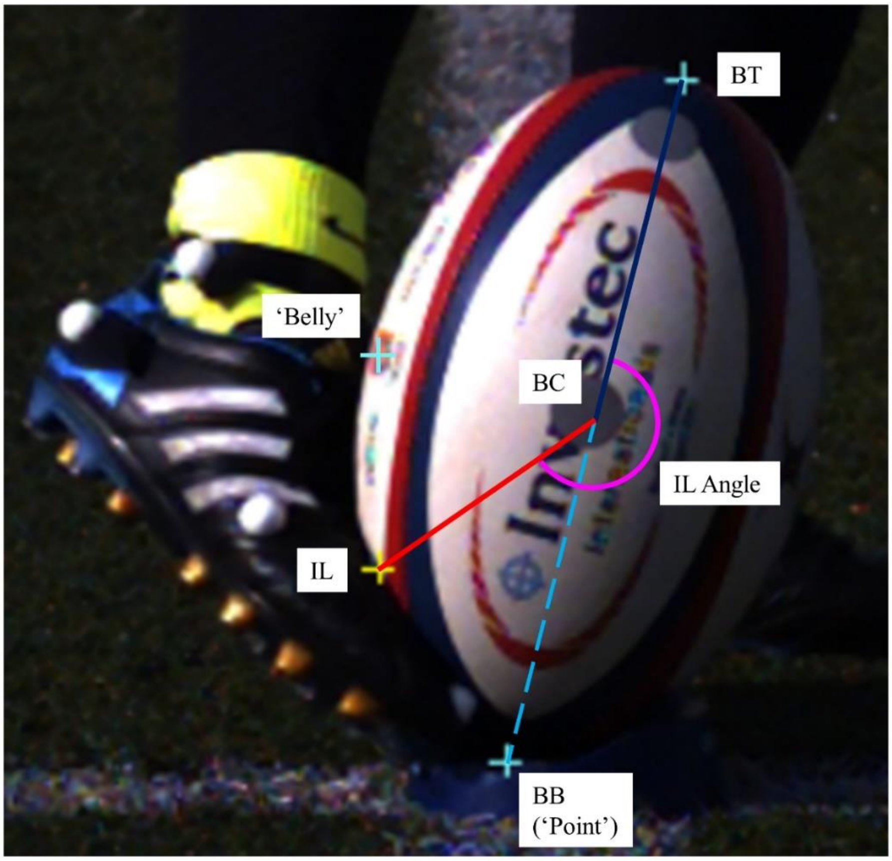


Figure 4.6. Determination of impact location for a kick. BT = top of the ball; BB = bottom of the ball; IL = visually identified impact location; BC = centre of the ball (halfway between BT and BB); IL Angle = impact location angle (angle between a vector from BC to BT and a vector form BC to IL). 'Belly' and 'point' of the ball also annotated for reference.

Impact efficiency and kick performance

Three-dimensional flight kinematics of the ball were determined about each of the global axes using digitised marker data that was reconstructed (Visual3D v2020.08.3, C-Motion, Inc., USA). Resultant velocity of the foot centre of mass was determined by taking the average of eight frames (i.e. 2 ms) of velocity data, calculated using the first order central difference method on the filtered displacement data. This was done either side of the visually identified impact start and end times. Resultant velocity of the ball geometric centre (determined as the midpoint between the three-dimensional top and bottom of the ball) was identified by fitting polynomial equations to the first 10 frames of raw ball flight displacement data immediately after it had visually left the foot (first order for both horizontal directions and second order for the vertical direction). Efficiency measures consisting of coefficient of restitution and foot–ball velocity ratio, like those used by Peacock and Ball (2018b), were subsequently calculated using equations 4.1 and 4.2. These two variables were used to quantify impact efficiency since they both represent a ratio between the velocities of the impacting bodies before and after the impact phase. The only difference between coefficient of restitution and foot–ball velocity ratio is that the former also considers the change in velocity of the foot during the impact phase.

$$\text{Coefficient of restitution} = \frac{v_b - v_f}{u_f} \tag{4.1}$$

$$\text{Foot–ball velocity ratio} = \frac{v_b}{u_f} \tag{4.2}$$

Where: v_b = resultant velocity of the ball geometric centre at the end of impact; v_f = resultant velocity of the foot centre of mass at the end of impact; u_f = resultant velocity of the foot centre of mass at the start of impact.

Kick performance was determined using the ball flight model of Atack et al. (2019b). After the ball's angular velocities at the start of the flight phase were determined about each of the global axes (first order polynomial equations fitted to the first 10 frames of raw ball flight angular displacement data), these values and the three initial linear velocities of the ball geometric centre were inputted into the model. The model output provided the modelled maximum distance of each kick, as if it had been taken from straight in front of the goal posts. This was defined as the maximum anterior displacement over which the kick was modelled to have been successful. The eventual reason for the failure of the kick was also noted as whether the ball would have fallen short of the crossbar or passed outside either of the upright posts if it was taken from a distance greater than the predicted maximum.

4.2.5 Statistical Analysis

For all variables, the mean values from all trials were calculated for each ball orientation condition for each kicker (i.e. typically $n = 3$ except for where trials were missing due to digitisation/reconstruction errors; Appendix B). These values were then used to calculate group means and standard deviations for each of the orientation conditions (as in Table 4.2). Paired-samples t tests were performed to identify any significant ($p < 0.05$) effects between the ball orientation conditions (SPSS Statistics version 26, IBM, USA). When comparing the forward and horizontal ball orientation conditions, three sets of comparisons were made using data from all kickers ($n = 8$), data from only the Rugby kickers ($n = 4$), and data from only the Soccer kickers ($n = 4$). For any comparisons that involved either the normal or backward ball orientation conditions, only data from the Rugby kickers ($n = 4$) or the Soccer kickers ($n = 4$) were used, respectively. Effect sizes between conditions were also calculated (Cohen, 1988) with the respective 95% confidence intervals. Effects sizes were interpreted as: < 0.20, trivial; 0.20 – 0.59, small; 0.60 – 1.19, medium; 1.20 – 1.99, large; and ≥ 2.00, very large (Hopkins, 2000). The absolute value of the mean effect size was used to determine the descriptor used – selected mean effect sizes and their descriptors are included in the results and discussion, whilst all effect sizes and their 95% confidence intervals are presented in Appendix E.

4.3 Results

4.3.1 Kicking Foot Swing Planes

There were generally only trivial or small differences in the inclination (overall median $d = 0.19$, overall mean $d = 0.21$) and direction (overall median $d = 0.26$, overall mean $d = 0.42$) angles of the kicking foot swing plane when different ball orientations were used on the kicking tee. The only significant differences in kicking foot swing planes between ball orientation conditions were seen in the direction angle for the Rugby kickers (Table 4.3). When using their normal ball orientation, the Rugby kickers produced a mean kicking foot swing plane that was directed 2.7° and 4.9° further to the right than when using a forward and horizontal ball orientation, respectively.

Table 4.3. Inclination and direction angles of the kicking foot swing plane for kicks taken using different ball orientations (mean ± *SD*).

		Ball Orientation Condition			
		Forward	Horizontal	Normal	Backward
All Kickers ($n = 8$)	Inclination (°)	49.6 ± 4.9	49.3 ± 3.7		
	Direction (°)	13.5 ± 7.1	12.0 ± 4.9		
Rugby Kickers ($n = 4$)	Inclination (°)	50.3 ± 7.3	49.1 ± 4.4	48.3 ± 5.0	
	Direction (°)	16.4 ± 5.6 ^{N}	14.2 ± 3.2 ^{N}	19.1 ± 4.7 ^{F,H}	
Soccer Kickers ($n = 4$)	Inclination (°)	48.9 ± 1.3	49.4 ± 3.6		48.4 ± 3.5
	Direction (°)	10.7 ± 8.0	9.8 ± 5.8		11.3 ± 7.1

F = significantly ($p < 0.05$) different to kicks taken with a forward ball orientation.
H = significantly ($p < 0.05$) different to kicks taken with a horizontal ball orientation.
N = significantly ($p < 0.05$) different to kicks taken with a normal ball orientation.
Inclination = angle between the global x-axis and the line of intersection between the swing plane and the x-z plane, where a greater value represents a more vertical plane.
Direction = angle between the global y-axis and the line of intersection between the swing plane and the x-y plane, where a positive value represents a plane directed to the right of the target.

4.3.2 Segment Orientations at the Start of the Impact Phase

There were no significant differences in foot elevation or shank elevation angles between any of the ball orientation conditions (Table 4.4). When group-wide comparisons were made across all kickers between the forward and horizontal ball orientation conditions, significant differences were observed for foot azimuth, shank azimuth and plantar flexion angles – small ($d = 0.39$), medium ($d = 0.73$) and trivial ($d = 0.16$) effect sizes were observed between the respective variables. Within the Rugby kickers, foot azimuth, shank azimuth and plantar flexion angles all displayed significant differences. However, these were between the forward orientation condition and when their normal ball orientation was used.

Table 4.4. Segment orientations and plantar flexion at the start of the impact phase for kicks taken using different ball orientations (mean ± *SD*).

		Ball Orientation Condition			
		Forward	Horizontal	Normal	Backward
All Kickers ($n = 8$)	Foot Azimuth (°)	24.8 ± 7.1 ^{H}	27.2 ± 5.2 ^{F}		
	Foot Elevation (°)	-15.0 ± 8.0	-15.5 ± 7.9		
	Shank Azimuth (°)	153.2 ± 5.6 ^{H}	156.8 ± 4.5 ^{F}		
	Shank Elevation (°)	57.0 ± 6.8	57.0 ± 6.4		
	Plantar flexion (°)	31.8 ± 8.0 ^{H}	33.0 ± 8.2 ^{F}		
Rugby Kickers ($n = 4$)	Foot Azimuth (°)	22.6 ± 7.5 ^{N}	26.5 ± 6.1	24.4 ± 7.9 ^{F}	
	Foot Elevation (°)	-11.2 ± 8.6	-10.9 ± 7.4	-10.6 ± 7.9	
	Shank Azimuth (°)	152.7 ± 5.4 ^{N}	156.6 ± 1.6	158.6 ± 2.4 ^{F}	
	Shank Elevation (°)	58.3 ± 9.7	57.7 ± 8.7	57.3 ± 8.0	
	Plantar flexion (°)	28.0 ± 8.6 ^{N}	28.6 ± 8.0	30.2 ± 8.4 ^{F}	
Soccer Kickers ($n = 4$)	Foot Azimuth (°)	27.0 ± 7.0	27.9 ± 4.9		27.4 ± 5.0
	Foot Elevation (°)	-18.8 ± 6.0	-20.2 ± 5.9		-17.5 ± 8.7
	Shank Azimuth (°)	153.7 ± 6.5 ^{H,B}	157.1 ± 6.6 ^{F}		160.3 ± 6.0 ^{F}
	Shank Elevation (°)	55.8 ± 3.0	56.3 ± 4.1		55.6 ± 2.6
	Plantar flexion (°)	35.5 ± 6.2 ^{H}	37.5 ± 6.2 ^{F}		37.7 ± 7.6

F = significantly ($p < 0.05$) different to kicks taken with a forward ball orientation.
H = significantly ($p < 0.05$) different to kicks taken with a horizontal ball orientation.
N = significantly ($p < 0.05$) different to kicks taken with a normal ball orientation.
B = significantly ($p < 0.05$) different to kicks taken with a backward ball orientation.
Azimuth = angle between a vector in the positive x direction (originating from the ankle or heel for the shank or foot, respectively) to the segment vector projected in the x-y plane.
Elevation = angle between the 3D segment vector and the x-y plane.

4.3.3 Impact Locations on the Ball

Impact location on the ball varied between ball orientation conditions by small ($d = 0.25$) to very large amounts ($d = 17.68$). Significant differences were observed between all conditions except when comparing the forward orientation in the Rugby kickers with their normal ball orientation (Table 4.5). The values for the horizontal condition demonstrate that the mean impact location across all kickers was close to the point of the ball (181.3 ± 3.7°; Figure 4.7). Impact location moved clockwise around the ball for the other conditions, with the impact occurring between the point and the belly of the ball for the forward and normal ball orientations (Figure 4.7). The impact occurred close to the middle of the ball's belly for the backward orientation condition (Figure 4.7). The range in impact locations between the ball orientation conditions was reduced when these were expressed irrespective of ball orientation (i.e. relative to the global vertical), but all conditions were all still significantly different from one another when considered in this way – except for the addition of comparing the forward and backward orientations in the Soccer kickers. The greatest difference in mean impact location with respect to the top of the ball was 72.3° (horizontal versus backward in the Soccer kickers). However, the greatest difference in mean global impact location was 20.2° (horizontal versus normal in the Rugby kickers).

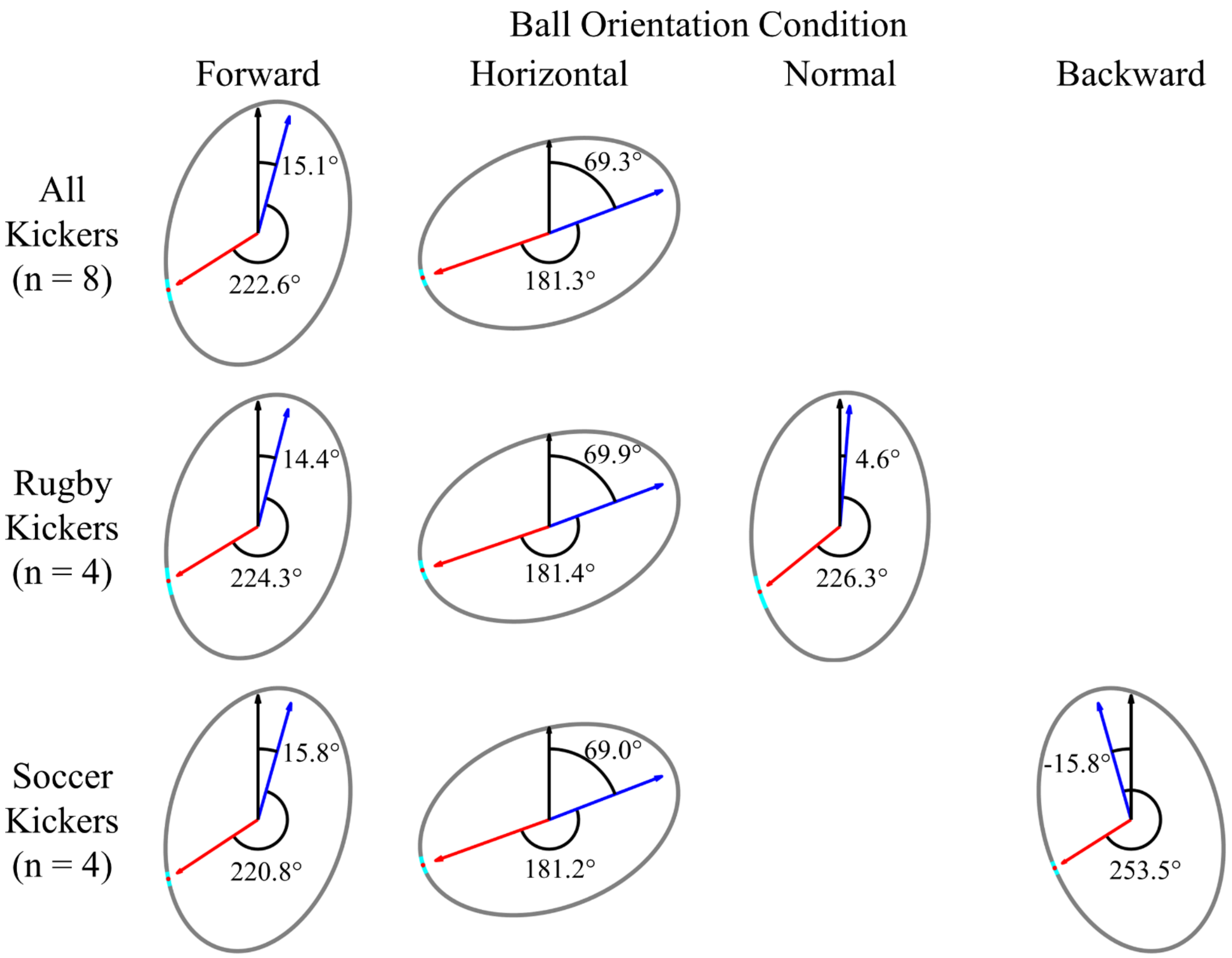


Figure 4.7. Impact location on the ball for kicks taken using different ball orientations. The black arrow is a vertical vector from the ball centre. The blue arrow is along the ball's long axis from the ball centre towards the top of the ball. The red arrow is pointed towards the mean impact location (red dot on the ball's shell) from the ball centre. Standard deviation of the impact location is represented by the cyan on the ball's shell.

Table 4.5. Visually identified local and global impact locations on the ball for kicks taken using different ball orientations (mean ± *SD*).

		Ball Orientation Condition			
		Forward	Horizontal	Normal	Backward
All Kickers ($n = 8$)	Local Impact Location (°)	222.6 ± 5.5 ^{H}	181.3 ± 3.7 ^{F}		
	Global Impact Location (°)	237.8 ± 5.6 ^{H}	250.6 ± 3.9 ^{F}		
Rugby Kickers ($n = 4$)	Local Impact Location (°)	224.3 ± 7.0 ^{H}	181.4 ± 4.3 ^{F,N}	226.3 ± 8.8 ^{H}	
	Global Impact Location (°)	239.3 ± 7.7 ^{H}	251.1 ± 4.7 ^{F,N}	230.9 ± 7.2 ^{H}	
Soccer Kickers ($n = 4$)	Local Impact Location (°)	220.8 ± 3.6 ^{H,B}	181.2 ± 3.8 ^{F,B}		253.5 ± 4.4 ^{F,H}
	Global Impact Location (°)	236.3 ± 2.9 ^{H}	250.1 ± 3.5 ^{F,B}		237.7 ± 4.1 ^{H}

F = significantly ($p < 0.05$) different to kicks taken with a forward ball orientation.
H = significantly ($p < 0.05$) different to kicks taken with a horizontal ball orientation.
N = significantly ($p < 0.05$) different to kicks taken with a normal ball orientation.
B = significantly ($p < 0.05$) different to kicks taken with a backward ball orientation.
Impact location = angle in the clockwise direction between the top of the ball's long axis and the identified impact location.
Global impact location = angle in the clockwise direction between a vector in the positive z direction (originating from the ball centre) and the identified impact location i.e. incorporating ball orientation.

4.3.4 Impact Durations

The duration of the impact phase differed between the ball orientation conditions by small (*d* = 0.35) to very large amounts (*d* = 2.13). The horizontal ball orientation resulted in the longest impact duration in all three group comparisons (Figures 4.8, 4.9, 4.10). Impact duration when the horizontal orientation (11.1 ± 1.3 ms) was used was significantly longer than the forward orientation (9.6 ± 1.0 ms) when compared across all eight kickers. The use of a horizontal orientation (11.8 ± 1.5 ms) also resulted in a significantly longer impact when compared to the forward (10.1 ± 1.1) and normal (10.7 ± 1.2) orientations within the Rugby kickers. No significant differences were observed between conditions in the Soccer kickers, but the use of a backward orientation led to the shortest impact duration (9.0 ± 0.8 ms) across all conditions and groups of kickers.

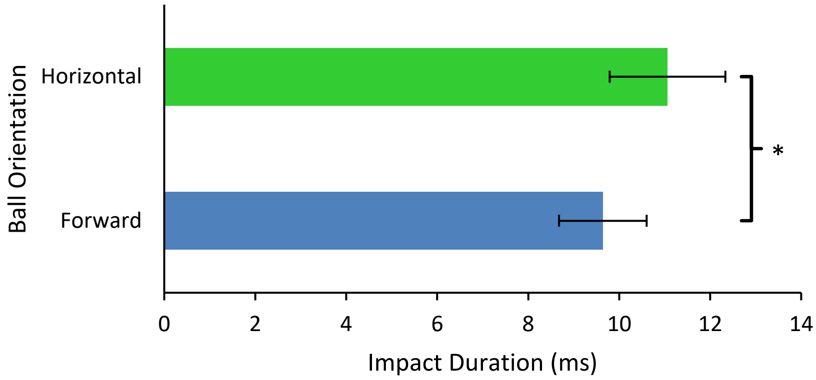


Figure 4.8. Mean impact duration ± *SD* for kicks taken by all kickers ($n = 8$) with each ball orientation. * = significant ($p < 0.05$) difference.

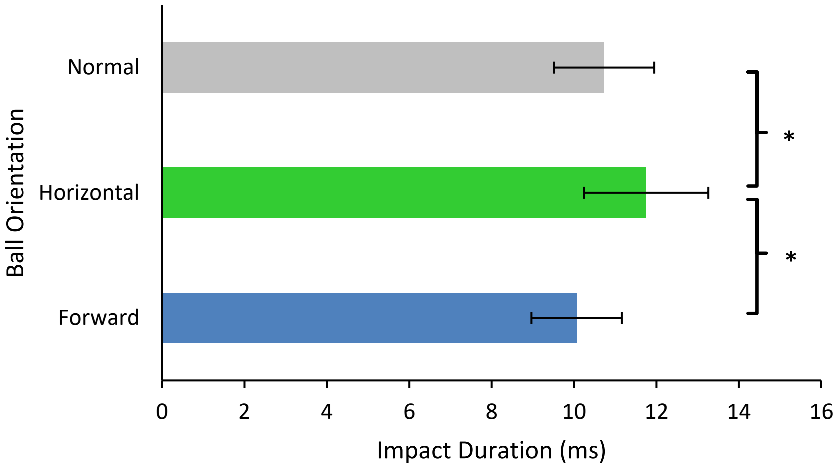


Figure 4.9. Mean impact duration ± *SD* for kicks taken by the Rugby kickers ($n = 4$). * = significant ($p < 0.05$) difference.

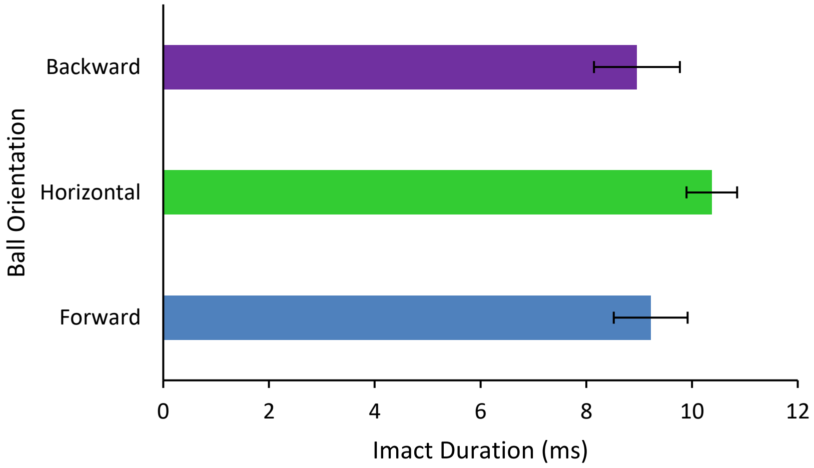


Figure 4.10. Mean impact duration ± *SD* for kicks taken by the Soccer kickers ($n = 4$).

4.3.5 Impact Efficiency Measures

When comparing impact efficiency, the only significant differences were observed in coefficient of restitution and foot–ball velocity ratio between the horizontal and backward ball orientation conditions in the Soccer kickers (Table 4.6) and these were by very large ($d = 2.52$) and medium ($d = 1.08$) amounts, respectively. Overall, the greatest coefficient of restitution (0.62 ± 0.04) and foot–ball velocity ratio (1.25 ± 0.05) values were achieved by the Soccer kickers during the backward orientation condition. The smallest values achieved by the Soccer kickers for these same two variables were during the forward condition (CoR = 0.49 ± 0.10; foot–ball velocity ratio = 1.16 ± 0.07), however the Rugby kickers achieved their greatest values during this forward ball orientation condition (CoR = 0.61 ± 0.05; foot–ball velocity ratio = 1.24 ± 0.02).

Table 4.6. Impact efficiency measures for kicks taken using different ball orientations (mean ± *SD*).

		Ball Orientation Condition			
		Forward	Horizontal	Normal	Backward
All Kickers ($n = 8$)	CoR	0.55 ± 0.10	0.54 ± 0.05		
	Foot–ball velocity ratio	1.20 ± 0.06	1.20 ± 0.04		
Rugby Kickers ($n = 4$)	CoR	0.61 ± 0.05	0.55 ± 0.07	0.57 ± 0.05	
	Foot–ball velocity ratio	1.24 ± 0.02	1.20 ± 0.04	1.21 ± 0.04	
Soccer Kickers ($n = 4$)	CoR	0.49 ± 0.10	0.52 ± 0.03 ^{B}		0.62 ± 0.04 ^{H}
	Foot–ball velocity ratio	1.16 ± 0.07	1.19 ± 0.05 ^{B}		1.25 ± 0.05 ^{H}

H = significantly ($p < 0.05$) different to kicks taken with a horizontal ball orientation.
B = significantly ($p < 0.05$) different to kicks taken with a backward ball orientation.
CoR = coefficient of restitution.
Foot–ball velocity ratio = ratio between resultant foot velocity at the start of the impact phase and resultant ball flight velocity.

4.3.6 Segment Orientations at the End of the Impact Phase

Shank azimuth angle was the only segment orientation that was significantly different, by a medium ($d = 0.76$) amount, at the end of impact between the forward and horizontal ball orientation conditions when compared across all eight kickers (Table 4.7). Shank azimuth angle was also significantly different between all orientation conditions except horizontal and backward in the Soccer kickers. In the Rugby kickers, significant differences were observed between the forward condition and their normal ball orientation for both shank elevation and plantar flexion angles. Significant differences were also identified in the plantar flexion range of motion from the start of the impact phase to the end of the impact phase in the Soccer kickers. When a forward ball orientation was used (11.8 ± 0.9°), plantar flexion range of motion across the impact phase was 87% greater than when a backward orientation was employed (6.3 ± 2.7°).

Table 4.7. Segment orientations and plantar flexion at the end of the impact phase for kicks taken using different ball orientations (mean ± *SD*).

		Ball Orientation Condition			
		Forward	Horizontal	Normal	Backward
All Kickers ($n = 8$)	Foot Azimuth (°)	24.0 ± 7.0	23.6 ± 7.9		
	Foot Elevation (°)	-10.4 ± 9.2	-8.5 ± 7.9		
	Shank Azimuth (°)	187.1 ± 9.5 ^{H}	193.8 ± 8.1 ^{F}		
	Shank Elevation (°)	55.1 ± 5.3	55.3 ± 5.2		
	Plantar flexion (°)	41.9 ± 9.7	41.1 ± 8.4		
	Plantar flexion range of motion (°)	10.2 ± 2.2	8.1 ± 2.4		
Rugby Kickers ($n = 4$)	Foot Azimuth (°)	23.5 ± 7.8	23.3 ± 3.8	25.3 ± 9.5	
	Foot Elevation (°)	-5.2 ± 9.7	-3.2 ± 7.7	-6.0 ± 9.6	
	Shank Azimuth (°)	189.3 ± 12.4	196.2 ± 10.7	194.3 ± 7.7	
	Shank Elevation (°)	54.8 ± 7.7 ^{N}	54.3 ± 6.5	52.6 ± 7.2 ^{F}	
	Plantar flexion (°)	36.6 ± 9.9 ^{N}	37.0 ± 10.0	40.2 ± 9.7 ^{F}	
	Plantar flexion range of motion (°)	8.6 ± 2.0	8.4 ± 3.2	10.0 ± 1.6	
Soccer Kickers ($n = 4$)	Foot Azimuth (°)	24.6 ± 7.3	23.9 ± 11.4		22.7 ± 7.2
	Foot Elevation (°)	-15.7 ± 5.4	-13.8 ± 3.5		-10.5 ± 7.7
	Shank Azimuth (°)	184.8 ± 6.7 ^{H,B}	191.5 ± 4.9 ^{F}		188.7 ± 4.9 ^{F}
	Shank Elevation (°)	55.4 ± 2.6	56.3 ± 4.3		54.3 ± 1.8
	Plantar flexion (°)	47.3 ± 6.7	45.3 ± 4.6		44.0 ± 7.6
	Plantar flexion range of motion (°)	11.8 ± 0.9 ^{H,B}	7.8 ± 1.7 ^{F}		6.3 ± 2.7 ^{F}

F = significantly ($p < 0.05$) different to kicks taken with a forward ball orientation.
H = significantly ($p < 0.05$) different to kicks taken with a horizontal ball orientation.
N = significantly ($p < 0.05$) different to kicks taken with a normal ball orientation.
B = significantly ($p < 0.05$) different to kicks taken with a backward ball orientation.
Azimuth = angle between a vector in the positive x direction (originating from the ankle or heel for the shank or foot, respectively) to the segment vector projected in the x-y plane.
Elevation = angle between the 3D segment vector and the x-y plane.
Plantar flexion range of motion = difference in plantar flexion angle between the start of the impact phase and the end of the impact phase.

4.3.7 Ball Flight Characteristics

No significant differences were identified between ball orientation conditions across all ball flight characteristics (Table 4.8). There was no clear pattern between the different ball orientation conditions and resultant ball velocity. Although ball orientation did not appear to have an effect on the medio-lateral component of ball velocity in the Soccer kickers, the Rugby kickers imparted a velocity vector to the ball that was directed towards the left of the target when using a forward orientation. The Rugby kickers produced a vector directed towards the right of the target with their normal orientation, something which the Soccer kickers achieved with all of the ball orientations they used. These differences and observations are further reflected by the ball azimuth launch angle.

Table 4.8. Ball flight characteristics for kicks taken using different ball orientations (mean ± *SD*).

		Ball Orientation Condition			
		Forward	Horizontal	Normal	Backward
All Kickers (*n* = 8)	Resultant (m/s)	26.6 ± 1.7	27.0 ± 2.4		
	Vx (m/s)	-0.6 ± 2.4	0.2 ± 2.3		
	Vy (m/s)	23.7 ± 2.2	23.8 ± 2.9		
	Vz (m/s)	11.2 ± 2.4	12.4 ± 1.2		
	Ball Elevation (°)	25.6 ± 6.0	27.7 ± 4.1		
	Ball Azimuth (°)	-1.5 ± 5.9	0.5 ± 5.6		
Rugby Kickers (*n* = 4)	Resultant (m/s)	26.0 ± 1.5	25.4 ± 0.7	25.6 ± 0.6	
	Vx (m/s)	-1.8 ± 2.5	-0.1 ± 2.6	1.3 ± 1.4	
	Vy (m/s)	22.6 ± 2.3	22.3 ± 0.9	21.4 ± 1.4	
	Vz (m/s)	11.8 ± 3.4	11.9 ± 0.3	13.8 ± 1.5	
	Ball Elevation (°)	27.8 ± 8.4	28.0 ± 1.5	32.9 ± 4.4	
	Ball Azimuth (°)	-4.4 ± 6.5	-0.5 ± 6.5	3.2 ± 3.5	
Soccer Kickers (*n* = 4)	Resultant (m/s)	27.2 ± 1.9	28.6 ± 2.6		29.6 ± 2.7
	Vx (m/s)	0.7 ± 1.8	0.5 ± 2.4		0.7 ± 3.0
	Vy (m/s)	24.8 ± 1.6	25.2 ± 3.6		26.8 ± 3.2
	Vz (m/s)	10.6 ± 0.7	12.8 ± 1.6		12.0 ± 1.4
	Ball Elevation (°)	23.3 ± 0.3	27.3 ± 6.0		24.5 ± 4.3
	Ball Azimuth (°)	1.4 ± 4.0	1.6 ± 5.3		1.7 ± 6.2

Resultant = resultant ball flight velocity.
Vx = medio-lateral component of initial ball flight velocity vector, where a positive value represents the velocity vector directed to the right of the target.
Vy = antero-posterior component of initial ball flight velocity vector.
Vz = vertical component of initial ball flight velocity vector.
Ball elevation = angle between the resultant ball flight velocity vector and the x-y plane.
Ball azimuth = angle between the resultant ball flight velocity vector and the y-z plane.

4.3.8 Modelled Ball Flight Distances

Across the group of all eight kickers, the forward ball orientation condition led to a trivial improvement in kick performance compared with the horizontal condition when combining all ball flight characteristics to model the flight of the ball (Table 4.9), and this difference was non-significant. The Rugby kickers performed best when a horizontal orientation was used. Using a horizontal orientation led to a 5.6 m (40%) increase in the maximum anterior displacement over which the kicks were modelled to have been successful when compared to the use of a forward orientation, that with which the Rugby kickers performed worst. The Soccer kickers performed best when using a backward ball orientation and worst when using a horizontal ball orientation. The difference in modelled anterior displacement between these two conditions was 12.9 m, an increase of 68%, and this was statistically significant.

Table 4.9. Maximum anterior displacement over which kicks taken using different ball orientations were modelled to have been successful using the ball flight model of Atack et al. (2019b; mean ± *SD*).

		Ball Orientation Condition			
		Forward	Horizontal	Normal	Backward
All Kickers (*n* = 8)	Displacement (m)	20.6 ± 9.0	19.4 ± 5.2		
Rugby Kickers (*n* = 4)	Displacement (m)	14.1 ± 4.7	19.7 ± 6.8	18.8 ± 6.6	
Soccer Kickers (*n* = 4)	Displacement (m)	27.2 ± 7.1	19.1 ± 4.1 ^{B}		32.0 ± 10.3 ^{H}

H = significantly ($p < 0.05$) different to kicks taken with a horizontal ball orientation.
B = significantly ($p < 0.05$) different to kicks taken with a backward ball orientation.

4.4 Discussion

The current chapter investigated how altering the orientation of the ball affects place kick technique, impact efficiency and kick performance to address research questions 2 and 3: *"How do individuals change their kick technique when different ball orientations are used?"* and *"How does ball orientation affect impact efficiency and resulting ball flight characteristics and kick performance?"*. The swing plane of the kicking foot during the downswing to the ball and orientations of the kicking shank and foot at the start and end of the impact phase were analysed in order to assess any changes in place kick technique. Coefficient of restitution and foot–ball velocity ratio were determined as measures of impact efficiency, and ball flight characteristics were used to quantify the potential influence of ball orientation on place kick performance. In this discussion, the key findings relating to place kick performance will first be addressed. Impact characteristics – including impact locations on the ball, impact efficiencies and impact durations – will then be discussed. Following this, place kick technique will be addressed starting with the orientations of the segments at initial foot–ball contact and then the swing planes of the kicking foot.

Resultant initial ball flight velocity is the variable that has generally been used to measure place kick performance (Baktash et al., 2009; Linthorne & Stokes, 2014; Padulo et al., 2013; Sinclair et al., 2014; Sinclair et al., 2016). In the current chapter, ball orientation did not appear to affect resultant ball flight velocity as there were no significant effects between orientation conditions (Table 4.8). The mean resultant ball velocities achieved by the kickers were comparable to those previously reported from a group of professional academy kickers (27.4 ± 1.9 m/s, Bezodis et al., 2018). There was a small difference (*d* = 0.20) in mean resultant velocity between the forward and horizontal orientation conditions when compared across the group of all eight kickers. The difference between these conditions in the Rugby kickers was greater (*d* = 0.46), although the greatest difference was seen between the forward and backward conditions in the Soccer kickers (*d* = 1.04). In addition to just a fast resultant ball flight velocity, the accuracy component of performance should also be considered. Combining the ball flight characteristics to determine the maximum anterior displacement over which each kick was modelled to have successfully passed between a set of Rugby Union posts (Atack et al., 2019b) identified that kicks taken with the backward orientation also produced the highest performance in this more complete measure (Table 4.9). The ball passing outside of either of the upright posts was the eventual reason for modelled kick failure in 75% of the trials. This was likely a result of a combination of a misdirected medio-lateral velocity vector and large spin rates (known to affect kick accuracy, Seo et al., 2006, 2007) about the global y and z axes being imparted to the ball. Direct comparisons were not made between the components of ball spin due to potential accuracy issues in measuring the spin rates (further discussion of this will be undertaken in Chapter 5). It should also be noted that the participants were kicking with maximal effort for maximum ball velocity and, whilst they were aiming to kick straight along a line on the surface of the pitch, they did not have goal posts as a physical target to kick towards. Nonetheless, based on both the resultant velocity and maximum modelled displacement results, the use of a backward ball orientation appears to be beneficial for place kick performance in kickers who have an established kicking movement pattern, but one which is not specific to Rugby Union place kicking (i.e. the Soccer players used in the current study). Whilst a backward ball orientation has not been seen to be used by Rugby kickers (Chapter 3) and the Rugby kickers of the current chapter did not use a backward orientation condition, based on the results achieved by the Soccer kickers the exploration of a backward ball orientation may be valuable for some Rugby Union place kickers.

Ball orientation on the tee clearly influenced the impact locations on the ball, both in local and global terms (Table 4.5 and Figure 4.7). Significant effects were identified between all ball orientation conditions, except between the forward and normal conditions (small effect size, *d* = 0.25), when comparing mean local impact location with respect to the top of the ball's long axis (Table 4.5). The same significant effects were observed when taking into account the ball orientation and measuring impact location globally with respect to the vertical, however the difference in mean global impact location between the forward and backward conditions was also not significantly different (small effect size, *d* = 0.39). These findings indicate that when the ball is orientated in different ways, kickers do impact different locations on the surface of the ball. Previous mechanical simulation studies have discovered that altering ball orientation, and so local impact location on the ball given the controlled nature of the kicking leg motion in these studies, affects measures of impact efficiency (Ball & Peacock, 2020; Holmes, 2008; Michelini et al., 2019). Whilst the coefficient of restitution values achieved by both the mechanical leg (range of 0.39 – 0.77, Michelini et al., 2019) and human kickers of this study (range of 0.31 – 0.74) are comparable, the results of the current chapter extend the current understanding by identifying the importance of considering the human element. Ball and Peacock (2020) found that impacts on the point of the ball (local impact location = approximately 180°; foot–ball velocity ratio = 1.32) resulted in a larger foot–ball velocity ratio than impacts between the point and belly (local impact location = approximately 210°; foot–ball velocity ratio = 1.25). Additionally, when investigating coefficient of restitution, both Holmes (2008) and Michelini et al. (2019) identified that impacts on the belly of the ball (local impact location = approximately 270°) led to greater values than impacts on the point of the ball. Michelini et al. (2019) further determined that impacts between the point and belly resulted in the smallest coefficient or restitution. The current chapter highlighted that despite affecting the impact location on the ball, the prescribed alterations to ball orientation only resulted in significant effects in coefficient of restitution and foot–ball velocity ratio between the horizontal (impact location near the point) and backward (impact location near the belly) conditions. There is therefore clearly a need to consider the human element since there are various additional human factors that are ignored in the mechanical kicking leg (discussed further later in this section).

When looking at individual kicker results, mean coefficient of restitution values (Table 4.6) were greatest when the local impact location angle was furthest clockwise from the ball top in its local coordinate system (Figure 4.7), regardless of which ball orientation was used. The Soccer kickers all individually achieved their largest mean coefficient of restitution when using a backward orientation, and two of the Rugby kickers produced their largest values when using a forward orientation whilst the other two Rugby kickers did so whilst using their normal ball orientation. This supports the previous findings of Holmes (2008) that impacting towards the belly of the ball results in increased coefficient of restitution. However, it also contradicts that of Michelini et al. (2019) since the Rugby kickers in the current study achieved their smallest mean coefficient of restitution when using a horizontal ball orientation (impact location closest to the point of the ball). Michelini et al. (2019) determined that placing the ball so that the mechanical kicking leg impacted the ball on the point (as seen with a horizontal orientation in the current chapter) led to a greater coefficient of restitution value (0.55) than when the ball was placed so that the impact occurred between the point and belly (as seen with a forward orientation in the current chapter) of the ball (0.41). Whilst the coefficient of restitution results of this chapter generally appear to agree with previous research, a consideration to be made is that the potential effects of soft tissue are ignored in the mechanical leg used by Michelini et al. (2019). Peacock and Ball (2018b) noted that soft tissue could affect the contribution of shank mass to the impact, but additionally soft tissue may provide more biological matter through which energy could be dissipated during the impact. It should further be noted that a human foot is quite different from a rigid, mechanical foot as it is not a single rigid segment and also contains soft tissue which can deform during impact. The ankle joint was also fixed in some of the mechanical leg trials (Peacock & Ball, 2018b) which disables the capacity for energy dissipation by forced plantar flexion during the impact phase, which has been well known to occur in human kicking (Peacock et al., 2017; Shinkai et al., 2007, 2009). The capacity for an active dorsiflexion torque is therefore also not possible in the mechanical leg (plantar flexion range of motion and related topics will be discussed further later in this section). Overall, while it is the case that use of the mechanical kicking leg has benefits such as the ability for controlled and systematic explorations into individual variables, the results of this chapter suggest that humans do not necessarily respond in the same manner as the mechanical leg during live place kicking trials.

Ball orientation, and subsequent impact location on the ball, influenced the duration of the impact phase (Figures 4.8, 4.9, 4.10). The use of a horizontal orientation resulted in the longest mean impact duration across all three group comparisons. Significant differences were observed between the forward and horizontal conditions when compared across all kickers (large effect size, $d = 1.26$), and between the forward and horizontal conditions (large effect size, $d = 1.28$), and horizontal and normal conditions (medium effect size, $d = 0.74$) in the Rugby kickers. Overall it was seen that impacts between the point and belly of the ball (Rugby kickers: forward = 10.1 ± 1.1 ms, normal = 10.7 ± 1.2 ms; Soccer kickers: forward = 9.2 ± 0.7 ms, backward = 9.0 ± 0.8 ms) resulted in similar mean impact durations within the sport specific groups of kickers, but that impacting near the point of the ball resulted in longer mean durations for each respective group (Rugby kickers: horizontal = 11.8 ± 1.5 ms; Soccer kickers: horizontal = 10.4 ± 0.5 ms). This pattern of increased impact duration when impacting the point of the ball has also been seen in mechanical kicking simulations. Ball and Peacock (2020) found that impacting on the point of the ball (11.8 ms) resulted in a longer impact duration than impacting between the point and the belly of the ball (10.9 ms) when all else was kept constant.

The potential relationship between impact duration and impact efficiency is something that should also be noted. Ball and Peacock (2020) further determined that impacting on the point of the ball led to a greater foot–ball velocity ratio (1.32) than impacting between the point and belly (1.25). These results of Ball and Peacock (2020) suggest that there is a positive relationship between impact duration and foot–ball velocity ratio, however the results of the current study appear to contradict this. In the current study, the use of a backward orientation in the Soccer kickers (mean foot–ball velocity ratio = 1.25 ± 0.05) and forward orientation in the Rugby kickers (mean foot–ball velocity ratio = 1.24 ± 0.02) led to their respective shortest mean impact durations but their greatest mean foot–ball velocity ratios within the kicker groups. Whilst the results of this chapter support those of Ball and Peacock (2020) that impacting on the point of the ball results in longer impacts, the relationship between impact duration and foot–ball velocity ratio is not consistent between the mechanical kicking limb and human kickers.

Nunome et al. (2013) observed that a longer impact duration was associated with a lower resultant ball velocity during Soccer kicking. This was concluded based on the findings of a negative relationship ($r = -0.438$) between the two variables. Slower ball flight velocities have also been observed after impacts of longer durations in Australian Football kickers when comparing kicking for accuracy (impact duration = 13.2 ± 1.4 ms, ball velocity = 17.7 ± 0.9 m/s) against kicking for maximal distance (impact duration = 12.1 ± 1.3 ms, ball velocity = 22.1 ± 1.6 m/s, Peacock et al., 2017). However, initial foot velocity at the start of the impact phase was not considered by Nunome et al. (2013) or Peacock et al. (2017) despite it likely being an interacting variable. In the current study the Soccer kickers produced an overall mean foot velocity of 23.1 m/s at initial foot–ball contact, whereas the Rugby kickers produced a lower mean velocity of 21.1 m/s. This difference in initial foot velocity may in part explain the shorter impact durations achieved by the Soccer kickers, and as such the greater resultant ball flight velocities previously discussed. Mechanical simulations in Soccer have further confirmed a negative linear relationship between relative velocities at the start and end of impact and impact duration. Iga et al. (2018) identified that increasing the velocity of a Soccer ball when fired onto a flat force plate resulted in an increase in the velocity of the ball after impact but a decrease in the impact duration ($r = -0.96$, $p < 0.01$). It can be assumed that impacting a stationary ball with a moving object is equivalent to impacting a stationary object with a moving ball

(Iga et al., 2018). Therefore, the overall implications for Rugby Union place kicking are that an increased initial foot velocity at the start of impact will result in a shorter impact duration but an increased subsequent ball flight velocity. The results of the current chapter suggest that, for a prolate spheroid ball such as a Rugby Union ball, ball orientation further influences this relationship as previously discussed. Nonetheless, the use of the mechanical kicking leg appears to produce contrasting results to those observed in human kickers in the current study. The mechanical leg produced a greater foot–ball velocity ratio when impact duration was longer (Ball & Peacock, 2020) but the results of the current study contradict this since a shorter impact duration appears to be beneficial for foot–ball velocity ratio. These opposing findings may suggest that there are factors in the design of the mechanical leg which do not truly reflect those that exist within humans, such as the effects of soft tissue and the use of rigid construction materials.

Plantar flexion range of motion (also referred to as forced plantar flexion, i.e. the difference in plantar flexion angle between the start of the impact phase and the end of the impact phase) is an important kinematic variable that relates to impact efficiency. As previously discussed, forced plantar flexion during the impact phase is a feature that is known to occur in human kickers (Peacock et al., 2017; Shinkai et al., 2006, 2007, 2009). The findings of the current study reinforce this further and show that this is also the case in Rugby Union place kicking (Table 4.7). Furthermore, it was evident that there was an inverse association between plantar flexion range of motion and impact efficiency measures (coefficient of restitution and foot–ball velocity ratio) when compared between the different ball orientation conditions, and that this was especially prominent in the Soccer kickers. The smallest mean plantar flexion range of motion (6.3 ± 2.7°) was recorded in the Soccer kickers when using a backward orientation, and this combination produced the greatest mean coefficient of restitution (0.62 ± 0.04) and mean foot–ball velocity ratio (1.25 ± 0.05). Conversely, the Soccer kickers also displayed the greatest overall mean plantar flexion range of motion (11.8 ± 0.9°) when using a forward orientation. This resulted in the smallest values of mean coefficient of restitution (0.49 ± 0.10) and mean foot–ball velocity ratio (1.16 ± 0.07). Therefore, it could be concluded that the use of a backward orientation leads to a reduced plantar flexion range of motion and that this subsequently improves impact efficiency. Plantar flexion range of motion during the impact phase may also in part explain some of the differences observed between this chapter and studies using the mechanical kicking leg (Ball & Peacock, 2020; Michelini et al., 2019). It appears to be an influential variable with respect to measures of impact efficiency, in particular, and so it may be the case that the plantar flexion movement during impact is oversimplified in the mechanical leg when used with a non-rigid ankle, and forced plantar flexion is even completely ignored when the rigid ankle setting is used.

A possible contributing factor to the observed reduction in plantar flexion range of motion when using a backward orientation is the contact area between the foot and the ball. Holmes (2008) identified that the contact area when applying a given force to the belly ($0.026\ m^2$) of a Rugby Union ball was greater than when applying the same force to the point of the ball ($0.017\ m^2$). Given that the use of a backward orientation led to impact locations closest to the belly, and assuming that the impacting surface of the foot was constant, it could be implied that the contact area between the foot and ball when using a backward orientation is greater than the other orientation conditions. As a result, some of the reaction force from the ball onto the foot may be applied to a more proximal position on the foot's surface when a backward orientation is employed. The moment arm about the ankle would consequently be reduced and this in turn would likely reduce the amount of forced plantar flexion that is experienced. Nonetheless, the trend observed in the current chapter between plantar flexion range of motion and impact efficiency measures was not as clearly evident in the Rugby kickers and one should also be aware of the initial plantar flexion angle at the start of the impact phase. The Rugby kickers demonstrated a less plantar flexed foot at the start of the impact phase (discussed further later in this section) compared to the Soccer kickers. This may in part explain the less evident trend between forced plantar flexion and foot–ball velocity ratio in the Rugby kickers since a foot that is initially less plantar flexed will allow for a greater plantar flexion range of motion during impact before possibly reaching its inherent anatomical plantar flexion limit. Additionally, the Soccer kickers demonstrated greater plantar flexion at the start of the impact phase when using a backward orientation (37.7 ± 7.6°) compared to when using a forward orientation (35.5 ± 6.2°). This preparation of increased plantar flexion before the impact phase, and a potentially more proximal impact location on the foot, may contribute to the reduced change in plantar flexion across the impact by limiting the amount of forced plantar flexion. Nonetheless, the relationship between reduced plantar flexion range of motion and increased impact efficiency is supported by the fact that increasing rigidity about the ankle joint, and thus reducing forced plantar flexion, is associated with greater values of coefficient of restitution, foot–ball velocity ratio and overall ball velocity when kicking a prolate spheroid ball in both humans (Ball et al., 2010; Peacock et al., 2017) and mechanical simulations (Peacock & Ball, 2019b, 2018b). The results of the current study further this by indicating that ball orientation and subsequent impact location further influence plantar flexion range of motion and impact efficiency measures, with a backward ball orientation appearing to be preferable.

To achieve increased rigidity about the ankle and counteract forced plantar flexion as the kicking leg is swinging through the impact phase, kickers are required to produce a dorsiflexion torque. Koike et al. (2019) identified that place kickers exhibited an active dorsiflexion torque about the ankle joint of the kicking leg during the time from final support-foot ground contact to the start of the impact phase. This torque was calculated to indirectly contribute to the positive generation of the kicking foot's velocity during its downswing to the ball. It was also stated that this dorsiflexion torque may aid in determining the orientation of the foot, as such controlling the impact location between the foot and the ball. Whilst the study by Koike et al. (2019) did not investigate the impact phase, it is likely that this active dorsiflexion torque continues during the period of foot–ball contact. When investigating the impact phase during Australian Football punt kicking, Peacock et al. (2017) identified that the kicking foot initially dorsiflexed before displaying plantar flexion. Although this was the case both when the kickers were kicking for maximal distance and for accuracy, initial dorsiflexion during impact was greater and overall plantar flexion range of motion was smaller in the distance condition kicks (plantar flexion range of motion: distance kicks = 2.2 ± 3.3°, accuracy kicks = 7.2 ± 6.4°). The observation of initial dorsiflexion is likely explained by the interacting forces during the impact phase. Peacock et al. (2017) concluded that the four sub-phases of the impact phase, as originally proposed by Shinkai et al. (2009) during Soccer kicking (discussed in Chapter 2), are also apparent during Australian Football punt kicking. It is likely that during the first two of these sub-phases that the force applied by the foot to the ball is greater than the reaction force of the ball and so the ball accelerates. However, during the latter two sub-phases the reaction force from the ball acting on the foot exceeds the combination of forces from the foot onto the ball and the possible active dorsiflexion torque, consequently arresting any dorsiflexion and causing forced plantar flexion. As suggested by Peacock et al. (2017), the smaller plantar flexion range of motion during distance condition kicks, when the reaction force produced by the ball was greater than the accuracy kicks, indicated that the kickers were actively trying to restrict forced plantar flexion during the impact phase. Combining the results of Ball et al. (2010), Koike et al. (2019), Peacock et al. (2017), and Peacock and Ball (2018b, 2019b) with the current findings, the practical implications are that coaches could try and encourage kickers to maintain as rigid an ankle as possible during impact through the production of a dorsiflexion torque. This would likely require interaction with strength and conditioning coaches to develop exercise programmes for kickers which aim to increase dorsiflexor strength about the ankle joint, particularly when eccentrically or isometrically trying to resist forced plantar flexion. Furthermore, it appears to be the case that the implementation of a backward ball orientation may further limit forced plantar flexion range of motion, and therefore enhance the efficiency of the foot–ball impact. However, it should be noted here that the Rugby kickers achieved a mean coefficient of restitution when using a forward orientation (0.61 ± 0.05) that was similar to the Soccer kickers when using a backward orientation (0.62 ± 0.04). From this it could be possible that there are other unexplored yet influential variables. Since the Rugby kickers produced a similar maximum mean coefficient of restitution to that of the Soccer kickers but a greater plantar flexion range of motion, this may suggest that the Rugby kickers produced differences in other parts of their technique in order to achieve these outcomes.

Mean segment orientations at the start of the impact phase varied little between ball orientation conditions. The only significant differences were observed in the mean foot and shank azimuth angles (segments projected onto the horizontal plane) and plantar flexion angles. Although some significant differences were observed, the effect sizes between ball orientation conditions for the segment orientations at the start of the impact phase were generally small or trivial (overall median $d = 0.19$, overall mean $d = 0.31$). As a result, it could be implied that each kicker generally only makes small or trivial adjustments in their three-dimensional lower leg kinematics at the point of initial foot–ball impact when ball orientation is systematically altered. However, one should be aware of other underlying biomechanical factors that may change with alterations in ball orientation in order to achieve a consistent delivery of the kicking foot to the ball. Although not measured in the current study due to the focus around the impact phase with high temporal and spatial resolution rather than a lower resolution consideration of the entire place kicking movement, such underlying factors may include the approach length and angle as well as the final placement of the support foot during the approach phase.

Larger differences in the segment orientations at the start of the impact phase were observed on an inter-individual level and between the sport specific groups of kickers than those within individuals between the different ball orientation conditions. The Soccer kickers demonstrated larger mean plantar flexion angles (overall mean = 37.1 ± 6.1°) than the Rugby kickers (overall mean = 29.3 ± 7.7°). This observation may in part explain some of the impact characteristics and performance differences between the sport specific kickers when considered in the context of previous findings. Peacock et al. (2017) identified that when kicking for maximal distance, kickers produced a greater plantar flexion angle (40.1 ± 5.8°) at the start of the impact phase and a greater foot–ball velocity ratio (1.28 ± 0.06) than when they kicked for accuracy (33.0 ± 7.9°; 1.25 ± 0.04). Significantly greater initial plantar flexion has additionally been observed in Rugby Union place kickers when kicking for maximal distance (41 ± 12°) compared to kicking for accuracy (32 ± 15°; Sinclair et al., 2017). The results surrounding plantar flexion at the start of the impact phase obtained by Peacock et al. (2017), Sinclair et al. (2017), and those of the current study likely link to the subsequent plantar flexion range of motion during impact. A greater plantar flexion angle at the start of the impact phase would potentially limit the amount of forced plantar flexion that possibly happens during the impact phase since the ankle joint is likely nearer its inherent anatomical limit of plantar flexion. Consequently, this would improve impact efficiency as previously discussed, and thus increase the achievable resultant ball velocity for a given foot velocity at the initial point of foot–ball contact.

The idea that the kickers may have aimed to consistently deliver the kicking foot to the ball is further supported by the analyses of the kicking foot's swing plane. Generally, small or trivial differences were observed in swing plane inclination (overall median d = 0.19, overall mean d = 0.21) and direction (overall median d = 0.26, overall mean d = 0.42) angles between ball orientation conditions. The values achieved in the current study were also similar to those that have been reported previously (Bezodis et al., 2019). Significant differences between ball orientation conditions were only revealed in the mean swing plane direction between the normal and forward orientations (small effect size, d = 0.52) and the normal and horizontal orientations (large effect size, d = 1.22) within the Rugby kickers (Table 4.3). The more positive swing plane direction when using a normal orientation may partly explain why the medio-lateral component of initial ball flight velocity was also directed further to the right for this ball orientation. A greater swing plane direction indicates that the kickers were likely ‘pushing’ the ball out to the right more during the subsequent impact phase. However, the use of a forward orientation resulted in a greater mean swing plane direction but a more negative medio-lateral component of ball flight velocity than the use of a horizontal ball orientation. This indicates that ball orientation on the tee may interact with the swing plane characteristics to affect the azimuth ball flight direction but there are also likely to be other influential factors involved.

Medio-lateral impact location on the foot is known to linearly influence ball flight azimuth angle (Peacock & Ball, 2017) and this can be explained by the oblique impact theory. The angles of the foot and ball surfaces will interact during the impact phase, and given the prolate spheroid shape of a Rugby Union ball and the non-uniform shape of the foot’s surface, these will influence the ball flight velocity in the medio-lateral direction. Peacock and Ball (2017) identified that as impact location on the foot moved laterally, ball flight azimuth angle increased to be further towards the right. Therefore, while the Rugby kickers may have produced a kicking foot swing plane directed further to the right with a forward orientation than with the other ball orientations, and one further to the right than all orientations within the Soccer kickers, they may have been impacting the ball on the medial aspect of the foot. Thus, this medial impact location on the foot may have produced the subsequent misdirected ball flight velocity vector. Coaches should therefore encourage kickers to aim to achieve a more central impact location on the foot and one that is near the ‘sweet spot’ (Peacock & Ball, 2019a) of the foot’s surface. Nonetheless, the results of the current chapter suggest that changing the orientation of the ball alters the impact location on the ball that is produced by the kickers. However, each kicker appears to only make small or trivial adjustments in their technique before the impact phase between ball orientation conditions and this includes generally small or trivial changes in the swing path of the kicking foot during the downswing to the ball.

The results of this chapter presented variables relating to place kick technique, impact characteristics and efficiency, and kick performance to investigate the effects of ball orientation. Soccer kickers were utilised since they do not already have a personal ball orientation preference and are not practised in Rugby Union place kicking. Thus, they would not have predetermined movement patterns for place kicking but would have established movement patterns for kicking a spherical ball; hence they were included in the current study instead of novice kickers. On the other hand, the Rugby kickers already have a practised ball orientation and place kick technique. The inclusion of these two groups of kickers made it possible to investigate whether different responses were produced by those who were familiar with and those who were not familiar with Rugby Union place kicking when ball orientation was altered. This therefore helped to enhance the understanding of the acute adaptations made by kickers between ball orientation conditions. It was identified that while impact location on the ball differed between ball orientation conditions, each kicker tended to only make small or trivial adjustments in their kick technique between conditions in order to achieve the different impact locations. Impact efficiency did not vary significantly between orientation conditions but there were generally medium-sized effects between the conditions (coefficient of restitution: overall median $d = 0.70$, overall mean $d = 0.98$; foot–ball velocity ratio: overall median $d = 0.93$, overall mean $d = 0.79$). The Rugby kickers produced their greatest coefficient of restitution when using a forward ball orientation, whilst the Soccer kickers did so with a backward orientation. From this it could be implied that different ball orientations result in improved efficiency, and subsequent ball velocity for a given foot velocity, for different kickers. Nonetheless, it seems to be the case that impacting closer to the belly of the ball consistently led to an improved impact efficiency within human kickers but that there are other kinematic factors that likely interact and influence this – such as plantar flexion range of motion during impact. As a result of the current study, practitioners should aim to encourage the exploration of a ball orientation that results in an impact location on the ball that is closer to its belly. They should however also remain cognisant of the underlying kinematics of the kicker’s technique and promote a plantar flexed foot and rigid ankle at the initial point of, and throughout the duration of, foot–ball impact.

4.5 Chapter Summary

This chapter aimed to explore how altering the orientation of the ball affects Rugby Union place kick technique, impact efficiency and resultant kick performance. Eight kickers (consisting of four Rugby kickers and four Soccer kickers) each performed nine maximal effort place kicks. Both groups of kickers used a forward and horizontal orientation, whilst the Rugby kickers also used their normal, preferred orientation and the Soccer kickers additionally used a backward ball orientation. The swing plane of the kicking foot and the orientations of the shank and foot segments at the start and end of the impact phase were analysed to quantify technique. Impact efficiency was assessed using coefficient of restitution and foot–ball velocity ratio and resulting place kick performance was measured using the flight characteristics of the ball. The impact location on the ball was also quantified and this varied between the ball orientation conditions. The use of a backward ball orientation resulted in the greatest impact efficiency and resultant ball velocity values within the Soccer kickers, whilst within the Rugby kickers these variables were greatest when a forward orientation was used. The results of the current chapter suggest that kickers aim to execute a consistent kick technique regardless of the orientation of the ball. The subsequent impact location on the ball is clearly influenced by the ball orientation but the effects on impact efficiency and place kick performance are more complicated.

CHAPTER 5: GENERAL DISCUSSION

5.1 Overview

The aim of this thesis was to *investigate the influence of ball orientation on Rugby Union place kicking technique, impact efficiency, and resulting kick performance, in order to further the understanding of why kickers use different ball orientations*. Three research questions were developed to address the overall aim, and this chapter will sequentially discuss each of these. Methodological considerations will then be reviewed before finally discussing possible future directions that could be taken and the practical implications of the present thesis.

5.2 Addressing the Research Questions

5.2.1 Research Question 1

To address the first research question, *"What are the ball setup preferences of elite international Rugby Union players, and how do these associate with kick performance?"*, this thesis investigated the ball orientations used by place kickers at the 2019 Rugby World Cup. The performance of place kicks taken with the identified orientations was assessed, primarily through the use of binomial logistic regression analysis. Logistic regression analysis was used since during place kicking there are several situational factors which can also influence kick success, as first shown by Pocock et al. (2018). Therefore, to be consistent with the methods used by Pocock et al. (2018), situational factors that were incorporated in to the current analysis consisted of time in the game, current match score, success of the kicker's previous kick, and kick distance and angle to the goal posts.

This thesis identified that a variety of ball orientations were employed by the elite place kickers and that each kicker was consistent in the implementation of their preferred ball orientation. A forward ball orientation was employed by 25.5% of the 51 studied kickers, whilst 27.5% of the kickers used a slanted orientation and 47.1% used a horizontal ball orientation. To assess the association between ball orientation and performance, each kick was categorised into one of these three categories which were additionally included in the logistic regression model. The results of the logistic regression analysis revealed that, when accounting for the aforementioned situational factors, kicks taken with a slanted ball orientation (approximately 45°) resulted in the greatest predicted kick success percentage (90.0%, from the tournament mean distance of 29.7 m and straight in front of the goal posts i.e. angle of 0°). Kicks taken with a forward orientation (approximately 15°) resulted in the worst predicted success percentage (84.4%, from 29.7 m in front of the goal posts) and kicks taken with a horizontal orientation (approximately 75°) resulted in the median predicted success percentage (86.8%, from 29.7 m in front of the goal posts). At face value, the implications for the differences in kick success are that the use of a slanted ball orientation is associated with increased kick performance and so kickers could be encouraged to explore the use of such a ball orientation during practice. However, the implemented regression model failed to correctly classify the outcome all of the recorded place kicks. This indicates that there are confounding variables which are influential to kick performance that were not included in the model. Such influential variables may be environmental (e.g. weather and pitch conditions), but they will also likely be directly related to the individual constraints of the kicker and include variables associated with their individual kicking technique. Whilst Chapter 3 revealed that there are different ball setup preferences of elite international kickers and that these are associated with different performance outcomes, the reasoning behind these preferences is not clear. It may be that kickers and coaches choose an orientation that they deem to suit the kicker’s technique, or that they choose an orientation that they believe is best for performance irrespective of technique. Nonetheless, the interactions between ball orientation and place kick technique were previously unknown and thus research question 2 was next to be addressed.

5.2.2 Research Question 2

Chapter 4 aimed to address the second research question, *“How do individuals change their kick technique when different ball orientations are used?”*. Eight kickers, consisting of four Rugby kickers and four Soccer kickers, carried out place kicks and used a combination of three out of a possible four different ball orientations which were experimentally manipulated in a counterbalanced fashion. Place kick technique was quantified by analysing the swing plane of the kicking foot during the approach phase (Bezodis et al., 2019) and the three-dimensional orientations of the kicking shank and foot at the start and end of the impact phase. The influence of ball orientation on the impact location on the ball was also assessed. It was identified that when ball orientation was altered the impact location on the ball changed both in local and global terms, and these effects were generally significant and very large between ball orientation conditions. The use of both forward and normal ball orientations resulted in impact locations that were between the belly and point of the ball. The use of a horizontal orientation resulted in impact locations that were near the ball's point and the use of a backward ball orientation led to impact locations that were nearest the belly of the ball.

Although impact location on the ball varied between ball orientation conditions, it was identified that each kicker demonstrated a relatively consistent kick technique regardless of the ball orientation that was being used. For the swing plane direction and inclination, and for the shank and foot orientations at the start of the impact phase, effect sizes between ball orientation conditions were generally all small or trivial. The use of a backward orientation led to the Soccer kickers producing the greatest overall mean plantar flexion angle at the start of the impact phase and this also resulted in the smallest mean plantar flexion range of motion during the impact. A more plantar flexed foot at initial foot–ball contact has previously been associated with kicks of greater distance during both Australian Football punt kicking (Peacock et al., 2017) and Rugby Union place kicking (Sinclair et al., 2017). Greater ball flight velocities, and so greater implied kick distances, have also been related to smaller plantar flexion range of motion in both controlled mechanical simulations (Peacock & Ball, 2019b, 2018b) and in human kicking (Ball et al., 2010; Peacock et al., 2017). These previous findings are supported by the results of this thesis since when using a backward ball orientation the Soccer kickers achieved the greatest mean resultant ball flight velocity. Therefore, the practical implications are that kickers should aim to adopt a more plantar flexed foot at the start of the impact phase and attempt to maintain a rigid ankle in order to reduce plantar flexion range of motion, and post hoc analysis revealed that this applies to all ball orientation conditions. It also appears that the use of a backward ball orientation may potentially aid in improving place kick performance by further enhancing the aforementioned plantar flexion kinematics, although this remains unknown within Rugby kickers.

5.2.3 Research Question 3

The third research question, *"How does ball orientation affect impact efficiency and resulting ball flight characteristics and kick performance?"*, was also addressed using the study described in Chapter 4. Ball flight characteristics, consisting of the three-dimensional components of ball flight velocity and flight direction and elevation, did not significantly differ between the ball orientation conditions. The greatest resultant ball flight velocity was achieved by the Soccer kickers when using a backward orientation and thus it could be implied that this orientation is preferable for kicking over greater distances. However, the Soccer kickers consistently produced greater mean resultant ball flight velocities than the Rugby kickers. This should be considered since it is likely a product of their greater kicking experience and years of kicking training, regardless of the fact that they were not practised at Rugby Union place kicking. The reason for the inclusion of both Rugby and Soccer kickers will be discussed in more detail in Section 5.3.

Measures of coefficient of restitution and foot–ball velocity ratio were used to account for initial kicking foot velocity at the start of the impact phase and quantify the efficiency of the impact between the foot and the ball. These impact efficiency measures did vary between ball orientation conditions, although differences between conditions were generally not significant. Previous studies which have used mechanical simulations (Ball & Peacock, 2020; Michelini et al., 2019) have reported somewhat larger efficiency measures than in the current thesis but have also observed that impacting between the point and belly of the ball resulted in reduced impact efficiency than impacting on the point of the ball. A difference in impact efficiency measures when impacting on the point as opposed to between the point and belly of the ball was not clearly apparent in the current thesis, however. When compared across all kickers, the use of a forward orientation (resulting impact location between the point and belly of the ball) resulted in comparable efficiency values to those when using a horizontal orientation (resulting impact location near the point of the ball). Therefore, the importance of considering the human element, likely the effects of soft tissue, is indicated since each kicker's technique differed little between orientation conditions. An additional consideration to be made is that the mechanical kicking leg repeatedly produces a consistent kick technique, yet differences in technique are evident between individual kickers. The mechanical kicking leg also follows a planar, vertical swing plane whilst the swing plane during Rugby Union place kicking is on a considerable inclination (overall mean ± *SD* from the data collected in Chapter 4 = 49.1 ± 4.1°) and is directed towards the right of the target (13.6 ± 6.3°). Impact efficiency and performance may therefore vary for a given ball orientation as a consequence of inter-individual differences in place kick technique. Nevertheless, during the present thesis it was identified that each kicker achieved their greatest values of coefficient of restitution and foot–ball velocity ratio when using a ball orientation which led to an impact location nearest the belly of the ball. This generally supports previous mechanical studies which have found that impacts occurring on (Holmes, 2008) and near (Michelini et al., 2019) the belly of the ball resulted in the greatest measures of impact efficiency. As a result of this study, kickers and practitioners could be encouraged to explore different ball orientations to identify one which enables them to achieve an impact location that is close to the belly of the ball given their individual technique of delivering the kicking leg to the ball. Although a backward orientation has not been investigated within Rugby kickers, based on the findings from the Soccer kickers in Chapter 4, Rugby kickers could also be encouraged to explore a backward ball orientation.

5.3 Methodological Considerations and Limitations

During Chapter 4, experimental trials were undertaken to investigate how kickers may alter their place kick technique when different ball orientations were used. The study included Rugby Union place kickers who were familiar with the task but also Soccer kickers who were not practised in place kicking of a prolate spheroid ball. As a result, the Rugby kickers had a personal ball orientation preference that they would have routinely practised with and so would likely have developed predetermined movement patterns that are more specific to such a ball orientation. However, it can be noted that the Rugby kickers did not achieve their greatest mean measures of impact efficiency, resultant ball velocity or modelled ball flight distance when using their normal orientation. On the other hand, the Soccer kickers would not have movement patterns specific to kicking a prolate spheroid Rugby Union ball, nor a certain ball orientation, and therefore it may be expected that they could display different responses in their technique to that of the Rugby kickers when the ball orientation is changed. The Soccer kickers were additionally included in the study over novice kickers since the Soccer kickers were still familiar with, and highly experienced at, the general kicking action but with a spherical ball. The methods of Chapter 4 did not allow the kickers to familiarise themselves with each of the ball orientation conditions. This was intentional so that the potential acute differences in place kick performance, impact efficiency and technique could be investigated when the ball orientation is altered. However, future studies may want to consider allowing time for the kickers to practise with each of the ball orientation conditions in order to allow consideration of how kickers might learn to adapt their technique in response to different ball orientations.

The current thesis is one of very few studies to implement advanced filtering methods during biomechanical kicking investigations. To the best of the author's knowledge, this thesis also contains the first biomechanical kicking-based study to implement a time-frequency filter on data sampled at a rate greater than 1000 Hz (the current thesis sampled at 4000 Hz). Movements that contain impacts, such as Rugby Union place kicking, contain a transition from low frequency data during the approach phase to high frequency data during the impact phase, and back again after the impact has finished. Furthermore, the impact only lasts for 10.2 ± 1.3 ms (overall mean ± *SD* from the data collected in Chapter 4) so sampling at 4000 Hz enables approximately 40 frames of data during this very short phase. As such, using a conventional filter, (for example a low-pass Butterworth filter) to filter data across the entire duration of a place kick will likely distort and reduce the accuracy of variables of interest (Knudson & Bahamonde, 2001; Nunome et al., 2006). However, the implementation of a time-frequency filter (in the case of the current thesis, a fractional Fourier filter adapted from Augustus et al., 2020b) means that the impact phase need not be considered entirely separately from the other phases of a place kick. Noisy data can still be sufficiently addressed throughout the impact phase, as well as during the lower frequency movement phases which occur prior to and after the impact, in order to obtain accurate representations of the true movement kinematics. Although a conventional filter can provide adequate results when investigating the swing phase (before and/or after impact) and impact phase separately, time-frequency filters enable accurate analyses to be made across the duration of movements that contain impacts (Augustus et al., 2020a, 2020b; Georgakis et al., 2002a; Georgakis & Subramaniam, 2009; Nunome et al., 2006) and so these are preferable when looking across the entire movement of place kicking.

In addition to the implementation of an advanced filtering method, the study in Chapter 4 is one of few to consider the accuracy component of place kick performance. Resultant ball velocity has generally been the only performance measure of interest in previous research (Baktash et al., 2009; Linthorne & Stokes, 2014; Padulo et al., 2013; Sinclair et al., 2014; Sinclair et al., 2016). However, for a kick to be successful and pass between the upright goal posts in a game situation a sufficient accuracy component is also necessary. The only previous studies that have considered a combination of all ball flight characteristics to measure kick accuracy were by Atack et al. (2019a), Bezodis et al. (2019) and Green et al. (2016); the former two studies used the ball flight model of Atack et al. (2019b), and the latter recorded the landing position of the ball. The present thesis is therefore also the first to study the impact phase and record the accuracy of place kicks. Although the current thesis also implemented the ball flight model of Atack et al. (2019b), the ball flight spin rates that were collected during Chapter 4 and input to the model may have been limited in their accuracy. This was likely due to challenges associated with the digitisation of the relevant ball landmarks over a relatively short displacement and time owing to the deliberately small field of view and high sampling frequency in order to enhance the quality of other spatial and temporal measures of impact (e.g. ball impact location and impact duration). Atack et al. (2019a) previously used a sampling rate of 240 Hz and subsequently the first four frames of raw ball flight data (16.7 ms) was used in the model. The current thesis sampled at 4000 Hz and used 10 frames of raw ball flight data (2.5 ms) when implementing the model. As a result of determining the ball flight characteristics, in particular spin rates, over such a short duration the potential effects of any noise in the raw data will have greater consequences. Although polynomial equations were fitted to these 10 frames of data in an attempt to alleviate the potential effects of noise as much as possible, where possible, future studies should aim to ensure that ball flight spin rates are determined over a longer duration to further reduce the potential effects of noise on the determined spin rates of the ball.

One limitation of the current thesis is that all kickers who attempted at least one place kick were included in the logistic regression model. Whilst this was done in line with the methods of Pocock et al. (2018), it is also a source of potential bias in the model. The model was trained using all kicks and therefore the resulting estimates seen in Table 3.2 are biased towards the kickers who attempted the most place kicks. Additionally, the number of place kicks attempted in each match of the tournament was also not constant. Both of these factors can be considered as random effects and future research may want to address these statistically; an example of which might be through the use of multi-level models.

There are environmental and task variables that would likely influence place kick performance that were not included in the logistic regression model of Chapter 3. Factors relating to the weather, particularly wind speed and direction, and stage in the tournament could be seen as important factors. For example, a place kick during the knockout stages is likely to have greater implications than one during the group stages and so this may increase the psychological stress experienced by the kicker. Some environmental and task characteristics were also not measured in the exploratory study of Chapter 4. Similarly, weather conditions were not recorded nor was the air pressure of the ball. These are characteristics that would be worth recording in future studies.

The exploratory approach taken and the relating small sample size in Chapter 4 are further limitations to be considered. Sample size directly relates to statistical power. Therefore, sample size influences whether a difference is determined to be significant and if this significant effect genuinely exists. The small sample sizes used in Chapter 4 will consequently have negative implications for the inferential statistics since it is possible that large differences in variables of interest between ball orientation conditions may have been deemed to be non-significant. Based on the medium and large effect size boundaries given in section 4.2.5, post hoc power analyses (G*Power v3.1.9.7, Germany) suggest that samples sizes between $n = 5$ and $n = 24$ are required to achieve statistical power ($1 - \beta$) of 0.8 for $\alpha = 0.05$. Future research in this area should therefore consider targeting such sample sizes.

5.4 Future Directions and Practical Implications

This section will first discuss the possible future directions that could be considered by researchers. Subsequently, the practical implications of this thesis will be discussed with the aim to inform the practice of place kickers, practitioners, and coaches. The current thesis identified that kickers appear to be consistent with their kicking action regardless of the orientation of the ball. However, the kinematic variables used to quantify technique were limited to those regarding the distal portion of the kicking leg during the end of the downswing and at the instances of the beginning and end of the impact phase. Whilst these did not vary greatly between ball orientation, it may be the case that kickers are adapting preceding elements of their technique in order to maintain a relatively consistent delivery of the kicking foot. These prior elements of technique may include the general approach direction towards the ball and the subsequent translation and orientation of the support foot and leg, particularly since altering the ball orientation likely results in changes to the three-dimensional position (primarily in the antero-posterior direction) of the impact location on the ball (with respect to the centre of the kicking tee). As a result, kickers may need to ensure they are correctly translated in the global space in order to achieve the varying impact locations on the ball that have been identified in the current thesis. Further technique variables that may differ with alterations to ball orientations could include angular displacements of the kicking hip and knee. Therefore, although the current thesis deliberately focused on the more distal and later-occurring aspects of technique owing to the direct influence these have on the impact between the foot and ball, it may be prudent for future studies to investigate the kinematics of the more proximal portion of the kicking leg as well as those of the support leg.

The current thesis focused on performance since improving place kick success should be of primary focus, but injury implications could be an additional area of consideration in future studies. Tol et al. (2002) identified that the repetition of kicking impacts has been linked to anterior ankle impingement syndrome in Soccer, and thus as the understanding of foot–ball impacts in Rugby Union kicking develops in the future, consideration should also be given to the potential injury effects of different ball orientations. Altering the ball orientation would likely result in differing amounts of ball deformation and so reaction force applied to the foot (Ball and Peacock, 2020; Holmes, 2008). If this force is applied to different locations on the foot, particularly in the proximal-distal direction (Peacock and Ball, 2019b), this would likely influence the extent of forced plantar flexion. These factors could in turn have implications for the risk of injury within Rugby Union place kickers since ankle impingement syndrome has been linked to both maximal plantar flexion/hyperplantar flexion and the direct recurrent impact force of the ball on the foot (Tol et al., 2002). Given the typical number of kicks performed by a Rugby Union place kicker during a match and training compared to the numbers in Soccer where ankle impingement syndrome has been identified, however, it may be that these injuries are of less concern.

The current thesis was the first to explore and identify the different ball orientation preferences within international Rugby Union place kickers and to associate these orientations with kick success. In this thesis it was also determined that there were few clear effects of ball orientation on the distal portion of place kick technique even though the local and global impact location achieved on the ball generally varied significantly between ball orientation conditions. Impact efficiency appeared to be influenced by the impact location on the ball, with impacts closer to the belly of the ball seemingly resulting in improved efficiency measures. However, there was not one ball orientation that resulted in the greatest efficiency or performance measures across all kickers. As a result of these findings, the practical implications are that kickers and coaches can therefore explore various ball orientations with the aim to identify one that achieves the best results for the kicker. Exploring orientations that result in an impact location closer to the belly of the ball may prove beneficial for impact efficiency and this exploration can be done without the need for, or causing, large alterations in the kicker's technique given the few clear effects of different ball orientation conditions on place kick technique.

5.5 Thesis Conclusion

This thesis aimed to investigate the different ball orientation preferences of elite Rugby Union place kickers and to explore the effects of ball orientation on place kick technique, impact efficiency and performance. An initial study was undertaken to identify the ball orientation preferences of place kickers at the 2019 Rugby World Cup. Whilst each kicker was consistent in the use of their chosen orientation, differences in ball orientation preferences clearly existed between kickers. The associations between the employed ball orientations and place kick success revealed that kicks taken with a slanted ball orientation (approximately 45°) had the greatest predicted kick success, although given the observational nature of this study, further experimental investigations were undertaken to better understand some of the biomechanical differences between different ball orientations. The second study therefore experimentally altered ball orientation and investigated the effects on place kick technique, impact efficiency and resulting performance. Although impact location on the ball was observed to vary between ball orientation conditions in both local and global terms, each kicker appeared to display a consistent kick technique irrespective of the orientation of the ball. Ball orientations that led to impact locations closer to the belly of the ball resulted in the greatest values of impact efficiency as measured by coefficient of restitution and foot–ball velocity ratio. This was especially evident within the Soccer kickers when the ball was orientated such that it was tilted backwards. However, there were individual kinematic factors that appeared to influence the efficiency of the foot–ball impact, such as the extent of plantar flexion at the start of, and the plantar flexion range of motion during, the impact phase. The current thesis identified the existence of different ball orientation preferences within international place kickers and determined that changing the ball orientation influences the impact location on the ball. Impact efficiency subsequently appears to be affected by the impact location, but kickers seem to be consistent with the delivery of the kicking foot to the ball regardless of the ball orientation.

REFERENCE LIST

Abdel-Aziz, Y. I., & Karara, H. M. (1971). Direct Linear Transformation from Comparator Coordinates into Object Space Coordinates in Close-Range Photogrammetry. *Proceedings of the ASP/UI Symposium on Close-Range Photogrammetry*, 1–18.

Angeloni, C., Riley, P. O., & Krebs, D. E. (1994). Frequency content of whole body gait kinematic data. *IEEE Transactions on Rehabilitation Engineering*, *2*(1), 40–46. https://doi.org/10.1109/86.296343

Atack, A. C. (2016). *The biomechanics of rugby place kicking* [PhD Thesis, St Mary's University]. https://research.stmarys.ac.uk/id/eprint/1407/

Atack, A. C., Trewartha, G., & Bezodis, N. E. (2019a). A joint kinetic analysis of rugby place kicking technique to understand why kickers achieve different performance outcomes. *Journal of Biomechanics*, *87*, 114–119. https://doi.org/10.1016/j.jbiomech.2019.02.020

Atack, A. C., Trewartha, G., & Bezodis, N. E. (2019b). Assessing rugby place kick performance from initial ball flight kinematics: Development, validation and application of a new measure. *Sports Biomechanics*, *18*(5), 457–469. https://doi.org/10.1080/14763141.2018.1433714

Augustus, S., Amca, A. M., Hudson, P. E., & Smith, N. (2020a). Choice of low-pass filter influences practical interpretation of ball kicking motions: The effect of a time-frequency filter method. *Sports Biomechanics*, *0*(0), 1–18. https://doi.org/10.1080/14763141.2020.1805507

Augustus, S., Amca, A. M., Hudson, P. E., & Smith, N. (2020b). Improved accuracy of biomechanical motion data obtained during impacts using a time-frequency low-pass filter. *Journal of Biomechanics*, 109639. https://doi.org/10.1016/j.jbiomech.2020.109639

Baktash, S., Hy, A., Muir, S., Walton, T., & Zhang, Y. (2009). *The Effects of Different Instep Foot Positions on Ball Velocity in Place Kicking*. *3*, 85–92.

Ball, K. (2008). Biomechanical considerations of distance kicking in Australian Rules football. *Sports Biomechanics*, *7*(1), 10–23.

Ball, K. (2010). Kick impact characteristics for different rugby league kicks. *XXVIII International Symposium on Biomechanics in Sports*, *28*. https://ojs.ub.uni-konstanz.de/cpa/article/view/4492

Ball, K., Smith, J., & MacMahon, C. (2010). Kick impact characteristics of junior kickers. *XXVIII International Symposium on Biomechanics in Sports*, *28*. https://ojs.ub.uni-konstanz.de/cpa/article/view/4495

Ball, K., Ingleton, C., Peacock, J. C. A., & Nunome, H. (2013a). Ball impact dynamics in the punt kick. *XXXI International Symposium on Biomechanics in Sports, 31*. https://ojs.ub.uni-konstanz.de/cpa/article/view/5608

Ball, K., & Peacock, J. C. A. (2020). Kick impact forces for different rugby ball sizes, impact points and inflations. *XXXVIII International Symposium on Biomechanics in Sports, 38*(1), 152-155.

Ball, K., Talbert, D., & Taylor, S. (2013b). Biomechanics of goal-kicking in rugby league. In B. Dawson, B. Durst, & H. Nunome (Eds.), *Science and Football VII* (pp. 47–53). Routledge. https://doi.org/10.4324/9780203131879-14

Barfield, W. R. (1998). The biomechanics of kicking in soccer. *Clinics in Sports Medicine*, *17*(4), 711–728. https://doi.org/10.1016/S0278-5919(05)70113-7

Bezodis, N. E., Atack, A. C., & Winter, S. (2018). The biomechanics of place kicking in Rugby Union. In H. Nunome, E. Hennig, & N. Smith (Eds.), *Football Biomechanics* (pp. 24–36). Routledge. https://doi.org/10.4324/9781315638553-4

Bezodis, N. E., Atack, A. C., Willmott, A. P., Callard, J. E. B., & Trewartha, G. (2019). Kicking foot swing planes and support leg kinematics in rugby place kicking: Differences between accurate and inaccurate kickers. *European Journal of Sport Science*, *19*(4), 451–460. https://doi.org/10.1080/17461391.2018.1519039

Bezodis, N. E., Willmott, A. P., Atack, A., & Trewartha, G. (2014). The kicking foot swing plane in rugby place kicking. *XXXII International Symposium on Biomechanics in Sports*, *32*, 304–307.

Bezodis, N. E., & Winter, S. (2014). Identifying the key technical aspects of rugby place kicking: a qualitative case study of an elite coach. *XXXII International Symposium on Biomechanics in Sports*, *32*, 425–428.

Bezodis, N. E., Trewartha, G., Wilson, C., & Irwin, G. (2007). Contributions of the non-kicking-side arm to rugby place-kicking technique. *Sports Biomechanics*, *6*(2), 171–186. https://doi.org/10.1080/14763140701324487

Bull Andersen, T., Dörge, & Thomsen. (1999). Collisions in soccer kicking. *Sports Engineering*, *2*(2), 121–125. https://doi.org/10.1046/j.1460-2687.1999.00015.x

Bull Andersen, T., Kristensen, L. B., & Sorensen, H. (2008). Biomechanical Differences Between Toe and Instep Kicking—Influence of Contact Area on the Coefficient of Restitution. *Football Science, 5*, 45–50.

Cockcroft, J., & van den Heever, D. (2016). A descriptive study of step alignment and foot positioning relative to the tee by professional rugby union goal-kickers. *Journal of Sports Sciences*, *34*(4), 321–329.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed). L. Erlbaum Associates.

de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics*, *29*(9), 1223–1230. https://doi.org/10.1016/0021-9290(95)00178-6

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behavior Research Methods, 39(2), 175–191. https://doi.org/10.3758/BF03193146

Ford, S., & Sayers, M. (2015). Lower limb movement variability during rugby union place kicking. *XXXIII International Symposium on Biomechanics in Sports*, *33*, 888–891.

Georgakis, A., Stergioulas, L. K., & Giakas, G. (2002b). Automatic algorithm for filtering kinematic signals with impacts in the Wigner representation. *Medical and Biological Engineering and Computing*, *40*(6), 625–633. https://doi.org/10.1007/BF02345300

Georgakis, A, Stergioulas, L. K., & Giakas, G. (2002a). Wigner filtering with smooth roll-off boundary for differentiation of noisy non-stationary signals. *Signal Processing*, *82*(10), 1411–1415. https://doi.org/10.1016/S0165-1684(02)00215-3

Georgakis, A., & Subramaniam, S. R. (2009). Estimation of the Second Derivative of Kinematic Impact Signals Using Fractional Fourier Domain Filtering. *IEEE Transactions on Biomedical Engineering*, *56*(4), 996–1004. https://doi.org/10.1109/TBME.2008.2006507

Green, A., Kerr, S., Olivier, B., Dafkin, C., & McKinon, W. (2016). The trade-off between distance and accuracy in the rugby union place kick: A cross-sectional, descriptive study. *Kinesiology : International Journal of Fundamental and Applied Kinesiology*, *48.*(2.), 251–257. https://doi.org/10.26582/k.48.2.4

Hay, J. G. (1993). *The biomechanics of sports techniques* (4th ed). Prentice-Hall.

Hébert-Losier, K., Lamb, P., & Beaven, C. M. (2020). Biomechanical determinants of placekicking success in professional Rugby Union players. *Sports Biomechanics*, *0*(0), 1–16. https://doi.org/10.1080/14763141.2020.1728368

Holmes, C. E. (2008). *Advanced modelling of ovoid balls* [PhD Thesis, Loughborough University]. https://repository.lboro.ac.uk/articles/Advanced_modelling_of_ovoid_balls/9539723

Hopkins, W. G. (2000). A new view of statistics. Internet Society for Sport Science: http://www.sportsci.org/resource/stats/

Iga, T., Nunome, H., Sano, S., Sato, N., & Ikegami, Y. (2018). Novel mathematical model to estimate ball impact force in soccer. *Sports Biomechanics*, *17*(4), 477–493. https://doi.org/10.1080/14763141.2017.1364415

Ishii, H., & Maruyama, T. (2007). Influence of Foot Angle and Impact Point on Ball Behavior in Side-Foot Soccer Kicking. In *The Impact of Technology on Sport II* (pp. 403–408).

Jackson, R. C. (2003). Pre-performance routine consistency: Temporal analysis of goal kicking in the Rugby Union World Cup. *Journal of Sports Sciences*, *21*(10), 803–814.

Jackson, R. C., & Baker, J. S. (2001). Routines, Rituals, and Rugby: Case Study of a World Class Goal Kicker. *Sport Psychologist*, *15*(1), 48.

Knudson, D., & Bahamonde, R. (2001). Effect of endpoint conditions on position and velocity near impact in tennis. *Journal of Sports Sciences*, *19*(11), 839–844. https://doi.org/10.1080/026404101753113787

Koike, S., Ishikawa, T., Willmott, A. P., & Bezodis, N. E. (2019). Direct and indirect effects of joint torque inputs during an induced speed analysis of a swinging motion. *Journal of Biomechanics*, *86*, 8–16. https://doi.org/10.1016/j.jbiomech.2019.01.032

Linthorne, N. P., & Stokes, T. G. (2014). Optimum Projection Angle for Attaining Maximum Distance in a Rugby Place Kick. *Journal of Sports Science & Medicine*, *13*(1), 211–216.

Marshall, S. (1958). Factors Affecting Place-Kicking in Football. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *29*(3), 302–308. https://doi.org/10.1080/10671188.1958.10762023

Michelini, R., Peacock, J. C. A., Taylor, S., & Ball, K. (2019). *Rugby ball impact point alters the co-efficient of restitution and ball speed*. World Congress of Science and Football 2019.

Minnaar, N., & van den Heever, D. J. (2015). A kicking simulator to investigate the foot-ball interaction during a rugby place kick. *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 6724–6727. https://doi.org/10.1109/EMBC.2015.7319936

Newell, K. M. (1986). Constraints on the Development of Coordination. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor Development in Children Aspects of Coordination and Control* (pp. 341–360).

Nunome, H., Lake, M., Georgakis, A., & Stergioulas, L. K. (2006). Impact phase kinematics of instep kicking in soccer. *Journal of Sports Sciences*, *24*(1), 11–22.

Nunome, H., Shinkai, H., & Ikegami, Y. (2013). Ball impact dynamics during soccer instep kicking. *Footwear Science*, *5*(sup1), S8–S9. https://doi.org/10.1080/19424280.2013.797933

Padulo, J., Granatelli, G., Ruscello, B., & D’Ottavio, S. (2013). The place kick in rugby. *The Journal of Sports Medicine and Physical Fitness*, *53*(3), 224–231.

Peacock, J. C. A., & Ball, K. (2019a). Is there a sweet spot on the foot in Australian football drop punt kicking? *Journal of Sports Sciences*, *37*(4), 467–476. https://doi.org/10.1080/02640414.2018.1505408

Peacock, J. C. A., & Ball, K. (2018a). Kick impact characteristics of accurate Australian football drop punt kicking. *Human Movement Science*, *61*, 99–108. https://doi.org/10.1016/j.humov.2018.07.009

Peacock, J. C. A., Ball, K., & Taylor, S. (2017). The impact phase of drop punt kicking for maximal distance and accuracy. *Journal of Sports Sciences*, *35*(23), 2289–2296. https://doi.org/10.1080/02640414.2016.1266015

Peacock, J. C. A., & Ball, K. (2019b). Strategies to improve impact efficiency in football kicking. *Sports Biomechanics*, *18*(6), 608–621. https://doi.org/10.1080/14763141.2018.1452970

Peacock, J. C. A., & Ball, K. (2018b). The influence of joint rigidity on impact efficiency and ball velocity in football kicking. *Journal of Biomechanics*, *71*, 245–250. https://doi.org/10.1016/j.jbiomech.2018.02.015

Peacock, J. C. A., & Ball, K. (2017). The relationship between foot-ball impact and flight characteristics in punt kicking. *Sports Engineering*, *20*(3), 221–230. https://doi.org/10.1007/s12283-017-0237-y

Pocock, C., Bezodis, N. E., Davids, K., & North, J. S. (2018). Hot hands, cold feet? Investigating effects of interacting constraints on place kicking performance at the 2015 Rugby Union World Cup. *European Journal of Sport Science*, *18*(10), 1309–1316. https://doi.org/10.1080/17461391.2018.1486459

Quarrie, K. L., & Hopkins, W. G. (2015). Evaluation of goal kicking performance in international rugby union matches. *Journal of Science and Medicine in Sport*, *18*(2), 195–198. https://doi.org/10.1016/j.jsams.2014.01.006

Roger-Lund, E., Preatoni, E., Cockcroft, J., van den Heever, D., & Venter, R. (2020). Hip-knee coupling in rugby place kicking at three different distances. *XXXVIII International Symposium on Biomechanics in Sports, 38*(1), 376-379.

Sakamoto, K., Geisler, G., Nakayama, M., & Asai, T. (2010). Kinematics of the foot joint in female soccer players during the ball impact phase of kicking. *Procedia Engineering*, *2*(2), 2549–2554. https://doi.org/10.1016/j.proeng.2010.04.030

Seo, K., Kobayashi, O., & Murakami, M. (2006). Flight dynamics of the screw kick in rugby. *Sports Engineering, 9*(1), 49–58. https://doi.org/10.1007/BF02844262

Seo, K., Kobayashi, O., & Murakami, M. (2007). Aerodynamic Characteristics of a Rugby Ball Spinning on Its Transverse Axis. *Transactions of the Japan Society of Mechanical Engineers Series B, 73*(734), 1999–2003. https://doi.org/10.1299/kikaib.73.1999

Shinkai, H, Nunome, H., Ikegami, Y., Sano, S., & Isokawa, M. (2007). Foot and ball behavior during impact phase of instep soccer kicking. *Journal of Biomechanics*, *40*, S198. https://doi.org/10.1016/S0021-9290(07)70194-X

Shinkai, H., Nunome, H., Ikegami, Y., & Isokawa, M. (2006). Foot movement in impact phase of instep kicking in soccer. *XXIV International Symposium on Biomechanics in Sports*, *24*. https://ojs.ub.uni-konstanz.de/cpa/article/view/162

Shinkai, H, Nunome, H., Isokawa, M., & Ikegami, Y. (2009). Ball Impact Dynamics of Instep Soccer Kicking. *Medicine & Science in Sports & Exercise*, *41*(4), 889–897. https://doi.org/10.1249/MSS.0b013e31818e8044

Sinclair, J., Taylor, P. J., Atkins, S., Bullen, J., Smith, A., & Hobbs, S. J. (2014). The influence of lower extremity kinematics on ball release velocity during in-step place kicking in rugby union. *International Journal of Performance Analysis in Sport*, *14*(1), 64–72. https://doi.org/10.1080/24748668.2014.11868703

Sinclair, J., Taylor, P. J., Atkins, S., Hobbs, S. J., & Ball, K. (2016). Biomechanical predictors of ball velocity during punt kicking in elite rugby league kickers. *International Journal of Sports Science & Coaching*, *11*(3), 356–364.

Sinclair, J., Taylor, P. J., Smith, A., Bullen, J., Bentley, I., & Hobbs, S. J. (2017). Three-dimensional kinematic differences between accurate and high velocity kicks in rugby union place kicking. *International Journal of Sports Science & Coaching*, *12*(3), 371–380.

Smith, J., Ball, K., & MacMahon, C. (2009). Foot-to-ball interaction in preferred and non-preferred leg Australian rules kicking. *XXVII International Symposium on Biomechanics in Sports*, *27*.

Tol, J. L., Slim, E., van Soest, A. J., & van Dijk, C. N. (2002). The Relationship of the Kicking Action in Soccer and Anterior Ankle Impingement Syndrome: A Biomechanical Analysis. *The American Journal of Sports Medicine*, *30*(1), 45–50. https://doi.org/10.1177/03635465020300012101

Tsaousidis, N., & Zatsiorsky, V. (1996). Two types of ball-effector interaction and their relative contribution to soccer kicking. *Human Movement Science*, *15*(6), 861–876. https://doi.org/10.1016/S0167-9457(96)00027-9

Willmott, A. P., & Dapena, J. (2012). The planarity of the stickface motion in the field hockey hit. *Journal of Sports Sciences*, *30*(4), 369–377. https://doi.org/10.1080/02640414.2011.642807

World Rugby Laws. (2020). Retrieved 5 August 2020, from https://laws.worldrugby.org/?

Zhang, Y., Liu, G., & Xie, S. (2012). Movement Sequences during Instep Rugby Kick: A 3 D Biomechanical Analysis. *International Journal of Sports Science and Engineering*, *6*(2), 89–95.

APPENDICES

Appendix A: Descriptive Statistics of the Individual Kickers at the 2019 Rugby World Cup

Descriptive statistics of the individual kickers analysed in Chapter 3.

Kicker No.	Position	Mass (kg)	Height (m)	Age (Years)	Total Kicks Taken	Total Kicks Scored	Total Kick Success (%)
1	Fly half	87	1.85	23	9	8	88.9
2	Fly half	95	1.86	26	1	0	0.0
3	Fly half	92	1.85	29	9	7	77.8
4	Full back	92	1.87	28	1	1	100.0
5	Fly half	89	1.91	28	16	9	56.3
6	Fly half	80	1.78	33	8	8	100.0
7	Fly half	89	1.82	30	2	1	50.0
8	Fly half	88	1.75	30	3	3	100.0
9	Fly half	93	1.91	27	5	3	60.0
10	Fly half	95	1.79	31	13	10	76.9
11	Fly half	85	1.76	22	6	4	66.7
12	Scrum half	93	1.9	30	3	1	33.3
13	Scrum half	70	1.75	24	3	3	100.0
14	Fly half	93	1.88	29	18	16	88.9
15	Full back	94	1.84	26	1	0	0.0
16	Fly half	92	1.87	29	19	14	73.7
17	Full back	91	1.91	24	2	1	50.0
18	Fly half	80	1.78	29	14	12	85.7
19	Fly half	87	1.82	26	1	1	100.0
20	Fly half	84	1.78	26	12	9	75.0
21	Scrum half	78	1.76	33	6	6	100.0
22	Fly half	98	1.89	25	34	25	73.5
23	Inside Centre	100	1.83	26	7	5	71.4
24	Fly half	88	1.83	27	5	4	80.0
25	Fly half	89	1.85	25	2	1	50.0
26	Fly half	87	1.84	23	2	2	100.0
27	Fly half	92	1.88	34	10	8	80.0
28	Full back	102	1.94	22	11	8	72.7
29	Fly half	93	1.84	28	4	1	25.0
30	Fly half	97	1.87	27	1	1	100.0
31	Full back	85	1.78	30	7	6	85.7
32	Fly half	90	1.82	29	11	8	72.7
33	Fly half	83	1.77	30	11	7	63.6
34	Inside Centre	92	1.88	27	29	23	79.3
35	Fly half	87	1.8	26	2	2	100.0
36	Fly half	77	1.74	28	1	0	0.0
37	Wing	90	1.89	25	2	1	50.0
38	Fly half	92	1.91	26	9	8	88.9
39	Fly half	85	1.79	25	29	23	79.3
40	Fly half	92	1.81	25	1	1	100.0

41	Fly half	81	1.86	20	15	11	73.3
42	Inside Centre	99	1.85	33	1	1	100.0
43	Scrum half	95	1.8	28	8	7	87.5
44	Full back	79	1.85	26	5	3	60.0
45	Fly half	74	1.74	20	7	6	85.7
46	Full back	82	1.78	24	2	1	50.0
47	Fly half	87	1.84	26	9	8	88.9
48	Fly half	93	1.85	37	6	2	33.3
49	Fly half	89	1.88	25	1	0	0.0
50	Fly half	87	1.81	30	28	20	71.4
51	Fly half	95	1.82	34	4	4	100.0

Appendix B: Variables of Interest Removed from Analyses in Chapter 4 and Reason for Removal

Variables of interest that were removed from analyses and the reason for removal.

Individual Variables removed from analyses	Reason for removal of variable	Number of trials in which the variables were removed
Foot segment orientations (at the end of impact)	Fifth metatarsal marker came off during impact	2
Knee segment orientations (at the start and end of impact)	Error during digitisation	1
Impact efficiency measures (CoR and EM)	Toe marker came off during impact	1
All variables involving ball data	Digitisation error when reconstructing the ball	2

Appendix C: Peak Cut-off Frequencies Used in the Fractional Fourier Filter

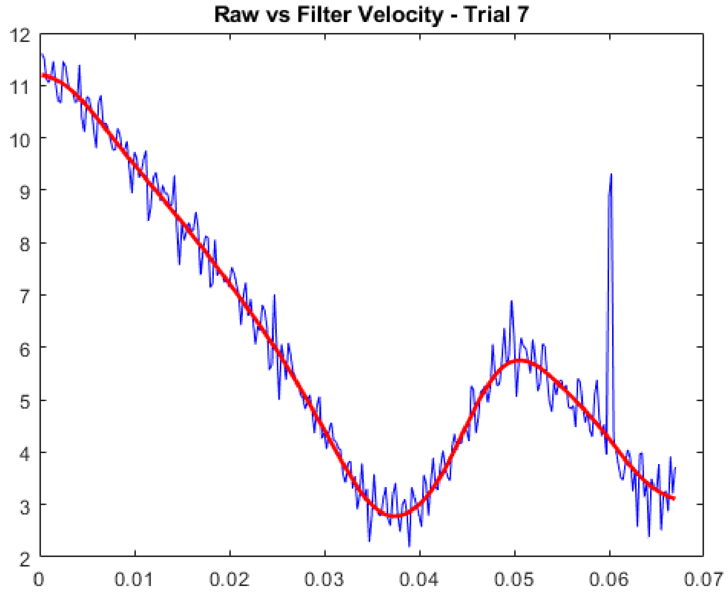
Peak cut-off frequency/height of impact (Hz) ranges used in the fractional Fourier filter when filtering the raw marker displacement data.

Marker	Peak cut-off frequency (Hz)
Knee	100 - 107
Shank	100 - 107
Ankle	125 - 152
Heel	125 - 153
Fifth Metatarsal	232 - 265
Toe	232 - 265

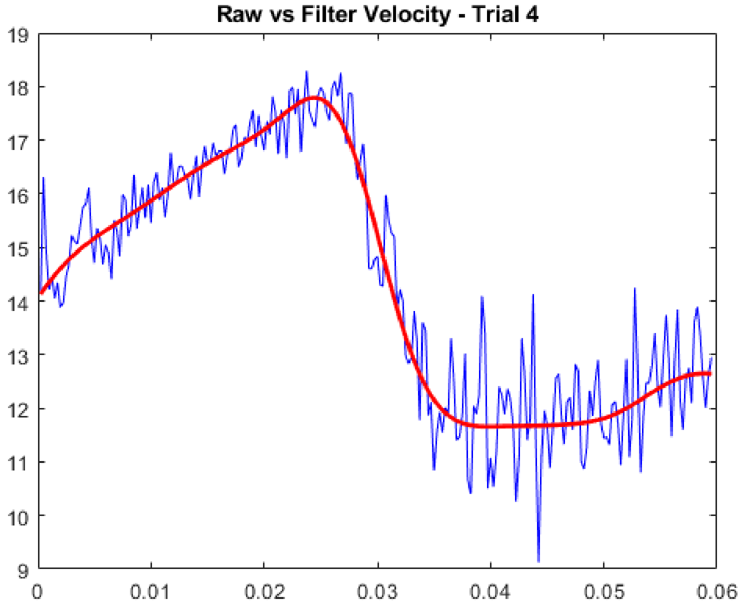
Appendix D: Examples of the Filtered Velocities Obtained Using the Fractional Fourier Filter, Plotted Against the Raw Velocities, for the Markers Used for the Segment Reconstructions

Filtered resultant velocities (red), obtained using the fractional Fourier filter, plotted against the raw resultant velocities (blue) over the duration of a kick for: **(a)** a knee marker; **(b)** an ankle marker; **(c)** a heel marker; **(d)** a fifth metatarsal marker.

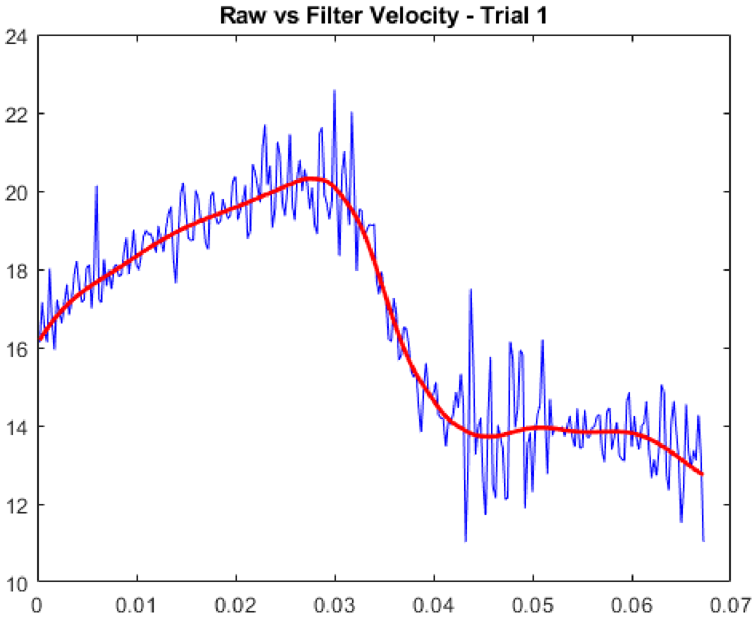
(a)



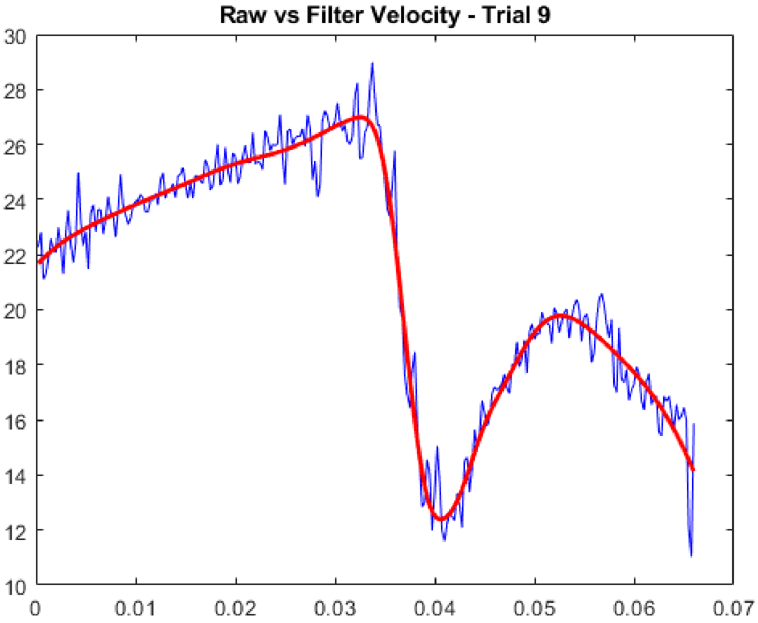
(b)



(c)


Raw vs Filter Velocity - Trial 1
24
22
20
18
16
14
12
10
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07

(d)


Raw vs Filter Velocity - Trial 9
30
28
26
24
22
20
18
16
14
12
10
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07

Appendix E: Mean Effects Sizes and 95% Confidence Intervals for Variables of Interest in Chapter 4

Mean effect sizes (mean ES) and 95% confidence intervals (95% CI) for swing plane inclination and direction when compared between the different ball orientation conditions.

		Ball Orientation Condition Comparison				
		Forward vs. Horizontal Mean ES (95% CI)	Forward vs. Normal Mean ES (95% CI)	Horizontal vs. Normal Mean ES (95% CI)	Forward vs. Backward Mean ES (95% CI)	Horizontal vs. Backward Mean ES (95% CI)
All Kickers (*n* = 8)	Inclination	-0.09 (-1.47, 1.30)				
	Direction	-0.26 (-1.65, 1.13)				
Rugby Kickers (*n* = 4)	Inclination	-0.21 (-2.17, 1.76)	-0.33 (-2.31, 1.64)	-0.18 (-2.14, 1.79)		
	Direction	-0.50 (-2.49, 1.50)	0.52 (-1.47, 2.51)	1.22 (-0.91, 3.36)		
Soccer Kickers (*n* = 4)	Inclination	0.19 (-1.78, 2.15)			-0.19 (-2.15, 1.78)	-0.28 (-2.25, 1.69)
	Direction	-0.13 (-2.09, 1.83)			0.08 (-1.88, 2.04)	0.23 (-1.74, 2.20)

Mean effect sizes (mean ES) and 95% confidence intervals (95% CI) for segment orientations at the start of the impact phase when compared between the different ball orientation conditions.

		Ball Orientation Condition Comparison				
		Forward vs. Horizontal Mean ES (95% CI)	Forward vs. Normal Mean ES (95% CI)	Horizontal vs. Normal Mean ES (95% CI)	Forward vs. Backward Mean ES (95% CI)	Horizontal vs. Backward Mean ES (95% CI)
All Kickers (*n* = 8)	Foot Azimuth	0.39 (-1.01, 1.79)				
	Foot Elevation	-0.07 (-1.46, 1.32)				
	Shank Azimuth	0.73 (-0.70, 2.16)				
	Shank Elevation	-0.01 (-1.39, 1.38)				
	Plantar flexion	0.16 (-1.23, 1.55)				
Rugby Kickers (*n* = 4)	Foot Azimuth	0.57 (-1.43, 2.57)	0.24 (-1.73, 2.21)	-0.30 (-2.27, 1.68)		
	Foot Elevation	0.03 (-1.93, 1.99)	0.07 (-1.89, 2.03)	0.04 (-1.92, 2.00)		
	Shank Azimuth	0.98 (-1.09, 3.06)	1.42 (-0.78, 3.61)	0.98 (-1.10, 3.05)		
	Shank Elevation	-0.07 (-2.03, 1.89)	-0.12 (-2.08, 1.84)	-0.05 (-2.01, 1.91)		
	Plantar flexion	0.07 (-1.89, 2.03)	0.25 (-1.71, 2.22)	0.19 (-1.77, 2.16)		
Soccer Kickers (*n* = 4)	Foot Azimuth	0.16 (-1.81, 2.12)			0.08 (-1.89, 2.04)	-0.10 (-2.06, 1.86)
	Foot Elevation	-0.23 (-2.20, 1.74)			0.17 (-1.79, 2.14)	0.36 (-1.62, 2.34)
	Shank Azimuth	0.52 (-1.47, 2.51)			1.06 (-1.03, 3.15)	0.51 (-1.48, 2.50)
	Shank Elevation	0.16 (-1.80, 2.13)			-0.05 (-2.01, 1.92)	-0.21 (-2.17, 1.76)
	Plantar flexion	0.32 (-1.65, 2.30)			0.31 (-1.66, 2.28)	0.02 (-1.94, 1.98)

Mean effect sizes (mean ES) and 95% confidence intervals (95% CI) for impact locations when compared between the different ball orientation conditions.

		Ball Orientation Condition Comparison				
		Forward vs. Horizontal Mean ES (95% CI)	Forward vs. Normal Mean ES (95% CI)	Horizontal vs. Normal Mean ES (95% CI)	Forward vs. Backward Mean ES (95% CI)	Horizontal vs. Backward Mean ES (95% CI)
All Kickers (*n* = 8)	Local Impact Location	-8.84 (-13.38, -4.29)				
	Global Impact Location	2.65 (0.75, 4.55)				
Rugby Kickers (*n* = 4)	Local Impact Location	-7.43 (-12.94, -1.92)	0.25 (-1.72, 2.22)	6.48 (1.58, 11.38)		
	Global Impact Location	1.85 (-0.49, 4.19)	-1.12 (-3.23, 0.99)	-3.32 (-6.34, -0.30)		
Soccer Kickers (*n* = 4)	Local Impact Location	-10.79 (-18.52, -3.06)			8.13 (2.17, 14.09)	17.68 (5.27, 30.09)
	Global Impact Location	4.29 (0.73, 7.85)			0.39 (-1.59, 2.36)	-3.27 (-6.26, -0.27)

Mean effect sizes (mean ES) and 95% confidence intervals (95% CI) for impact durations when compared between the different ball orientation conditions.

		Ball Orientation Condition Comparison				
		Forward vs. Horizontal Mean ES (95% CI)	Forward vs. Normal Mean ES (95% CI)	Horizontal vs. Normal Mean ES (95% CI)	Forward vs. Backward Mean ES (95% CI)	Horizontal vs. Backward Mean ES (95% CI)
All Kickers (*n* = 8)	Impact Duration	1.26 (-0.26, 2.78)				
Rugby Kickers (*n* = 4)	Impact Duration	1.28 (-0.87, 3.43)	0.57 (-1.43, 2.57)	-0.74 (-2.77, 1.28)		
Soccer Kickers (*n* = 4)	Impact Duration	1.93 (-0.44, 4.30)			-0.35 (-2.32, 1.63)	-2.13 (-4.58, 0.33)

Mean effect sizes (mean ES) and 95% confidence intervals (95% CI) for impact efficiency measures when compared between the different ball orientation conditions.

		Ball Orientation Condition Comparison				
		Forward vs. Horizontal Mean ES (95% CI)	Forward vs. Normal Mean ES (95% CI)	Horizontal vs. Normal Mean ES (95% CI)	Forward vs. Backward Mean ES (95% CI)	Horizontal vs. Backward Mean ES (95% CI)
All Kickers (*n* = 8)	CoR	-0.16 (-1.55, 1.2)				
	Foot–ball velocity ratio	-0.10 (-1.49, 1.29)				
Rugby Kickers (*n* = 4)	CoR	-0.93 (-3.00, 1.13)	-0.70 (-2.72, 1.32)	0.35 (-1.63, 2.32)		
	Foot–ball velocity ratio	-1.34 (-3.50, 0.83)	-0.93 (-3.00, 1.13)	0.25 (-1.72, 2.22)		
Soccer Kickers (*n* = 4)	CoR	0.45 (-1.54, 2.43)			1.72 (-0.58, 4.01)	2.52 (-0.10, 5.15)
	Foot–ball velocity ratio	0.46 (-1.53, 2.45)			1.39 (-0.79, 3.58)	1.08 (-1.02, 3.17)

Mean effect sizes (mean ES) and 95% confidence intervals (95% CI) for segment orientations at the end of the impact phase when compared between the different ball orientation conditions.

		Ball Orientation Condition Comparison				
		Forward vs. Horizontal Mean ES (95% CI)	Forward vs. Normal Mean ES (95% CI)	Horizontal vs. Normal Mean ES (95% CI)	Forward vs. Backward Mean ES (95% CI)	Horizontal vs. Backward Mean ES (95% CI)
All Kickers (*n* = 8)	Foot Azimuth	-0.06 (-1.44, 1.33)				
	Foot Elevation	0.23 (-1.17, 1.62)				
	Shank Azimuth	0.76 (-0.67, 2.20)				
	Shank Elevation	0.05 (-1.34, 1.44)				
	Plantar flexion	-0.09 (-1.48, 1.30)				
	Plantar flexion range of motion	-0.91 (-2.36, 0.55)				
Rugby Kickers (*n* = 4)	Foot Azimuth	-0.03 (-1.99, 1.93)	0.21 (-1.75, 2.18)	0.28 (-1.69, 2.25)		
	Foot Elevation	0.23 (-1.74, 2.20)	-0.09 (-2.05, 1.87)	-0.33 (-2.30, 1.65)		
	Shank Azimuth	0.59 (-1.41, 2.59)	0.48 (-1.51, 2.46)	-0.21 (-2.17, 1.76)		
	Shank Elevation	-0.06 (-2.02, 1.90)	-0.29 (-2.26, 1.68)	-0.26 (-2.22, 1.71)		
	Plantar flexion	0.04 (-1.92, 2.00)	0.37 (-1.61, 2.34)	0.32 (-1.65, 2.29)		
	Plantar flexion range of motion	-0.06 (-2.02, 1.90)	0.78 (-1.25, 2.81)	0.63 (-1.38, 2.64)		
Soccer Kickers (*n* = 4)	Foot Azimuth	-0.07 (-2.03, 1.89)			-0.27 (-2.23, 1.70)	-0.13 (-2.09, 1.83)
	Foot Elevation	0.42 (-1.57, 2.40)			0.79 (-1.25, 2.82)	0.56 (-1.44, 2.56)
	Shank Azimuth	1.14 (-0.98, 3.25)			0.66 (-1.35, 2.67)	-0.57 (-2.56, 1.43)
	Shank Elevation	0.27 (-1.70, 2.24)			-0.47 (-2.45, 1.52)	-0.61 (-2.61, 1.40)
	Plantar flexion	-0.36 (-2.33, 1.62)			-0.46 (-2.45, 1.52)	-0.2 (-2.16, 1.77)
	Plantar flexion range of motion	-2.95 (-5.78, -0.12)			-2.70 (-5.41, 0.01)	-0.63 (-2.63, 1.38)

Mean effect sizes (mean ES) and 95% confidence intervals (95% CI) for ball flight characteristics when compared between the different ball orientation conditions.

		Ball Orientation Condition Comparison				
		Forward vs. Horizontal Mean ES (95% CI)	Forward vs. Normal Mean ES (95% CI)	Horizontal vs. Normal Mean ES (95% CI)	Forward vs. Backward Mean ES (95% CI)	Horizontal vs. Backward Mean ES (95% CI)
All Kickers (*n* = 8)	Resultant	0.31 (-1.09, 1.70)				
	Vx	0.04 (-1.35, 1.42)				
	Vy	0.60 (-0.82, 2.02)				
	Vz	0.20 (-1.19, 1.59)				
	Ball Elevation	0.41 (-0.99, 1.81)				
	Ball Azimuth	0.35 (-1.05, 1.75)				
Rugby Kickers (*n* = 4)	Resultant	0.64 (-1.37, 2.65)	1.50 (-0.72, 3.72)	0.68 (-1.34, 2.70)		
	Vx	-0.13 (-2.10, 1.83)	-0.59 (-2.60, 1.41)	-0.76 (-2.79, 1.27)		
	Vy	0.01 (-1.95, 1.97)	0.74 (-1.29, 2.77)	1.76 (-0.55, 4.07)		
	Vz	-0.46 (-2.45, 1.52)	-0.30 (-2.27, 1.68)	0.32 (-1.65, 2.29)		
	Ball Elevation	0.04 (-1.93, 2.00)	0.75 (-1.28, 2.78)	1.48 (-0.73, 3.70)		
	Ball Azimuth	0.60 (-1.41, 2.60)	1.46 (-0.75, 3.67)	0.72 (-1.30, 2.74)		
Soccer Kickers (*n* = 4)	Resultant	-0.08 (-2.04, 1.88)			0.02 (-1.94, 1.98)	0.08 (-1.88, 2.05)
	Vx	0.15 (-1.81, 2.11)			0.79 (-1.24, 2.83)	0.46 (-1.52, 2.45)
	Vy	1.76 (-0.55, 4.06)			1.27 (-0.88, 3.41)	-0.53 (-2.52, 1.47)
	Vz	0.60 (-1.40, 2.61)			1.04 (-1.05, 3.13)	0.39 (-1.59, 2.37)
	Ball Elevation	0.93 (-1.13, 2.99)			0.38 (-1.60, 2.36)	-0.54 (-2.54, 1.46)
	Ball Azimuth	0.03 (-1.93, 1.99)			0.06 (-1.91, 2.02)	0.03 (-1.93, 1.99)

Mean effect sizes (mean ES) and 95% confidence intervals (95% CI) for modelled ball flight distance when compared between the different ball orientation conditions.

		Ball Orientation Condition Comparison				
		Forward vs. Horizontal Mean ES (95% CI)	Forward vs. Normal Mean ES (95% CI)	Horizontal vs. Normal Mean ES (95% CI)	Forward vs. Backward Mean ES (95% CI)	Horizontal vs. Backward Mean ES (95% CI)
All Kickers (*n* = 8)	Displacement	-0.16 (-1.55, 1.23)				
Rugby Kickers (*n* = 4)	Displacement	0.97 (-1.11, 3.04)	0.82 (-1.22, 2.86)	-0.14 (-2.10, 1.83)		
Soccer Kickers (*n* = 4)	Displacement	-1.39 (-3.57, 0.80)			0.55 (-1.44, 2.55)	1.65 (-0.62, 3.92)