Biomechanical Considerations in Goal-Kicking Accuracy: Application of an Inertial Measurement System

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DOCTOR OF PHILOSOPHY

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Abstract

Goal-kicking is an important skill in Australian Football (AF), accounting for approximately 62% of points scored during a match (Anderson et al., 2018). Despite its importance, little biomechanical research has examined the key technical characteristics underpinning the skill. The aims of this thesis were to validate a methodological approach to enable quantification of goal-kicking kinematics in a field environment, and examine goal-kicking technique and identify technical factors associated with accuracy. In **Chapters 3** and **4**, the Xsens inertial measurement system (IMS) was validated against a Vicon motion capture system (MAS) when measuring lower extremity and pelvis kinematics. Trivial to small mean differences (0.2-10.1%) and measurement error (0.1-7.9%) were found between the IMS and MAS across all parameters, advocating the use of IMS to quantify kicking kinematics. In **Chapter 5,** the effect of modifying the task constraints on accurate goal-kicking was explored. Increasing the distance of the shot from goals (30 m to 40 m) required substantially greater joint range of motion (knee and hip), with higher linear (foot speed) and angular (knee and shank) velocities. Altering the angle of the shot (0 to 45°) had no substantial influence on accurate goal-kicking technique. Findings indicated adjustments in goal-kicking technique may be required dependent on the location of the shot. In **Chapter 6**, 18 elite to sub-elite AF players performed 15 x 30 m goal-kicks in-front of goals and technique was examined on group-basis. A number of substantial kinematic differences were identified between accurate and inaccurate goal-kicks. For example, accurate goal-kicks were characterised by substantially less kick-leg joint range of motion (ankle, knee and hip), lower linear (com, foot speed) and angular (knee and shank) velocities, with less support-leg knee flexion during the kicking phase. In addition, a number of substantial linear and quadratic relationships were reported between technical parameters and accuracy. Findings indicated that many factors influence goal-kicking accuracy in AF; ranging from technical errors in the player's approach, configuration of their support-leg and kick-leg motions, through to follow-through position. In **Chapter 7,** goal-kicking data from chapter 6 was examined on individual-basis. All players demonstrated substantial kinematic differences between accurate and inaccurate goal-kicks, along with substantial relationships between kinematic parameters and accuracy, but these were individual-specific. A combination of both a group and individual-based analysis provided a more thorough understanding of technical factors which influence goal-kicking technique in AF. The body of work in this thesis provides: 1) validation of a methodological approach to quantify kicking biomechanics, and 2) a comprehensive understanding of technical factors associated with goal-kicking accuracy in AF, and 3) recommendations for both research and coaching practice.

Declaration

Doctor of Philosophy Declaration

I, Stephanie Jayne Blair declare that the PhD thesis entitled "Biomechanical Considerations in Goal-kicking Accuracy: Application of an Inertial Measurement System" is no more than 100,000 words in length including quotes and exclusive tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Signature: [redacted] **Date:** 01/03/2019

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List of Publications and Awards

Publications

The following work has been presented at scientific conferences and/or is published in peer-reviewed journals in support of this thesis:

Chapter 3 & 4

- **Blair, S**., Duthie, G., Robertson, S., Hopkins, W. & Ball, K. (2018). Concurrent Validation of an Inertial Measurement System to Measure Kicking Biomechanics in Four Football Codes. *Journal of Biomechanics*, 17, 24-32.
- **Blair, S**., Duthie, G., Robertson, S., & Ball, K. (2017). Validity of Wearable technologies to measure kicking biomechanics. *XXVI Congress of the International Society of Biomechanics*, Australia, 23-27th July.
- **Blair, S**., Robertson, S., Duthie, G. & Ball, K. (2016). Validation of wearable technologies to measure goal-kicking biomechanics in Australian Rules Football. *10th Australasian Biomechanics Conference*, Australia, 4-6th Dec.

Chapter 5

- **Blair, S**., Robertson, S., Duthie, G., & Ball, K. (2018). The effect of altering distance on goal-kicking technique in Australian Football. *36th International Society on Biomechanics in Sports Conference*, New Zealand, 10-14th September.
- Ball, K. **& Blair, S.** (2018). Shot success and kinematic differences with altering kicking angle on goal-kicking technique in Australian football. *36th International Society on Biomechanics in Sports Conference*, New Zealand, 10-14th September.

Chapter 6 & 7

- **Blair, S**., Duthie, G., Robertson, S., & Ball, K. (2017). Biomechanics of goal-kicking accuracy in Australian Football using an inertial measurement system. *35th International Society on Biomechanics in Sports Conference*, Germany, 14-18th June.

Invited talks

- **Blair, S**. (2017). Talk entitled: Application of the Xsens MVN link system: Australian Football, Rugby Codes & Soccer. Presented during the Xsens session. *XXVI Congress of the International Society of Biomechanics*, Australia, 23-27 July.

Media

- Herald Sun article: How to kick goals: Answering footy's biggest question (page 10: 2/6/2018)
- Biomechanics kicking analyst on the Women's AFL Footy Show: Spearheads (Episode 6: 5/3/2018)
- Biomechanics kicking analyst on the Women's AFL Footy Show: High-Performance match-up (Episode 6: 12/3/2017)

Awards

- Best student submission in the International Biomechanics Day 2018 2-minute tweet competition for the International Society of Biomechanics in Sport.
- Recipient of the International Society of Biomechanics in Sports Conference Student Travel Grant, 2018
- Recipient of the International Society of Biomechanics in Sports Conference Student Travel Grant, 2017.
- ISEAL HDR Poster presentation award.
- 2015 - 2018 Victoria University International Postgraduate Scholarship.

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Abbreviations

AF	Australian football
AFL	Australian football league
BC	Ball contact
COM	Centre of mass
CV	Coefficient of variation
DOF	Degrees of Freedom
Hz	Hertz
KFTO	Kick-foot toe-off
KL	Kick-leg
ICC	Intra-class correlation coefficient
IMU	Inertial measurement unit
IMS	Inertial measurement system
ISB	International Society of Biomechanics
MAS	Motion analysis system
MBI	Magnitude-based inferences
$m.s^{-1}$	Metres per second
$m.s^{-2}$	Metres per second squared
NHST	Null hypothesis significance testing
r	Pearson correlation coefficient
RMSE	Root mean square error

ROM	Range of motion
SAS	Statistical analysis system
SEE	Standard error of the estimate
SHS	Support-leg heel strike
SL	Support-leg
2D	Two-dimensional
3D	Three-dimensional
º/s	Degrees per second
º	Degrees

Chapter 1: Introduction

Australian football (AF) is one of the most popular team-sports played in Australia, having the highest participation rate (approximately 1.5 million players across all levels) and spectator attendance (approximately 7.2 million per AFL season) (Australian Bureau of Statistics 2017 report). It is a dynamic invasion game played between two opposing teams consisting of 18 players (18 on the field and 4 interchange) on an oval field. An ovoid-shaped ball is moved about the field by kicking, handballing and running with the ball, with the aim of any given sequence of play is to kick a goal between the two large posts located at the opposition's end of the field (Robertson et al., 2006).

Goal-kicking forms an important component of winning games in AF, as it provides a means through which to score points. There are two broad categories of goal-kicking in AF: general play and set-shots goal-kicks. The set-shot is of particular interest, as it comprises approximately 62% of points scored during a game and has been identified as the most influential performance indicator in match outcome (Anderson et al., 2018; Robertson et al., 2016). Consequently, a player's goal-kicking ability can have a major bearing on a team's success in competition. However, as the success rate for set-shot goal-kicks during the 2018 Australian Football league (AFL) season was only 47.0% (Champion Data statistics), there is clear scope for research to examine set-shot goal-kicking to support improvements in performance.

The set-shot goal-kick (hereafter, the set-shot goal-kick will be referred as just the goal-kick) is taken when a player is awarded a free kick or has taken a mark within goal range. It is a self-paced closed skill, where the player is given 30 seconds to perform the shot without any physical pressure from opponents (Baker & Ball, 1996). Consequently, the success of the shot has been suggested to be largely influenced by a player's technique

(Baker & Ball, 1996; Ball, 2013; Peacock et al., 2017). The goal-kick is typically performed using a drop-punt kick and involves the combined technical aspects of a running approach, release of the ball from the hands in the final step and a forceful impact with the kick-leg as it swings through in the direction goals (Ball, 2013). Possible reasons for the kick to miss the goal, are due to a technical issue that leads to a poor impact with the ball (Baker & Ball, 1996; Peacock & Ball, 2018a, 2018b).

Despite the importance of goal-kicking, it remains a largely unexplored area in sport biomechanics. To date, only one study has examined technical aspects of goal-kicking ($n = 8$ elite AF players) using an in-field notational analysis (Ball et al., 2002). Whilst this type of analysis provided an initial understanding of goal-kicking technique, only a limited number of parameters were used to assess performance as the investigation was restricted to frontal plane analysis only. This substantially limited this exploration of the biomechanical characteristics of goal-kicking technique. Expanding upon this study and investigating the biomechanical characteristics of the complete goal-kicking action is needed to provide a more comprehensive understanding of goal-kicking technique. This work is needed to establish an evidence base to define the technical elements that may be important for improving goal-kicking performance. Furthermore, providing specific kinematic information is important in the evaluation and provision of current coaching cues to assist with the development of the skill (Ball, 2011).

An important methodological consideration needed in the examination of goal-kicking technique is that the location of the shot can have a major influence on performance (Anderson et al., 2018; Galbraith & Lockward, 2010). Goal-kicking accuracy has been reported to significantly decrease with increasing the distance (30 m to 40 m: 87% to 67%, $p < 0.001$) and the angle (0˚ to 30˚: 87% to 46%, $p < 0.001$) from the goals

(Anderson et al., 2018). This was partly attributed to reduction in the relative width of the goal-line from the different positions (Galbraith & Lockward, 2010). However, biomechanical studies that have examined other aspects of punting kicking technique would indicate that a change in technique may also be occurring in response to a changes in the task (distance kicking: Baker & Ball, 1996). As the success of the shot has been suggested to be largely influenced by a player's technique (Baker & Ball, 1966; Ball, 2013; Peacock et al., 2017), understanding if players vary their technique at different distances and angles may also help explain changes in accuracy, and provide additional information to aid improvements in goal-kicking performance.

The examination of goal-kicking technique needs both a group and individual-based analysis approach. A group-based analysis is needed to gain an initial insight into technique and enable generalisation of the biomechanical findings to a larger population (Vincent, 2012). This information can then be used to objectively guide development programmes designed to improve goal-kicking performance across a range of skill levels. Individual-based analysis is needed to account for individual variations in technique to highlight important technical factors for an individual, which can often be masked in a group-based analysis (Ball & Best, 2012; Ball et al., 2003a, 2003b). This approach can be used to provide a more direct approach to aid performance improvement within a player. A combination of both approaches has been recommended to ensure all important information associated with a skill are extracted (Ball & Best, 2012; Ball et al., 2003a, 2003b). Traditionally, biomechanical kicking investigations have used a group-based analysis approach (eg: Baker & Ball, 1996; Bezodis et al., 2018; Dicheria et al., 2006; Lees & Nolan, 2002) to examine and identify statistical differences between groups. However, the existence of individual-specific differences has been reported in AF kicking (Ball, 2008, 2013; Ball et al., 2002, 2013; Lees & Nolan, 1998), supporting the inclusion of an individual-based analysis approach when investigating kicking technique in AF. If individual differences exist in goal-kicking, it will directly affect how the skill should be coached and recommendations may need to be tailored to the individual rather than applying a theoretical model of a 'good' kick.

A likely reason for the limited biomechanical research investigating goal-kicking technique, is due to the limitations with traditional biomechanical analysis tools, such as camera-based motions analysis systems (MAS). Whilst these systems provide an accurate analysis of movement and have been used effectively in studies to date, they have limited portability, require complex set-ups, are constrained to small test areas and are confined to one testing location per system. As a result, biomechanical investigations are often confined to a laboratory environment or in one section of the field where the MAS was set-up. This is a particular issue when assessing the technical factors associated with goal-kicking performance in AF as, 1) a laboratory data collection rarely allows players to kick towards their usual target (upright goal posts) making it difficult to elcudiate techical factors associated with accuracy without the need for complex post-modelling procedures, and 2) as MAS are confined to one testing location per system, this makes it unfeasible to test across a range of contexts (such as from different positions) in one session. Exploring other measurement methods that can provide an in-field biomechanical analysis of goal-kicking technique across multiple positions, will help overcome previous challenges, to help extend the limited research in this area.

The use of wearable inertial measurement systems (IMS) to capture full-body biomechanics in an applied context has emerged (Chambers et al., 2015; Cuesta-Vargas et al., 2010). These systems provide the ability to capture data in an in-field setting across a wide measurement area (~50 m^2), making testing in training environments more accessible. Validation of IMS has demonstrated good agreement (RMSE: 0.6 - 5.0°) with MAS in quantifying lower extremity kinematics during certain football-related activities, such as walking (Picerno et al., 2008; Zhang et al., 2013) and running (Cooper et al., 2009; Ferrari et al., 2010). There is potential application of IMS to quantify goal-kicking kicking, however, currently the rapid movement experienced during kicking occurs outside of the validated ranges of the IMS. Thereby, validation is firstly warranted to ensure the IMS can adequately measure the kicking action.

The overall aim of this thesis is to validate a methodological approach to enable quantification of goal-kicking kinematics in a field environment, and examine goal-kicking technique and identify technical factors associated with accuracy. Following a review of the literature, this thesis is comprised of five experimental chapters outlining the studies undertaken:

Chapter 3: Concurrent validation of an inertial measurement system to measure kicking biomechanics in four football codes[1]

Chapter 4: Concurrent validation of an inertial measurement system to quantify lower extremity times-series profiles during kicking in Australia Football.

Chapter 5: Alterations in goal-kicking technique with varying kick location on the pitch.

Chapter 6: Biomechanics of accurate and inaccurate goal-kicking in Australian Football: Group-based analysis.

Chapter 7: Biomechanics of accurate and inaccurate goal-kicking in Australian Football: Individual-based analysis.

In the final chapter, the main findings of the experimental chapters are discussed, identifying limitations, practical applications and future directions of each study, followed by the overall conclusions of this thesis.

[1] This thesis initially proposed to examine goal-kicking in four football codes, hence validation was performed for all four codes. However due the expanded scope of the AF component of this thesis, along with logistical issues with access to certain codes, the focus of the thesis changed to include AF only.

Chapter 2: Review of Literature

2.1. Chapter Overview

This review of the literature is comprised of five sections. The first section begins with an explanation of the importance of understanding goal-kicking technique in Australian football (AF), reviews the current biomechanical kicking literature, and identifies potential technical factors that may influence accurate goal-kicking in AF. The second section explores methodological considerations with assessing goal-kicking technique, discussing the shortcomings of previous kicking research. The third section identifies the current methodological approaches used to assess kicking biomechanics, highlighting the limitations that have restricted goal-kicking research in AF. The fourth section examines the use of inertial measurement systems (IMS) in providing a full-body biomechanical analysis and reviews the applications, validations and limitations of these systems. The final section provides an overall summary and details the aims of this thesis.

2.2. Goal-Kicking in Australian Rules Football

Goal-kicking is an important skill in Australian Football (AF) as it provides a means to score points during a game. Given a successful shot at goal equates to six points compared to only one point for a 'behind' (when the ball passes between the goal and point post) or no score beyond the point post, accurate goal-kicking is clearly advantageous in competition (**Figure 2.1**). Accurate goal-kicking has match-based statistical support, with performance analysis research identifying accurate goal-kicks as the most influential performance indicator in AF match outcome (Robertson et al., 2016). Furthermore, accurate goal-kicking can have a major bearing on a team's success in competition; Champion Data (official statistics for the AFL) indicated that in 39 matches' during the 2017 season, winning teams had the same number or fewer shots at goal than their opposition. Goal-kicking is clearly advantageous, therefore understanding and improving goal-kicking performance provides a means for improving a team's success in competition. In technical terms, goal-kicking performance refers to the technical aspects which contribute to a successful goal-kick.

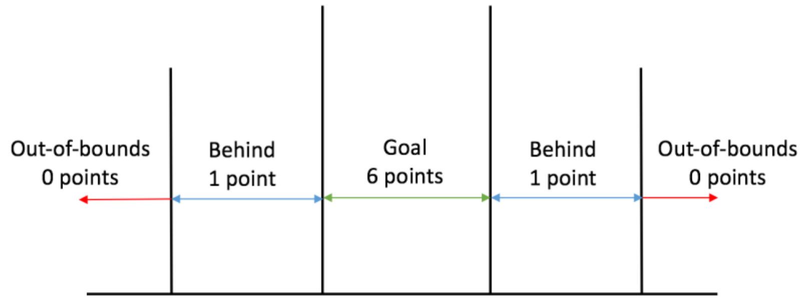


Figure 2.1. The point scoring scheme for a goal-kick in Australian Football.

The goal-kick is typically performed using a drop-punt kick and involves the combined technical aspects of a running approach, release of the ball from the hands at approximately hip height so it drops towards the kick foot (with ball-impact occurring 0.1 - 0.3 m from the ground) and forceful impact with the kick-leg as it swings through in the direction of the goals (Ball, 2008, 2013; Ball et al., 2002). The goal-kick can be broadly separated into three sequential phases: approach phase, kick phase and follow-through phase (**Figure 2.2**). The fundamental measure for performance in accurate set-shot kicking is the final position of the ball relative to the goal-line/target (Peacock & Ball, 2018a). Possible reasons for the kick to miss the goal, are due to a technical issue that leads to a poor impact with the ball resulting in a poor ball flight trajectory (Baker & Ball, 2006; Ball, 2017, 2013; Peacock & Ball, 2018a, 2018b, 2018c, 2017; Peacock et al., 2017). As the success rate for goal-kicks in the 2017 Australian Football league

(AFL) season was only 49.1% (2017 Champion Data), there is clearly scope for research to understand the technical factors associated with accurate goal-kicking to support improvements in performance.

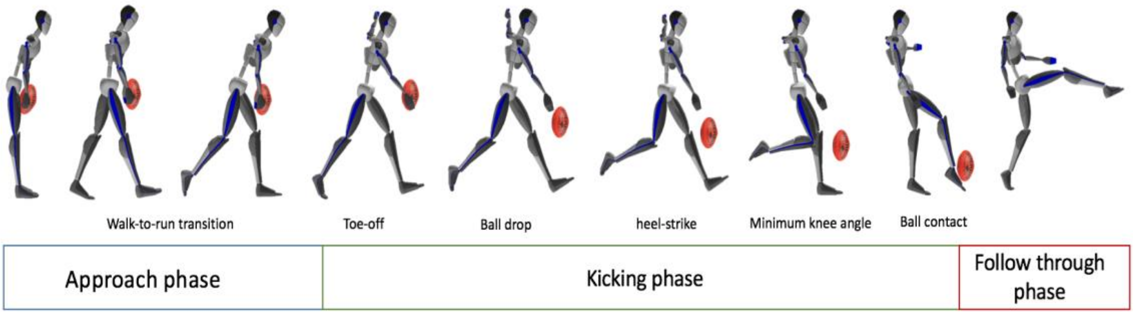


Figure 2.2. The three main phases of the set shot goal-kick, with the key events identified in each phase.

2.2.1. Biomechanical factors associated with goal-kicking accuracy

Despite the important role of goal-kicking in AF, only one study has examined the biomechanics of goal-kicking in AF (Ball et al., 2002). An in-field notational analysis (video footage of frontal plane: 50 Hz) was used to evaluate six technical aspects of accurate and inaccurate goal-kicking in eight elite AFL players; approach line, ball movement throughout approach, last stride characteristics, height and lateral position of the ball drop, ball position at contact and follow through. Accurate kickers were reported to adopt a straighter approach line, drop the ball in line with the kicking thigh and finish with the leg pointing towards goals. Contrastingly, inaccurate kickers demonstrated an angled approach line and finished with the leg pointed across the body away from the goal direction in the follow through. Whilst the use of notational analysis provided an understanding of the influence of specific parameters on aspects of goal-kicking performance it only permitted a 2 D analysis (frontal plane analysis). As a result, only a limited number of parameters were used to assess performance. This substantially limited this exploration of the important technical factors associated with goal-kicking technique in AF. The authors suggested analysis of other planes (such as sagittal plane characteristics) and other aspects of technique (such as run-up characteristics, support leg mechanics) would provide a more comprehensive understanding of important technical factors associated with goal-kicking. Given the important role of goal-kicking, research is warranted to further investigate the 3D characteristics of the complete goal-kicking action to further advance the understanding of the underlying factors which influence technique, to support improvements in performance.

As only one biomechanical study has been published in goal-kicking in AF (Ball et al., 2002), there is currently limited experimental evidence to explicitly inform future research on the potential technical factors which may influence goal-kicking technique in AF. As a result, scientific information from other relevant punt kicking research investigating other aspects technique (such as distance kicking or accuracy in other tasks) and coaching manuals will be utilised in order to provide coherent support and rationale for the selection of technical factors explored in this thesis when investigating goal-kicking technique. In addition, despite utilising different kicking styles (i.e., place kick, instep kick, punt kicking), similarities between important technical factors and kicking technique (such as, the importance of foot speed prior to ball contact in maximising ball velocity) have been reported across the kicking literature. It is plausible that findings from other kicking literature outside of the punt kick can also be relevant to goal-kicking performance in AF.

2.2.2. General technical factors associated with kicking technique

Technical aspects in the approach phase (Anderson & Dörge, 2011; Alcock et al., 2002; Baker & Ball, 1996; Ball, 2008, 2013; Ball et al., 2002; Lees et al., 2010; Scurr & Hall, 2009), kicking phase (Baker & Ball, 1996; Ball, 2008, 2011; Bezodis et al., 2007, 2018; Dicheria et al., 2006; Falloon et al., 2013; Inoue et al., 2014; Kellis & Katis, 2007; Lees & Nolan, 2002; Lees et al., 2010; Macmillan, 1976; Nunome et al., 2002, 2006; Putnam, 1991; Sinclair et al., 2016; Zhang et al., 2012) and follow-through phase (Baker & Ball, 1996; Ball et al., 2002; Bezodis et al., 2017) have been reported across the kicking literature to provide important contributions to kicking technique and performance.

2.2.2.1. The approach phase

In AF, the approach phase refers to the walk-to-run transition pattern leading up to the point of the kick. Coaching literature indicates that AF players commonly adopt a straight line approach consisting of 8-12 steps when kicking for goal (Hosford & Meikle, 2007; Parkin et al., 1984). The nature of the run-up differs slightly between the football codes with rugby players reported to take between a 2-3 step approach (Atack, 2016), while soccer players take a 5-8 stride running approach for maximal kicks (Lees et al., 2010). Despite different variations in approach style, across all football codes, the approach is used to orientate the body and develop whole-body momentum, which is transferred to the kicking phase to facilitate the control and regulation of the proximal-to-distal sequencing of the kicking-leg until ball contact (BC) (Anderson & Dörge, 2011; Asami & Nolte, 1983; Lees et al., 2010).

A straight approach line is emphasised through scientific (Baker & Ball, 1996; Ball et al., 2002) and coaching literature (Hosford & Meikle, 2007; Parkin et al., 1984) for AF kicking, as it is suggested to increase the time the kick-leg is in the plane of the target to increasing the chance of a straighter kick (Baker & Ball, 2002). Ball et al. (2002) investigated the relationship between approach angle and accuracy during goal-kicking directly in-front of goals in eight elite AF players. The authors found accurate goal-kickers maintained a straighter approach line compared to inaccurate kickers, however no quantitative data was provided. Supporting this finding, in soccer kicking, Alcock et al. (2012) reported a straighter ball flight trajectory (3.0 ± 0.4 º vs 7.4 ± 0.2º, $p < 0.001$) was associated with a straighter approach line (18.0 ± 7.3º) compared to a curved approach line (42.2 ± 7.5º) with instep kicking in international female footballers (n = 15). These findings suggest a straighter line of approach may be important in goal-kicking performance, however research is needed to provide experimental data to appraise this.

A factor that has not been examined in goal-kicking, but might hold useful information is the magnitude of a player's approach velocity. In soccer kicking, the approach velocity of two professional soccer kickers was significantly ($p < 0.001$) slower when they performed 10 instep kicks in-front of goals (task: hit a 1 x 1 m square in the top right corner) with a focus on accuracy (2.5 ± 0.1 $m.s^{-1}$) compared to achieving maximum ball velocity (3.4 ± 0.1 $m.s^{-1}$) (Lees & Nolan, 2002). Similarly, Anderson and Dörge (2011), found a 15% decrease in ball speed when players kicked for accuracy compared to achieving maximum ball velocity. The authors suggested that this could be related to the control and regulation needed of the intersegmental movement of the kick-leg to optimise foot placement at BC (Anderson & Dörge, 2011). Slower approach speeds have also been found when the demands of the task increase. Alcock et al. (2012) found the speed of approach significantly decreased when players were required to perform curved kick compared to an instep kick (3.0 vs 3.3 $m.s^{-1}$, $p = 0.002$). The authors suggested that this was due to higher task demands in the curve kick (to achieve a curved ball flight compared to a straight ball flight in the instep kick), where a slower speed of approach could be a control mechanism to regulate the kick-leg motion during the kicking phase. Investigation of the magnitude of approach velocity goal-kicks would provide an initial understanding of how it might influence goal-kicking in AF.

Last step characteristics have been reported to influence kicking performance. Ball (2008) reported a longer final step was associated with longer kick distances (n = 28 elite AF players, $r = 0.41$, $p = 0.03$). The author suggested a longer last step might enable greater kick-leg hip extension and thigh range of motion (ROM) during the kicking phase, helping to develop greater foot speeds at initial BC. This was supported by significant relationships reported between last step distance and maximum thigh angle ($r = 0.41$, $p = 0.03$). The relationship between last step distance and accuracy has not yet been investigated in AF. However, in soccer, the final step length of two professional soccer players was shorter when performing instep kicks (in-front of the goal mouth) with an accuracy focus compared with maximising ball velocity (final step lengths of 0.53 - 0.55 m (accuracy) and 0.72 - 0.81 m (maximising ball velocity) (Lees & Nolan, 2002). The authors suggested a smaller step would allow a slower, more precise movement to assist with accuracy. In contrast, a greater step length with a higher degree of pelvic retraction, would allow greater range of pelvic protraction to achieve greater foot speeds. The results of these studies suggest that length of the last step plays an important role in the orientation and configuration of the kick-leg, which in turn, influences the its motion during the kicking phase.

2.2.2.2. The kicking phase

The kicking phase starts from instance of kick-foot toe-off until ball impact. The motion of the kick-leg, support-leg, pelvis and upper body during this phase have been reported to provide important contributions to the kicking skill in AF (Baker & Ball, 1996; Ball, 2008, 2011, 2013; Ball et al., 2002; Dicheria et al., 2006; Peacock et al., 2017; Peacock & Ball, 2018a, 2018b) and across the other football codes (Ball et al., 2013; Bezodis et al., 2007; Cockcroft et al., 2016; Kellis & Katis, 2007; Lees et al., 2010; Nunome et al., 2018; Putnam, 1991; Sinclair et al., 2016, 2017; Zhang et al., 2012). The majority of research has investigated the contributions of these segments and limbs in maximising ball velocity, with less attention on accuracy. The motion of a player during the kicking phase has not been examined in goal-kicking in AF, however, as the motion of the kicker during this phase directly influences ball flight characteristics, it is clearly worthy of a comprehensive investigation.

2.2.2.2.1. Kick-leg kinematics

Kicking-leg mechanics are of particular interest, as it is the distal segment (foot) of this limb which contacts the ball and directly influences the ball flight characteristics (Peacock & Ball, 2018a, 2018b, 2017). The kick-leg undergoes a highly coordinated proximal-to-distal sequencing (whip-like motion), in which the proximal segment (thigh) initiates the movement, causing the distal segments (shank and foot) to lag behind, followed by a deceleration of the proximal segment and an acceleration of the more distal segment just before BC (Kellis & Katis, 2007; Lees & Nolan, 1998; Putnam, 1991).

Foot and ankle mechanics play a vital role in the success of a kick; by impacting the ball with their foot, a player impacts a combination of ball flight characteristics on the ball which ultimately determine the outcome of a kick (Ball, 2008; Peacock & Ball, 2017; Peacock & Ball, 2018a, 2017). Only one investigation has examined the relationship between ankle mechanics and kicking accuracy in AF (Peacock et al., 2017). When kicking for accuracy (task: 20 m kick to a player), 11 elite AF players demonstrated significantly lower ankle plantarflexion at BC compared to when kicking for maximal distance (123 ± 8° vs 130 ± 6°; p = 0.008; large effect). Similar findings have been reported between accurate and maximal velocity kicks in rugby union place kicking (32

± 54° vs 41 ± 12°; $p < 0.0005$; Sinclair et al., 2017). Peacock et al. (2017) suggested that this may be a mechanism adopted by players to even out pressure applied to the ball during the impact phase to improve accuracy. This explanation also shares similarity with the suggestion in soccer kicking, that increased plantar flexion allows players to "apply a more homogenous force" to the ball (Hennig, 2011; Hennig et al., 2009; Sterzing & Hennig, 2008; Sterzing et al., 2009). However, the authors also suggested this strategy may be used to achieve a flatter ball flight trajectory, which would increase the relative target area to improve accuracy. In contrast, a rigid ankle (greater plantar flexion) would result in a more lofted kick trajectory to enable a player to maximise kick distance. This premise is also emphasised through coaching literature, were the coaching cue 'kick with a firm foot' is used to encourage players to make the kick foot and ankle as rigid to maximise distance, whilst decreasing kick errors (Hosford & Meikle, 2007; Parkin et al., 1984). This coaching cue has theoretical support, were reducing the ankle foot ROM during impact has been suggested to increase impact efficiency, through increasing the effective mass of the striking limb (Asami & Nolte, 1983; Ball, 2010; Kellis & Katis, 2007; Lees & Nolan, 1998; Peacock & Ball, 2017; Peacock et al., 2017; Sterzing & Hennig, 2008; Sterzing et al., 2009). Differences between ankle and foot motion in accurate and inaccurate goal-kicks has not been investigated in AF, however these studies indicate that it may be an important factor.

In addition to ankle position, linear foot velocity has been identified as an important technical component in final ball velocity and kicking performance (Baker & Ball, 1996; Ball, 2008, 2011, 2013; Peacock & Ball, 2018b, 2017). When kicking for maximal distance (n = 28 elite AF players), Ball (2008) reported a strong correlation between foot speed and distance ($r = 0.68$, $p < 0.01$; large effect). The authors suggested that to increase kick distance, players should increase foot speed. The relationship between foot and ball velocity has been identified in several experimental designs across the football codes; correlations within groups, comparisons of different players and comparisons within players performing different tasks (Andersen et al., 1999; Nunome et al., 2006; Peacock et al., 2017; Shinkai et al., 2009; Smith et al., 2009; Zhang et al., 2012). In a comparison between kicks for accuracy (kicking to a 20 m target) and distance (kicking for maximal distance) among 11 elite AF players, Peacock et al. (2017) reported a significant difference in foot speed (-4.4 $m.s^{-1}$, $p = 0.001$, large effect) and ball (-6 $m.s^{-1}$, $p = 0.001$, large effect) velocity when kicking for accuracy compared to maximal distance. The authors suggested this was representative of a speed–accuracy trade-off (Fitt's law). Similar findings have been reported in soccer (Anderson & Dörge, 2011; Lees & Nolan, 2002) and rugby kicking (Sinclair et al., 2017). In goal-kicking in AF, players are often required to kick at longer distances from goals (which will be further discussed in **section 2.3,** *pp. 26-30*), requiring players to perform simultaneously under both speed and accuracy constraints. In addition, Teixiera et al. (1999) found that when soccer players (n = 5) kicked toward a defined target (40 cm target in a 4 x 3 m goal) compared to an undefined target (to anywhere in the 4 x 3 m goal), a reduction in foot velocity was evident prior to BC (12.9 vs 15.4 $m.s^{-1}$). The authors suggested this was a preparation strategy to control the position of the foot for impact. However, the authors suggested that further work was required in a larger sample to establish statistically significant results. Supporting this notion, when comparing accurate and inaccurate instep kicks in soccer players (n = 7 male, n = 7 female), Gheidi & Sadgehi (2010) reported a reduction in linear foot speeds (male: 15.5 vs 17.6 $m.s^{-1}$, $p = 0.03$, female: 14.6 vs 15.4 $m.s^{-1}$, $p = 0.05$) for accurate kicks at impact. This may be also evident in accurate goal-kicks, however, whether differences exist between the linear foot velocity in AF goal-kicking has not been investigated, and if undertaken, would provide an initial understanding of how the speed of the movement might influence goal-kicking in AF.

The importance of knee and shank motion has been described through the distance and accuracy punt kicking literature in AF (Baker & Ball, 1996; Ball, 2008, 2011; Dicheria et al., 2006; Macmillan, 1976). When performing a 15 m drop punt kick to a player, Dicheria et al. (2006) found accurate kickers (n = 6 elite AF players) had greater knee flexion (+6°, $p = 0.06$) throughout the swing phase (from kick-foot toe off until ball contact) compared to inaccurate kickers (n = 6 elite AF players). Increased flexion of the kicking limb was suggested to be a necessary adaptation to ensure toe-clearance of the kicking limb during swing phase, as accurate kickers also adopted a more flexed support-leg. In a comparison between long (n = 12, 50 m) and short kickers (n = 10, 40 m) in a group of elite junior AF players, the long kicking group exhibited greater knee flexion (116° vs. 111°, $p < 0.05$) than the short kicking group (Baker & Ball, 1996). The biomechanical advantage of increased knee flexion during swing phase, is that it reduces the moment of inertia of the leg about the hip joint to enhance rotation (Baker & Ball, 1996). This would increase the distance through which the foot is accelerated during forward swing to increase the work done on the ball to maximise velocity (Ball, 2008; Baker & Ball, 1996). Similar findings have been reported across the soccer (Kellis & Katis, 2007; Lees et al., 2010) and rugby kicking literature (Sinclair et al., 2016, 2017). Whilst no study has examined the differences of knee and shank motion between accurate and inaccurate goal-kicks, the study by Dicheria et al. (2006) provides initial indication of how it differs between accurate and inaccurate kickers.

Differences in hip motion have been reported between elite AF accurate and inaccurate elite AF kickers, when performing a 15 m drop punt kick to a player (Dicheria et al., 2006). Accurate kickers had significantly more hip flexion at support-leg heel-strike

(SHS) (3 ± 3º vs -12 ± 5º, $p < 0.05$) that remained more flexed throughout the swing phase until BC (36 ± 5º vs 30 ± 2º, $p < 0.05$) compared to inaccurate kickers. Despite showing differences in the hip motion, the authors did not discuss its contribution to accuracy. In soccer kicking, players (n=10 professional soccer players) were found to have significantly less hip ROM when they performed an accuracy task compared to a maximal velocity task (34 ± 2º vs 51 ± 2º, $p < 0.001$) (Button et al., 2005), supporting previous findings in soccer (Lees & Nolan, 2002) and rugby place kicking (Sinclair et al., 2017). Less hip ROM (flexion/extension) was suggested to enable kickers to control and regulate the motion of the kicking limb in order to optimise ball impact. It is plausible that players actively control hip motion (reduce ROM) from the top of backswing until BC to control and regulate the motion of the kicking limb, therefore examining hip motion may help to explain differences between accurate and inaccurate goal-kicks.

The importance of the regulation and control of the proximal-to-distal sequencing of the kick-leg has been highlighted across the kicking literature (Ball, 2008, 2011; Kellis & Katis, 2007; Lees & Nolan, 2002; Nunome et al., 2018; Putnam, 1991). In an examination of kick-leg motion in 17 elite AF players, Ball (2011) reported a proximal-to-distal sequencing of segmental motions during the kicking phase (**Figure 2.3)**. Before the initial forward swing, the shank experiences acceleration during backswing, up to the point when the thigh is perpendicular to the ground. After backswing, the thigh swings forward (increased angular velocity) followed by the passive movement of the shank through the knee as power is transferred from the thigh to the shank to enable a rapid extension of the shank to BC, while the thigh decelerates. Ball (2008) reported shank angular velocity at BC provided a strong contribution to maximising kick distance (r = 0.44, $p = 0.02$) in AF (n = 28). In a comparison between accurate and maximal velocity instep kicks in soccer in two elite soccer players, Lees and Nolan (2002) reported reduced peak angular velocities of the hip (169 vs 318 °/s) and knee (790 vs 1060 °/s) when taking accurate kicks as opposed to when maximising ball velocity. The authors suggested that slower joint rotations may enable kickers to control and regulate the motion of the kicking foot prior to initial BC, in order optimise impact location. However, as only two players were used, only a small sample of kicks would have been available to determine the relationship between knee/ hip angular velocity and accuracy. Consequently, results should be treated with caution, as a sample size exposes researchers to falsely concluding that significant differences do (Type I error) and do not (Type II error) exist (Batterham & Hopkins, 2006). When comparing accurate and inaccurate instep kicks in male (n=7) and female (n=7) soccer players, a reduction in shank (male: 1457 vs 1507 °/s, p = 0.07, female: 880 vs 984 °/s, p = 0.04) and thigh (male: 559 vs 631 °/s, p = 0.07, female: 570 vs 648 °/s, p = 0.046) angular velocities for accurate kicks was reported (Gheidi & Sadgehi, 2010). In addition, Nunome et al. (2018) systematically controlled the effort levels (50, 75 and 100%) of instep kicks in eight experienced university soccer players, to provide information regarding leg-swing regulations. Players were found to precisely control the hip muscle moment, as well as the knee muscle moment, suggesting regulation of kicking intensity must be done in the context of a whip-like proximal-to-distal segmental sequential system. Assessment of joint (knee and hip) and segment (shank and thigh) angular velocities would provide an initial understanding of how the speed of the movement might be regulated to influence goal-kicking performance in AF.

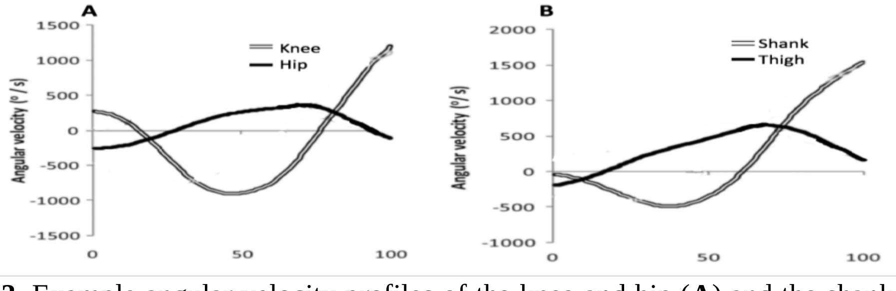


Figure 2.3. Example angular velocity profiles of the knee and hip (**A**) and the shank and thigh (**B**) from kick leg toe-off (0%) to BC (100%). Figures taken from Ball (2011).

Another finding worthy of further consideration, is that different movement patterns have been reported between players performing the same task (Ball, 2008) and within players between the preferred and non-preferred leg kicks in AF (Ball, 2011). Ball (2008) identified a knee-thigh angular velocity continuum when kicking for maximal distance. The authors then examined both ends of the continuum (knee strategy and thigh strategy) by sorting players by their ratios between thigh and knee angular velocity at BC. Ball (2008) reported technical differences between knee strategy (n = 10; a large knee angular velocity (1616 °/s, $p < 0.05$) and a low thigh angular velocity (117 °/s, $p < 0.05$) at BC) and thigh strategy (n = 10; large thigh angular velocity (485 °/s, $p < 0.05$) with a low knee angular velocity (1151 ° /s, $p < 0.05$) at BC) players. Whilst technical differences existed between the knee and thigh strategy groups, the performance indicators (foot speed at BC and distance) were not significantly different between groups. The authors suggested that further work was needed to explore the existence of the knee-thigh angular velocity continuum in AF kicking. In addition, in a group of 17 elite AF players, when kicking with the preferred-leg, players produced significantly ($p < 0.05$) larger knee (1355 vs 1126 ° /s, large effect) and shank (1548 vs 1387 °/s, large effect) angular velocities at BC with greater pelvis ROM (47 vs 40°, large effect) compared to the non-preferred leg. In contrast, the non-preferred leg produced significantly ($p < 0.05$) larger hip (236 vs 158 °/s, medium effect) and thigh (138 vs 56 °/s, medium effect) angular velocities and employed greater hip ROM (32 vs 40 °, large effect) during the forward swing compared to the preferred-leg. Ball (2011) suggested that this might be linked to Bernstein's (1967) theory of locking degrees of freedom, where players reduced the involvement of the pelvis and knee, focusing more on hip control to perform the movement successfully. It is unknown if similar movement patterns exist between accurate and inaccurate goal-kicks in AF. If multiple strategies exist in goal-kicking, different movement cues and conditioning recommendations might exist for different strategies.

2.2.2.2.2. Support-leg kinematics

Support-leg motion has been identified in both scientific (Ball, 2011, 2013; Dicheria et al., 2018) and coaching literature (Hosford & Meikle, 2007) as providing important contributions to punt-kicking performance in AF. The support-leg has been suggested to have two important roles during kicking; 1) to resist large ground reaction forces to stabilise the body and 2) to transfer the momentum generated during the approach phase to the proximal segment, thereby contributing to the proximal-to distal sequencing motion of the kick-leg (Ball, 2013; Inoue et al., 2014; Lees et al., 2010; Putnam, 1991). It has been suggested that a stronger support-leg can provide greater stabilisation to enable larger forces to be developed (Ball, 2013; Inoue et al., 2014; Lees et al., 2010) to achieve these two roles.

Support-leg mechanics has been reported to influence kicking accuracy in AF. Dicheria and colleagues (2016) compared support-leg kinematics of accurate (n = 6 elite AF players) and inaccurate kickers (n = 6 elite AF players) when kicking to a target 15 m away. Accurate kickers produced significantly greater knee flexion at SHS (10 ± 3º vs 4 ± 3º, $p < 0.05$) which was maintained through to BC (32 ± 6º vs 21 ± 5º, $p < 0.05$) during the stance phase (from SHS to BC) compared to inaccurate kickers. Additionally, accurate kickers demonstrated significantly greater hip flexion at SHS (49 ± 1º vs 39 ± 5º, $p < 0.05$) and at BC (8 ± 3º vs 3 ± 2º, $p < 0.05$) compared to inaccurate kickers. The authors suggested this might be a strategy utilised by players to lower their COM to improve stability and balance during the kick. This explanation also shares similarity with the ‘increased stability’ suggestions associated in soccer instep kicking (Lees et al., 1998; Lees et al., 2010), which may be beneficial when kicking for accuracy (Chew-Bullock et al., 2012).

Of interest, the finding that a more flexed support-leg is advantageous for accuracy is in contrast to the suggestion that a more extended support-leg is beneficial for distance kicking in AF (Ball, 2013). When seven elite AF players performed maximal punt kicks, Ball (2013) found players demonstrated a more extended knee at SHS (22 ± 3º) that remained a more extended knee throughout the kick phase (43 ± 6º). The authors suggested this could be indicating a stronger and more stable support-leg, as identified in soccer literature (Lees et al., 1998, 2010). Ball (2013) suggested this could also be an effective action to assist with maintaining higher kick hip position, which in turn would allow for a more extended kick leg during swing phase to generate faster foot speeds. Post-hoc analysis supported this notion by identifying a strong relationship between support-leg motion and foot speed at BC (at SHS: $r = -0.73$, $p = 0.004$; at BC: $r = -0.71$, $p = 0.006$). These findings support assertions made in soccer and rugby kicking literature (Augustus et al., 2017; Inoue et al., 2014; Nunome et al., 2006; Sinclair et al., 2016; Sinclair et al., 2017). Nunome et al. (2006) suggested that in order to achieve a fluent action of the motion-dependent interaction moment acting on the kicking-leg, lifting the whole body upward using the support-leg motion would be an effective action, particularly during the final phase of kicking. Ball (2013) suggested the conflicting findings could also be indicative of different strategies adopted by players when kicking for accuracy or distance. The underlying mechanism for this finding requires more research to substantiate this assertion.

The role of the support-leg has not yet been investigated in goal-kicking in AF, but it is clear the orientation of the support-leg during stance phase may be important in accurate goal-kicking to control and regulate the motion of the kick-leg (Augustus et al., 2017; Ball, 2013; Dicheria et al., 2006; Inoue et al., 2014; Nunome et al., 2006; Sinclair et al., 2016, 2017). Investigating kinematic differences between support-leg mechanics in accurate and inaccurate kicks will also help address the conflicting findings in the literature.

2.2.2.2.3. Pelvis kinematics and upper body kinematics

The motion of the pelvis has been identified as important in kicking in AF (Ball, 2011; Baker & Ball, 1996; Dicheria et al., 2006; Falloon et al., 2011) and across the other football codes (Bezodis et al., 2007; Lees & Nolan, 2002; Lees et al., 2010; Zhang et al., 2012). In a comparison of pelvis kinematics between accurate and inaccurate kickers in AF, Dicheria et al. (2016) reported accurate kickers demonstrated significantly greater pelvic tilt (+8°, $p < 0.05$) during the kicking phase compared to inaccurate kickers. However, the authors suggested that these differences may be due to differences in the player's natural pelvic alignment (accurate kickers had greater pelvic anterior tilt during standing). As the authors did not normalise the joint angles to the player's neutral position (standing position), it is unknown if some of these differences can be attributed to accuracy. Normalisation of angles to the standing posture would control for any physical differences between players, and determine if pelvis kinematics were associated with accuracy. The motion of the pelvis has been identified as an important technical factor in generating higher foot velocities in AF kicking (Ball, 2011; Falloon et al., 2013). It was suggested that greater pelvis ROM would allow greater knee extension to generate more power at BC (Falloon et al., 2013). Similar findings were reported in soccer instep kicking (Lees & Nolan, 2002; Lees et al., 2010). It is currently unknown if pelvis motion differs between accurate and inaccurate goal-kicks in AF.

Upper-body motion has been shown to demonstrate important characteristics of technique in rugby and soccer kicking. In rugby place kicking, Bezodis et al. (2007) used a 3D laboratory-based analysis to investigate upper-body motion during goal-kicking in five rugby union players, with accuracy and distance considerations. Accurate kickers were found to exhibit greater angular momentum in the non-kicking side arm, in both the anterior-posterior axis (axis direction in the kick direction) and in the longitudinal axis (vertical line through the trunk), which opposed the kick-leg longitudinal angular momentum. Similar findings have been documented in soccer instep kicking (Shan & Westerhoff, 2005). In addition, accurate kickers demonstrated minimal longitudinal trunk angular momentum at BC. The authors suggested that this was due to better control of whole body momentum and enabled players to position their body more appropriately at BC. The authors also reported increased trunk lean towards the kick side in accurate kickers. However, this was in contrast to findings that a more upright trunk was beneficial for accuracy in goal-kicking in rugby league (Ball et al., 2013). Ball et al., 2013 suggested a more upright trunk position might allow a kick-leg motion more aligned with the intended path of the ball, allowing players to achieve a more balanced position or position the hip and pelvis joints better for an accuracy task. Further research is needed to attempt to resolve these conflicting findings across the football codes. These studies investigating upper body motion (Ball et al., 2013; Bezodis et al., 2007) indicate that it may be important to consider the role of the trunk in goal-kicking technique. However, as the AF goal-kicking is a more linear movement compared to the need for the rotational aspect of goal-kicking in rugby, it may not pose a substantial influence on technique.

2.2.2.2.4. Ball drop characteristics

In comparison to the goal-kicking movement in the rugby codes, AF involves the distinct aspect of dropping the ball during the kick. This adds an additional task constraint which may influence accuracy. When examining ball drop characteristics between accurate and inaccurate goal kickers (n = 8 eight elite AF players), Ball et al. (2002) found that accurate kickers dropped the ball in line with the kicking thigh, which was suggested to influence orientation at ball impact. Both ball orientation and the nature of impact between the ball and the foot have been highlighted as important when kicking for maximal distance (Ball, 2008). The ovoid shape of the ball means that contact on different parts of the ball would cause the oblique spin about the balls long or short axis (Ball, 2008; Peacock & Ball, 2018b) which influences the ball flight trajectory.

2.2.2.3. The follow through phase

The position of the kick-leg during the follow-through has been shown to differ between accurate and inaccurate kickers. Ball et al., 2002 found accurate kickers finished with the leg pointing towards goals, while inaccurate kickers had a tendency for the leg to swing across the mid-line of the body in the follow-through. Similar findings were reported by Baker & Ball (1996), who found the kick-leg stayed in-line towards the target and did not cross the body for the better kickers. Finishing with the leg pointing towards the goals is emphasised in the coaching literature (Hosford & Meikle, 2007), as it is suggested to influence the movements prior to impact (achieve a straighter leg swing motion). In rugby place kicking, Bezodis and colleagues (2017) supported this finding by suggesting that follow through manipulations could affect movements during kicking phase. The above studies suggest that follow-through kick-leg position may be important in goal-kicking performance, however research is needed to provide experimental data to appraise this. However, it is important to consider that the follow-through itself cannot directly influence goal-kicking performance as the player can no longer influence ball motion (ball is in flight). Although, the motion of the kicker through this phase is still of interest as it can provide an indication of what has happened prior to contact.

2.2.3. Technical factors which may influence goal-kicking accuracy

Based on this review of the literature, a deterministic model was developed to identify technical factors which may be potentially important when investigating goal-kicking technique in AF (**Figure 2.4**). This work is needed to establish an evidence base to further advance the understanding of the underlying factors which influence goal-kicking performance. This knowledge can be used to objectively guide development programmes aimed at improving goal-kicking performance. Importantly, kinematic information can provide specific cues for coaches and players that they can more readily relate to.

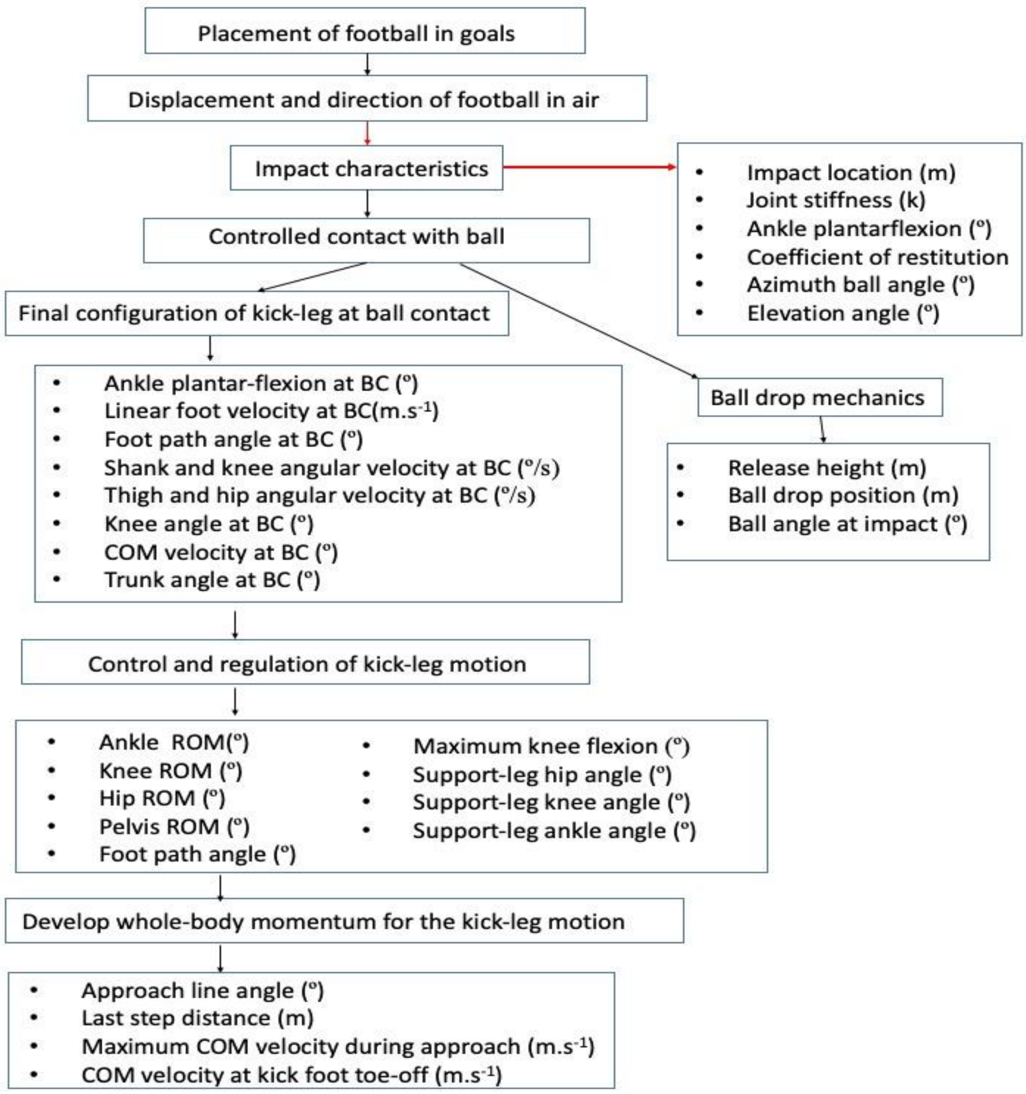


Figure 2.4. Deterministic model of important technical factors in accurate goal-kicking Australian Football. Red arrows indicate important technical factor but beyond the scope of this thesis.

2.3. Methodological Considerations for Assessing Goal-Kicking Technique

2.3.1. Goal-kicking positions

During competitive AF matches, players are required to perform goal-kicks with high technical proficiency under varying task constraints. These task constraints include; the 30 s time limit to perform the shot and the location of the goal-kick from goals (Anderson et al., 2017; Galbraith & Lockward, 2010). Aside from the rules surrounding a goal-kick (such as the time limit for skill execution), the location of the shot has been shown to have a major influence on goal-kicking performance (Anderson et al., 2018; Galbraith & Lockward, 2010). A statistical analysis of 198 matches during the 2012 Australian Football league season (Anderson et al., 2018) indicated a significant decrease in set-shot accuracy with increasing the distance (30 m to 40 m: 87% to 67%, $p < 0.001$) and the angle away from the mid-line of the goals (0˚ to 30˚: 87% to 46%, $p < 0.001$). Similar fluctuations in goal-kicking success were evident in 2017 AFL season (Champion Data statistics) (**Figure 2.5**).

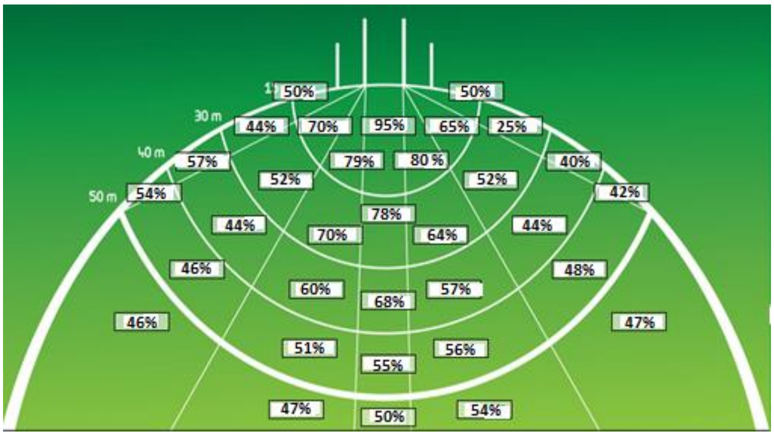


Figure 2.5. Changes in goal-kicking accuracy from different positions in-front of goals indicated in Champion data statistics during the entire 2017 Australian Football League season (total shots at goals: 10,112).

The decrease in goal-kicking accuracy associated with increasing the distance and/or angle from goals has been partly attributed to the angle of opportunity (relative width of the goal-line) available to players at different positions (Anderson et al., 2018; Galbraith & Lockward, 2010). Galbraith and Lockwood (2010) used a mathematical model to explore the angle of opportunity of a given kick by describing the interaction between the angle subtended by the goal-line and the player's point of contact with the ball (**Figure 2.6**). The angle of opportunity was reported to decrease as either kick distance or angle increased, which was suggested to contribute to the decreased accuracy at certain positions. However, the authors solely focused on task difficulty and suggested that changes in goal-kicking technique may also be a contributing factors. Researchers have highlighted the need to investigate changes in goal-kicking technique with varying task position (Bezodis et al., 2018). As the ball is in projectile motion after it leaves the foot, it is likely the success of the shot is largely influenced by a player's technique (Baker & Ball, 2006; Ball, 2017; Ball, 2013; Peacock et al., 2017; Peacock & Ball, 2018; Peacock & Ball, 2017), thereby examination of a player's goal-kicking technique may help further explain changes in accuracy with altering position, and provide additional information to aid improvement of goal-kicking performance.

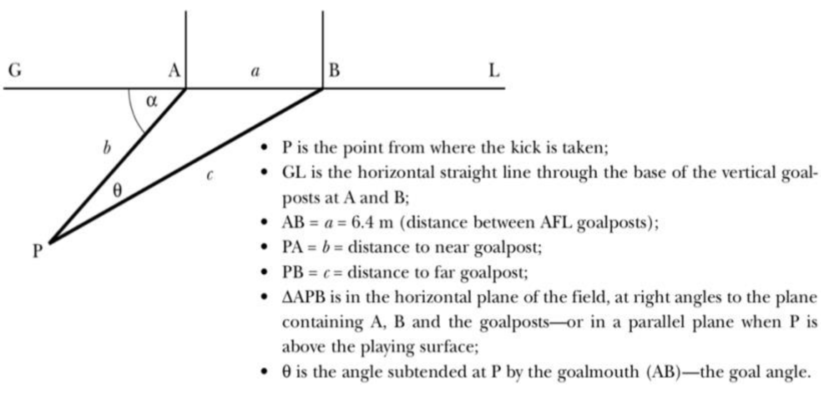


Figure 2.6. Angle of opportunity of a given kick. Figure taken from Galbraith & Lockward (2010).

Technical differences have been found when performing punt kicks over different distances (40 m vs 50 m) (Baker & Ball, 1996). Longer kicks were reported to have significantly greater kick-leg knee extension (69 vs 64º; $p < 0.05$) and higher peak kick-leg thigh angular velocity (973 vs 907 º/s; $p < 0.05$) during forward swing, with greater knee angular velocity (1554 vs 1390 º /s; $p < 0.05$) and foot momentum (20.7 vs 17.3 kg.m/s; $p < 0.05$) at impact. Similar findings have been reported in juniors (boys = 12; girls = 7) when performing soccer instep kicking over different distances (20 m to 50 m) (Mally et al., 2011). Foot speed prior to impact is the most important contributor to increasing ball speed, and consequently, kick distance (Ball, 2008, 2013; De Witt et al., 2012; Kellis & Katis, 2007; Peacock & Ball, 2018c; Peacock et al., 2017; Lees et al., 2010; Sinclair et al., 2014; Zhang et al., 2012). However, these studies determined the relationship between foot speed and distance without imposing an accuracy constraint on players during the task. When kicking for goal, players are required to simultaneously perform under both distance and accuracy constraints, to achieve a successful outcome. Kicking accurately over different distances has not yet been examined, however, given the importance of accuracy in goal-kicking, research is warranted to examine the link between distance and accurate goal-kicking performance.

Technical adjustments with altering the angle of a kick from goals has not yet been examined, however understanding if players vary their technique on an angle may also help explain kicking accuracy. In soccer instep kicking, technical adjustments (lower ankle velocities at BC: 2.5 $m.s^{-1}$, $p < 0.05$) have been reported when the size of the target was reduced (from 4x3 m to 0.4 x 0.4 m) (Texieria et al., 1999). The authors suggested that as the difficulty of a task increases, a reduction in movement speed is needed, which was linked to the speed-accuracy trade-off. Given something similar happens when the angle of shot at goal becomes more acute in AF (i.e. the effective target size reduces) examining if technical changes exist at different angles is warranted.

Task constraints, such as distance and angle have also been reported to change technique in other skills, such as, basketball shooting (Liu &Burton, 1999; Miller & Bartlett, 1996), table tennis (Raab et al., 2005), throwing (Lorson & Goodway, 2007). For example, Miller and Bartlett (1996) examined kinematic changes in basketball shooting across three distances (2.74, 4.57 and 6.40 m) from the basket (n = 15). Players demonstrated significantly increased release speed, higher arm and shoulder angular velocities and increased speed of the centre of mass with increasing distance. The authors suggested that players may be required to adjust their technique dependent on the location of the throw to achieve a successful outcome. These studies also provide an indication that task constraints can influence the execution of a skill.

Of the 36 biomechanical studies discussed throughout **section 2.2**, only one (Baker & Ball, 1996) has examined kicking technique from different distances on the pitch (40 m vs 50 m). The findings from Baker & Ball, (1996) would indicate that players may be required to adjust their technique dependent on the location of a kick. Understanding if players vary their technique at different distances and angles may also help explain changes in accuracy, and provide additional information to aid improvements in goal-kicking performance. Thereby, analysis of goal-kicking technique across different locations of the pitch will be included in this thesis.

2.3.2. Individual-based analysis

In sports biomechanics, the use of individual-based analysis (evaluation of a problem within a single-subject) has been highlighted as important factor which needs to be included when examining technical aspects associated with a skilled performance (Ball & Best, 2012; Ball et al., 2003a, 2003b; Bates et al., 2004; Caster & Bates, 1995; Dufek et al., 1995). While group based analyses provide important information related to a skill, biomechanical investigations have shown that individual analyses can also detect important technical characteristics of performance, that might have been masked in a group-based analysis (Ball & Best, 2012; Bates & Stergiou, 1996; Ball et al., 2003, 2003b; Dufek et al., 1995; James & Bates, 1997; Miller & Schwarz, 2018). For example, in golf, Ball & Best (2012) reported individual-specific relationships with centre of pressure parameters and club head velocity, with golfers returning different combinations of significant factors which were not evident on a group-basis (Ball & Best, 2007). As a result, the authors suggested the use of both types of analysis (individual and group) can provide a more thorough investigation of a skilled performance (Ball & Best, 2012). Individual-based analysis can also avoid statistical errors that are produced when different movement strategies are used by participants to achieve the same performance outcome (Bates et al., 2004). Different movement strategies adopted by individuals can lead to increased inter-subject variability that will reduce statistical power in a group-based analysis which could result in the false support for null hypotheses depending on the distribution of subjects (Bates et al., 2004; Caster & Bates, 1995).

Along with important group-based differences in punt kicking in AF, important individual differences have been reported between players (Ball et al., 2002; Ball, 2008, 2013). As previously discussed in **section 2.2** (*pp. 18 - 20*), different movement strategies (i.e. thigh and knee strategy) were identified in a group of elite AF players when kicking for maximal distance (Ball, 2008, 2013). Similar findings were reported between preferred and non-preferred leg kicks during a sub-maximal kicking task (Ball, 2013). These studies provide evidence for the existence of different strategies in punt kicking AF. These strategies may also be present in goal-kicking in AF, however research is needed to provide experimental data to appraise this. However, it is worthy to note that Ball (2008) and Ball (2013) both analysed technical differences between the thigh and knee strategy groups (i.e. footspeed) on a group-basis (for example, Ball, (2008) sorted kickers by their ratio of thigh and knee angular velocity at BC, and then split them into two groups of 10 to be analysed). It is unknown if individual-specific technical differences exist within these strategies, warranting further investigation of kicking on an individual level.

Individual-specific findings have also been reported in rugby and soccer kicking. In rugby league, individual differences were found between four elite kickers when kicking towards goals (Ball et al., 2013). Amongst the group, preparation time (5 – 10 s), run-up (3 - 8 steps) and approach angle (20 - 41º) varied. In addition, individual specific patterns were found in support foot position and arm motion between successful and unsuccessful goal-kicks, however no clear patterns emerged between players. The authors proposed that further work was required in a larger sample of kicks to establish statistically significant results. Based on these findings, Ball and colleagues (2013) stated goal-kicking technique was individual and it is clearly important to coach the skill on an individual basis rather than applying a theoretical model of a ‘perfect’ kick. Similar assertions were made in soccer. Lees and Nolan (1998) reported individual differences between two professional soccer players when taking accurate kicks as opposed to when maximising ball velocity magnitude. These differences were evident in speed of the movement (one player produced faster knee angular velocities, ankle and foot speeds under both conditions compared to the other player) and the orientation of the kick-leg at impact (one player was more upright in the sagittal plane but leaning more to the support leg compared to the other player). However, it was worthy to note that conclusions in this study were drawn from a small sample ($n = 2$). The findings between the two players may represent one of three things; 1) identified differences as a result of an outlier (Hopkins, 2006), 2) one player may represent a small percentage of the population which utilises a different technique, or 3) true individual differences (Batterham & Hopkins, 2006; Hopkins & Batterham, 2016; Hopkins et al., 2009; Hopkins et al., 1999). This study presented preliminary insight into individual-specific differences in maximal soccer kicker and the authors acknowledged that further work was required in a larger sample to establish if individual differences exist in soccer kicking. In addition, when examining the effect of the speed of approach on kicking performance, Anderson & Dörge (2011), reported subject-specific approach speeds in relation to generating maximal ball speed during instep kicking. It was suggested that an increase or decrease of the speed of approach compared with the optimal speed of approach for each individual would result in a decrease in the speed of the ball. These studies also provide some indication of the presence of individual patterns in kicking.

Important group and individual-specific findings have also been reported in other sports, such as, pistol shooting (Ball et al., 2003b), golf (Ball & Best, 2012), javelin (Morris et al., 1997) and volley ball (Dufek & Zhang, 1996). In an elite sport example, Ball et al. (2003a) examined rifle shooters on a group and an individual basis. Six elite shooters performed 20 shots at a target and body sway and aim point fluctuation measures were correlated with performance to identify important factors in rifle shooting. While there were no significant relationships between body sway and performance on a group-basis, all shooters returned significant correlations and regressions when the relationships were examined on an individual basis (Ball et al., 2003a). Further, important technical information was found in the group-based analysis that was not evident in the individual-based analysis. The authors stated that individual-based analysis is most appropriate in terms of aiding improvements in performance for the individual, and should form part of performance-based biomechanical analysis (use of both individual and group-based analysis) to extract all the available information. These studies above provide strong support for the inclusion of an individual-based analysis approach.

There has been no individual-based statistical analysis of goal-kicking technique in AF, however the above studies provide strong support for including an individual-based analysis in the assessment of a sporting performance. If different techniques exist, it will directly affect how the kicking skill should be trained and coaching recommendations may need to be tailored to the individual rather than applying a theoretical model of 'good' technique. This thesis will use both individual and group-based analysis methods to provide an in-depth analysis of the goal-kicking skill.

2.4. Methodological Approach for Quantifying Kicking Biomechanics

2.4.1 Optoelectronic motion analysis systems

Accurate measurement is critical when trying to understand the key technical factors associated with a skilled performance. Optoelectronic motion analysis systems (MAS) are commonly used in biomechanical research to quantify the three-dimensional (3-D) characteristics of the kicking skill in Australian football (Ball, 2011, 2013; Coventry et al., 2013; Dicheria et al., 2006) and across the other football codes (eg: Atack et al., 2017; Baktash et al., 2009; Bezodis et al., 2007; Ghedid & Sadeghi, 2010; Kellis & Katis, 2007; Lees et al., 2010; Sinclair et al., 2017; Zhang et al., 2012). These systems are widely used across the biomechanics discipline, as they are considered 'gold standard' for 3D analysis of human movement (Cappozzo et al., 2005; Chiari et al., 2005; Colyer et al., 2018; Cuesta-Vargas et al., 2010; Grimshaw et al., 2007).

Optoelectronic MAS utilise cameras (typically between 6-14) to track body-worn reflective markers (active or passive) through a calibrated space (Cappozzo et al., 2005;

Chiari et al., 2005; Colyer et al., 2018; Ren et al., 2014). Markers are placed on specific anatomical locations to locate and define the underlying anatomy of a segment(s) of interest. For biomechanical investigations, researchers use specific marker sets (dependent on their application) to define a biomechanical model to enable six-degrees-of-freedom calculations of joints and segment kinematics (Cappozzo et al., 2005; Colyer et al., 2018) (**Figure 2.7**). The structure of the human body is usually simplified into a series of rigid bodies, as whole-body movement can be a difficult to quantify, as the human body is an extremely complex, highly articulated, self-occluding and only partially rigid entity (Colyer et al., 2018). Through digitization techniques, the local 3D (x, y, z) coordinate location of each marker can be determined to provide instantaneous position and orientation measurements of body segments relative to a fixed frame (global coordinate system) (Cappozzo et al., 2005; Colyer et al., 2018; Grimshaw et al., 2007; Windolf et al., 2008). Other quantities, such as linear acceleration and angular velocity can be calculated by through differentiation of the linear and angular displacement measurements (Woltring, 1985).

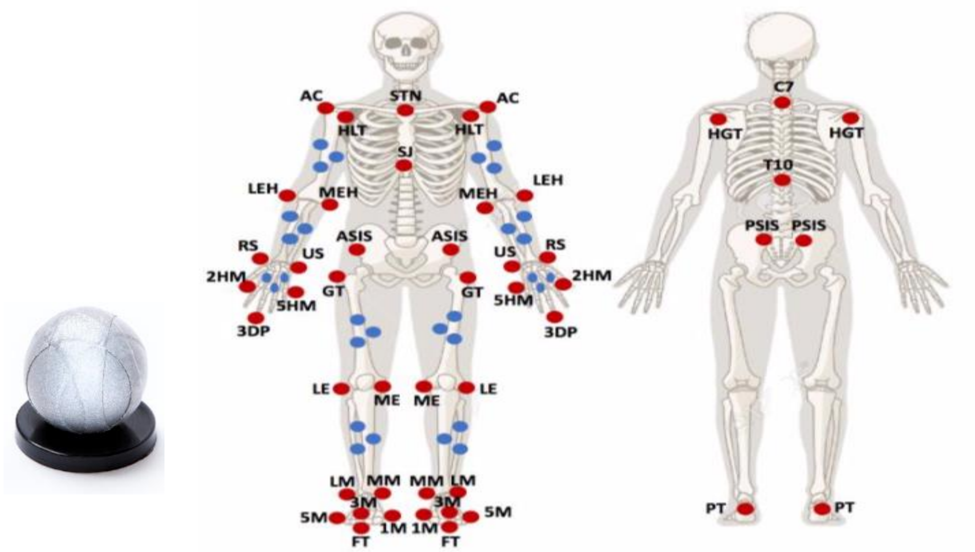


Figure 2.7. A typical marker set used to define a 11-segment biomechanical model (left) in kicking research. Individual markers (red) are placed on anatomical locations and marker clusters (blue) are placed on different body segments. Model abbreviations are provided in Appendix A.

Optoelectronic MAS have been shown to provide an accurate and comprehensive 3D analysis of human movement in biomechanics (Cappozzo et al., 2005; Chiari et al., 2005; Croce et al., 2005; Colyer et al., 2018; Grimshaw et al., 2017; Ren et al., 2014). The accuracy and validity of different commercial MAS (such as Vicon, Qualysis or Optotrak) are widely documented in biomechanical research; Low measurements errors have been reported in MAS data during static (RMSE: <2.1 mm and 0.8°) and dynamic (RMSE: <5.3mm and 2.5°) measurements (Aurand et al., 2017; Cappozzo et al., 2005; Dorociak & Cuddleford, 1995; Eichelberger et al., 2016; Ehara et al., 1997; Everaert et al., 1999; Liu et al., 2007; Richards, 1999; Small et al., 1996; Thewlis et al., 2013; Windolf et al., 2008). As a result of the high accuracy in measurement, optoelectronic MAS are regarded as the accepted 'gold standard' for 3D movement analysis.

2.4.1.1. Limitations of optoelectronic motion analysis systems

Whlist Optoelectronic MAS have substantially evolved over the last decade, these systems have several disadvantages (**Figure 2.8**), which can influence how a biomechanical analysis is conducted. With the limited portability of these systems, along with the complex set-ups and the need for multiple power sources, is a potential reason why only a few studies have examined kicking biomechanics outside the laboratory.

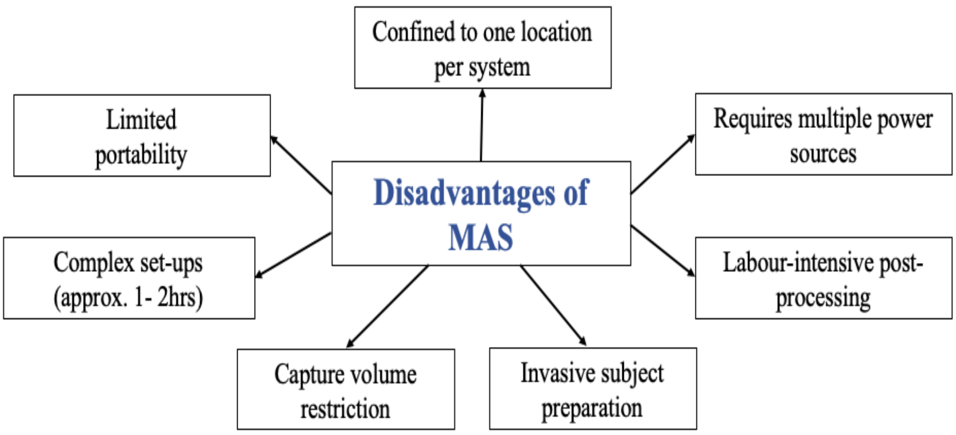


Figure 2.8. Disadvantages of an optoelectronic motion analysis systems (MAS) for biomechanical research.

An indoor laboratory provides a controlled environment (eg. no wind) to examine technical factors associated maximal velocity kicking when the outcome measure (such as accuracy) is not required (Baktash et al., 2009; Cockcroft & van den Heever, 2015; Padulo et al., 2013; Zhang et al., 2012). However, it can be a particular issue when assessing the technical factors associated with kicking accuracy. Firstly, a laboratory data collection rarely allows players to kick towards their usual target (upright goal posts). Investigations have used altered targets investigating technical factors associated with goal-kicking accuracy (Atack et al., 2018; Bezodis et al., 2007; Sinclair et al., 2017), such as towards a 0.5 x 0.5 m square target on the wall (Sinclair et al., 2017). However this can place ecologically invalid constraints on performance, as kicking into a net or at a small target on a wall is not fully representative of true goal-kicking performance when performing the shot in-front of goals (Baktash et al., 2009; Cockcroft & van den Heever, 2015; Zhang et al., 2012). Secondly, to reach the goals, the ball must travel on a necessary flight path once it leaves contact with the foot. However, the full flight path of the ball can often not be tracked due to the restricted capture volume of the laboratory (Atack et al., 2018). As a result, the extact location of the shot in the target can not be determined. This prevents researchers utilising continuous measures of performance (such as, radial distance measures), and consequently the application regression-based statistics (Ball & Ball, 2018; Hancock et al., 1995), which can provide more information about the magnitude and direction of the error associated with missing the target (Ball & Blair, 2017). Developments in flight prediction models have been made in order to overcome this limitation, and predict the exact location of the shot (Atack et al., 2018). However, a 4% error margin was reported with the model, which is equivalent to 0.13 m. This could have implications for kicks that pass either side of the post, which could be incorrectly classified due to the error in the model.

Of the limited number of kicking studies performed in a field-based settings (Ball et al., 2013; Giagazoglou et al., 2011), these were, by necessity, undertaken in one section of the field where the MAS was set-up. Ball et al. (2013) identified this as a issue when assessing goal-kicking in AF, as during competition shots are taken from a variety of distances and angles from goals. As previously discussed in **section 2.3** (*pp. 26 – 30*), given the different kicking positions, it is currently unknown if the technical aspects of goal-kicking performance change depending on the location of the kick on the pitch to achieve a successful outcome. To effectively measure data over multiple positions, an investigation would require multiple systems set-up at different locations or change the set-up of one system after each kick. As MAS are expensive, biomechanics laboratory's rarely have more than one system, resulting in one system set-up at one location, and with the complex set-ups required for MAS, it would not be practical to measure across multiple test locations during one test session. Furthermore, with the constraint of a small capture volume, analysis is often limited to one aspect of a movement, such as one gait cycle during running or just the kicking phase during a punt kick. This can be a particular issue when trying to elucidate technical factors associated with goal-kicking technique in AF, as the nature of a player's run-up, support-leg and kick-leg mechanics can all contribute to the success of the goal-kick (as detailed in **section 2.2**, *pp. 8 - 25*). As a player's approach during a goal-kick in AF can range from 3 - 20 steps (Baker & Ball, 1996), capturing the whole movement becomes difficult unless equiped with 30 or more cameras. As a result, it is often necessary to limit analysis to just the intersegmental movement of the kick-leg (Anderson & Dörge, 2011).

The performance of a camera-based MAS may be affected by different sources; occlusion, projection error, sunlight, optoelectronic distortions, electronic noise, marker placement, the digitising process and soft tissue movement artefact (Chiari et al., 2005;

Colyer et al., 2018; Windolf, 2008). Each source may add an element of noise into the measurement, resulting in measurement error. This noise, whilst present in raw data, is amplified during differentiation (calculation of velocities and accelerations) (Winter, 2009), leading to significant errors in kinematic data outputs. These errors in measurement can be minimised by selection of an appropriate experimental setup (i.e. appropriate number and placement of cameras and sufficient capture volume size), camera calibration (to help reduce projection error and camera distortion) (Chiari et al., 2005; Heikkila & Silven, 1997; Pedersini et al., 1999; Milner, 2008) and use of marker clusters during measurement (to reduce skin movement artefact as they are typically placed on areas with lower skin movement) (Benoit et al., 2016). Additionally, different smoothing or filtering techniques (such as, polynomial functions, spline functions, Fourier analysis and digital filters) may be applied to the raw positional data to compensate for the measurement error or signal noise (Chiari et al., 2005; Winter, 2009; Woltring, 1985). However, the addition of marker clusters can increase the required number of markers needed to perform the biomechanical analysis, which in turn can increase the invasiveness of the protocol (as the markers need to be attached directly to the participant), can encumber the natural movement pattern of the participant (Colyer et al., 2018) and can restrict the use of these system in competition environments (Lieberman et al., 2015; Richards, 1999).

In summary, the use of optoelectronic MAS methods have limited the types of kick analysed, the situations in which they are examined, the phases of the kick analysed and have restricted assessment of kick outcomes, such as accuracy across the football codes (Numone et al., 2017). Despite the importance of understanding the key technical characteristics associated with goal-kicking accuracy in AF, research has been limited due to practicality of MAS available. Thereby, this thesis will explore the use of another method that can provide an in-field biomechanical analysis of kicking performance, to help extend the limited goal-kicking research in AF.

2.5. Inertial Measurement Systems

The use of wearable inertial measurement systems (IMS) to provide a full-body biomechanical analysis of movement has emerged in scientific research (Chambers et al., 2015; Cuesta-Vargas et al, 2010). These systems surpass the limitations of traditional biomechanical analysis methods, offering various advantages for biomechanical investigations (**Figure 2.9**). Thereby, wearable IMS have gained popularity as alternative performance analysis tools to MAS in scientific research, to permit the analysis of movement in an applied context (Chambers et al., 2015; Cuesta-Vargas et al, 2010; Liebermann et al., 2015; Magalhaes et al., 2014; Schepers et al., 2018).

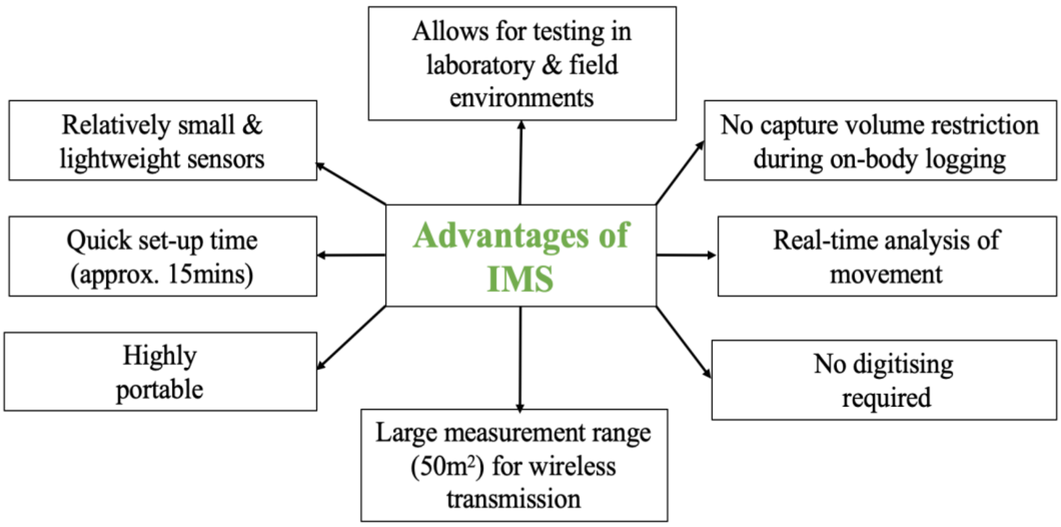


Figure 2.9. Advantages of an inertial measurement system (IMS) for biomechanical research applications.

Different commercial IMS are available to provide a full-body biomechanical analysis of human movement; MVN link (Xsens Technologies B.V., Enschede, the Netherlands), Myo motion (Noraxon, Arizona, USA), iSen (zFlo Motion, Portland, USA), F.A.B (Biosyn systems, Surrey, Canada) and 3D Suit (Inertial labs, Virginia, USA). The Xsens MVN link system has been suggested to be the leading IMS in the area of human movement, in terms of the analytical solutions to human movement, sensor fusion algorithms, biomechanical models, higher sample frequencies and enhanced sensor specifications (Cuesta-Vargas et al, 2010; Howard et al., 2016; Roetenberg et al., 2013; Schepers et al., 2018). As a result, the use of the Xsens IMS system will be explored in this thesis.

This section of the literature review will focus on the Xsens IMS, as the different commercial IMS available utilise different fusion algorithms, IMU sensors specifications, sensor placements, calibration processes and biomechanical models, which can influence the validity and accuracy of the kinematic outputs (Cuesta-Vargas et al, 2010; Howard et al., 2016; Roetenberg et al., 2013; Schepers et al., 2018).

2.5.1. Xsens MVN link inertial measurement system

The Xsens IMS (Xsens Technologies B.V., Enschede, the Netherlands) is a full-body motion capture system, which provides six-degree-of-freedom tracking of body segments. The system is composed of 17 inertial sensors placed on each body segment (**Figure 2.10**), which are daisy chain connected to a transmission body pack (160 x 72 x 25 mm: 150 g) and powered by a battery (95 x 59 x 25 mm: 70 g). Each sensor (36 × 24 × 10 mm: 10 g) integrates a 3D accelerometer (scale: ± 160 m.s$_{-2}$, noise: 0.003 m.s$_{-2}$/√Hz), 3D gyroscope (± 2000 ° /s, 0.05 ° /s/√Hz) and 3D magnetometer (± 1.9 Gauss, 0.15 m Gauss/√Hz), internally sampling at 1000 Hz. The cables, sensors, body pack and battery are zipped into a full-body compression suit (to help reduce movement artefact in the signals) which is worn by participant during data collection. The compression suit acts similar to compression garments worn by team-sports athletes during training and has been reported not to impose any constraint on a free movement (Roetenberg et al., 2013; Schepers et al., 2018). During data collection, sensor data is transmitted wirelessly from the transmission pack to a laptop PC via a router. Data from each sensor undergoes a strap-down integration (a process to down-sample the signals whilst preserving the accuracy of the kinematic output (i.e., > 1 kHz) to enable wireless transmission of data (Xsens MVN User Manual, 2016). The Xsens IMS has an overall output rate of 240 Hz.

Figure 2.10. The Xsens MVN link system; **Left:** compression garment worn by the individual during a testing session with sensors built into it; **Right:** Location of sensors on body each segments. Figure taken from http//:www.xsens.com.

The Xsens system is relatively lightweight and sensors can be fixed on each body segment without affecting its movement during a given task, making the system fully ambulatory. As sensors can be placed in the Xsens suit prior to the athletes putting them on, the IMS test set-up is potentially less invasive that MAS testing procedures. Furthermore, adjustments to sensor location can be made and specified in the Xsens software in scenarios where sensors will become obstructed, for example, to avoid contact with the ball during kicking, foot sensors will be required to be moved.

2.5.1.1. Inertial tracking

Inertial tracking works on the principle of inertia; the reluctance of an object to a change in its state of motion (F = m.a) (Newton's law). 'Inertial' refers to the fact the sensors can measure the movement of a rigid body (in which the sensor is fixed) by utilising the reluctance of a free mass to move (inertia) when contained in the sensor, while it is accelerated (accelerometer) or rotated (gyroscope) by an external force (Grimshaw et al., 2007). "Inertial sensor" refers to the group of sensors (accelerometers, gyroscopes and magnetometers contained within one housing unit (Picerno et al., 2017; Roetenberg et al., 2013). Each sensor provides a direct measure of acceleration (from the 3D accelerometer), angular velocity (from the 3D gyroscope) and magnetic field strength (from the 3D magnetometers). The IMS works on opposite principles to an optoelectronic MAS, where orientation and position of segments is determined by integration of gyroscope and accelerometer data (integrating the gyroscope data and double integrating the accelerometer data in time) (Roetenberg et al., 2013). As integration of gyroscope data leads to drift errors over time (due to the presence of signal noise and offsets) (Ferrari et al., 2010; Picerno et al., 2008; Roetenberg et al., 2013; Schepers et al., 2018), the magnetometer data (estimates changes in the orientation in relation to the local magnetic North) is then combined to reset the drift about the vertical direction (Tao et al., 2012). The output of magnetometers has been previously reported to be affected by ferromagnetic objects (resulting in distortion of the detected magnetic field and the perceived global north) (Roetenberg et al., 2013; Tao et al., 2012). Magnetic distortions can be checked in MVN software (Xsens MVN Analyze), however in new release of MVN software, the manufactures have reported that the Xsens IMS is magnetically immune to ferromagnetic objects (Schepers et al., 2018).

2.5.1.2. Calculation of segment and joint kinematics

All sensor data is processed in the Xsens software engine, MVN Analyse or MVN Biomech, which allows for real-time and automatic processing of data. As the position and orientation of anatomical landmarks are unknown with inertial sensors, a calibration process is firstly used to determine orientation and alignment of each sensor to the corresponding segment (Picerno et al., 2017; Roetenberg et al., 2013; Schepers et al., 2018). Prior to calibration, segment lengths are manually defined in the Xsens software using anthropometric measures (body height, arm span, shoulder width, foot length, leg length, knee height and hip width), in order to scale the information to a biomechanical model of the human body. During the calibration procedure, joint segmental anatomical frame axes are defined, sensor-to-segment anatomical alignment are determined, relation of the segment with the global frame and the position in relation to the two adjacent segments using prior knowledge is established (MVN User Manual, 2016; Roetenberg, 2013; Schepers et al., 2018; Zhang et al., 2013). During this process, the orientation of each body segment with respect to the orientation of the sensor axis (sensor coordinate system) is determined to generate a local axis frame (body coordinate system), which can then be expressed in relation to a global coordinate system (**Figure 2.11**) (MVN User Manual, 2016; Picerno et al., 2017; Schepers et al., 2018). The processes of determining the joint segmental anatomical frame axes, sensor-to-segment orientation and sensor-to-segment anatomical alignment is achieved by having participants stand in an *a priori* known pose (Roetenberg, 2013; Schepers et al., 2018). The Xsens MVN IMS offers two types of calibration; T-pose (upright with arms) and N-pose (arms neutral besides body).

Both poses have been shown to have high repeatability (ICC = 0.94) and low standard error of measurement (1 - 2º) (Robert- Lachaine et al., 2017).

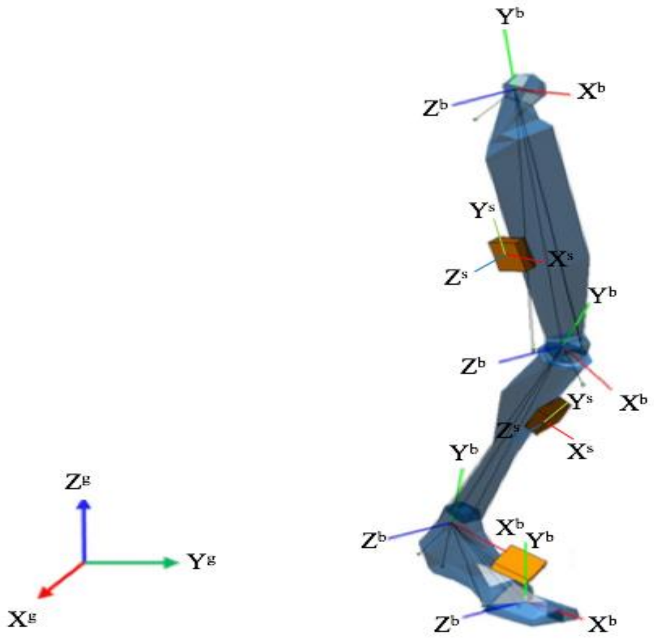


Figure 2.11. Orientation of the sensor (X_s, Y_s, Z_s), body (X_b, Y_b, Z_b), and global (X_g, Y_g, Z_g) coordinate systems for the lower extremities as calculated by Xsens software. Figure taken from the Xsens MVN User manual (2016).

To estimate 3D joint kinematics, the orientation (1) and position (2) of each body segment (${}^{L}p_{B}$ and ${}^{LB}q$) with respect to the orientation of the sensors (${}^{L}p_{S}$ and ${}^{LS}q$) is determined by applying the results of a sensor-to-segment calibration (MVN User Manual, 2016; Picerno et al., 2017; Roetenberg et al., 2013; Schepers et al., 2018):

$$ {}^{LB}q = {}^{LS}q \otimes {}^{BS}q^{*} \tag{1} $$

$$ {}^{L}p_{B} = {}^{L}p_{S} + {}^{LB}q \otimes {}^{B}r_{BS} \otimes {}^{LB}q^{*} \tag{2} $$

where ${}^{BS}q$ denotes the orientation of the sensor with respect to the body, ${}^{B}r_{BS}$ denotes the position of the sensor with respect to the segment origin expressed in the body frame, * denotes the conjugate of the quaternion, and ⊗ denotes the quaternion multiplication. Three-dimensional joint kinematics are determined as the relative orientation between the proximal (^{LB1}q) and distal (^{LB2}q) sensor-embedded frames (expressed with respect to the body reference frame) by multiplying the transposed rotation matrix of the proximal segment by that of the distal segment to obtain a joint orientation matrix (Roetenberg et al., 2013; Schepers et al., 2018):

$$^{B_1B_2}q = {}^{LB_1}q^* \otimes {}^{LB_2}q \tag{3}$$

Joint kinematics are retrieved by decomposing the joint orientation matrix into three consecutive rotations (X, Y, Z) about specified anatomical axes (Euler angles), which is similar to optoelectronic MAS methods (Picerno et al., 2017; Roetenberg et al., 2013). Three-dimensional joint kinematics requires the estimate of the 3D sensor's orientation in space, which is based on a sensor fusion process (a process that uses a mathematical algorithm (Xsens Kalman filter: XKF-HM) to combine multiple sources of information). The Xsens IMS uses information from each sensor, which is continuously updated with a biomechanical model to enable tracking of body segments, correct for signal drift and improve the estimate of IMS output. During the sensor fusion process, a prediction and correction step are applied to signals (**Figure 2.12**). In the prediction step, the accelerometer and gyroscope signals are processed using inertial navigation system (INS) algorithms and the prediction of the segment kinematics are determined using a known sensor to body alignment (which is determined in the calibration) and a biomechanical model (Robert - Lachaine et al., 2017). In the correction step, orientation, velocity and position estimates are continuously updated based on *priori* knowledge of the biomechanical characteristics of the human body, detection of contact points with an external world and magnetometer data to stabilise the output (MVN User Manual, 2016; Robert- Lachaine et al., 2017). The sensor fusion process works in a homogenous manner, where multiple sensors are implemented to work in parallel to enhance the data outputs (Roetenberg et al., 2013). This process allows the system to gather accurate and inaccurate information from multiple sensors to produce an improved estimate of the IMS kinematics, to enable the calculation of the position, velocity, acceleration, angular velocity and angular acceleration of each body segment with respect to a global reference coordinate frame (Roetenberg et al., 2013; MVN user manual, 2016).

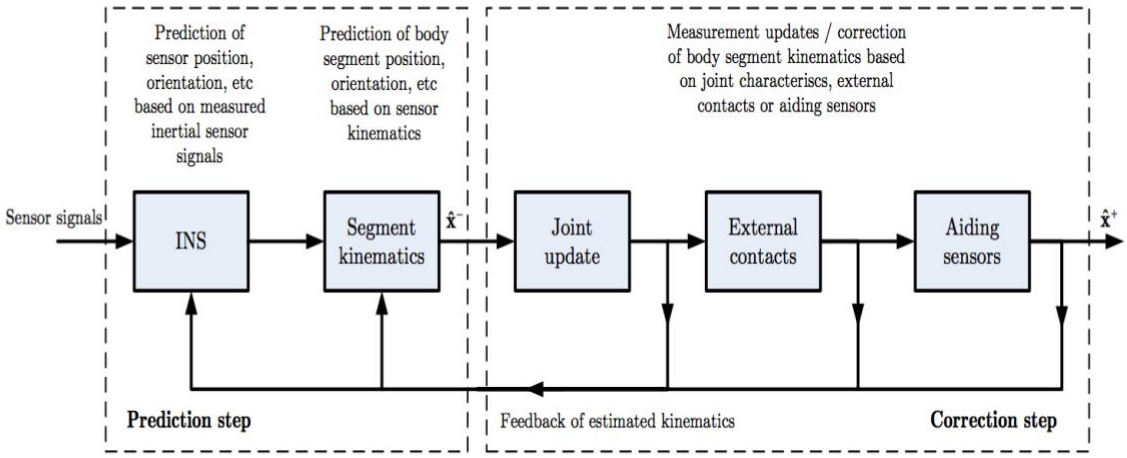


Figure 2.12. The Xsens sensor fusion process. Figure taken from Roetenberg et al., 2013.

2.5.1.3. Xsens Biomechanical model.

To describe the kinematic data in a clinically meaningful way, the Xsens IMS utilises a pre-defined biomechanical model, which consists of 23 segments (toes, feet, lower legs, upper legs, pelvis, L5, L3, T12, T8, shoulders, neck, head, upper arms, lower arms and hands) to define joint centres, joint rotations, the coordinate system for segment and the linking between segments (**Figure 2.13**) (Schepers et al., 2018). The movement of the toes, L5, L3, T12, T8 and neck segments are estimated by combining the information from connected segments and the biomechanical model as these segments do not have an inertial sensor attached to them (Schepers et al., 2018). The Xsens body segment axes definition and origins is based on the standards of the International Society of Biomechanics (ISB).

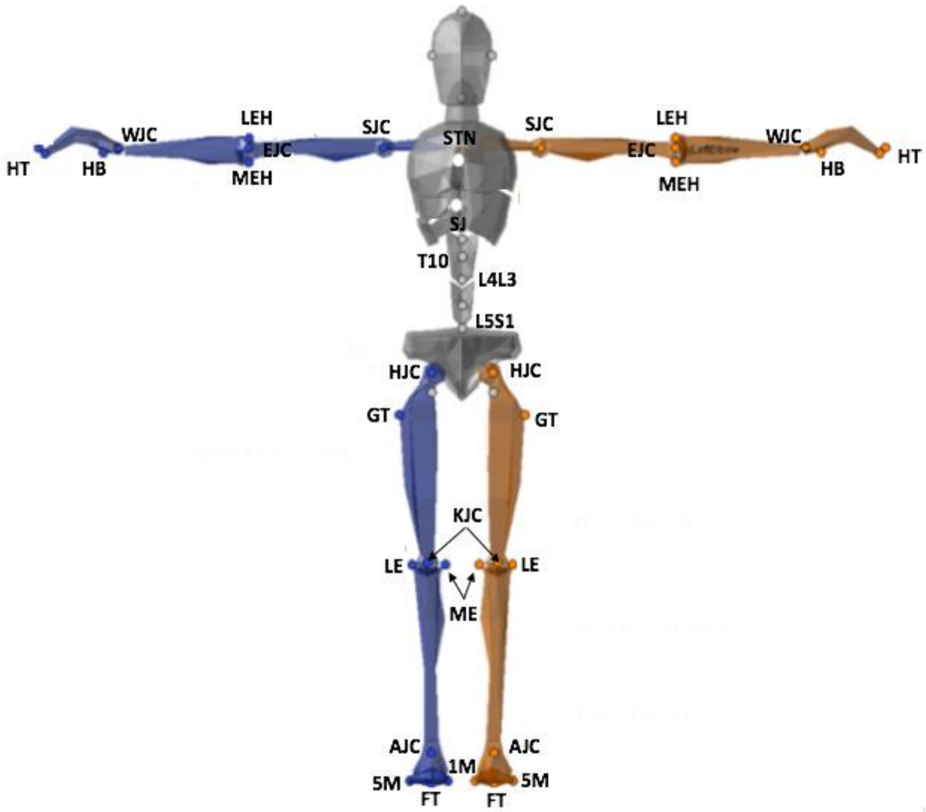


Figure 2.13. The Xsens biomechanical model in MVN Biomech software with joint centres and specific anatomical landmarks identified**.** Model abbreviations are provided in Appendix A.

For each body segment, segment kinematics are expressed in relation to the local coordinate frame (body frame) of the segment, which is a right-handed Cartesian coordinate system defined by:

- X - positive when moving forward, and lying in the horizontal plane.
- Y- pointing lateral, and orthogonal to X and Z according to the right-handed coordinate system.
- Z - along the vertical, gravity referenced, positive when pointing up.

2.5.2. Application of inertial measurement systems in biomechanical research

With the development of IMS, the use of these systems has become increasingly prevalent in scientific research. In sporting applications, the Xsens IMS was utilised to provide measurements of upper and lower extremity 3D measurements of continuous (Brodie et al., 2008; Eckardt et al., 2014; Kruger & Edelmann-Nusser, 2010; Reenalda et al., 2016; Supej, 2010) and discrete (Brodie et al., 2008; Carson et al., 2014a; Carson et al., 2014b; Helton et al., 2011) movements (**Table 2.1**). For the majority of investigations, the system enabled assessment of movements in the applied context rather than in a controlled laboratory environment (Brodie et al., 2008; Carson et al., 2014; Carson et al., 2015; Carson et al., 2016; Eckardt et al., 2014; Helton et al., 2011; Kruger & Edelmann-Nusser, 2010; Reenalda et al., 2016; Supej, 2010), to provide a more ecologically valid assessment of performance. This has important implications when trying to elucidate technical factors associated with an athlete's true performance, as it is more representative of how they perform in competition. Researchers identified that the Xsens IMS could be used to further advance specific areas of research, through facilitating more in-field studies, long-term monitoring of sporting movements and enabling assessment of skills across a wider range of contexts (Brodie et al., 2008; Eckardt et al., 2014; Helton et al., 2011; Ganter et al., 2010; Kruger & Edelmann-Nusser, 2010; Reenalda et al., 2016; Supej, 2010). In each investigation, the authors highlighted the suitability of using inertial sensors to quantify the 3D characteristics of movement in sport research.

Table 2.1. Summary of sport and clinical biomechanical studies that have utilised the Xsens MVN Inertial measurement system (17 sensor set-up).

	Application	Environment	Aim	Participants/ data collection	Parameters calculated
Sport					
Brodie et al., 2008	Skiing	Outside snow environment	The purpose of our project was to overcome the technological difficulties associated with athlete performance monitoring in an alpine environment by using a new system to capture 3D kinematics of alpine ski racing.	1 elite male skier (age: 20 yrs; mass: 78 kg) completed five runs through a 10-gate giant slalom training course. Full-body kinematics were collected over the entire 300 m course (60 Hz)	- COM path (°) - COM velocity ($m.s^{-1}$) - Ski orientation (°)
Carson et al., 2014a	Golf	Outdoor golf course	To exemplify how tracking trends in such a process may be utilised in the applied setting, we now provide a brief account of pilot work in high-level golf examining the effect of attentional focus on movement co-variability using inertial sensors.	3 professional right-handed male golfers (age: 31 ± 9 yrs) completed 10- full swing executions. Upper body kinematics were collected for each swing (120 Hz)	- Shoulder & elbow angles (°) - Hand position (°)
Carson et al., 2014b	Golf	Outdoor golf course	The aim of this study was to examine whether practice swings shared equivalent levels of control to real golf swings, when attempting the same target behaviour.	9 right-handed male golfers (age: 26 ± 8 yrs) completed 10-full swing practice and proper executions in a driving range. Upper body kinematics were collected for each swing (120 Hz)	- Shoulder and elbow angles (°) - Hand position (°)
Eckardt et al., 2014	Dressage riding	Indoor riding arena	The aim of the current study was to evaluate the application and performance of a full-body inertial system in dressage riding and additionally to investigate the selected rider kinematics in sitting trot.	10 professional male and female dressage riders (age: 23 ± 5 yrs) four times in sitting trot straight along a 30-m sand track. Full-body kinematics were collected over the entire course (120 Hz)	- Head, trunk, elbow, knee pelvis angles (°) - COM accelerations ($m.s^{-2}$)
Ganter et al., 2010	Discus	Indoor laboratory	The purpose of this pilot study was the application of an IMS for a kinematic analysis of the discus throw (characterized as a complex rotational movement).	One male sports student (22 yrs, 1.88 m, 84 kg) performed three discus throws Full-body kinematics were collected during each throw (60 Hz).	- Separation, trunk and knee angles (°) - Hip, shoulder & elbow velocities ($m.s^{-1}$) and accelerations ($m.s^{-2}$)
Helton et al., 2011	Trampolining	Indoor gym environment	To provide a motion classification system for automatically classifying trampoline routines based on inertial sensor output.	4 non-professional females completed 109 routines were measured between participants. Full-body kinematics were collected during across 750 jumps (100 Hz)	- lower spine, lower leg, forearm angles (°) - Angular velocity around the body's longitudinal axis (°/s)

Table 2.1. *Continued*

	Application	Environment	Aim	Participants/ data collection	Parameters calculated
Kruger & Edelmann-Nusser, 2010	Snowboarding	Outdoor snow environment	The aim of this study was to collect and analyze data with these systems during the 'on-snow' performance of one free-style snowboarding manoeuvre, to provide biomechanical information for the development of enhanced snowboarding equipment.	1 male recreational snowboarder (age: 28 yrs; mass: 73 kg) performed a single test run (360 indie grab) in a prepared snowboard park. Lower extremity kinematics were continuously recorded over the 8 m course (120 Hz)	- Ankle and knee angles (°)
Reenalda et al., 2016	Marathon running	Outdoor road environment	The aim of this study is to present a measurement set-up based on inertial magnetic measurement units, to perform a continuous 3D kinematic analysis of running technique during the course of an actual marathon to objectify changes in running mechanics.	5 trained runners (age: 16 yrs; height: 1.6 m; mass: 62 kg) completed a marathon. Lower extremity kinematics were continuously recorded during the entire 42.2 km (60 Hz).	- Velocity (km/h) - Stride length (m) & Step frequency. - COM vertical displacement (m) & acceleration ($m.s^{-2}$) - Hip, knee & ankle angles (°)
Supej, 2010	Skiing	Outdoor snow environment	The aim was to measure an entire alpine ski race course and retrieve the results regarding skiing performance shortly after the measurements, thereby overcoming a major limitation of camcorder-based techniques.	2 elite male alpine skiers (age: 16 yrs; height: 1.6 m mass: 62 ± 2 kg) completed five through a 20-gate giant slalom training course. Full-body kinematics were continuously recorded over were collected over the 280 m course (120 Hz)	- Ski velocity ($m.s^{-1}$) - Hip and knee angles (°)
Slawinski et al., 2015	Basketball	Indoor basketball court	The purpose of this study was to measure the effect of fatigue on basketball shooting kinematics	8 male and female elite athletes (age: 16.3 ± 1.2 yrs, mass: 76 ± 12 kg, height: 1.90 ± 0.13 m) performed repetitions of 20 m sprints immediately followed by five consecutive vertical jumps between each sprints. Full-body kinematics recorded (240 Hz)	- Shoulder, wrist, elbow, hip, knee and ankle angles (°)
Clinical					
Amelia et al., 2013	Gait analysis	Indoor laboratory	The aim of this study was to use inertial sensors to measure gait and posture characteristics before and after a repeated sit and stand task to measure the degree of fatigue induced.	A continuous and repeated sit-to-stand fatigue task with high speed between two walking tests was followed immediately by a 6-minute walking test. Full-body kinematics recorded (60 Hz)	- sternum velocity ($m.s^{-1}$) - knee angles (°) - Upper body posture (°)

Table 2.1. *Continued*

	Application	Environment	Aim	Participants/ data collection	Parameters calculated
Hamacher et al., 2017	Gait variability	Indoor laboratory	The aim of the current study was to explore whether phase-dependent functional variability can be verified in human gait.	25 older male and female participants (age: 70 ± 6 yrs, Mass: 77 ± 13 kg) were asked to walk normally and continuously on the 22-m track for three mins.	Thigh, shank, foot segment angles (°)
Hamacher et al., 2016a	Gait variability	Indoor laboratory	The aim of this study was to examine the effect of auditory cues on the variability of foot clearance versus the variability of other gait parameters.	12 healthy males (age: 24 ± 4 yrs) performed 4 walking conditions of comprised walking forth and back on an 18-m-long track. Kinematics of 96 strides were measured (60 Hz)	Stride length (m) Stride time (s)
Hamacher et al., 2016b	Chronic back pain	Indoor sport hall	The aim of the study was to examine the effects of diminishing visual feedback on variability of stride time, stride length, and minimum foot clearance in patients with chronic lower back pain.	14 healthy and chronic back pain sufferer's participants (age: 59 ± 16 yrs) walked for two minutes on a 25 m long pathway. Kinematics of 96 strides were measured (60 Hz)	Stride length (m) Stride time (s) Walking speed ($m.s^{-1}$) Toe clearance (%)
Hamacher et al., 2014	Mechanics of toe-clearance	Indoor laboratory	The aim of the current study was to explore whether the central nervous system of healthy elderly individuals minimises variability in toe clearance when an increase of gait variability is experimentally provoked.	40 elderly males walked back and forth along a 25 m track at their preferred walking speed for five minutes. Kinematics of 200 strides were measured (60 Hz)	Stride length (m) Stride time (s) Walking speed ($m.s^{-1}$) Walking speed
Kawano et al., 2008	ACL injuries	Indoor physiotherapy room	The aim of this study, was to use inertial sensors to provide a quantitative evaluation of the pivot shift test.	23 females underwent a Pivot shift test. Lower extremity kinematics were measured (100 Hz).	Knee and thigh accelerations ($m.s^{-2}$)
Moore et al., 2006	Gait patterns	Indoor laboratory	The aim of this study was to develop a new method for ambulatory gait analysis in Parkinson disease (PD) patients based on body fixed sensors	10 PD patients stood up from a sitting position on a chair, walked 20 m on a straight line toward a second chair, and sat on it. Kinematics were measured (100 Hz)	Gait cycle & stance time (s) Thigh rotation (°) Shank angular velocity (°/s) Stride velocity ($m.s^{-1}$)
Özdemir & Barshan, 2014	Fall detection	Indoor laboratory	The aim of this study was to develop an automated fall detection system using inertial sensors.	Seven males (age: 24 ± 3 yrs) performed 200 fall actions. Kinematics were measured (100 Hz) and 1400 falls were analysed.	Acceleration vectors from the leg and body sensors ($m.s^{-2}$)

In clinical research applications, the Xsens IMS was used to derive a range of spatiotemporal gait parameters and 3D joint kinematics to address the specific research question(s) (Amelia et al., 2013; Hamacher et al., 2017, 2016a, 2016b; Kawano et al., 2008; Özdemir & Barshan, 2014; van den Noort, 2013). The suitability of using these sensors has been demonstrated in both a laboratory environment (Hamacher et al., 2017, 2016a, 2016b) and in an applied context (Hamacher et al., 2016b; Kawano et al., 2008). Without the restriction of a capture volume, Hamacher and colleagues (2016a) collected continuous lower extremity walking data to assess stride-to-stride variability in different populations when walking along an 18 m track. The authors stated the Xsens IMS allowed for a more natural assessment of gait compared to studying changing in walking mechanics of a treadmill surface. Amelia et al. (2013), Kawano et al. (2008) and Moore et al., (2006) concluded the Xsens IMS could easily be implemented in research investigations to enable continuous and long-term monitoring of patients with pathological conditions in their natural environment, to further understand the aetiology of specific conditions and/or assess the effective of therapeutic interventions. In each investigation, the authors highlighted the suitability of using the Xsens IMS to provide a comprehensive 3D assessment of gait for clinical applications.

In most cases the IMS has been specifically utilised to overcome the challenges posed by other MAS to gain a more in-depth analysis of movement outside the laboratory environment. For example; Reenalda et al. (2017) captured full-body running mechanics during an entire marathon (42.2 km) in three male distance runners. This was the first study to measure continuous 3D running kinematics outside the laboratory, as it has not been feasible with other MAS. Results identified changes in running mechanics (increased hip maximum flexion ($\geq 2.2^{\circ}$, $p < 0.05$) and COM vertical acceleration) within different sub-sections of the run (between the 8 km to 36 km). The authors suggested this was an adaptive strategy to maintain shock absorption and this finding has important implications when training for a marathon from an injury prevention perspective. Additionally, in snow sports, ankle and knee kinematics during freestyle snowboarding (Kruger & Edelmann-Nusser, 2009) have been measured in an outdoor snow environment using the Xsens IMS. Results identified a potential injury risk associated with excess ankle joint motion during the landing phase of a jump, which has not been previously reported during laboratory-based testing. In these investigations, researchers highlighted the applicability of using the Xsens IMS to provide a continuous 3D kinematic analysis of technique throughout the entire event (over the course of a marathon and the full ski slope) which has not been feasible with other camera-based MAS methods. As a result, the authors gained a more in-depth, ecological valid representation of performance.

Collectively, the studies in **Table 2.1** demonstrate the applicability of using IMS to provide a biomechanical analysis of upper and lower movements across a range activities and environments. Thereby, there is potential application of the Xsens IMS to quantify in-field goal-kicking biomechanics across a wider context, such as shooting from different distance and angles from goals.

2.5.3. Validity of the Xsens MVN inertial measurement system

Accurate data collection is important in all biomechanical investigations, which can be achieved through a valid measurement system. The validity of a measurement tool reflects its the ability of a measurement system to provide a true assessment of what it is designed to measure (Atkinson & Nevill, 1998; Sarfit et al., 1989). When assessing the validity of a measurement system, there are two main components of measurement error which should be evaluated; systematic error (consistent bias or offset in the reading compared to another measurement) and random error (noise in the measurement; biological and/or mechanical variation) (Atkinson & Nevill, 1998; Chiari et al., 2005; Paton & Hopkins, 2001; Smith & Hopkins, 2011). Consideration of acceptable levels of validity should be reported in the context of the given scenarios tested (Atkinson & Nevill, 1998; Paton & Hopkins, 2001).

The Xsens MVN IMS has been validated in both clinical and sport research applications (**Table 2.2**) to measure upper and lower extremity kinematics. Across each investigation, the validity of the Xsens MVN IMS has been assessed against an optoelectronic MAS system (such as Vicon), as these systems are considered the current accepted 'gold' standard for measuring 3D kinematics of human movement in biomechanical research (Chiari et al., 2005; Cuesta-Vargas et al., 2010; Eichelberger et al., 2016; Windolf et al., 2008; Taylor et al., 2017). The demographics of participants used included healthy male and female subjects aged 18 – 30 and the validity of the Xsens MVN IMS was tested across a range of activities; walking, running, jumping, stair walking, lifting.

Table 2.2. Summary of validations of the Xsens MVN IMS compared with an optoelectronic MAS, across different activities for upper and lower extremities.

	N	MA System	SR	Trials	Parameters	Mean difference	RMSE	*CMC*	*r*
Walking									
Picerno et al., 2008	1	9-camera Vicon system (200Hz)	120	2	Ankle, knee, hip angles	0.5- 8.3º	0.8 - 3.6º	0.94 - 0.99	
Ferrari et al., 2010	4	Vicon (camera N not specified) (100Hz)	100	14	Ankle, knee, hip angles	1.1 - 11.8º		0.74 - 0.91	
Zhang et al., 2013	10	NDI Optotrak system (100Hz)	100	3	Ankle, knee, hip angles	0.03 - 5.47º	1.81 - 5.09º	0.71 - 0.99	
Lu & Zhang, 2014	10	NDI Optotrak system (100Hz)	100	3	Ankle, knee, hip angles		2.01 -10.02º	0.81 - 0.99	
Al-Amri et al., 2018	24	10-camera Vicon system (120Hz)	120	8	Ankle, knee, hip angles	0.2 - 4.5º		0.90 - 0.99	> 0.90
Running									
Marreiro et al., 2017	8	8-camera Qualysis system (240Hz)	240	5	Ankle, knee, hip angles		2.36 - 11.94º	0.47 - 0.99	
Jumping									
Dinu et al., 2016	20	8-camera Vicon system (100Hz)	120	3	COM displacement	0.73 - 5.45 mm			> 0.99
Al-Amri et al., 2018	24	10-camera Vicon system (120Hz)	120	8	Ankle, knee, hip angles	0.2 - 6.9º		0.80 - 0.99	> 0.84
Squatting									
Al-Amri et al., 2018	24	10-camera Vicon system (120Hz)	120	8	Ankle, knee, hip angles	0.2 – 5.1º		0.82 - 0.99	
Stair walking									
Zhang et al., 2013	10	NDI Optotrak 3020 system (100Hz)	100	3	Ankle, knee, hip angles	0.01 - 3.17º	1.45 - 5.15º	0.49 - 0.99	
Lifting									
Kim & Nussbaum, 2013	14	7-camera Vicon system (100Hz)	120	3	Ankle, knee, hip, shoulder, elbow angles	0.93 - 5.13º	1.29 - 4.86º		
Thies et al., 2007	1	Vicon (N cameras not specified) (100Hz)	100	10	Forearm accelerations		0.27- 0.43 $m.s^{-2}$		> 0.98

SR: Sample rate (Hz); **RMSE**: root mean square error; **CMC:** coefficient of multiple correlations; ***r*** : Pearson's correlations

Table 2.2. *Continued*

	N	MA System	SR	Trials	Parameters	Mean difference	RMSE	*CMC*	*r*
Snow sports									
Kruger & Edelmann-Nusser, 2010	1	4-camera video system (50 Hz) (make not specified)	120	2	Knee angles Knee linear velocities	0.6 - 4.9º 0.7-1.5 $m.s^{-1}$			
Kruger & Edelmann-Nusser, 2009.	1	3-camera video system (50 Hz) (make not specified)	120	2	Knee angles	0.8 - 3.1º			> 0.77
Axis movement									
Robert-Lachaine et al., 2017	12	8-camera Optotrak system (120Hz)	120	3	Ankle, knee, hip, shoulder, elbow, wrist angles		2.3 - 40.2º	0.39 - 0.98	
Table 2. Continued.									
Standing Posture									
Picerno et al., 2008	1	9-camera Vicon system (200Hz)	120	2	Ankle, knee, hip angles	0.2 - 6.6º		0.94 - 0.99	

SR: Sample rate (Hz); **RMSE**: root mean square error; **CMC:** coefficient of multiple correlations; ***r*** : Pearson’s correlations

Good agreement has been reported for the Xsens IMS in quantifying ankle, knee, hip and pelvis kinematics compared to an optoelectronic MAS, during different static and dynamic movements (Al-Amri et al., 2018; Ferrari et al., 2010; Kim & Nussbaum, 2013; Kruger & Edelmann-Nusser, 2009, 2010; Lu & Zhang et al., 2014; Marreiro et al., 2017 Picerno et al., 2008; Robert-Lachaine et al., 2017; Zhang et al., 2013). Low to moderate levels of systematic errors (Mean bias: 0.5 - 11.8º; CMC = 0.47) and random measurement errors (RMSE: 0.01 - 11.17º) have been reported across each axis movement across each investigation. In addition, low levels of systematic errors (Mean bias: 0.73-5.45 mm; r = 0.99) and low random measurement errors were found when measuring centre of mass position during jumping (Dinu et al., 2016). Overall, it was concluded in each investigation that the level of systematic and random error within the Xsens MVN IMS measurement is suggested to lie within an acceptable range to utilise the system to analysis ankle, knee, hip and pelvis kinematics during when compared to a MAS (Ferrari et al., 2010; Kim & Nussbaum, 2013; Lu & Zhang et al., 2014; Marreiro et al., 2017 Picerno et al., 2008; Robert-Lachaine et al., 2017; Zhang et al., 2013). However, the authors provided no indication what an acceptable range was for the given application.

Flexion and extension movements have demonstrated the lowest systematic errors (Mean bias: 0.01 - 4.9º; CMC = 0.93 - 0.99) and random errors (RMSE: 0.8 - 5.1º) between the Xsens MVN IMS and a MAS (Ferrari et al., 2010; Kim & Nussbaum, 2013; Lu & Zhang et al., 2014; Marreiro et al., 2017; Picerno et al., 2008; Robert-Lachaine et al., 2017; Zhang et al., 2013). The mean differences between the Xsens MVN IMS and MAS were reported to increase when measuring adduction/abduction and internal/ external rotation angles (Mean bias: 3.8 – 11.8º; CMC = 0.76 - 0.86; RMSE: 4.6 - 10.02º). Ferrari et al. (2010), reported these differences between the Xsens MVN IMS and a MAS were higher in knee varus-valgus (CMC = 0.87) internal-external rotation (CMC = 0.76) compared to other lower extremity joints (**Figure 2.14**), supporting Al-Amri et al. (2018), Lu & Zhang et al. (2014) and Marreiro et al. (2017) findings. These differences have been attributed to slight variations between the Xsens MVN biomechanical model and the ISB biomechanical model (Lu & Zhang, 2014; Robert-Lachaine et al., 2017; Zhang et al., 2013). However, these errors in were reported to lie within an acceptable range for gait analysis (Cuesta-Vargas et al., 2010).

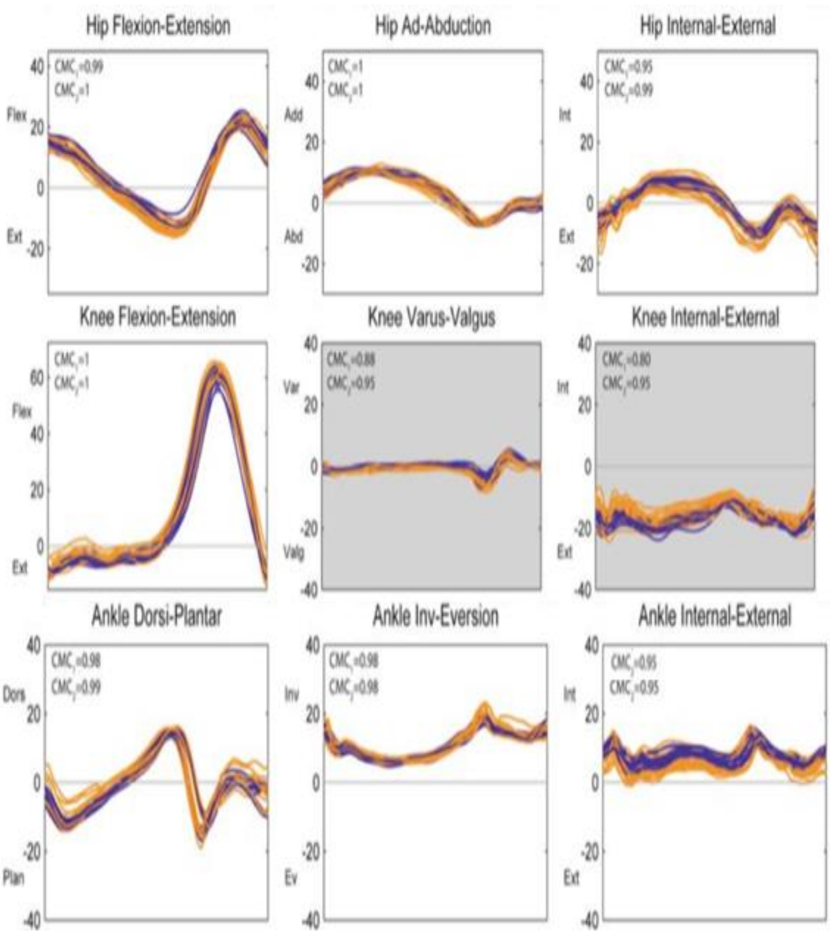


Figure 2.14. Example of hip, knee and ankle kinematics measured by Xsens (orange lines) and Vicon (purple lines). Higher CMC values indicate higher validity between systems. Grey background indicates low accuracy. Figure taken from Ferrari et al., (2010).

Three studies have investigated the validity of upper extremity kinematics measured by the Xsens MVN IMS compared to a MAS (Kim & Nussbaum, 2013; Robert-Lachaine et al., 2017; Thies et al., 2007). Good agreement between the Xsens MVN IMS and a MAS has been reported when measuring elbow angles (RMSE: 5.4 - 12.1 º; CMC: 0.81 - 0.96), wrist angles (RMSE: 4.8 - 14.0º; CMC: 0.80 - 0.89) and forearm accelerations (RMSE: 0.27 - 0.43 m.s^{-2}; r = 0.98 - 0.99). However, large systematic (CMC: 0.39 - 0.68) and random errors (RMSE: 19.7 - 40.2º) were reported in the shoulder joint kinematics, specifically when measuring internal and external rotation. This has been attributed to differences in the orientation of the glen-humeral coordinate system and variations in the centre of joint rotations defined by the Xsens and ISB biomechanical model (Brennan et al., 2011; Robert Lachine et al., 2017). The authors suggested applying a realignment technique to improve the output of the shoulder joint kinematics. Apart from shoulder rotations, good validity between the Xsens MVN IMS and an MAS has been reported when measuring elbow, wrist and forearm kinematics and sagittal shoulder kinematics (Kim & Nussbaum, 2013; Robert-Lachaine et al., 2017; Thies et al., 2007).

The kicking action occurs outside the validated movement and speed ranges of IMS (**Table 2.2**). The rapid movement of the kick-leg (e.g. foot speeds ranging up to 27 m.s^{-1} (Ball, 2008; Lees et al., 2010) occurs outside the validated speed (up to 12.8 m.s^{-1} validated) ranges of IMS. As the performance of the IMS is dependent on a Kalman filter, which can be negatively influenced by speed (Ferrari et al., 2010; Schall et al., 2015), validation is warranted to ensure the IMS can adequately measure the high-velocity movement experienced during kicking. In addition, the segmental actions (eg: greater knee ROM; 120º flexion/extension, Ball, 2008; Sinclair et al., 2017) during kicking differ from any of the tasks previously validated (**Table 2.2**). Thereby, validation is also warranted to ensure the IMS can adequately measure the full movement of the joints during kicking. In this thesis, acceptable levels of validity will be determined through comparisons of error to kinematic ranges reported across the kicking literature.

Table 2.3. Comparison of joint and movement speed ranges reported across the kicking (Australian football, sand the rugby codes) literature and validated ranges of the Xsens MVN IMS.

Parameters	Kicking ranges reported in the literature	Validated Xsens MVN IMS ranges
Segment and joint movement speeds		
Linear velocities	≤ 27 $m.s^{-1}$ • Linear foot velocity: 15 - 27 $m.s^{-1}$ • Linear hip velocity: 1.2 - 7.1 $m.s^{-1}$ • Linear centre of motion (COM) velocity: 0.2 - 3.8 $m.s^{-1}$	≤ 12.8 $m.s^{-1}$ • Linear knee velocity: 0.3 - 12.8 $m.s^{-1}$
Angular velocities	≤ 1731 °/s • Knee angular velocity: 1355 - 1731 °/s • Shank angular velocity: 1548 - 1859 °/s • Thigh angular velocity: 313 - 742 °/s • Hip angular velocity: 182- 522 °/s	Not validated
Joint and segment ROM, Max		
MAX	≤ 134° • Hip angle: 16.1 - 65.2° • Knee angle: 64.6 – 150° • Ankle angle: 15.2 - 74°	≤ 81.3° • Hip angle: 7.5 - 20.1° • Knee angle: 8.4 - 81.3° • Ankle angle: 2.7 - 29.3°
ROM	≤ 53° • Hip angle: 33 - 53.0° • Knee angle: 37 - 50° • Ankle angle: 2.2 - 35.5°	≤ 35° • Hip angle: 9.0 - 21.7° • Knee angle: 10.3 - 22.0° • Ankle angle: 17.4 - 35.1°
Corresponding literature:	Atack et al., 2017; Atack et al., 2015; Ball, 2008; 2011; 2010; 2013; Baktash et al., 2009; Coventry et al., 2015; Peacock et al., 2017; Peacock & Ball, 2017 De Witt & Hinrichs, 2012; Gheidi & Sadeghi, 2010; Dörge et al., 2002; Kellis & Katis, 2007; Lees et al., 1998; 2010; Nunome et al., 2006. Ball, 2010; Sinclair et al., 2017; Zhang et al., 2012; Macmillan, 1976; Baker & Ball, 1996; Dicheria et al., 2006.	Al-Amri et al., 2018; Ferrari et al., 2010; Kim & Nussbaum, 2013; Kruger & Edelmann-Nusser, 2009, 2010; Lu & Zhang et al., 2014; Marreiro et al., 2017 Picerno et al., 2008; Robert-Lachaine et al., 2017; Thies et al., 2007; Zhang et al., 2013.

2.5.4. Limitations of the Xsens inertial measurement system

Only two limitations for the Xsens IMS have been reported in the literature. Reenalda et al. (2017) reported a loss in battery-life and loss of sensor connection (due to distance or interference on transmitting) during continuous marathon running, resulting in loss of data from two subjects. The Xsens IMS has a battery-life of 4 hours, which can be problematic when measuring continuous activities, such as marathon running which can last over 4 hours. However, this timeframe would not affect many sports-based scenarios, including the kicking testing in this thesis, which would require 3 hours of testing. Further, the Xsens IMS suggests transmission can be received over a 50 m^2 area when capturing in real-time. Goal-kicks taken in AF are typically taken within the 50 m line in front of goals, thereby setting up different measurement positions within this area should enable transmission of IMS data without signal drop out to enable real-time collection of data. On-body logging can overcome this issue, however this removes the ability to watch the data capture in real-time and play data back immediately. Regardless, moving the receiver would be an option for many testing scenarios to overcome this situation.

Signal saturation of the accelerometers in the Xsens IMS occurs at >16 g (160 $m.s^{-2}$) and typically IMS have a lower maximum sampling frequency compared to optical MAS (240 Hz vs 1200 Hz), which may restrict analysis of specific aspects of the kicking phase (such as, ball impact phase) (Ellens et al., 2017). Ellens et al. (2017) reported accelerometers (with a ± 16 g range) can be utilised to accurately track the motion of the kicking foot during the kicking action prior to ball impact. When foot speed's exceeded 5.9 $m.s^{-1}$, signal saturation occurred. The authors suggested a range of ± 200 g was needed to facilitate measurement through the ball impact phase. Furthermore, capture of kinematic data through the ball impact requires sampling frequencies of over 4500 Hz, in order to provide a detailed analysis of the impact phase (Nunome et al., 2014).

Sampling frequencies from optical MAS (1000 Hz) have been suggested to be insufficient for a detailed analysis of impact, requiring the need for ultrahigh-speed cameras to be utilised (Nunome et al., 2014). Biomechanical kicking studies typically capture lower and upper extremity movements at rates between 100 - 400 Hz (Dörge et al., 2002; Lees & Nolan, 2002; Lees et al., 2010; Nunome et al., 2002; Teixeira, 1999), which has been suggested appropriate for the study of the kicking movement (Nunome et al., 2006). Despite the saturation of the signal during ball impact and the lower sample frequency, the Xsens IMS may be appropriate for the study of kicking biomechanics up until the instant before ball impact.

Unlike MAS motion data files (which contain raw motion analysis data), the IMS motion data files will contain processed and filtered data (Xsens Kalman Filter and LXsolver filtering). In football kicking, obtaining accurate kick-leg kinematic data near impact can be problematic due to the large accelerations experienced during the foot-to-ball impact (Knudson & Bahamonde, 2001). Studies have applied different smoothing techniques (Butterworth digital filters, cubic spline smoothing) to treat signals that experience an impact, however, distortions in kinematic outputs before, during and after at impact were still evident, resulting in inaccuracies in the movement patterns reported (Knudson & Bahamonde, 2001; Woltring, 1985). Terminating raw data at the instant prior to impact has been identified as an appropriate solution to avoid smoothing issues through impact (Knudson & Bahamonde, 2001). As a result, raw motion analysis data in kicking literature is typically cut-off immediately before ball impact to avoid smoothing issues around impact (Ball, 2008, 2011, 2013). As the Xsens IMS data is automatically processed and filtered when exported out of the Xsens software, it is unknown if significant signal distortions will occur due to impact. Examining the validity of kinematic signals at the instance before impact would determine if significant distortions occur and determine the IMS can be used to measure these parameters.

2.6. Summary

Goal-kicking in AF remains a largely unexplored area in sports biomechanics. This review of the literature highlighted the importance of understanding the technical factors associated with goal-kicking to facilitate improvement in performance. Based on this review, a deterministic model was developed, identifying the key technical factors which may be potentially important when investigating goal-kicking in AF (**Figure 2.4**, *pp*. 25). Examining the parameters detailed in **Figure 2.4** will help further advance the understanding of the underlying technical factors which influence accurate goal-kicking.

Two methodological considerations were identified with regards to the assessment of goal-kicking technique. Firstly, given the different goal-kicking positions used in AF, it is currently unknown if technical adjustments are also made due to the position of the kick on the pitch in order to achieve a successful outcome. Thereby, research is warranted to explore the effect of distance and angle from goals influences goal-kicking performance. Secondly, this review also identified that the use of individual-based analysis is an important factor which needs to be considered when examining technical aspects associated with a skilled performance. Use of both individual and group-based analysis methods will be utilised in this thesis to provide an in-depth analysis of the goal-kicking skill.

The limited biomechanical studies investigating goal-kicking in AF, has been attributed to the inherent limitations within traditional biomechanical analysis techniques, such as camera-based MAS. This review of the literature highlighted the applicability of using wearable IMS to overcome the previous challenges of MAS, to enable measurement of in-field goal-kicking kinematics in AF. However, as the kicking movement currently occurs outside of the validated ranges of these systems, validation is firstly warranted to ensure IMS can adequately measure the kicking action.

2.6.1. Aims of the thesis

The general aims of this thesis are to:

1. To examine the concurrent validity of an inertial measurement system in measuring kicking biomechanics in Australian Football.
2. To examine goal-kicking technique in Australian Football and determine technical factors associated with accuracy.

The specific aims of this thesis are to:

- To examine the concurrent validity of an inertial measurement system in quantifying discrete joint and segment kinematics in comparison to a motion analysis system during different kicking tasks (Chapter 3).
- To examine the concurrent validity of an inertial measurement system in quantifying lower extremity joint time-series profiles in comparison to a motion analysis system during kicking (Chapter 4).
- To determine if differences exist in accurate goal-kicking kinematics with altering kicking position (angle and distance) in Australian Football (Chapter 5).
- To identify if technical differences exist between accurate and inaccurate goal-kicking and examine the relationship between technical factors and goal-kicking accuracy on a group basis (Chapter 6).
- To identify if technical differences exist between accurate and inaccurate goal-kicking and examine the relationship between technical factors and goal-kicking accuracy on an individual basis (Chapter 7).

Chapter 3: Concurrent Validation of an Inertial Measurement System to Quantify Kicking Biomechanics in Four Football Codes

This chapter has been published in the Journal of Biomechanics: Blair, S., Duthie, G., Robertson, S., Hopkins, W. & Ball, K. (2018). Concurrent validation of an inertial measurement system to quantify kicking biomechanics in four football codes. Journal of Biomechanics, 17, 24-32. This journal has been adapted to suit the thesis format and include additional findings and discussion relevant to the thesis.

3.1. Introduction

Kicking is an important skill used in Australian football (AF), soccer, rugby league and rugby union. Across these codes, players either kick from the ground (place kicks) or after the ball has been released from the hand (punt kicks). Variations of both kick types are evident in each football code to achieve different performance outcomes, such as accuracy when passing and goalshooting, or distance when trying to clear a defensive zone and shooting further from goal (Ball, 2008; Bezodis et al., 2007; Kellis & Katis, 2007; Lees et al., 2010). Thereby, improvement of kicking technique offers a player/team a distinct advantage in competition.

Optoelectronic motion analysis systems (MAS) are commonly used in biomechanical research to quantify the three-dimensional (3-D) characteristics of the kicking skill in AF (Ball, 2011, 2013; Coventry et al., 2013; Dicheria et al., 2006), soccer (Giagazoglou et al., 2011; Inoue et al., 2014; Lees et al., 2010; Kellis & Katis, 2007) and the rugby codes (Baktash et al., 2009; Ball et al., 2013; Bezodis et al., 2007; Zhang et al., 2012). These systems track body-worn markers through a calibrated space, to provide position and orientation measurements of body segments (Chiari et al., 2005). Optoelectronic MAS provide an accurate and comprehensive analysis of the skill, however they have limited portability, require complex set-ups, are constrained to small test areas and are confined to one testing location per system, which is a potential reason why only few studies have examined kicking biomechanics outside the laboratory environment. Of the limited number of studies performed in field-based settings (Ball et al., 2013; Giagazoglou et al., 2011), these were, by necessity, undertaken in one section of the field where the MAS was set-up. Ball et al. (2013) identified this as a particular issue when assessing goal-kicking, as during competition shots are taken from a variety of distances and angles from goals, which can increase the difficulty of scoring a goal (Quarrie & Hopkins, 2015). Thereby, use of MAS methods have limited the situations in which kicks have been examined and restricted assessment of kick outcomes, such as accuracy across the football codes.

Wearable inertial measurement systems (IMS) overcome the limitations of MAS by allowing measurement in sport-specific settings without the restriction of a capture volume (Chambers et al., 2015; Cuesta-Vargas et al, 2010; Fong & Chan, 2010). These systems combine multiple inertial sensors (3D accelerometers, 3D gyroscopes and 3D magnetometers) fixed to body segments, to provide direct acceleration, angular velocity and magnetic-field measurements (Roetenberg et al., 2007; 2013). Through integration, 3D position and orientation of each segment can be obtained (Roetenberg et al., 2013). When combined with sensor fusion algorithms (a process that combines the three sources of information to improve the estimate of IMS output, e.g. Kalman filters) and a biomechanical model, full-body 3D kinematics can be obtained (Roetenberg et al., 2013; Takeda et al., 2009; Zhang et al., 2013). These systems have been used to quantify sport-specific movements in their applied context in skiing (Brodie et al., 2008), snowboarding (Krüger & Edelmann-Nusser, 2009), marathon running (Reenalda et al., 2016) and swimming (De Magalhaes et al., 2015). There is potential application of IMS to quantify in-field kicking biomechanics, across a wider range of contexts (such as from different positions in-front of goals and assess accuracy under realistic conditions), which has been previously limited by MAS methods.

Validation of IMS has demonstrated good agreement with MAS in quantifying lower extremity kinematics during certain football-related activities, such as walking (RMSE: Picerno et al., 2008, 0.8-3.6°; Zhang et al., 2013, 1.8-2.4°) and running (RMSE: Cooper et al., 2009, 0.7-3.4°; Ferrari et al., 2010, 0.6-5.0°). However, the validity of IMS has reported to be specific to the speed of the movement investigated (Cuesta-Vargas et al, 2010). Currently, the rapid movement of the kick-leg (e.g. knee angular velocities up to 1960 °/s and foot speeds ranging up to 27m/s (Ball, 2008; Lees et al., 2010; Sinclair et al., 2017) occurs outside the validated speed (up to 12.8 m/s validated) ranges of IMS. As the performance of the IMS is dependent on a Kalman filter, which can be negatively influenced by speed (Ferrari et al., 2010; Schall et al., 2015), validation is warranted to ensure the IMS can adequately measure the high-velocity movement experienced during kicking. Therefore, the aim of this research was to examine the concurrent validity of an IMS for quantifying joint and segment kinematics in comparison to a MAS during kicking in Australian football, soccer, and the rugby codes.

3.2. Methodology

3.2.1. Participants

Thirty team-sport male athletes (age: 22.5 ± 3.0 yrs; height: 181 ± 5.7 cm; mass: 79.6 ± 6.5 kg) from AF (n=10), soccer (n=10), rugby league and rugby union (n=10) clubs provided written informed consent to participate in this research (*see* **Appendix B**, **Table 1**, *pp. 238; and* **Appendix C**, *pp 240 - 248*). All participants were competing regularly in competition and had no injuries in the previous six months. Ethical approval (HRE17-046) was granted from the corresponding University Human Research Ethics Committee.

3.2.2. Equipment

Participants wore the MVN Link IMS (Xsens Technologies B.V., Enschede, the Netherlands), which is composed 17 inertial sensors, a transmission pack (160 x 72 x 25 mm: 150 g) and battery (95 x 59 x 25 mm: 70 g), zipped into a compression suit. Each sensor (36 × 24 × 10 mm: 10 g) integrates a 3-D accelerometer (scale: ±160 $m.s^{-2}$, noise: 0.003 $m.s^{-2}/\sqrt{Hz}$), 3D gyroscope (±2000 °/s, 0.05 °/s/√Hz) and 3D magnetometer (±1.9Gauss, 0.15m Gauss/√Hz), internally sampling at 1000 Hz. The overall system update rate is 240Hz. Sensors were placed following the manufacturers recommended placements; shanks (medial surface of the tibias), thighs (lateral side above the knees), pelvis (middle of both the posterior superior iliac spines), shoulders (middle of the scapula spine), upper arms (lateral side above elbow), forearms (lateral side of wrist), hands (posterior side), sternum and the back of the head. To avoid contact with the ball, foot sensors were placed on the lateral side of the player's boot inferior the malleolus. To scale the Xsens biomechanical model, anthropometric measures were collected from each participant (cm); body height, arm span (left to right tip of the third distal phalanx on the hands), shoulder width (right to left distal tip of acromion), leg length (ground to the lateral bony prominence of the greater trochanter), knee height (ground to the lateral femoral epicondyles) and hip width (right to the left anterior superior iliac spine) (Roetenberg et al., 2013).

Concurrent validity was assessed by comparing with kinematic data from a 12-camera MAS (T-40 series, Vicon Nexus v2, Oxford, UK). Cameras (mounted at 1.5±0.9 m) were placed in an arc around an indoor testing area (**Figure 3.1.**). Seventy-four reflective markers (diameter: 14 mm) were attached to the outside of the Xsens suit using double-sided tape. The Xsens suit is a compression garment which aims to reduce underlining soft tissue artefact during highly dynamic movements (Roetenberg et al., 2013), which would help minimise error in MAS data (Lui et al., 2011). Further, to minimise movement artefacts created between the suit and skin, the tightness of the suit was maximised for each individual. Anatomical markers were placed on the posterior heel, tip of foot, 1st, 2nd and 5th metatarsal heads, femoral greater trochanter, lateral and medial femoral epicondyles, lateral and medial malleoli, clavicular, C7, T10, sternum, anterior and posterior superior iliac spines, lateral and medial head of the 2nd and 5th metacarpal, wrist radius, ulna, acromion, epicondyle of the humerus, and humerus lesser and greater tubercle (Cappozzo et al., 1995). Rigid, lightweight plates with three markers were strapped laterally on the thighs, shanks, upper arms, forearms and hands. Seven markers were placed on the anterior, posterior, medial, lateral axis of the ball to allow identification of ball contact (BC) for MAS data (Ball, 2011; Bezodis et al., 2007; Inoue et al., 2014).

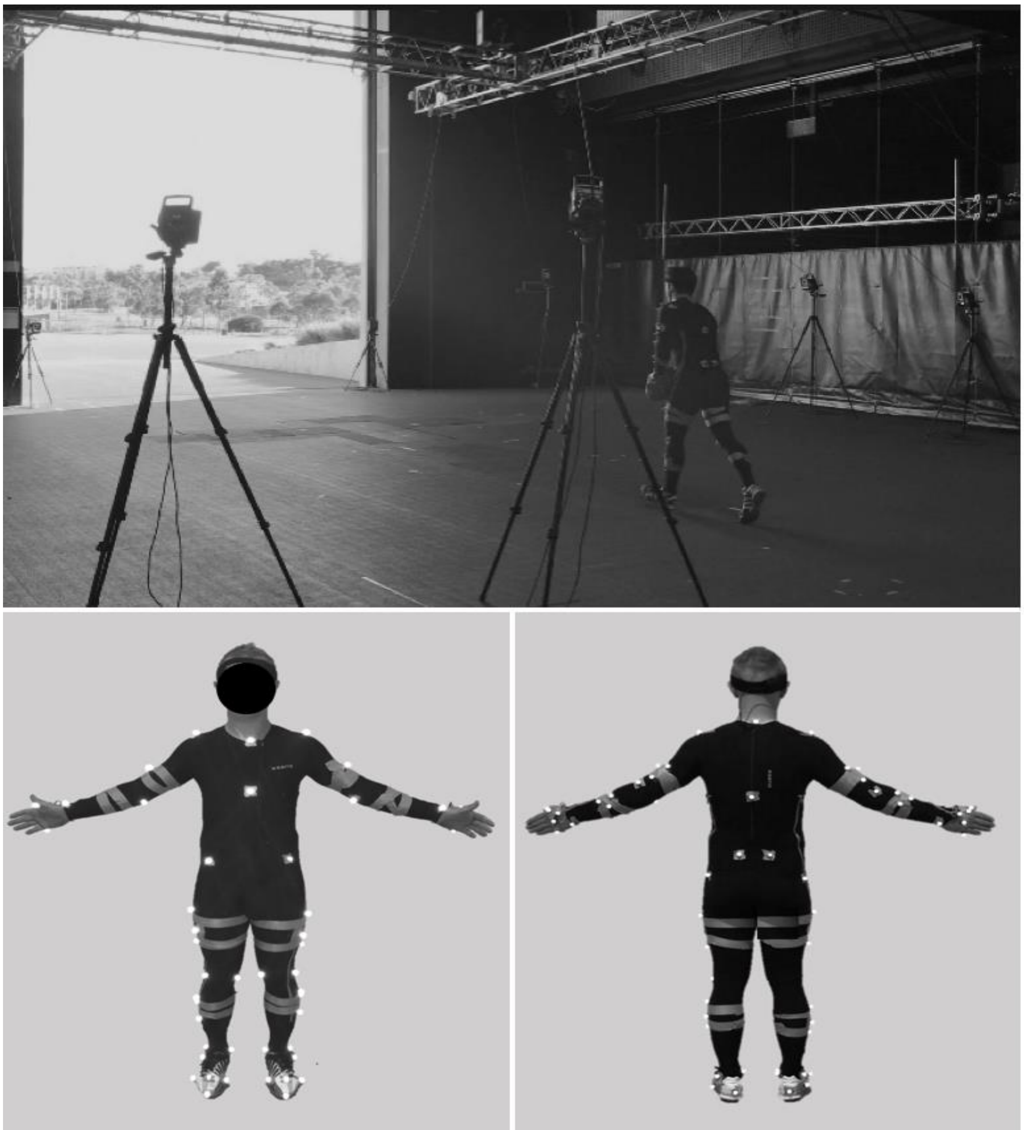


Figure 3.1. Experimental set-up used in this study. The indoor test area (top) and participant marker set-up (Bottom left & right).

Individual calibrations (T-pose) were performed for both systems. During the IMS calibration, sensor to segment orientations were determined using regression equations (Roetenberg et al., 2013). Both systems were time-synchronised via the Xsens Sync Station and triggered (pulse polarity: 5 V) in the Xsens software (v 4.4 MVN Biomech studio). No magnetic disturbances were reported in the testing environment. Set-up time for the IMS (including sensor set-up and calibration) is approx. 15 mins compared to approx. 1 hour (including camera set-up, subject marker preparation camera and subject calibration) for the MAS.

3.2.3. Testing Protocol

All participants wore indoor football shoes without cleats/studs and official match balls were used for each kick; Sherrin AF footballs (Sherrin, Scoresby, Australia), Adidas Beau Jeu soccer footballs (Adidas, Herzogenaurach, Germany), Gilbert (Gilbert, East Sussex, UK) and Steeden rugby footballs (Steeden, Cheltenham, Australia).

All participants performed a standardised warm-up followed by several familiarisation kicks. Participants were then instructed to perform 20 kicks across four conditions specific to their football code (**Table 3.1**), using their preferred foot. Kicking tasks and types were selected based on those performed in competition (Ball 2008; Bezodis et al., 2007; Lees et al., 2010). Code-specific goal-posts were set-up at the different distances and participants were instructed to perform kicks under game-like conditions. During each kick, concurrent acquisition of IMS and MAS data were made at 240 Hz.

Table 3.1. The four kicking tasks used for each football code (n=5 per kick task).

Australian football	Soccer	Rugby codes
20m drop punt kicks (20m_punt)	12m Instep kicks (12m_instep)	20m drop kicks (20m_drop)
40m drop punt kicks (40m_punt)	12m Inside kicks (12m_inside)	20m place kicks (20m_place)
Maximal punt kicks (max_punt)	20m Instep kicks (20m_instep)	40m place kicks (40m_place)
20m kicks ‘on the run’(20m_Run)	Maximal instep kicks (max_instep)	Maximal place kicks (max_place)

3.2.4. Data Analysis

Modelling procedures for the MAS data were consistent with previous biomechanical kicking studies (Ball, 2011; Lees et al., 2010; Coventry et al., 2013; Inoue et al., 2014). Raw motion analysis data were digitised in Nexus (v.2.0, Vicon, Oxford, UK) and processed in Visual 3D (C-motion, Inc. Germantown, USA). Raw motion analysis data were cut-off immediately before BC to avoid smoothing issues through impact (Knudson & Bahamonde, 2001) and filtered using a low-pass 4th order Butterworth filter (cut-off frequency: 12 Hz). Cut-off frequency was chosen based on spectral and residual analyses that indicated a range between 10-15 Hz (Winter, 2009), visual inspection and previous literature (12Hz) (Ball, 2011; Coventry et al., 2013; Dicheria et al., 2006; Zhang et al., 2012). Position and orientation of anatomical markers relative to tracking markers were determined from a static trial to create a six-degree-of-freedom model (Cappozzo et al., 1995) and model-based calculations were computed using the X-Y-Z Cardan sequence (Lees et al., 2010).

Modelling procedures for the IMS data were based on the manufacturer's recommendations. Motion files were cut-off at the instant before BC in MVN Biomech Studio. Sensor fusion of the IMS data was made using the manufactures proprietary algorithms (Xsens Kalman Filter) and filtered using the LXsolver (minimise soft tissue artefact) and in MVN Biomech Studio. The Xsens biomechanical model was assigned to motion files in Visual 3D and model-based calculations were computed using the Y-X-Z Cardan sequence, which corresponded to the ML-AP-Axial rotations computed in the MA data (c-motion, 2016).

For both systems, all kicks (n = 600) were analysed from kick foot toe-off (TO) until the instant before BC (Ball, 2008; Nunome et al., 2006). For MAS, TO was determined using an acceleration-based detection algorithm (Maiwald et al., 2009) and BC corresponded to the peak linear velocity of the 5Th metatarsal and (Ball, 2011). For IMS data, TO corresponded a peak in the gyroscope signal from the foot sensor (Bergammi et al., 2012; Reenalda et al., 2017; Sabatinit et al., 2005) and BC corresponded to the instant prior to a peak in the anterior-posterior and vertical acceleration signal from the kick-foot sensor.

Events were visually inspected with model representation in Visual 3D and cross-confirmed between systems from the time between TO and BC.

Twelve discrete parameters were chosen based on technical parameters identified important to kicking performance across the football codes (**Table 3.2**). For the MAS data, the three-point central difference method was used to calculate linear foot speed, pelvis velocity and angular velocities of the thigh, shank and knee (Ball, 2011). For IMS data, linear foot speed, pelvis velocity and angular velocities of the thigh, shank and knee were computed using model-based calculations. For both systems, sagittal plane knee and hip joint angles were calculated as anatomical angles, with the knee measured as the angle between the thigh and shank and the pelvis used as the coordinate systems for the hip. Sagittal pelvis and shank segment angles were calculated in relation to the global axis.

Table 3.2. Measured parameters, along with parameter definitions and reason for choice. All parameters relate to the kick-leg unless stated.

Parameter	**Definition**	**Reason for choice**
At ball contact		*Parameters significant in kicking studies in*:
Foot speed (m.s-1)	Linear velocity of the foot segment	AF (Ball, 2008; 2011; Coventry et al., 2015; Peacock et al., 2017; Peacock & Ball, 2017; Soccer (De Witt & Hinrichs, 2012; Gheidi & Sadeghi, 2010; Dörge et al., 2002; Kellis & Katis, 2007; Lees et al., 2010; Nunome et al., 2006) Rugby (Ball, 2010; Sinclair et al., 2017; Zhang et al., 2012)
Pelvis velocity (m.s-1)	Linear velocity of the pelvis segment	AF (Ball, 2011; Coventry et al., 2015) Soccer (De Witt & Hinrichs, 2012; Gheidi & Sadeghi, 2010; Kellis & Katis, 2007; Lees et al., 2010) Rugby (Zhang et al., 2012)
Shank angular velocity (º/s)	Angular velocity of the shank segment	AF (Baker & Ball, 1996; Ball, 2008; 2011) Soccer (De Witt & Hinrichs, 2012; Gheidi & Sadeghi, 2010; Kellis & Katis, 2007; Lees et al., 1998; 2010; Nunome et al., 2006) Rugby (Bezodis et al., 2007; Zhang et al., 2012)
Thigh angular velocity (º /s)	Angular velocity of the thigh segment	AF (Ball, 2008; 2011) Soccer (De Witt & Hinrichs, 2012; Dörge et al., 2002; Gheidi & Sadeghi, 2010; Kellis & Katis, 2007; Lees et al., 2010; Nunome et al., 2006) Rugby (Bezodis et al., 2007; Sinclair et al., 2014; 2016; Zhang et al., 2012)
Knee angular velocity (º/s)	Angular velocity of the knee joint	AF (Ball, 2008; 2011; Coventry et al., 2015; Macmillan, 1976) Soccer (De Witt & Hinrichs, 2012; Kellis & Katis, 2007; Lees et al., 2010) Rugby (Sinclair et al., 2014b; 2016; 2017)
Shank sagittal angle (º)	Angle between the shank and the lab global axis	AF (Ball, 2011; Coventry et al., 2006) Soccer (De Witt & Hinrichs, 2012; Kellis & Katis, 2007; Lees et al., 2010)
Thigh sagittal angle (º)	Angle between the thigh and the lab global axis	AF (Ball, 2011; Coventry et al., 2006) Soccer (De Witt & Hinrichs, 2012; Kellis & Katis, 2007; Lees et al., 2010) Rugby (Atack et al., 2017; Bezodis et al., 2007; Zhang et al., 2012)
Pelvis sagittal angle (º)	Angle between the pelvis and the lab global axis	AF (Ball, 2011; Coventry et al., 2015) Soccer (Gheidi & Sadeghi, 2010; Kellis & Katis, 2007; Lees et al., 2010) Rugby (Atack et al., 2017; Bezodis et al., 2007; Zhang et al., 2012)
Trunk sagittal angle (º)	Angle between the trunk and the lab global axis	AF (Ball, 2013; Coventry et al., 2015) Rugby (Bezodis et al., 2007; Zhang et al., 2012)
Minima & Maxima		
Maximum support-knee extension (º)	Angle between the shank and thigh	AF (Ball, 2013; Dicheria et al., 2006) Soccer (Gheidi & Sadeghi, 2010; Lees et al., 2010) Rugby (Bezodis et al., 2007; Sinclair et al., 2017)

Table 3.2. *Continued*

Parameter	**Definition**	**Reason for choice**
Minimum kick-leg knee angle (º)	Angle between the shank and thigh	AF (Dicheria et al., 2006; Ball, 2008; 2011; Coventry et al., 2015) Soccer (Gheidi & Sadeghi, 2010; Kellis & Katis, 2007; Lees et al., 1998; 2010) Rugby (Baktash et al., 2009; Sinclair et al., 2014b; 2016; 2017)
Maximum hip extension (º)	Angle between the thigh and pelvis	AF (Baker and Ball, 1996; Ball, 2008; 2011; Coventry et al., 2015; Dicheria et al., 2006) Soccer (Gheidi & Sadeghi, 2010; Kellis & Katis, 2007; Lees et al., 1998; 2010) in Rugby (Baktash et al., 2009; Sinclair et al., 2014b; 2016; 2017; Zhang et al., 2012)

Table 3.2. Measured parameters, along with parameter definitions and reason for choice. All parameters relate to the kick-leg unless stated.

3.2.5. Statistical analysis

Concurrent validity was assessed using the general linear mixed-model procedure (Proc Mixed) in the Statistical Analysis System (version 9.4, SAS 186 Institute, Cary NC). The model provided estimates of the mean differences between the measurement devices and variability arising separately from the subjects and devices (Paton & Hopkins, 2001). The fixed effects in the model were kick number (five levels, to estimate habituation effects), the interaction with sport (three levels: AF, soccer, rugby), kick type (four levels for each sport: *see table 1*) and device (two levels: IMS and MAS). The random effects, estimated as independent variances and allowing for negative variance, were subject identity (between-subject differences), kick type within subjects (within-subject differences between kick types), kick number within kick type (within-subjects changes between kicks) and residuals for the two devices (pure device measurement error). Variances were converted to standard deviations (SD) for evaluations. The pure device measurement (or root-mean-square error) for each device was derived from fitting a least-squares line to the device's residuals and then finding the square standard deviation of the residuals from the least-squares line (Paton & Hopkins, 2001; Hopkins, 2011; Hopkins et al., 2009, 1999). Studentised residual vs predicted plots were used to assess the systematic bias in the measurement; the distribution (homoscedastic or heteroscedastic trend) indicates the relationship between the measurement error and the magnitude of the measured value (Atkinson & Nevill, 1998). All data showed no obvious non-uniformity of error, therefore all parameters were not log-transformed.

Magnitudes of the effects (mean differences, SD) were evaluated by standardization, which was performed by dividing each effect by the observed between-subject standard deviation free of device error (derived by summing all the between- and within-subject variances). Threshold values for assessing magnitudes of mean differences were 0.20, small; 0.60, moderate; 1.2, large; 2.0, very large (Hopkins et al., 2009). Thresholds for SD were half these values (Smith and Hopkins, 2011). Uncertainty in each effect was expressed as 90% confidence limits and as probabilities that the true effect was substantially positive and negative (derived from standard errors). These probabilities were used to make a qualitative probabilistic non-clinical magnitude-based inference about the true effect (Hopkins et al., 2009): if the probabilities of the effect being substantially positive and negative were both >5%, the effect was reported as unclear; the effect was otherwise clear and reported as the magnitude of the observed value, with the qualitative probability that the true effect was a substantial increase, a substantial decrease, or a trivial. The scale for interpreting the probabilities was: 25–75%, possible; 75–95%, likely; 95–99.5%, very likely; >99.5%, most likely.

3.3. Results

3.3.1. Differences in discrete means

Differences in the means ranged from 0.2–5.8% between the IMS and MAS across all parameters (**Table 3.3**). These differences were classified as *most likely* trivial for all AF and soccer kick parameters and eleven out of twelve rugby code kick parameters. For the remaining parameter, foot speed at BC, a *possibly* small difference (0.2 $m.s^{-1}$, 90% confidence limits: ±0.1 $m.s^{-1}$) was indicated.

Table 3.3 Kinematic means for the MAS and IMS, mean difference between systems (MAS-IMS) with 90% confidence limits (CL) and the magnitude of the inference for each parameter between the MA and IMS system for each sport.

Parameter	Sport	MAS Mean	IMS Mean	Mean difference ± 90% CL
At Ball Contact				
Foot speed (m.s-1)	AF	20.4	20.3	-0.1 ± 0.1; Trivial
	Soccer	17.8	17.8	-0.1 ± 0.1; Trivial
	Rugby	19.7	19.5	-0.2 ± 0.1; Small↓*
Pelvis velocity (m.s-1)	AF	2.39	2.33	-0.06 ± 0.03; Trivial
	Soccer	2.21	2.15	-0.06 ± 0.03; Trivial
	Rugby	1.68	1.67	-0.01 ± 0.03; Trivial
Shank angular velocity (º/s)	AF	1680	1686	6 ± 4; Trivial
	Soccer	1556	1562	8 ± 4; Trivial
	Rugby	1815	1824	8 ± 4; Trivial
Thigh angular velocity (º /s)	AF	196	195	-1 ± 2; Trivial
	Soccer	104	103	-1 ± 2; Trivial
	Rugby	204	200	-5 ± 2; Trivial
Knee angular velocity (º /s)	AF	1369	1371	3 ± 11; Trivial
	Soccer	1295	1309	15 ± 11; Trivial
	Rugby	1412	1428	16 ± 11; Trivial
Shank sagittal angle (º)	AF	-3.0	-4.6	0.9 ± 0.5; Trivial
	Soccer	-24.2	-24.7	0.5 ± 0.5; Trivial
	Rugby	-13.3	-13.4	0.1 ± 0.5; Trivial
Thigh sagittal angle (º)	AF	58	59	0.1 ± 0.5; Trivial
	Soccer	63	63	0.1 ± 0.5; Trivial
	Rugby	61	61	0.1 ± 0.5; Trivial
Pelvis sagittal angle (º)	AF	-21.0	-21.9	0.9 ± 0.7; Trivial
	Soccer	-18.2	-18.3	0.1 ± 0.7; Trivial
	Rugby	-19.7	-20.0	0.3 ± 0.7; Trivial
Trunk sagittal angle (º)	AF	2.0	2.1	0.1 ± 0.3; Trivial
	Soccer	4.5	4.7	0.2 ± 0.6; Trivial
	Rugby	4.9	5.2	0.3 ± 0.8; Trivial

All inferences were clear at 99% and a *most likely* chance the true effect was trivial was found unless stated otherwise.
Symbols denote: ↓ Decrease; * *possible* chance the true effect was substantial.

Table 3.3 *Continued*

Parameter	Sport	MAS Mean	IMS Mean	Mean difference ± 90% CL
Minima & Maxima				
Maximum support-knee extension (º)	AF	13.2	13.4	0.2 ± 0.2; Trivial
	Soccer	18.8	19.2	0.4 ± 0.2; Trivial
	Rugby	18.6	18.7	0.1 ± 0.2; Trivial
Minimum kick-leg knee angle (º)	AF	109	109	0.1 ± 1.1; Trivial
	Soccer	102	104	0.3 ± 1.1; Trivial
	Rugby	107	108	0.2 ± 1.1; Trivial
Maximum hip extension (º)	AF	44.5	43.1	-1.4 ± 0.3; Trivial
	Soccer	49.4	47.9	-1.7 ± 0.3; Trivial
	Rugby	59.9	58.2	-1.5 ± 0.3; Trivial

All inferences were clear at 99% and a *most likely* chance the true effect was trivial was found unless stated otherwise.
Symbols denote: ↓ Decrease; * *possible* chance the true effect was substantial.

3.3.2. Measurement errors

Between-device measurement errors ranged from 0.1-5.8% across all parameters (**Table 3.4**). These errors were classified as *most likely* trivial for ten out of twelve parameters. For the remaining parameters, a *likely* small measurement error between the IMS and MAS was found for maximum support-leg knee extension (0.8°, ±0.3°) and minimum kick-leg knee angle (1.4°, ±1.3°). Within-device measurement errors for the IMS (1.7-15.4%) and MAS (1.5-14.8%) were found to be *most likely* small to moderate for all parameters.

Table 3.4. Observed between-subject SD for standardising, within-subject variance, measurement errors for each system and measurement error between systems (IMS-MAS) (reported as SD), with the magnitude of the inferences indicated. Values reported as raw units ± 90% confidence limits.

Parameter	Between-subject SD	Within-subject SD	MAS measurement error	IMS measurement error	IMS-MAS measurement error
At Ball Contact					
Foot speed (m.s-1)	1.3	0.7 ± 0.1; mod	0.5 ± 0.1; mod	0.6 ± 0.1; mod	0.1 ± 0.1; trivial
Pelvis velocity (m.s-1)	0.52	0.22 ± 0.02; mod	0.12 ± 0.03; small	0.21 ± 0.02; mod	0.09 ± 0.03; trivial
Shank angular velocity (°/s)	180	84 ± 5; mod	26 ± 6; small	27 ± 5.1; small	2 ± 8; trivial
Thigh angular velocity (°/s)	60	43 ± 2; mod	10 ± 3; small	15.9 ± 2.1; small	6 ± 4; trivial
Knee angular velocity (°/s)	200	104 ± 7; mod	60 ± 7; small	74 ± 7; small	14 ± 10; trivial
Shank sagittal angle (°)	9.5	4.7 ± 0.3; mod	2.5 ± 0.4; mod	3.1 ± 0.3; mod	0.7 ± 0.5; trivial
Thigh sagittal angle (°)	7.4	3.5 ± 0.3; mod	2.8 ± 0.4; mod	2.9 ± 0.2; mod	0.2 ± 0.3; trivial
Pelvis sagittal angle (°)	7.8	2.8 ± 0.2; mod	2.1 ± 0.3; small	2.7 ± 0.3; mod	0.6 ± 0.5; trivial
Trunk sagittal angle (°)	6.4	1.1 ± 0.2; mod	0.6 ± 0.2; small	0.7 ± 0.2; mod	0.2 ± 0.3; trivial
Minima & Maxima					
Maximum support-knee extension (°)	5.1	2.1 ± 0.1; mod	1.1 ± 0.3; small	1.9 ± 0.2; mod	0.8 ± 0.3; small ↑**
Minimum kick-leg knee angle (°)	10.2	4.2 ± 0.2; mod	3.4 ± 1.1; mod	4.8 ± 0.8; mod	1.4 ± 1.2; small ↑**
Maximum hip extension (°)	9.6	2.7 ± 0.2 small	1.6 ± 0.3; small	2.1 ± 0.2; small	0.5 ± 0.4; trivial

All inferences were clear at 99% and a *most likely* chance the true effect was substantial or trivial was found unless stated otherwise.
Symbols denote: ↑ Increase; ** *likely* chance the true effect was substantial. **mod:** Moderate

3.3.4 Systematic bias

Minimal heteroscedasticity was found in pelvis angle at BC, maximum support-leg knee extension and minimum kick-leg knee flexion residuals (**Figure 3.2**). There was a tendency for foot speed, pelvis velocity, shank, thigh and knee angular velocity at BC to display positive skewness with increasing linear and angular velocity. Similar trends were found in MAS data (**Figure 3.3**).

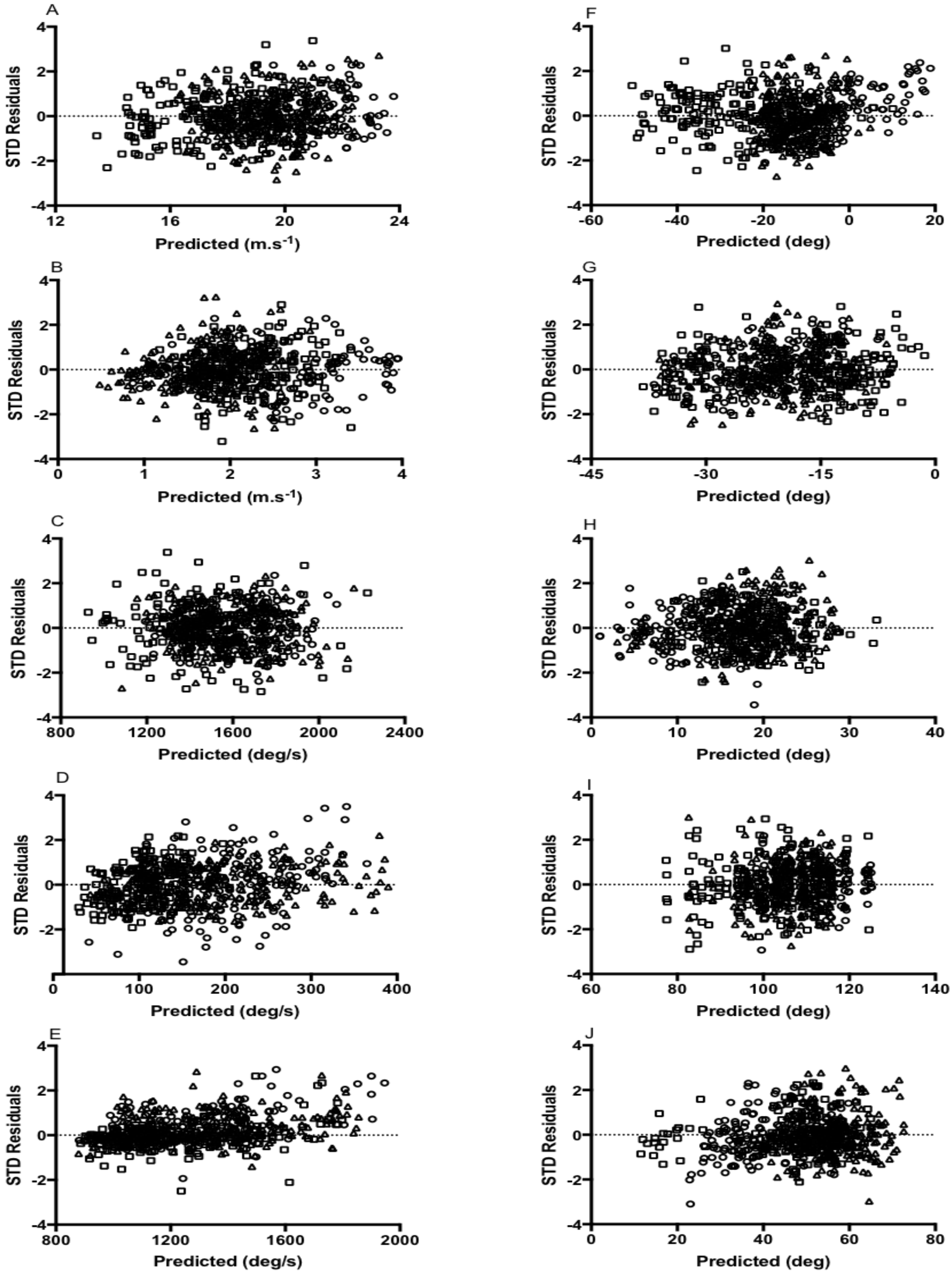


Figure 3.2. Studentised (**STD**) residuals vs predicted plots for each variable for the IMS; a) foot speed at BC, b) pelvis velocity at BC, c) shank angular velocity at BC, d) thigh angular velocity at BC, e) knee angular velocity at BC, f) shank sagittal angle at BC, g) pelvis sagittal angle at BC, h) maximum support-leg knee extension, i) minimum kick-leg knee angle, (j) maximum hip extension. The distribution (normal, positive skewness or negative skewness indicates the relationship between the measurement error and magnitude of the measured value. Symbols denote: ○ AF; □ Soccer; △ Rugby.

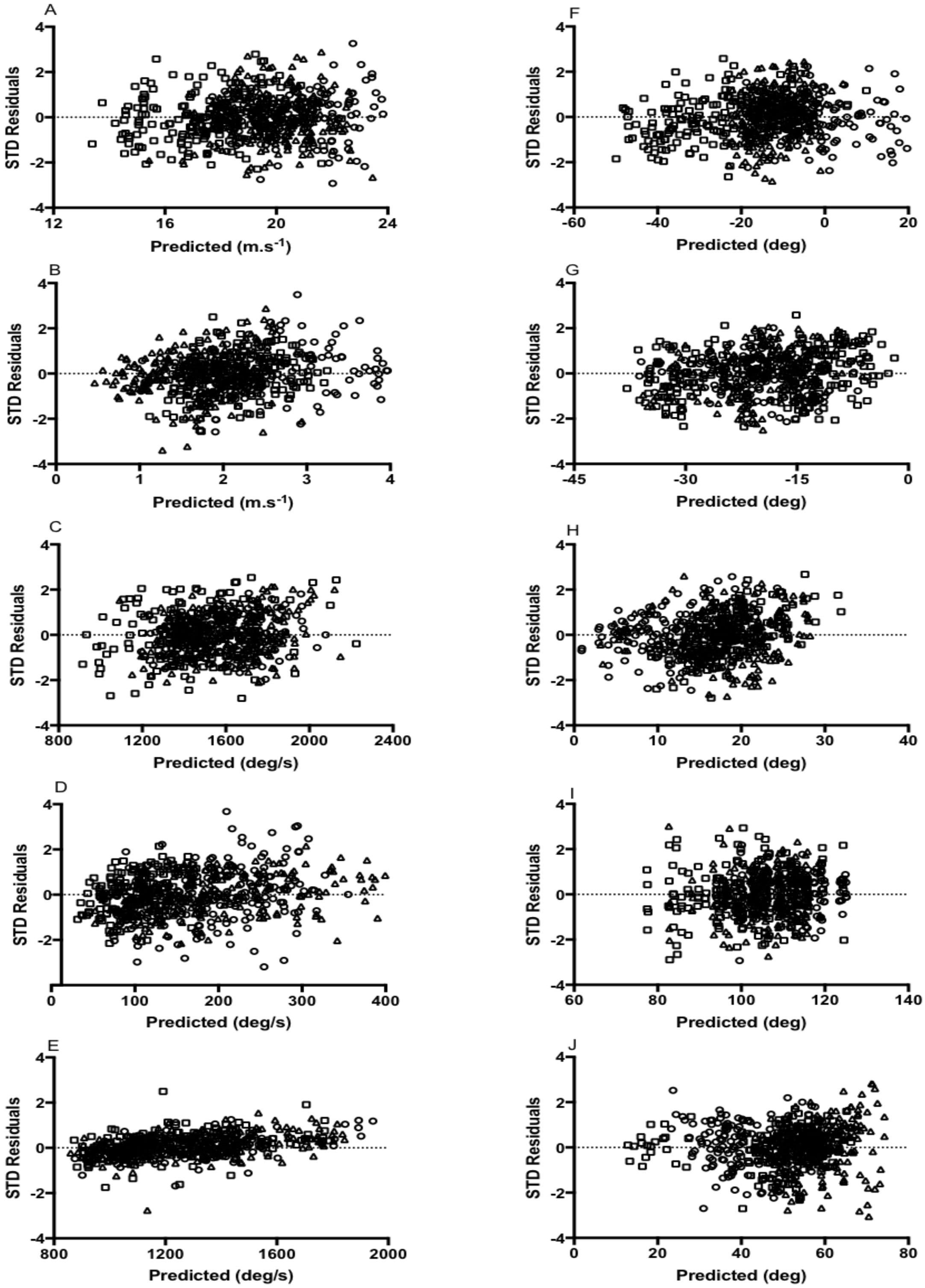


Figure 3.3. Studentised (**STD**) residuals vs predicted plots for each variable for the MAS; a) foot speed at BC, b) pelvis velocity at BC, c) shank angular velocity at BC, d) thigh angular velocity at BC, e) knee angular velocity at BC, f) shank sagittal angle at BC, g) pelvis sagittal angle at BC, h) maximum support-leg knee extension, i) minimum kick-leg knee angle, (j) maximum hip extension. The distribution (normal, positive skewness or negative skewness indicates the relationship between the measurement error and magnitude of the measured value. Symbols denote: ○ AF; □ Soccer; △ Rugby.

3.4. Discussion

The purpose of this study was to investigate the concurrent validity of joint and segment kinematics measured by a IMS compared to a MAS during kicking in AF, soccer and the rugby codes. Findings demonstrated that the IMS had good concurrent validity compared to a MAS for measuring kicking biomechanics across the four football codes.

The IMS and MAS produced similar results when measuring kicking kinematics in AF, soccer and the rugby codes. These findings are comparable to previous work comparing IMS and MAS when measuring sagittal ankle, knee and hip joint kinematics during walking (Picerno et al., 2009: 0.5 - 2.9°, CMC > 0.94; Zhang et al., 2013: 1.8-6.7°, CMC > 0.96) and running (Cooper et al., 2009: 0.1- 4.5°, CMC > 0.94; Ferrari et al., 2010: CMC > 0.91). As trivial differences were found in all parameters in AF and soccer, and nine out of ten for the rugby codes, this indicated the IMS performed similarly across the football codes. The *possibly* small difference found in foot speed at BC (-0.2 ± 0.1 $m.s^{-1}$) in the rugby codes is within ranges previously reported in rugby literature (< 3.2 $m.s^{-1}$; Ball, 2010; Sinclair et al., 2017), indicating the IMS would derive similar results to previous research. This indicates that either system would perform similarly for all parameters measured in this study. As these parameters are commonly used in football research to assess kicking performance, the IMS could be used as alternative measurement tool to other MAS to measure kicking biomechanics.

Despite reporting small to moderate measurement errors within the IMS data (1.7-15.4%), the magnitude of error is comparable to the error present within MAS data (1.5-14.8%). Trivial to small differences (0.1 - 5.8%) were found between the systems, across all parameters, which is similar previous findings in walking and running (RMSE: Cooper et al., 2009: 0.7 - 3.4°; Ferrari et al., 2010: 0.6 - 5.2°; Picerno et al., 2008: 0.8 -

3.6°; Zhang et al., 2013: 1.8 - 2.4°). Measurement errors in the IMS arise from magnetic distortions caused by ferromagnetic objects in the testing area (Robert-Lachaine et al., 2017). Conversely, the performance of the MAS is dependent on various sources; occlusion, electronic noise, calibration, optoelectronic distortions and the digitizing process (Chiari et al., 2005; Windolf, 2008). In MAS data, measurement error is compensated by filtering positional data (Chiari et al., 2005). Further exploration of data filtering procedures may help reduce the measurement errors in IMS data. However, despite both systems producing measurement error from different sources, the magnitude of errors between systems were comparable, indicating the IMS had good concurrent validity to the MAS.

The level of measurement error was similar between the IMS and MAS, with trivial measurement errors reported in ten parameters. For the remaining parameters, *likely* small measurement errors were found between systems, however the level of error across these parameters is smaller than previously reported differences in the kicking literature (**Table 3.5**). In the majority of cases, the difference between groups and tasks exceeded the possible error in the IMS measurement, suggesting either system could be used with confidence to derive similar results when measuring kicking biomechanics.

Table 3.5. Comparison of device measurement error between the IMS and MA system in relation to group-based differences reported in the literature across the football codes.

	N	Group comparison	Kick Type	Max SL knee flexion (°)	Min KL knee angle (°)
Measurement error				*0.8 ± 0.3*	*1.4 ± 1.4*
AF					
Ball et al., 2013	7	Preferred vs non-preferred	Punt	49 vs 49	
Coventry et al., 2015	8	No fatigue vs fatigue	Punt		116 vs 122+
Dicheria et al., 2006	1	Accurate vs inaccurate	Punt	36 vs 24+	80 vs 90+
Soccer					
Sinclair et al., 2014	3	Preferred vs non-preferred	Instep	47 vs 44+	99 vs 100+
Kellis et al., 2005	1	No fatigue vs fatigue	Instep		130 vs 133+
Rugby codes					
Baktash et al., 2009	3	Different foot positions	Place		95 vs 105+
Sinclair et al., 2017	1	Accurate vs maximal	Place	40 vs 45+	110 vs 100+

Max: Maximum; **Min**: Minimum; **SL**: Support-leg; **KL**: Kick Leg
+ Denotes when difference in literature group comparison exceeds measurement error between the IMS and MAS

Systematic bias was found in the IMS and MAS, with both systems responding similarly with increasing linear and angular velocities. This has also been found during walking and running (Cooper et al., 2009; Ferrari et al., 2010), where the error in the measurement increased from 0.6 to 5.0° with increasing gait speed. Higher measurement error was also found in segments, such as the shank, that experienced higher movement velocities (up to 1615 °/s), compared to segments, such as the thigh that undergo slower velocities (up to 204 °/s) during the kicking action. This has been attributed to the Kalman filter's inability to converge a solution at faster speeds (Ferrari et al., 2010; Schall et al., 2015), leading to greater instability in the output at higher speeds. In the MAS high-velocity movements are more susceptible soft-tissue motion artefacts (Chiari et al., 2005), resulting in higher error in the measurement. However, the magnitude of systematic bias was similar between systems indicating both systems produce similar results at faster kicking speeds. Future research should consider exploring if different filter cut-off frequencies could account for this systematic bias.

This study builds upon current validations of IMS, indicating these systems maintain good concurrent validity when measuring at higher velocities. Trivial differences between the IMS and MAS where found when measuring up to linear velocities of 20 $m.s^{-1}$ and angular velocities of 1815 °/s. Findings from this research may be generalisable across other movement tasks were high-velocity movements exist, such as sprinting (knee angular velocities (flexion/extension) of up to 1400 °/s: Slawinski et al., 2010), supporting the use of IMS in other biomechanical research applications outside of kicking tasks. Future research is warranted to explore the validity of IMS in quantifying movements that involve long axis rotations, such as during throwing (Humeral angular velocities of up to 1600 °/s reported: Seroyer et al., 2010), to extend the applications of IMS.

The IMS offers various benefits over camera-based MAS, such as, quick set-up and data output, out-of-laboratory testing, high portability and larger measurement range. This will facilitate more assessments of movements in an applied context to improve the ecological validity of biomechanical testing. With the added advantage of gaining real-time feedback, IMS could be used by practitioners and applied sport scientists to support the timing of feedback in the coaching environment (Phillips et al., 2013). For football research, IMS will help advance the current body of knowledge in football kicking by facilitating more in-field studies to examine kicking across a wider range of contexts (Nunome et al., 2017). However, the use of IMS in competitive team-sport is currently limited to the training environment. Vision-based systems may still offer an analogous solution to providing gross movement analysis of kicking during game-play. This study chose to validate important discrete technical parameters associated with kicking performance. Further research is warranted to assess the ability of IMS for measuring continuous time-series parameters to ensure the IMS is valid in the quantification of segment and joint co-ordination.

3.5. Conclusion

The findings indicated good concurrent validity between the IMS and MAS, with small to trivial differences reported between kinematic means, when measuring kicking kinematics in Australia football, soccer and the rugby codes. Low levels of measurement error between the IMS and MAS lay inside many ranges reported across the kicking literature, suggesting the same results would have emerged if the IMS were utilised. This study builds upon current validations of IMS, indicating these systems maintain good validity when measuring at higher velocities. The results of this study advocate the use of IMS to measure kinematics of high-velocity movements in sport-specific settings.

3.6. Contribution of Chapter to the Aims of the Thesis

The specific aim of Chapter 3 was to examine the concurrent validity of an IMS in quantifying discrete joint and segment kinematics in comparison to a MAS during different kicking tasks. The findings of Chapter 3 contribute to answering the first main aim of this thesis, indicating that the Xsens IMS demonstrates acceptable levels of validity when measuring discrete kicking biomechanics in AF. Further examination of continuous time-series parameters is warranted to ensure the IMS is valid in the quantification of segment and joint range of movement, which will be explored in Chapter 4.

Chapter 4: Concurrent Validation of an Inertial Measurement System to Quantify Lower Extremity Times-Series Profiles Kicking Kinematic in Australian Football

4.1. Introduction

Determining the validity of time-series profiles measured by the Xsens IMS would extend the findings in Chapter 3, to provide a more comprehensive validation of the Xsens IMS for the measurement of kicking biomechanics. Currently, the segmental actions (eg: greater knee range of movement (ROM); 120º flexion/extension, 22º abduction/ adduction, 24º internal/external rotation; Ball, 2008; Kellis & Katis, 2007; Shan & Westerhoff, 2005; Sinclair et al., 2017) during kicking differ from any of the tasks previously validated (Al-Amri et al., 2018; Ferrari et al., 2010; Kim & Nussbaum, 2013; Kruger & Edelmann-Nusser, 2009, 2010; Lu & Zhang et al., 2014; Marreiro et al., 2017 Picerno et al., 2008; Robert-Lachaine et al., 2017; Zhang et al., 2013), requiring an additional validation of these parameters. As lower extremity joint and segment ROM has been identified as important to kicking performance across the football codes (Baker & Ball, 1996; Button et al., 2005; Dicheria et al., 2006; Lees & Nolan, 2002; Peacock & Ball, 2018a, 2017), validation is also warranted to ensure the IMS can adequately measure the full movement of the joints experienced during kicking. Therefore, the aim of this Chapter was to extend the previous validation and examine the concurrent validity of an IMS for quantifying lower extremity joint time-series profiles in comparison to a MAS during kicking in AF.

4.2. Methodology

4.2.1. Participants

Ten male amateur AF players (age: 21.1 ± 3.5 yrs; height: 182.0 ± 5.2 cm; mass: 82.3 ± 6.1 kg) volunteered to participate in this research. All participants were competing regularly in competition and had no lower extremity injuries in the previous six months. Ethical approval (HRE17-046) was granted from the corresponding University Human Research Ethics Committee and all participants provided written informed consent.

4.2.2. Experimental set-up and protocol

The equipment and testing procedure were consistent with the methodology section in Chapter 3 (see **Methodology, section 3.2.2** and **3.2.3**, *pp. 68 - 71*).

4.2.3. Data analysis

Data analysis and modelling procedures for the MAS and IMS data were consistent with the data analysis section in Chapter 3 (see **Methodology, section 3.2.4**, *pp. 71 - 75*). However only the AF data was utilised in this chapter.

Joint and segment kick-leg angles were chosen based on technical parameters identified important for in kicking in AF (Ball, 2011, 2013; Coventry et al., 2013). For both systems, ankle, knee and hip joint angles were calculated as anatomical angles; with the ankle measured as the angle between the foot and shank, the knee measured as the angle between the thigh and shank and the pelvis used as the coordinate systems for the hip. Pelvis angles were calculated in relation to the global axis.

4.2.4. Statistical analysis

Concurrent validity was assessed using the general linear mixed-model procedure (Proc Mixed) in the Statistical Analysis System (version 9.4, SAS 186 Institute, Cary NC) to provide estimates of the mean signal differences (overall and throughout the signal) between the measurement devices (throughout the signal) and variability arising separately from the subjects and devices (Paton & Hopkins, 2001). The fixed effects in the model were kick number (five levels, to estimate habituation effects), kick type (four levels for: 20_punt, 40_punt, max_punt, run_punt) and device (two levels: IMS and MAS). The random effects, estimated as independent variances and allowing for negative variance, were subject identity (between-subject SD), kick type within-subjects (within-subject differences between kick types), kick number within kick type (within-subjects changes between kicks) and residuals for the two devices (pure device measurement error). The pure device measurement (or root-mean-square error) for each device was derived from fitting a least-squares line to the device's residuals and then finding the square standard deviation of the residuals from the least-squares line (Paton & Hopkins, 2001; Hopkins, 2011; Hopkins et al., 2009, 1999). To facilitate a continuous signal analysis, signals were time-normalised from 0% (kick-foot toe-off) to 100% (the instance before BC) (101 data points) and the signals were analysed by averaging 3% time-signal sections. Changes in kinematics means throughout the signals were compared for each of these 3 % time segments between the IMS and MAS. Variances were converted to SD for evaluation. All data showed no obvious non-uniformity of error, therefore all parameters were not log-transformed.

Magnitudes of the effects (mean differences, SD) were evaluated by standardisation, which was performed by dividing each effect by the observed between-subject standard deviation free of device error (derived by summing all the between- and within-subject variances). Threshold values for assessing magnitudes of mean differences were 0.20, small; 0.60, moderate; 1.2, large; 2.0, very large (Hopkins et al., 2009). Thresholds for SD were half these values (Smith & Hopkins, 2011). Uncertainty in each effect was expressed as 90% confidence limits and as probabilities that the true effect was substantially positive and negative. These probabilities were used to make a qualitative probabilistic non-clinical magnitude-based inference about the true effect: if the probabilities of the effect being substantially positive and negative were both >5%, the effect was reported as unclear; the effect was otherwise clear and reported as the magnitude of the observed value, with the qualitative probability that the true effect was a substantial increase, a substantial decrease, or trivial. The scale for interpreting the probabilities was: 25–75%, possible; 75–95%, likely; 95–99.5%, very likely; >99.5%, most likely.

4.3. Results

4.3.1. Differences in time-series signal means

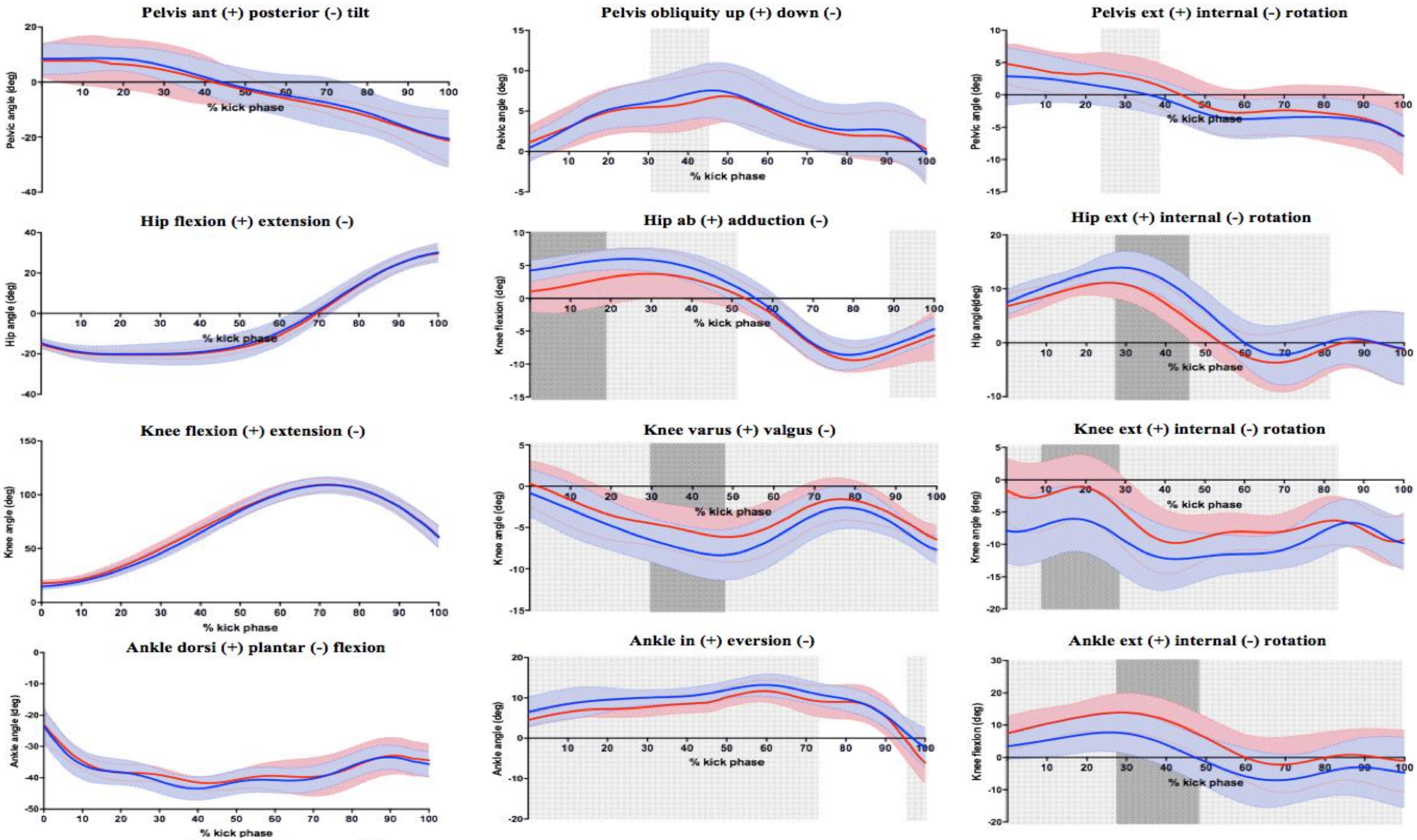
Overall mean differences ranged from 0.1 - 10.1% between the IMS and MAS across all parameters (**Table 4.1**). These differences were classified as *most likely* trivial for six out of twelve parameters. For the remaining parameters, a *possibly* small difference was indicated for ankle inversion-eversion (1.8°, 90% confidence limits: ± 0.7°), a *likely* small difference was indicated for hip abduction-adduction (1.4°, 90% confidence limits: ± 1.0°) and a *most likely* small difference was indicated for knee valgus-varus (-1.9°, 90% confidence limits: ± 0.5°) and knee internal-external rotation (3.9°, 90% confidence limits: ± 0.9°), hip internal-external rotation (2.1°, 90% confidence limits: ± 1.3°) and ankle internal-external rotation (supination-pronation) (4.5°, 90% confidence limits: ± 1.3°) was indicated. Additionally, *most likely* trivial differences were reported throughout the kick phase for all sagittal plane kinematics, while for frontal and transverse plane kinematics, differences between IMS and MAS measurement ranged from *most likely* trivial to *likely* moderate (**Figure 4.1**).

Table 4.1. Mean difference between systems (MAS-IMS) averaged across the signal, with 90% confidence limits (CL) and the magnitude of the inference for each parameter between the MA and IMS system reported for each parameter.

Joint/ Segment	Axis	Movement	Mean difference, ± 90% CL
Pelvis	X	Posterior – anterior tilt (º)	1.0 ± 0.4; Trivial
	Y	Pelvic obliquity (up – down) (º)	1.3 ± 0.6; Trivial
	Z	Internal – external rotation (º)	1.2 ± 0.5; Trivial
Hip	X	Flexion – extension (º)	0.6 ± 0.4; Trivial
	Y	Abduction – adduction (º)	1.4 ± 1.0; Small↑**
	Z	Internal – external rotation (º)	2.1 ± 1.3; Small↑
Knee	X	Flexion – extension (º)	-1.2 ± 1.4; Trivial
	Y	Valgus – varus (º)	-1.9 ± 0.5; Small↓
	Z	Internal – external rotation (º)	3.9 ± 0.9; Small↑
Ankle	X	Dorsiflexion – plantarflexion (º)	0.9 ± 0.5; Trivial
	Y	Inversion – eversion (º)	1.8 ± 0.7; Small↑*
	Z	Internal – external rotation (º)	4.5 ± 1.3; Small↑

All inferences were clear at 99% and a *most likely* chance the true effect was substantial or trivial was found unless stated otherwise. Symbols denote: ↓ ↑ Increase; * *possibly* ** *likely* chance or *** *very likely* the true effect was substantial.

Figure 4.1. Mean ±SD times-series data for the pelvis, hip, knee and ankle angles for the IMS (red) and MAS (Blue).



***Shading denotes:** ☐ trivial, ☐ small or ▩ moderate difference between IMS and MAS measurement during the kick phase.

4.3.2. Measurement errors

Between-device measurement errors ranged from 0.2 – 7.9% across all parameters (**Table 4.2**). These errors were classified as *likely to most likely* trivial for nine parameters. For the remaining parameters, the measurement error between the IMS and MAS was found to *likely* small for knee valgus-varus (Y) (1.3°, ± 0.5°) and a *most likely* small for knee (2.9°, ± 0.3°) and hip (Z) (1.8°, ± 0.7°) internal rotation. Within-device measurement errors for the IMS (1.2 - 14.9%) and MAS (1.5 - 20.6 %) were found to be *most likely* small to moderate for all parameters.

Table 4.2. Average observed between-subject SD for standardising, within-subject variance, average measurement errors for each system and measurement error between systems (IMS-MAS) (reported as SD), with the magnitude of the inferences indicated. Values reported as raw units ± 90% confidence limits.

Joint/ Segment	Axis	Movement	Between-subject SD	Within-subject SD	MAS measurement error	IMS measurement error	IMS-MAS measurement error
Pelvis	X	Posterior – anterior tilt (º)	8.9	3.2 ± 0.2; mod	1.4 ± 0.3; small	2.3 ± 0.3; small	0.8 ± 0.3; trivial
	Y	Pelvic obliquity (up – down) (º)	9.4	4.1 ± 0.3; mod	1.2 ± 0.5; small	2.3 ± 0.3; small	0.9 ± 0.4; trivial***
	Z	Internal – external rotation (º)	11.0	3.1 ± 0.3; mod	1.5 ± 0.3; small	2.7 ± 0.6; small	1.2 ± 0.7; trivial***
Hip	X	Flexion – extension (º)	10.2	3.4 ± 0.4; mod	2.4 ± 0.3; small	2.9 ± 2.9; small	0.5 ± 0.5; trivial
	Y	Abduction – adduction (º)	10.4	4.6 ± 0.3; mod	1.6 ± 0.6; small	2.8 ± 0.3; small	1.2 ± 0.3 trivial***
	Z	Internal – external rotation (º)	11.0	4.1 ± 0.3; mod	2.4 ± 0.3; mod	4.2 ± 0.3; mod	1.8 ± 0.7; small↑
Knee	X	Flexion – extension (º)	8.2	2.9 ± 0.2; mod	1.7 ± 0.2; mod	2.7 ± 0.2; mod	1.0 ± 0.3; small**
	Y	Valgus – varus (º)	10.6	4.7 ± 0.3; mod	1.1 ± 0.5; small	2.4 ± 0.5; mod	1.3 ± 0.5; small↑**
	Z	Internal – external rotation (º)	15.5	4.9 ± 0.3; mod	1.3 ± 0.3; small	4.0 ± 3.7; mod	2.9 ± 0.3; small↑
Ankle	X	Dorsiflexion – plantarflexion (º)	10.7	4.8 ± 0.3; mod	1.8 ± 0.4; small	2.2 ± 0.3; small	0.4 ± 0.5; trivial**
	Y	Inversion – eversion (º)	6.5	3.2 ± 0.2; mod	1.9 ± 0.5; mod	2.3 ± 0.2; mod	0.4 ± 0.6; trivial***
	Z	Internal – external rotation (º)	10.9	4.7 ± 0.3; mod	1.9 ± 0.4; mod	3.0 ± 0.2; mod	1.1 ± 0.5; trivial

All inferences were clear at 99% and a *most likely* chance the true effect was substantial or trivial was found unless stated otherwise.
Symbols denote: ↓ Decrease, ↑ Increase; ** *likely* chance or *** *very likely* the true effect was substantial. **mod:** Moderate

4.4. Discussion

The purpose of this study was to extend our validation of discrete parameters in Chapter 3 and investigate the concurrent validity of time-series profiles of lower extremity kinematics measured by an IMS compared to a MAS during kicking. Good concurrent validity was found between the IMS compared to a MAS when measuring time-series kicking kinematics in AF, supporting the findings for discrete parameters in kicking (Blair et al., 2018).

The IMS demonstrated good validity (0.1 - 10.1% mean difference) in quantifying time-series profiles for the ankle, knee, hip and pelvis during kicking compared to the MAS. These findings are comparable to previous work comparing the IMS and MAS when measuring continuous lower extremity data during walking (Al-Armi et al., 0.2 – 4.5°, CMC > 0.90; Picerno et al., 2009: 0.5 – 8.3°, CMC > 0.94; Ferrari et al., 2010: CMC>0.91; Zhang et al., 2013: 0.1 – 5.7°, CMC > 0.71) and running (Cooper et al., 2009: 0.1 – 4.5°, CMC > 0.94; Marrerio et al., 2017; r =0.49 – 0.99). Sagittal plane kinematics demonstrated the lowest differences mean differences (0.5 – 1.2º) across each joint, supporting previous findings (Ferrari et al., 2010; Kim & Nussbaum, 2013; Li & Zhang et al., 2014; Marreiro et al., 2017; Picerno et al., 2008; Robert-Lachaine et al., 2017; Zhang et al., 2013). Mean differences between the IMS and MAS were found to increase when measuring ankle, knee and hip frontal (Y) and transverse plane (Z) (0.4 – 4.5º), which has also been found by Ferrari et al. (2010), Al-Amri et al. (2018) and Lu & Zhang et al. 2014. This disparity has been attributed to differences in the anatomical frames and kinematical constraints of the IMS and MAS biomechanical model (Li & Zhang et al., 2014; Marreiro et al., 2017; Robert-Lachaine et al., 2017; Zhang et al., 2013). Additionally, the assumption of defined joint angles during the static calibration of IMS has also been identified to influence the difference in measured joint angles compared to the MAS (Marreiro et al., 2017; Robert-Lachaine et al., 2017). Further investigation of the differences between the two models and the assumptions made by the IMS could be used to minimise these difference in the measured joint angles.

The magnitude of mean differences between IMS and MAS measurement differed at various phases throughout the kick (**Figure 4.1**), which was more apparent in frontal and transverse kinematic time-series profiles. This is also evident in other validations of the IMS (Al-Amari et al., 2018; Ferrari et al., 2010) in time-series signals, however it was not quantified or discussed. Typically, higher mean differences occur within the first half of the kicking phase (30 - 50%) across all joint/ axis. For the frontal and transverse kinematics, this higher mean difference between the IMS and MAS typically occurs around maximum values, where the IMS is underestimating the size of the angle. One possible reason could be related to the biomechanical constraints of the model in these axis (Marreiro et al., 2017; Robert-Lachaine et al., 2017). However, this is not evident during maximum values in the sagittal plane kinematics, thereby, future research is warranted to further examine changes in IMS and MAS outputs throughout the signal.

Interestingly, pelvis kinematics demonstrated the lowest mean differences between the IMS and MAS across each axis compared to the other joints, supporting Ferrari et al. (2010) findings (CMC > 0.92). Whilst the authors made no comment on this, it could be potentially related to the lower movement ranges experienced in this segment compared to the other joints. It could also be due to the calculation of pelvis kinematics in relation to a global (fixed) reference, rather than using an angle between to segments. As a result, the measurement is only influenced by movement around one segments axis (pelvis) rather than taking into consideration the anatomical frames and kinematical constraints from a proximal segment. This suggests the IMS may also perform better when measuring segment kinematics, however further work is warranted to support this assertion.

Trivial to small measurement errors were found between the IMS and MAS (0.1 – 7.9%), across all parameters, supporting previous findings in kicking when measuring discrete kinematics (0.1 - 5.8%: Blair et al., 2018), walking (RMSE: 0.8 – 10.0º: Al-Amri et al., 2018; Ferrari et al., 2010; Li & Zhang et al., 2014; Picerno et al., 2008; Zhang et al., 2013) and running (RMSE: 0.6 – 11.94° Ferrari et al., 2010; Picerno et al., 2008; Marreiro et al., 2017) when measuring continuous time-series profiles. The level of measurement error between the IMS and MAS was similar (trivial differences) for eight parameters. For the remaining parameters, *likely to most likely* small measurement errors were found between systems. However, the level of error across these parameters (< 2.8º) is smaller than previously reported differences between groups (*accurate vs inaccurate*: >º Dicheria et al., 2006; *fatigue vs non-fatigue*: Coventry et al., 2015:) and tasks (*preferred vs non-preferred*: Ball et al., 2011; Falloon et al., 2013:) in the kicking literature, indicating that the IMS could be used with confidence to derive similar results when measuring kicking kinematics in AF. Additionally, this level of error found in this study has been reported acceptable across other movement tasks in the literature (Al-Amri et al., 2018; Cuesta-Vargas et al., 2010; Ferrari et al., 2010; Kruger & Edelmann-Nusser, 2009, 2010; Lu & Zhang et al., 2014; Marreiro et al., 2017; Picerno et al., 2008; Robert-Lachaine et al., 2017; Zhang et al., 2013).

This study builds upon current validations of IMS, indicating these systems maintain good concurrent validity when measuring continuous data during high-speed movements that undergo larger ROM. Findings from this research may be generalisable across other skilled movements where large joint ROM exist, such as sprinting (knee ROM up to: 104º: Kivi et al., 2002), supporting the use of IMS in other biomechanical research applications outside of kicking tasks validated in this research. Typically, IMS have been tested under controlled scenarios, where participants experience no external high-impact contacts. Future work is warranted to assess the validity of data when players are exposed to external contacts, such as during ball impact or during tackling. Determining the validity of the IMS under these scenarios could be used to further examine the technical aspects which influence performance (such as, foot motion through impact) (Peacock et al., 2018a; Peacock et al., 2018b).

4.5. Conclusion

Findings indicated good concurrent validity was indicated between the IMS and MAS, with trivial to small differences reported between time-series profiles (0.1 - 10.1%) and low levels of measurement error (0.2 - 7.9%), when measuring kicking kinematics in AF. Sagittal plane kinematics demonstrated the lowest means differences (0.1- 3.5%) between the IMS and MAS compared to frontal (3.8 - 8.7%) and transverse (4.6 - 10.1%) kinematics. Additionally, the IMS performed better across each axis when measuring a segment angle (pelvis) compared to ankle, knee and hip joint angles.

4.6. Contribution of Chapter to the Aims of the Thesis

The aim of Chapter 4 was to examine the concurrent validity of the Xsens IMS system in quantifying lower extremity joint time-series profiles in comparison to a MAS. This study builds upon the previous validation in Chapter 3 moving from discrete to time-series (continuous) measures, which are increasingly becoming more relevant for biomechanical studies (Knudson, 2017; Pataky et al., 2013). The IMS demonstrated good levels of validity when measuring time-series kinematics during kicking, with 6 of 12 parameters reporting trivial differences between the IMS and MAS. For the remaining parameters, a small difference was found between the IMS and MAS. Findings from Chapter 3 and 4 address the first main aim of this thesis, indicating that the Xsens IMS demonstrates good levels of validity when measuring kicking biomechanics in Australian Football. Further discussion of the application and implications of the findings from these can be found in Chapter 8 (see **Section 8.1**, *pp 181 - 186*). The results from Chapters 3 and 4 supported the use of the Xsens IMS in the kicking experimental Chapters (5, 6 and 7), to measure the key discrete and continuous technical parameters identified in the deterministic model in Chapter 2 (see **Section 2.2.3**, **Figure 2.4,** *pp. 25*).

Chapter 5: Alterations in Goal-Kicking Technique with Varying Kick Location on the Pitch

This chapter is adapted from and supported by two peer-reviewed proceedings from the 36th International Society of Biomechanics in Sport Conference, New Zealand: Blair, S., Robertson, S., Duthie, G. & Ball, K. (2018). The effect of altering distance on goal-kicking technique in Australian Football. Ball, K. & Blair, S. (2018). Shot success and kinematic differences with altering kicking angle on goal-kicking technique in Australian football.

5.1. Introduction

During competitive AF matches, goal-kicks are executed from various locations, which can influence the perceived difficulty of scoring a goal (Anderson et al., 2018; Galbraith & Lockwood, 2010). A statistical analysis of 198 matches during the 2012 Australian Football league season (Anderson et al., 2018) reported a significant ($p < 0.001$) decrease in goal-kicking accuracy with increasing the distance (30 m to 40 m: 87% to 67%) and the angle away from the goals (0˚ to 30˚: 87% to 46%). This has been partly attributed to a reduction in the relative width of the goal-line (scoring angle of opportunity) available to players from the different positions (Galbraith & Lockwood, 2010) (**Table 5.1**). However, the authors solely focused on task difficulty, and suggested further work was warranted to explore if changes in goal-kicking technique occur, to help further explain changes in accuracy (Anderson et al., 2018). Additionally, the need to investigate changes in goal-kicking technique with varying task position has been highlighted in the kicking literature (Bezodis et al., 2018).

Table 5.1. Changes in angle of opportunity and relative width of the goal-line from different positions in-front of goals. Calculations taken from Galbraith & Lockwood (2010).

Position from goal posts (distance, angle)	Relative width of the goal-line	Angle of opportunity
30 m, 0°	6.40 m	13.20°
40 m, 0°	6.33 m	9.15°
50 m, 0°	6.28 m	6.38°
30 m, 10°	6.39 m	12.18°
30 m, 45°	6.35 m	10.15°
30 m, 55°	6.27 m	6.32°

Technical differences in punt kicking have been reported when kicking over different distances (40 m vs 50 m) in AF (Baker & Ball, 1996). Longer kicks were reported to have significantly greater kick-leg knee extension (69 vs 64º; $p < 0.05$) and peak kick-leg thigh angular velocity (973 vs 907 º/s; $p < 0.05$) during forward swing, with greater knee angular velocity (1554 vs 1390 º /s; $p < 0.05$) and foot momentum (20.7 vs 17.3 kg.m/s; $p < 0.05$) at ball contact (BC). Foot speed prior to impact has been widely reported across the kicking literature as the most important contributor to increasing ball speed, and consequently kick distance (Ball, 2008, 2013; De Witt et al., 2012; Kellis & Katis, 2007; Peacock & Ball, 2018b; Peacock et al., 2017; Lees et al., 2010; Sinclair et al., 2014; Zhang et al., 2012). These studies determined the relationship between foot speed and distance without imposing an accuracy constraint on players. When kicking for goal, the ball is often required to travel over considerable distances (ranging from 10 - 50 m), whilst maintaining a sufficiently accurate ball flight trajectory towards the goals, in order to achieve a successful outcome (Bezodis et al., 2018). Kicking accurately over different distances has not yet been examined, however, given the importance of accuracy in goal-kicking, research is warranted to examine the link between distance and accurate goal-kicking.

Technical adjustments with a reduction in target size have been reported in soccer. During soccer instep kicking (n = 5 experienced soccer players), when the size of the target was reduced from 4 x 3 m to 0.4 x 0.4 m (Texieria et al., 1999), players demonstrated lower ankle velocities at BC (2.5 $m.s^{-1}$, $p < 0.05$). The authors suggested that as the difficulty of a task increases (target size reduced), a reduction in movement speed is needed in order to control and regulate the kicking action prior to impact, to improve the accuracy of the kick. When kicking at an angle towards the goal-posts, there is a reduction in relative width of the goals (smaller target), which may require similar technical adjustments as reported by Texieria et al. (1999), however research is needed to provide experimental data to appraise this.

No studies have examined the effect of different task constraints (distance and angle to the goal-posts) on the execution of the goal-kicking skill, yet understanding if a player varies their technique over several positions is an important area to address (Bezodis et al., 2018). Therefore, the aims of this study were (1) to determine if changing position influences goal-kicking success and (2) to determine if differences exist in accurate goal-kicking kinematics with altering kicking position (angle and distance) in Australian Football.

5.2. Methodology

5.2.1. Participants

Eighteen male AF players (age: 17.0 ± 0.8 yrs; height: 183.2 ± 4.6 cm; mass: 70.1 ± 6.8 kg) volunteered and provided written informed consent to participate in this research. Players ranged from elite (AFL Academy squad), to club and school pooled from first grade teams representing an elite and sub-elite cohort (Appendix B). Players were chosen based on game demands (players that regularly perform set-shots) and had no lower extremity injuries in the previous six months. Ethical approval (HRE17-046) was granted from the corresponding University Human Research Ethics Committee.

5.2.2. Experimental protocol

The testing venue was the regular training ground for the players. Testing was conducted using new Sherrin footballs (size 5, Sherrin, Australia; official ball used in AF competition), inflated within the specified pressure range of 67-75 kPa (Ball, 2008) and all players wore attire and boots that they currently used at training. Testing was performed during low wind and dry conditions.

Each player wore the Xsens MVN link system (Xsens Technologies B.V., Enschede, the Netherlands), which is composed if 17 inertial sensors placed on each body segment, a transmission pack (160 x 72 x 25 mm) and battery (95 x 59 x 25 mm), zipped into a compression suit. Sensors were placed on each segment following recommendations from Blair et al. (2018) and Roetenberg et al. (2013). Anthropometric measures were collected from each participant to scale the Xsens Biomechanical model. System calibration was made via a static (N-Pose) and a dynamic (walking) procedure (MVN Analyze 2018). As the IMS is unable to identify the location of the goal posts during data collection (as sensors are only placed on the player), the N-pose calibration was performed facing the goals directly in the centre, to enable identification and calculation of the goal-centre during data analysis. During data acquisition, sensor data was synchronised by the body pack and transmitted wirelessly to a laptop computer (240 Hz).

All players performed a warm-up, comprised of phases of running-based activities interspersed with static and dynamic stretching, followed by familiarisation kicks from different positions in-front of goals. Players were then instructed to use a self-selected run-up and perform 20 goal-kicks from four different positions (two distances (30 m and 40 m) and three angles (0°, 45° left and 45° right)) in-front of goals (**Figure 5.1**). Kicks taken at the different angles were at 30 m. Goal-kicking positions were representative of typical positions used in competition (as identified by Champion Data from the 2017 AFL season). Players were asked to perform kicks under game-like conditions (including the 30 s period players are given to perform this kick from when the mark is taken) using their preferred foot. The order of kicking positions was randomised to prevent order and sequence effects. To avoid the possible influence of fatigue, players were given 1 min between each trial (Numone et al., 2018). Accuracy was assessed using a hit vs miss criterion, which corresponds to how kicks are classified in competition (Blair et al., 2017).

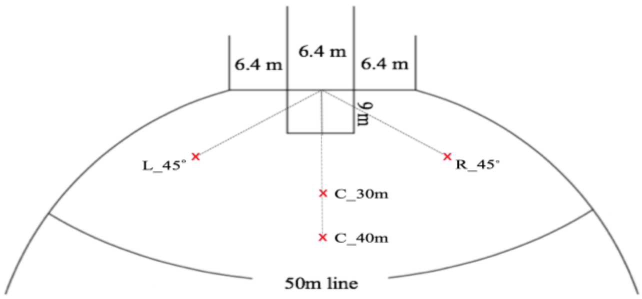


Figure 5.1. Schematic of goal-kicking used in this study (n=5 kicks from each position). Kicks taken at the 45-degree angle were 30 m from the goals. Kicks taken in the centre were directly in-front of goal.

5.2.3. Data analysis

Sensor fusion for the IMS data were made using the Xsens Kalman Filter and further filtered using the LXsolver (to minimise soft tissue artefact and joint laxity) in MVN Analyze 2018. The Xsens biomechanical model was assigned to motion files in Visual 3D and model-based calculations were computed using the Y-X-Z Cardan sequence, which corresponded to the ML-AP-Axial rotations computed in the MA data (c-motion, 2016). To avoid measurement issues that exist when analysing kinematic data across impacts, no evaluation of the impact phase was performed (e.g. Knudson and Bahamonde, 2001) and parameters during swing phase were analysed until the instant before ball contact (BC) (Ball, 2008; Nunome et al., 2006). Thirty-three discrete parameters identified important to kicking performance in AF (Baker & Ball, 1996; Ball, 2008; Ball, 2011, 2013; Ball et al., 2002; Dicheria et al., 2006; Peacock & Ball, 2017, 2018; Peacock et al., 2017) and across the other football codes (Bezodis et al., 2018; Lees et al., 2010; Sinclair et al., 2017, 2015; Zhang et al., 2012) were calculated. Parameters were calculated from the approach phase, kicking phase and follow-through phase of each kick. For kicks taken at an angle, a virtual axis was created to correct the principle axes and align it with the direction of goals (aligned with the direction of progression). This was computed via the position of the origin of the pelvis at each position utilising a method (method 2) recommended in visual 3D WIKI documentation (c-motion, 2014). Goal-centre was defined through creating a virtual laboratory segment (c-motion, 2013). Linear foot speed, pelvis velocity and angular velocities of the thigh, shank, knee and hip were computed using model-based calculations (Blair et al., 2018). Sagittal plane ankle, knee and hip joint angles were calculated as anatomical angles, with the knee measured as the angle between the thigh and shank and the pelvis used as the coordinate systems for the hip. Sagittal pelvis, thigh and shank segment angles were calculated in relation to the global axis (Blair et al., 2018). Range of motion (ROM) parameters were calculated as the differences between the angle maxima and minima from top of backswing to the instance before BC (during forward swing) in the kicking phase.

5.2.4. Statistical analysis

Descriptive statistics were used to assess accuracy scores across the different positions. Mean ± standard deviations (SD) were calculated for each parameter at each position to determine the success rate for kicks. Mean differences between kick angles and distances were analysed and interpreted using non-clinical magnitude-based inferences (reference Bayesian with a dispersed uniform prior) and evaluated via standardisation (Batterham & Hopkins, 2006, 2018a, 2018b; Hopkins et al., 2009), with a threshold of 0.2 set as a practically important effect (Bezodis et al., 2018; Hopkins at al., 2009). Only successful (hit) kicks were included in the analysis to control for accuracy (C_30 m: n = 58; C_40 m: n = 42; R_45: n = 50; L_45: n = 53). The thresholds for assessing the magnitude of mean differences were: <0.19, trivial; 0.20 - 0.59, small; 0.60 - 1.1, moderate; 1.2 – 1.9, large; and 2.0, very large (Hopkins et al., 2009). Uncertainty in each effect was expressed as 90% confidence limits and as probabilities that the true effect was substantially positive and negative. These probabilities were used to make a qualitative probabilistic non-clinical magnitude-based inferences about the true effect (Hopkins et al., 2009): if the probabilities were >5% the effect was reported unclear; the effect was otherwise clear and reported as the magnitude of the observed value, with the qualitative probability that the true effect was a substantial increase, a substantial decrease, or trivial. The scale for interpreting the probabilities was: 25–75%, possible; 75–95%, likely; 95–99.5%, very likely; and >99.5%, most likely.

5.3. Results

The average success rate of goal-kicks (n = 360: all kicks) across all positions was 56.6 %. Kicks taken in the centre at 30 m had the highest accuracy rate (64.3 %) (**Table 7.2**) compared to the other positions. Goal-kicks taken in the centre at 40 m were least accurate (47 %) across the group. The majority of inaccurate kicks were classified as behinds (average: 41.8 %) compared to out-of-bounds kicks (average: 1.8%).

Table 5.2. Percentage of accurate (hit) and inaccurate (miss) goal-kicks from each kicking position.

Position	Accurate kicks (%)	Inaccurate Kicks (%)
C_30m	64	36
C_40m	47	53
R_45	56	44
L_45	59	41

5.3.1. The effect of altering kicking distance

When increasing the distance from goals (from 30 m to 40 m), players demonstrated a substantially longer last step (1.55 vs 1.42 m, *possibly* moderate increase), with higher COM velocity at kick-foot toe-off (4.7 vs 3.4 $m.s^{-1}$, *very likely* moderate increase) and maximum COM velocity (5.9 vs 4.2 $m.s^{-1}$, *likely* moderate increase) during the approach phase (**Table 5.3**). During the kicking phase, players exhibited substantially greater kick-leg knee (+8°, *very likely* large increase) and hip (+6°, *very likely* large increase) ROM, with lower maximum support-leg knee flexion (-6°, *very likely* large increase) when distance from goals increased. Players also demonstrated higher kick-leg knee flexion (65 vs 62°, *very likely* moderate increase), with lower COM velocity (2.4 vs 2.7 $m.s^{-1}$, *likely* moderate decrease) and knee (1459 vs 1632°/s, *very likely* moderate decrease) and shank angular velocities (1643 vs 1736 °/s, *very likely* moderate decrease) at BC during 30 m kicks compared to 40 m kicks. The remaining technical parameters returned small-trivial differences between 30 m and 40 m goal-kicks.

Table 5.3. Kinematic means (SD) for each distance, mean difference between distance (C_40m – C_30m) with 90% confidence limits (CL) and the magnitude of the inference for each parameter indicated. All parameters refer to the kick-leg unless stated otherwise.

Parameter	C_30 m Mean (SD)	C_40 m Mean (SD)	Mean diff, ± 90% CL	Inference
Approach phase				
Last step distance (m)	1.42 (0.23)	1.55 (0.21)	0.13, ± 0.09	mod↑*
Average COM velocity ($m.s^{-1}$)	1.9 (0.6)	2.7 (0.7)	0.2, ± 0.2	small↑*
Max COM velocity ($m.s^{-1}$)	4.2 (0.7)	5.9 (0.5)	1.7, ± 0.4	mod↑**
COM velocity at KTO ($m.s^{-1}$)	3.4 (1.0)	4.7 (1.3)	1.3, ± 0.8	mod↑***
Approach angle (º)	5 (8)	7 (11)	2, ± 5	trivial***
Kicking phase				
At ball contact				
Ankle plantar-flexion (º)	39 (16)	42 (17)	4, ± 2	small↑****
Knee flexion (º)	65 (5)	62 (7)	-3, ± 3	mod↑***
Hip flexion (º)	14 (10)	10 (9)	-5, ± 2	small↓***
Pelvic posterior tilt (º)	48 (14)	47 (10)	-1, ± 4	trivial
Trunk posterior lean (º)	3 (5)	1 (7)	-2, ± 1	small↓****
Shank angle (º)	-3 (8)	-2 (9)	1, ± 2	trivial***
Thigh angle (º)	58 (12)	58 (14)	0, ± 1	trivial***
Linear foot velocity ($m.s^{-1}$)	18.0 (1.8)	19.9 (1.8)	1.9, ± 0.4	mod↑****
COM velocity ($m.s^{-1}$)	2.4 (0.4)	2.7 (0.5)	0.3, ± 0.1	mod↑*
Knee angular velocity (º/s)	1459 (225)	1632 (251)	183, ± 34	mod↑****
Hip angular velocity (º/s)	53 (119)	91 (174)	144, ± 31	mod↑**
Shank angular velocity (º/s)	1643 (126)	1736 (161)	107, ± 3	mod↑****
Thigh angular velocity (º/s)	147 (160)	186 (167)	86, ± 25	trivial
Support-leg ankle angle (º)	-2 (9)	-5 (18)	-3, ± 14	trivial
Support-leg knee flexion (º)	41 (5)	36 (3)	-5, ± 3	large↓****
Support-leg hip angle (º)	35 (9)	36 (11)	1, ± 2	trivial***
At Support Heel Strike				
Support-leg ankle dorsiflexion (º)	20 (18)	18 (7)	2, ± 1	trivial***
Support-leg knee flexion (º)	23 (14)	22 (13)	1, ± 5	trivial+
Support-leg hip flexion (º)	33 (19)	36 (16)	3, ± 4	trivial+
Maxima & Minima				
Max support-leg knee flexion (º)	43 (6)	37 (4)	-6, ± 1.3	large↓***
Max knee flexion (º)	117 (8)	122 (9)	5, ± 2	mod↑***
Max hip extension (º)	30 (6)	32 (7)	2, ± 1	small↑****
Range of Motion				
Ankle ROM (º)	33 (11)	32 (14)	1, ± 2	trivial****
Knee ROM (º)	52 (8)	60 (7)	8, ± 3	large↑***
Hip ROM(º)	36 (5)	42 (6)	6, ± 2	large↑***
Pelvis ROM (º)	44 (12)	46 (14)	2, ± 3	trivial**
Follow-through phase				
Leg position at end (º)	7 (18)	10 (19)	3, ± 3	trivial*
Ankle angle at end (º)	23 (15)	24 (16)	1, ± 6	trivial+

Direction of effect: ↑ positive, ↓ negative; **mod**: moderate
Symbols denote: * possibly, ** likely, *** very likely and **** most likely chance of the true effect was substantial, + true effect was unclear

5.3.2. The effect of altering kicking angle

For 30 out of 33 parameters, kick angle comparisons were classified as *most likely* to *likely* trivial/ unclear **(Table 5.4)**. During the kicking phase, a *small* difference was reported in COM velocity (2.2 vs 2.4 $m.s^{-1}$, *possibly*), knee angular velocity (1425 vs 1476°/s, *likely*) and shank angular velocity (1608 vs 1658°/s, *very likely* decrease) at BC, between kicks taken to the right (R_45) and left (L_45) of goals. Similar *small* differences were evident between kicks taken on the right compared to directly in the centre (C_30m) of goals.

Table 5.4. Kinematic means (SD) for each angle, mean difference between angles with 90% confidence limits (CL) and the magnitude of the inference for each parameter indicated. All parameters refer to the kick-leg unless stated otherwise.

Parameter	C_30 m	R_45	L_45	Mean diff, ± 90%CL; Inference		
	Mean (SD)	Mean (SD)	Mean (SD)	R_45 vs L_45	R_45 vs C_30m	L_45 vs C_30m
Approach phase						
Last step distance (m)	1.42 (0.26)	1.44 (0.23)	1.42 (0.25)	0.01, ± 0.04; trivial+	0.01, ± 0.03; trivial+	0.00, ± 0.04; trivial+
Average COM velocity (m.s^{-1})	1.9 (0.6)	1.8 (0.7)	1.9 (0.6)	-0.1, ± 0.1; trivial***	-0.1, ± 0.0; trivial****	0.0, ± 0.1; trivial****
Max COM velocity (m.s^{-1})	4.2 (1.4)	4.0 (1.2)	4.1 (0.7)	-0.1, ± 0.3; trivial**	-0.2, ± 0.1; trivial**	-0.1, ± 0.1; trivial**
COM velocity at KTO (m.s^{-1})	3.4 (2.0)	3.3 (1.8)	3.2 (1.9)	0.2, ± 0.1; trivial****	-0.1, ± 0.0; trivial****	-0.2, ± 0.1; trivial****
Approach angle (°)	5 (8)	8 (7)	6 (5)	2, ± 0; trivial**	3, ± 1; trivial**	2, ± 0; trivial****
Kicking phase						
At ball contact						
Ankle plantar-flexion (°)	39 (16)	41 (14)	40 (15)	1, ± 0; trivial**	2, ± 0; trivial**	1, ± 0; trivial**
Knee flexion (°)	65 (17)	64 (13)	64 (16)	0, ± 1; trivial****	-1, ± 1; trivial***	-1, ± 0; trivial****
Hip flexion (°)	14 (10)	13 (11)	14 (9)	-1, ± 0; trivial***	-1, ± 1; trivial***	0, ± 0; trivial***
Pelvic posterior tilt (°)	48 (14)	49 (15)	48 (13)	1, ± 3; trivial+	1, ± 4; trivial+	0, ± 1; trivial+
Trunk posterior lean (°)	3 (8)	2 (5)	2 (7)	0, ± 2; trivial+	-1, ± 1; trivial+	-1, ± 1; trivial+
Shank angle (°)	-3 (8)	-2 (6)	-2 (9)	0, ± 1; trivial**	1, ± 1; trivial**	0, ± 1; trivial**
Thigh angle (°)	58 (13)	57 (8)	58 (12)	-1, ± 1; trivial****	-1 ± 1; trivial****	0, ± 1; trivial****
Linear foot velocity (m.s^{-1})	18.0 (1.9)	17.9 (1.8)	18.1 (1.8)	-0.2, ± 1; trivial****	-0.1, ± 1; trivial****	0.1, ± 1; trivial****
COM velocity (m.s^{-1})	2.4 (1.6)	2.2 (1.0)	2.4 (0.4)	-0.2, ± 0.6; small*	-0.2, ± 0.6; small*	0, ± 0.2; trivial***
Knee angular velocity (°/s)	1459 (225)	1425 (212)	1476 (207)	-51, ± 30; small**	-44, ± 30; small*	17, ± 1; trivial**
Hip angular velocity (°/s)	53 (119)	41 (128)	64 (100)	-23, ± 43; trivial+	-12, ± 1; trivial+	11, ± 32; trivial+
Shank angular velocity (°/s)	1643 (163)	1608 (123)	1658 (142)	-50, ± 33; small**	-35, ± 23; small*	15, ± 13; trivial****
Thigh angular velocity (°/s)	147 (110)	132 (95)	141 (99)	-11, ± 25; trivial+	15, ± 19; trivial*	-6, ± 11; trivial**
Support-leg ankle angle (°)	-2 (9)	-3 (5)	-3 (4)	1, ± 1; trivial	1, ± 1; trivial**	1, ± 4; trivial+
Support-leg knee flexion (°)	41 (8)	42 (6)	41 (5)	1, ± 2; trivial***	1, ± 1; trivial****	1, ± 3; trivial***
Support-leg hip angle (°)	35 (9)	35 (6)	36(11)	0, ± 4; trivial**	1, ± 3; trivial*	1, ± 3; trivial*
At Support Heel Strike						
Support-leg ankle dorsiflexion (°)	20 (8)	19 (5)	18 (7)	1, ± 2; trivial***	-1, ± 2; trivial***	-2, ± 1; trivial***
Support-leg knee flexion (°)	23 (14)	23 (9)	24 (13)	-1, ± 2; trivial***	0, ± 2; trivial***	-1, ± 0; trivial****
Support-leg hip flexion (°)	33 (16)	34 (13)	33 (16)	0, ± 1; trivial**	0, ± 2; trivial**	0, ± 2; trivial**

Direction of effect: ↑ positive, ↓ negative; **mod**: moderate

Symbols denote: * possibly, ** likely, *** very likely and **** most likely chance of the true effect was substantial, + the true effect was unclear

Table 5.4. *Continued*

Parameter	C_30 m	R_45	L_45	Mean diff, ± 90%CL; Inference		
	Mean (SD)	Mean (SD)	Mean (SD)	R_45 vs L_45	R_45 vs C_30m	L_45 vs C_30m
Kicking Phase						
Maxima & Minima						
Max support-leg knee flexion (º)	43 (7)	43 (8)	44 (6)	1, ± 2; trivial**	2, ± 1; trivial+	1, ± 2; trivial**
Max knee flexion (º)	117 (14)	118 (12)	118 (14)	0, ± 1; trivial***	1, ± 1; trivial***	1, ± 1; trivial***
Max hip extension (º)	30 (6)	30 (7)	30 (8)	0, ± 1; trivial+	0, ± 1; trivial**	0, ± 2; trivial+
Range of Motion						
Ankle ROM (º)	33 (14)	32 (11)	33 (11)	-1, ± 4; trivial+	-1, ± 4; trivial+	0, ± 1; trivial****
Knee ROM (º)	52 (8)	50 (7)	52 (8)	-2, ± 1; trivial****	-2, ± 1; trivial****	1, ± 0; trivial****
Hip ROM(º)	36 (12)	32 (6)	36 (10)	-3, ± 3; trivial+	-3, ± 3; trivial+	0, ± 2; trivial**
Pelvis ROM (º)	44 (12)	46 (13)	44 (12)	2, ± 1; trivial***	2, ± 1; trivial***	0, ± 1; trivial****
Follow-through phase						
Leg position at end (º)	7 (8)	9 (9)	6 (6)	3, ± 3; trivial+	2, ± 2; trivial+	-1, ± 2; trivial+
Ankle angle at end (º)	23 (15)	24 (11)	25 (10)	1, ± 1; trivial***	1, ± 1; trivial***	2, ± 2; trivial***

Direction of effect: ↑ positive, ↓ negative; **mod**: moderate
Symbols denote: * possibly, ** likely, *** very likely and **** most likely chance of the true effect was substantial, + the true effect was unclear.

5.4. Discussion

The purpose of this study was to investigate the effect of altering kicking position (angle and distance from goals) on goal-kicking technique and success, and determine if technical adjustments are made dependent on the location on the pitch to achieve a successful outcome. Anecdotal reports from coaches and players would suggest that the kicking skill should be invariant regardless of kicking position (Anderson et al., 2018; Bezodis et al., 2018; Hosford & Meikle, 2007). However, findings from this research indicated that the location of the goal-kick can have an influence on the technique adopted by a player to achieve a successful outcome.

Goal-kicking accuracy differed between each position on the pitch tested in this research. Kicks taken directly in the centre at 30 m were most successful (64%), with kicks taken in the centre at 40 m least successful (47%). Increasing the distance (30 m to 40 m) and angle (0º to 45 º) from goals resulted in a decrease in goal-kicking accuracy (17% and 7%, respectively), supporting previous findings in performance analysis research in AFL matches (Anderson et al., 2018; Bedford & Schembri, 2006) and international Rugby Union games (Nel, 2013; Pocock et al., 2018; Quarrie & Hopkins et al., 2015). This drop in success has been attributed to changes in the angle of opportunity/ relative width of the goal-line at the given locations, where reductions in the margin for error increase the difficulty of the shot (Galbraith & Lockwood, 2010). Given that the angle of opportunity is smallest at 40 m (9.15°) compared to the other positions (>10.15°), may be a contributing factor to the higher percentage of kicks missed at this position. Furthermore, higher accuracy was reported on the left hand side of the pitch compared to the right (59 vs 56%), despite having similar angles of opportunity. This could be related to the suggestion that left and right footed kicks are better placed on a specific side of the pitch

(Flemmer & Flemmer, 2015). Coaching manuals suggest right-footed kickers are more accurate from the left side of the pitch due to their alignment of their kick-leg and the goals (Hosford & Meikle, 2007). All kickers tested in this study were right-footed, supporting this assertion. Similar findings have been found in rugby place kicking (Flemmer & Flemmer, 2015), where the authors attributed the change in accuracy from the right to the left side of a pitch to the preferred foot of the kickers. However, as this study only had right-footed kickers, further investigation of left-foot kickers is needed to further support this assertion. The practical implication of these findings could be used to inform in-game decision making strategies, where encouraging players to direct the ball through centre corridor (the middle of the ground) and closer to goal may increase the probability of scoring a goal, rather than running the ball along the wing or boundary line (50 m).

5.4.1. The effect of altering kicking distance

Support-leg knee motion differed between 30 m and 40 m kicks. Players demonstrated a more extended support-leg knee at heel strike, that remained more extended throughout (substantially lower max knee flexion: 37 vs 43˚, large effect) the stance phase until BC (substantially lower max knee flexion: 36 vs 41˚, large effect) during 40 m kicks compared to 30 m (**Figure 5.2**), supporting previous findings in distance kicking in AF (Ball, 2013) and soccer (Numone et al., 2006; Inoue et al., 2014). Lifting the whole-body upward through the motion of the support-leg has been suggested to be an effective action to assist with maintaining a higher hip position, which in turn, helps generate faster foot speed's through achieving a more extended kick-leg (and hence a longer lever arm/ moment arm) during the swing phase without striking the ground (Ball, 2013; Inoue et al., 2014). Post-hoc analysis identified a moderate relationship (r_2 = -0.71) between maximum support-leg knee flexion and foot speed. As distance increases, players need to generate and apply more force to the ball, in order to achieve the desired distance. A more extended support-leg may be beneficial when increasing the distance from goals, to achieve a stronger and more stable base of support for the kicker (Ball, 2013; Lees et al., 2010), which may facilitate a more efficient transfer of momentum to proximal-to-distal sequencing of the kick-leg, enabling players to generate higher forces during swing phase of the kick-leg. These findings provide support for the possibility that a continuum of technique strategy exists, where at one end (short kicks for accuracy) a more flexed support-leg is beneficial while at the other end (maximising distance) a more extended support-leg is beneficial. In between, depends on how far the kick is required to travel. This is another useful future direction for biomechanical kicking research. Further investigation of the underlying joint kinetics of the support-leg is warranted to help explain how these observed motions are achieved.

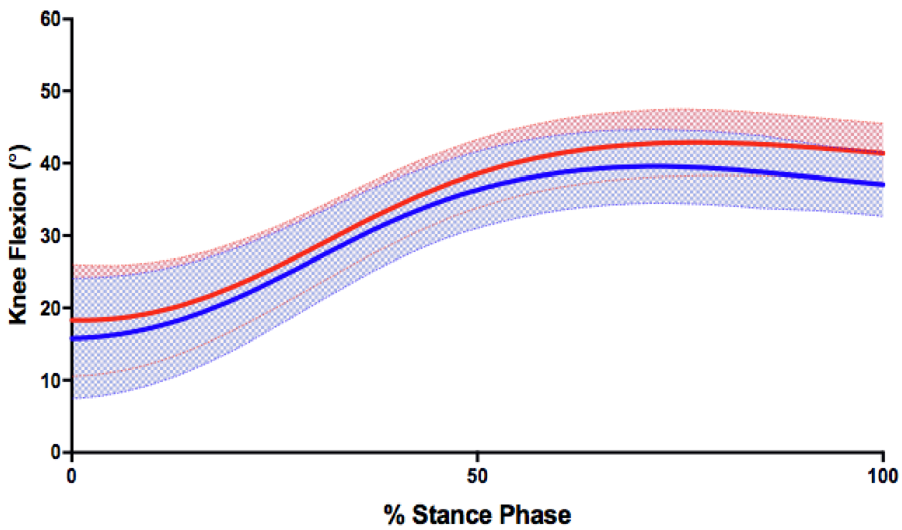


Figure 5.2. Group average mean and SD support-leg flexion angle throughout stance phase for 40 m (red line) and 30 m (blue line) kicks.

Last step characteristics were associated with increasing kick distance, where longer kicks demonstrated a longer last step distance, supporting previous findings by Ball

(2008). A longer last step may have contributed to the increase in joint ROM that was evident during swing phase, which in turn, increases the potential to develop greater foot speed (Lees & Nolan, 2002). Post-hoc analysis identified a moderate relationship between hip ROM and last step length (r = 0.53) supporting this suggestion. Furthermore, a moderate increase in foot speed (1.9 $m.s^{-1}$) was also evident at 40 m, along with higher COM velocity through the kicking action. This support the ‘principles of movement’ (Bunn, 1972), were greater range of motions of the joints can be used to increase segment speed and the end-point speed of a limb (foot). Faster foot speeds have been highlighted in the kicking literature as an important performance indicator to kicking distance (Ball, 2008; Ball, 2013; Peacock et al., 2017).

Increasing the distance of the goal-kick also resulted in greater maximum knee flexion in the kick-leg during swing phase, supporting previous findings by Baker & Ball (1996). The biomechanical advantage of greater knee flexion would reduce the moment of inertia of the thigh/leg about the hip joint to increase rotation (Baker & Ball, 1996). This is likely a strategy used by players to increase the angular velocities of the segments within the kick-leg, to cope with the increased distance of the kick. The smaller moment of inertia created by the knee could be one contributing factor to the higher knee (40 m: 1632°/s vs; 30 m: 1459°/s) and shank (40 m: 1736°/s; 30 m: 1643°/s) angular velocities reported at impact during 40 m goal-kicks. This also supports the assertion by Parkin et al. (1987), who stated the speed of the kick-leg segment is important when kicking for distance. Findings in this research indicate that when increasing distance from goals, players are required to generate higher speeds to achieve the distance.

Based on the current findings, it is suggested conditioning the support-leg to maintain a more extended position may assist kickers to attain a stronger base of support when kicking from further distances from goals. Ball (2013) suggested the use of task-specific movement, such as single-legged landing tasks whilst maintaining a more extended knee (knee angle greater than 45º) might assist in developing this strength using a similar motor pattern. When kicking further from goal, it is recommended to increase the speed of the kick-leg movement; increase foot speed and shank angular velocities at BC. Conditioning drills that promote greater foot speeds and shank angular velocities, such as having players simply kick for maximal distance have been found effective when training this skill (Ball, 2008), as well as increasing the speed of approach and last step distance. However, Ball (2013) suggested that the last step distance should be proportional to approach speed as over-striding may be detrimental to the kicking action. Future work should examine the differences between successful and unsuccessful kicks at each distance to determine if faster speeds are maintained in accurate kicks compared to inaccurate kicks.

5.4.2. The effect of altering kicking angle

Altering the angle of the goal-kick (from 0º (directly in-front of goals) to 45º to the left or right) had no substantial influence on technique. Theoretically, the only apparent change that players have to contend with is a reduction in the angle of opportunity/relative width of the goal-line available (13.20 to 10.15°/6.4 m to 6.35 m) (Galbraith & Lockwood, 2010). As a result, the same technique would be required to place the ball directly in the centre of the goal, however, it would require players to be more consistent in their goal-kicking technique, as they have less margin for error (smaller target). The idea of a more consistent technique was reflected through lower standard deviations across technical parameters in goal-kicks taken at a 45°. Similar findings were found in throwing, where Hamilton and Tate (2002) found that altering the angle of a throw from a target did not significantly affect throwing pattern, however increasing distance from the target significantly altered trunk foot and arm kinematics, in order to promote higher speeds, which are in-line with our distance findings.

Small differences in the speed of the goal-kick were evident between kicks taken on the right compared to the other positions. Players demonstrated a lower COM velocity (0.2 vs 0.2 $m.s^{-1}$), and knee (1425 vs 1476°/s, *likely*) and shank angular velocity (1608 vs 1658°/s, *very likely* decrease) at BC when kicking at the right side. This could be related to the notion that right-footed kickers may find it harder when kicking on the right hand side of the pitch due to their alignment of their kick-leg and the goals (Hosford & Meikle, 2007), thus the perceived difficulty of the task may be greater. It is plausible that players may have actively controlled the motion of the kicking limb to optimise ball and impact improve accuracy at this position, if the task difficulty was perceived to be higher. However, this is only speculation as the perceived difficulty of the task was not assessed in this study. In addition, it is acknowledged that these differences in technical parameters were only small in magnitude. The practical implications of this finding suggest that kickers can be coached to execute kicks in a consistent manner across angles at the same distance.

This study provided an insight into the effect of altering task constraints (distance and angle from goals) on goal-kicking technique and performance in AF. Within a competitive performance environment, players also need to successfully adapt to numerous other fluctuating constraints such as, task constraints (changes in fatigue), environmental constraints (wind, rain, crowd noise, and the stadium where the match is contested), personal constraints (anxiety, decision-making skills) and contextual factors (e.g. score margin and time remaining) (Anderson et al., 2018; Nel, 2013; Quarrie & Hopkins, 2015). Biomechanical theorists have suggested that a skilled movement is a result of the complex interactions between the task goal, performer, contextual and environmental constraints (Davids et al., 2003; Davis & Burton, 1991; Gagen & Getchell, 2004). Given that specific task constraints influence theoretical frameworks such as, the dynamical systems theory (Davids et al., 2005; Davids et al., 2003) may offer a useful framework to investigate how technique is affected by the interaction of constraints (such as, the task, morphological and environmental constraints) and provide an interesting avenue for further investigation in goal-kicking research.

The findings of this study should be interpreted in light of several limitations. Firstly, the results are limited to the kicking positions tested in this study. Assessment of technique over a wider range of positions, would provide a more comprehensive understanding how the position of the shot influences goal-kicking technique in AF. For example, examination of technique over a range of distances would help determine if a continuum strategy exists for the support-leg knee motion. In addition, when kicking from angles > 60° players are often required to perform a different kick type (i.e. banana kick) to achieve a curved ball flight trajectory, in order to score the goal. Further examination of other goal-kicking techniques outside of the punt kick are warranted. Furthermore, this study chose to analyse accurate kicks only to control for accuracy across all positions, but also due to a limited number of accurate and inaccurate kicks from each position. It is unknown technical errors across positions are similar. If different technical errors exist at the different positions it may help further explain changes in accuracy.

5.5. Conclusion

The effect of altering the location of a goal kick (change in angle and distance from goals) was explored. Increasing the distance (30 m to 40 m) and angle (0º to 45º) from goals resulted in a decrease in goal-kicking accuracy (17% and 7%, respectively). Increasing the distance of a goal-kick has a greater influence on technique compared to altering the angle of the kick from goals. When increasing the distance from goals (from 30 m to 40 m), players demonstrated a longer last step (1.55 vs 1.47 m), with higher approach speed (as indicated by COM velocity at kick foot toe off, 4.7 vs 3.4 $m.s^{-1}$) and maximum COM velocity (5.9 vs 4.2 $m.s^{-1}$) during the approach phase. Players also demonstrated a substantially more extended support-leg during the stance phase, with greater hip and knee ROM during swing phase when kicking at 40 m compared to at 30 m. In addition, moderately higher linear foot speeds and COM velocities, with higher shank and knee angular velocities at BC were associated with increasing the distance of the goal-kick. For the majority of technical parameters examined in this study, no substantial differences were found when changing the angle of the kick from 0 to 45 degrees. Findings indicated that players may be required to adjust goal-technique when kicking further from goals, in order to achieve a successful outcome.

5.6. Contribution of Chapter to the Aims of the Thesis

The specific aim of Chapter 5 was to examine the effect of altering kicking position on goal-kicking technique and success in AF. The findings of Chapter 5 contribute to answering the second main aim of this thesis, indicating that the location of the goal-kick can have an influence on the technique adopted by a player to achieve a successful outcome. Specifically, players require substantially greater joint range of motion (knee and hip), with higher linear (foot speed) and angular (knee and shank) velocities when the distance of the kick increases. Further discussion of how task constraints influence goal-kicking performance can be found in Chapter 8 (**Section 8.2.3**, *pp 197 - 199*). The results from this Chapter were also used to inform the kicking positions chosen to analyse in Chapters 5 and 6. Based on the results from this Chapter, to facilitate analysis of accurate and inaccurate goal-kicks in subsequent Chapters, goal-kicks taken at 30 m and at a 45° angle were grouped to increase kick number and statistical power of the sample.

Chapter 6: Biomechanics of Accurate and Inaccurate Goal-Kicking in Australian Football: Group-Based Analysis

6.1. Introduction

Goal-kicking forms an important component of winning games in AF, as it provides a means through which to score points. Given a successful shot at goal equates to six points compared to only one point for a 'behind' (when the ball passes between the goal and point post) or no score beyond the point post, accurate goal-kicking is clearly advantageous in competition. There are two broad categories of goal-kicking in AF: general play and set-shot goal-kicks. The set-shot is of particular interest, as it comprises approximately 62% of points scored during a game and has been identified as the most influential performance indicator in match outcome (Anderson et al., 2018; Robertson et al., 2016). Consequently, a player's goal-kicking ability can have a major bearing on a team's success in competition. However, as the success rate for goal-kicks in the 2018 Australian Football league (AFL) season was only 47.0% (Champion Data statistics, 2018), there is clear scope for scientific research to explore set-shot goal-kicking to support improvement in performance.

The set-shot goal-kick (hereafter, the set-shot goal-kick will be referred as just the goal-kick) is a self-paced closed skill, where the player has 30 seconds to perform the shot without any physical pressure from opponents (Baker & Ball, 1996; Hosford & Meikle, 2007). It is typically performed using a drop-punt kick due to its superior accuracy over other kick types such as the torpedo (spiral – spins about the ball's long axis) and banana (spins about a vertical axis so deviates sideways in flight). The goal-kick involves the combined technical aspects of a running approach of between three and 20 steps depending on player preference, release of the ball from the hands at approximately hip height so it drops towards the kick foot, and forceful impact with the foot of the kick-leg as it swings through in the direction of the goals (Ball, 2008, 2013; Ball et al., 2002). As the ball is in projectile motion after it leaves the foot, evidence from literature suggests that one of the main possible reasons for the kick to miss the goal, are due to a technical error that leads to a poor impact with the ball (Baker & Ball, 2006; Ball, 2013; Peacock & Ball, 2018a, 2018b, 2017). Consequently, understanding goal-kicking technique is important for improving performance.

Despite the important role of goal-kicking in AF, only two studies have examined the biomechanics of the skill (Ball et al., 2002; Blair et al., 2017). Ball and colleagues (2002) utilised an in-field notational analysis (video footage of frontal plane: 50 Hz) to evaluate six technical aspects of accurate and inaccurate goal-kicks in eight elite AF players; approach line, ball movement throughout approach, last stride characteristics, height and lateral position of the ball drop, ball position at contact and follow through. Accurate kickers were reported to adopt a straighter approach line, drop the ball in line with the kicking thigh and finish with the leg pointing towards goals. Whilst the use of a notational analysis provided an understanding of the influence of specific parameters on goal-kicking performance, it only permitted a 2D analysis (frontal plane analysis). As a result, only a limited number of parameters were used to assess performance, which substantially limited this exploration of the important technical factors associated with goal-kicking technique in AF. The authors suggested further analysis of other planes (such as sagittal plane characteristics) and other aspects of technique (such as run-up characteristics, support-leg and kick-leg mechanics) would provide a more comprehensive understanding of important technical factors associated with goal-kicking. Additionally, in a comparison of accurate (hits) and inaccurate (misses) 20 m goal-kicks in small sample (n = 2 two junior AF kickers), accurate kicks were associated with greater support-leg (p = 0.04; d = 1.0) and kick-leg (d = 1.0) knee flexion (Blair et al., 2017). The authors proposed that further work was required in a larger sample to establish statistically significant results, making the information more generalisable to the AF population.

Research examining the technical aspects of accurate and inaccurate punt-kicking during other tasks is also limited. Dicheria and colleagues (2006) compared lower extremity kinematics of accurate and inaccurate kickers (n = 12 elite AF players) when kicking to a target 15 m (task representative of kicking to a player). Accurate kickers produced significantly greater support knee flexion (> 5.3º, $p < 0.05$), hip flexion (> 5 º, $p < 0.05$) during the stance phase, with greater anterior pelvic tilt (+8.1°, $p < 0.05$) compared to inaccurate kickers. The authors suggested this might be a strategy utilised by players to lower their COM, to improve stability and balance during the kick and contribute to accuracy. In addition, Peacock and colleagues (2017) examined the relationship between ankle mechanics and kicking accuracy and distance in 11 elite AF players. When kicking for accuracy (task: 20 m kick to a player), players demonstrated significantly lower ankle plantarflexion at BC (123° vs 130°; p = 0.008) and higher ankle ROM (7° vs 2°; p = 0.02) compared to when kicking for maximal distance. The authors suggested that this may be a mechanism adopted by players to achieve a flatter ball flight trajectory to improve the accuracy of the kick.

Over the last decade, goal-kicking technique has received increasing interest across the rugby literature. Biomechanical investigations have analysed contributions from the approach phase (Baktash et al., 2009), kick-leg and support-leg mechanics during the swing phase (Atack, 2016; Atack et al., 2017, 2015; Bezodis et al., 2018, 2017; Cockcroft & Van Den Heever, 2016; Ford & Sayers, 2015; Padulo et al., 2013; Sinclair et al., 2017, 2016, 2014; Zhang et al., 2012), whole-body orientation at ball contact (Ball et al., 2013; Green et al., 2016), impact characteristics (Ball, 2010), motion of the non-kicking-side arm (Bezodis et al., 2007) and initial ball flight characteristics (Atack et al., 2018), in an attempt to better understand the key technical characteristics underpinning goal-kicking performance in rugby. Despite utilising different kicking styles (i.e., place kick in rugby compared to the punt kicking in AF), it is plausible that the findings from the goal-kicking literature in rugby can also be relevant to goal-kicking performance in AF. However, separate investigation is warranted due to the distinct differences between the goal-kicking actions (such as, ball drop in AF), which may substantially influence technique and performance.

Given the importance of goal-kicking in AF, research is needed to establish an evidence base to further advance the understanding of the underlying factors which influence performance. This knowledge can be used to objectively guide development programmes aimed at improve goal-kicking performance at all levels, as well as providing readily usable coaching cues (Ball, 2013). Furthermore, examination of inaccurate kicks is needed as it can identify what technical errors are made when players miss the goals (Numone et al., 2017). This also provides important information that can be used by coaches and practitioners to prompt modifications to a player's technique to reduce the presence of such undesirable technical factors. Therefore, the purpose of this research was to examine goal-kicking technique in AF and determine technical factors associated with performance. The specific aims were to (1) compare and identify if kinematic differences exist between accurate and inaccurate goal-kicks, and (2) examine the relationship between technical factors and goal-kicking accuracy.

6.2. Methodology

6.2.1. Participants

Eighteen male AF players (age: 17.4 ± 0.5 yrs; height: 184.5 ± 5.4 cm; mass: 73.1 ± 6.9 kg) volunteered to participate in this research. Players ranged in skill level from elite (AFL Academy squad), to school and club first grade teams representing an elite and sub-elite cohort (*see* **Appendix B**, **Table 2**, *pp. 241)*. Players were selected based on game demands (players that regularly performed the goal-kick during a match) rather than playing level, to represent a higher skilled cohort of goal-kicks[2]. All players were competing regularly in competition and had no lower extremity injuries in the previous six months. Ethical approval (HRE17-046) was granted from the corresponding University Human Research Ethics Committee and all players provided written informed consent.

6.2.2. Equipment

Three-dimensional kinematics were collected using the Xsens MVN link inertial measurement system (IMS) (Xsens Technologies B.V., Enschede, the Netherlands), which has been previously validated to measure kicking kinematics in AF (see **Chapters 3 and 4**, *pp. 64 – 102*: Blair et al., 2018). The system is composed 17 inertial sensors, a transmission pack (160 x 72 x 25 mm: 150 g) and battery (95 x 59 x 25 mm: 70 g), zipped into a compression suit which is worn by each player. Each sensor (36 × 24 × 10 mm: 10 g) integrates a 3D accelerometer (scale: ± 160 $m.s^{-2}$, noise: 0.003 $m.s^{-2}/\sqrt{Hz}$), 3D gyroscope (± 2000 °/s, 0.05 °/s/√Hz) and 3D magnetometer (± 1.9 Gauss, 0.15m

2 Note for reader: The implications of selecting players based on skill level rather than playing level is discussed in more detail in the general discussion (Chapter 8, section 8.3.2., *pp 206-207*).

Gauss/√Hz). Sensors were placed on both feet (lateral side of the boot), shanks (medial surface of the tibias), thighs (lateral side above the knees), pelvis (middle of both the posterior superior iliac spines), shoulders (middle of the scapula spine), upper arms (lateral side above elbow), forearms (lateral and flat side of wrist), hands (posterior side), sternum and back of the head (Blair et al., 2018; Roetenberg et al., 2013). The tightness of the Xsens suit was maximised for each individual to reduce underlining soft tissue artefact and sensor movement (Roetenberg et al., 2013). Anthropometric measures were collected from each participant to scale the Xsens biomechanical model (cm); body height, shoulder height, arm span, shoulder width, leg length, knee height and hip width. System calibration was made via a static (N-Pose) and a dynamic (walking) procedure (MVN Analyze 2018). As the IMS is unable to identify the location of the goal-posts during data collection (as sensors are only placed on the player), the N-pose calibration was performed directly in-front of the goals in the centre, in order to define the global laboratory axis. This enabled identification and calculation of the goal-centre during data analysis through creating a virtual laboratory segment 30 m from away from the global laboratory axis (c-motion, 2013). During data acquisition, sensor data was synchronised by the body pack and transmitted wirelessly to a laptop computer (240 Hz).

6.2.3. Testing protocol

The testing venue was the regular training and playing ground for the players. Testing was conducted using new Sherrin footballs (size 5, Sherrin, Australia; official ball in AF competition), inflated within the specified pressure range of 67-75 kPa (Ball, 2008). Testing was performed during low wind and dry conditions and all players wore attire and boots that they currently used at training.

All players performed a standardised warm-up, comprised of phases of running-based activities, interspersed with static and dynamic stretching, followed by a minimum of 10 familiarisation goal-kicks from different positions in-front of goals. Players were then instructed to perform 15 x 30 m goal-kicks from three different positions in-front of goals (**Figure 6.1**). Two cones were placed on the ground to define the location from where players were required to perform the goal-kick. Goal-kicking positions were representative of typical positions used in competition (as identified by Champion Data from the 2017 AFL season). Players were asked to perform goal-kicks under game-like conditions, including the 30 s period players are given to perform this kick from when the mark is taken. All players used a self-selected run-up and performed kicks using their preferred foot. The order of kicking positions were randomised to prevent order and sequence effects, and players were given a 1-minute rest period between each trial to avoid the possible influence of fatigue (Nunome et al., 2018).

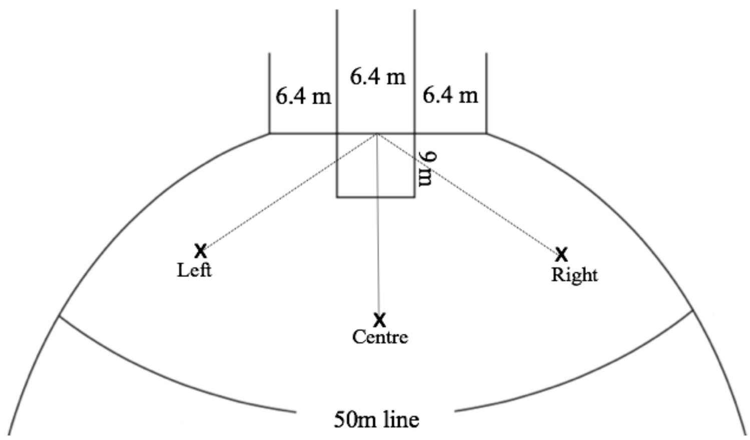


Figure 6.1. Schematic of the experimental set-up; each kicking position was 30 m from the goal and kicks taken at the right and left positions were at a 45-degree angle to the goal.

During each kick, accuracy was assessed using two criteria: 1) hit vs miss (Blair et al., 2017; Dicheria et al., 2006; Gheidi & Sadeghi, 2010; Katis et al., 2013; Lees & Nolan, 2002; Sinclair et al., 2017), and 2) by measuring the horizontal distance from the centre of a target (Bezodis et al., 2007; Izovska et al., 2016) (**Figure 6.2**)[3].

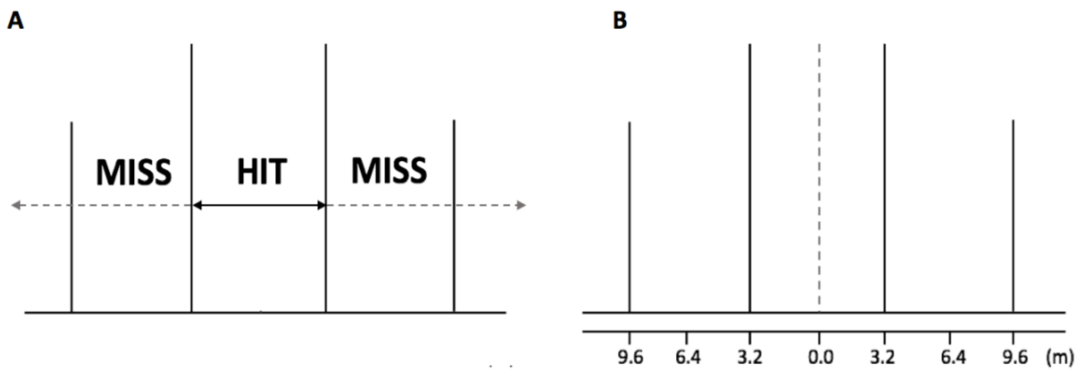


Figure 6.2. Accuracy grading; a) hit vs miss and, b) lateral horizontal distance measured from the centre of goals (m).

6.2.4. Data analysis

Sensor fusion for the IMS data were made using the Xsens Kalman Filter and filtered using the LXsolver (to minimise soft tissue artefact and joint laxity) in MVN Analyze 2018. The Xsens biomechanical model was assigned to motion files in Visual 3D and model-based calculations were computed using the Y-X-Z Cardan sequence, which corresponded to the ML-AP-Axial rotations computed in the MA data (c-motion, 2016). To avoid measurement issues that exist when analysing kinematic data across impacts, no evaluation of the impact phase was performed (Knudson and Bahamonde, 2001) and parameters during the kicking phase were analysed until the instant before ball contact (BC) (Ball, 2008; Nunome et al., 2006). For IMS data, toe-off (TO) corresponded a peak in the gyroscope signal from the foot sensor (Bergammi et al., 2012; Reenalda et al.,

[3] Note for reader: The selection of these two criterion measures are discussed in more detail in the general discussion (Chapter 8, section 8.3.1, *pp. 200-206*).

2017; Sabatinit et al., 2005) and BC corresponded to the instant prior to a peak in the anterior-posterior and vertical acceleration signal from the kick-foot sensor (Blair et al., 2018). Thirty-three kinematic parameters were chosen based on technical parameters identified as important in kicking performance across the football codes (Anderson & Dörge, 2011; Alcock et al., 2012; Atack et al., 2017; Ball, 2008; Ball, 2013; Ball et al., 2002; Baker & Ball, 2006; Bezodis et al., 2007; Dicheria et al., 2006; Inoue et al., 2014; Kellis & Katis, 2007; Lees et al., 2010; Lees & Nolan, 2002; Nunome et al., 2006; Nunome et al., 2018; Peacock et al., 2017; Peacock & Ball, 2018; Peacock & Ball, 2017; Sinclair et al., 2015; Sinclair et al., 2017; Zhang et al., 2012); as identified in the deterministic model in Chapter 2 (see **Section 2.2.3**, **Figure 2.4,** *pp. 25*). A description of all parameters is provided in **Table 6.1**. Parameters were computed using model-based calculations (Blair et al., 2018). For kicks taken at an angle, a virtual axis was created to correct the principle axes and align it with the direction of goals (aligned with the direction of progression). This was computed via the position of the origin of the pelvis at each position utilising a method (method 2) recommended in visual 3D WIKI documentation (c-motion, 2014). Sagittal plane ankle, knee and hip joint angles were calculated as anatomical angles, with the knee measured as the angle between the thigh and shank and the pelvis used as the coordinate systems for the hip. Pelvis, thigh, shank and foot segment angles were calculated in relation to the global axis (Blair et al., 2018). Range of motion (ROM) parameters were calculated as the differences between the angle maxima and minima from the top of backswing to the instance before BC (during forward swing).

Table 6.1. Definitions of technical parameters calculated in this study.

Parameter	Definitions
Approach phase	
Approach angle (°)	Angle between start of approach and start of the kicking phase
COM velocity ($m.s^{-1}$)	Velocity of the centre of mass
Last step distance (m)	Distance between the heel of the kick foot when in contact with the ground to the toe of the support foot when in contact with the ground.
Kicking phase	
Linear velocities ($m.s^{-1}$)	**Linear velocity measured at the instance prior to BC of kick-leg joints/segments**
Foot speed	Velocity of the centre of mass of the foot segment
COM velocity	Velocity of the centre of mass
Angular velocities (º/s)	**Angular velocities of the kick leg measured at BC and maxima**
Ankle angular velocity	Angular velocity of the ankle (represents plantarflexion)
Knee angular velocity	Angular velocity of the knee (represents extension)
Shank angular velocity	Angular velocity of the shank segment about the global y-axis
Thigh angular velocity	Angular velocity of the thigh segment about the global y-axis
Hip angular velocity	Angular velocity of the hip (represents flexion)
Range of motion (º)	**Differences between angle maxima and minima during forward swing phase**
Ankle ROM	Ankle joint (flexion/extension)
Knee ROM	Knee joint (flexion/extension)
Hip ROM	Hip joint (flexion/extension)
Pelvis ROM	Pelvis angle about the global y-axis
Joint angles (º)	**Joint angles for the kick-leg and support-leg, (at BC, Maxima and SHS)**
Ankle angle	Angle between the foot and shank, plantar-dorsi flexion angle
Knee angle	Angle between the shank and thigh, flexion-extension angle
Hip angle	Angle between the thigh and pelvis, flexion-extension angle
Segment angles (º)	**Kick-leg segment angles measured at BC**
Shank angle	Shank angle about the global y-axis
Thigh angle	Thigh angle about the global y-axis
Pelvis angle	Pelvis angle about the global y-axis
Trunk angle	Trunk angle about the global y-axis
Angles (º)	**Direction (vector path, º)**
Foot-path	Angle defined by the linear velocity vector of the kick foot and the line between the foot and the global goal centre in the X-Y plane
Follow through phase	
Leg position	Angle between hip and ankle joint about the local z-axis to indicate the 'straightness of the follow through'
Ankle angle	Angle between the foot and shank, plantar-dorsi flexion angle

6.2.5. Statistical analysis

Data were divided into two sets for subsequent analysis. Based on the results in Chapter 5 (*pp.* 110 – 112: no substantial effect of the angle of the kick from goals on technique) and Ball & Blair (2018), kicks were grouped across the three positions to increase kick number and statistical power of the sample. To identify if differences exist between accurate and inaccurate goal-kicks, the first data set was divided into accurate (hit, n = 134) and inaccurate (miss, n = 106) kicks (*see* **Appendix D, Table 3,** *pp. 251)* for each player's accuracy scores*)*. Subjects 3, and 15 were excluded from the hit vs miss analysis as they had successfully converted most of their kicks, with few (2 - 3) missed kicks. Differences between accurate and inaccurate goal-kicks were assessed using the general mixed-model procedure (Proc Mixed) in the Statistical Analysis System (SAS) studio (version 9.4, SAS 186 Institute, Cary NC). The fixed effects in the model were kick number (five levels, to estimate habituation effects), position (left, right and centre), and accuracy (two levels: Hit and Miss). The random effects, estimated as independent variances and allowing for negative variance, were subject identity (between-subject differences), kick position within subjects (within-subject differences between kick position), kick number within kick position (within-subjects changes between kicks) and residuals for each position. Low intra-class correlation co-efficients (ICC: <0.12) were reported for the residuals for position, supporting the grouping of kicking position in the analysis. All data showed no obvious non-uniformity of error, therefore all parameters were not log-transformed. Magnitudes of the effects (mean differences, SD) were evaluated by standardisation, which was performed by dividing each effect by the observed SD (derived by summing all the between and within-subject variances). A threshold of 0.2 was set as a practically important effect (Bezodis et al., 2018; Hopkins at al., 2009). Threshold values for assessing magnitudes of mean differences were: <0.19, trivial; 0.20 – 0.59, small; 0.60 – 1.1, moderate; 1.2 – 1.9, large; 2.0 – 4.0, very large; and >0.4 extremely large (Hopkins et al., 2009) (**Figure 6.3**). Uncertainty in each effect was expressed as 90% confidence limits and as probabilities that the true effect was substantially positive, negative or trivial (derived from standard errors). These probabilities were used to make a qualitative probabilistic non-clinical magnitude-based inference about the true effect (Hopkins et al., 2009): if the probabilities of the effect being substantially positive and negative were both >5%, the effect was reported as unclear; the effect was otherwise clear and reported as the magnitude of the observed value, with the qualitative probability that the true effect was a substantial increase, a substantial decrease, or a trivial. The scale for interpreting the probabilities was: 25–75%, possible; 75–95%, likely; 95–99.5%, very likely; >99.5%, most likely.

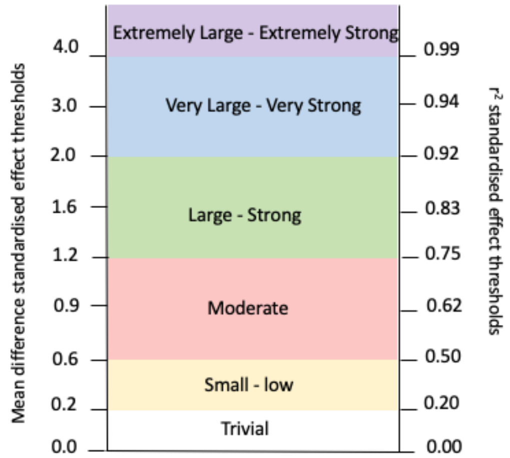


Figure 6.3. Thresholds and associated colour bands used for interpreting the magnitude of the standardised effects throughout this thesis.

To examine the relationship between the lateral distance from the goal centre and each parameter, linear (first - order), quadratic (second - order) and cubic (third - order) polynomial curves were calculated in SAS studio. The choice of which curve fit best described the relationship (linear, second- or third-order polynomial) was based on r^2 values produced, standard error of the estimates (SEE), and residual plots were screened to confirm if the plotted relationship suited the data (Hopkins et al., 2009). Since *r* = variance explained = $SD^2 / (SD^2 + SEE^2)$, substituting threshold values of 0.1, 0.3, 0.6, 1.0 and 2.0 for SEE gives thresholds for interpreting a given r^2 of <0.20, trivial; 0.21 –

0.49, low; 0.50 – 0.74, moderate; 0.75 – 0.92, strong; 0.92 – 0.98, very strong; and >0.99, extremely strong (Hopkins et al., 2009) (**Figure 6.3**).

6.3. Results

6.3.1. Accurate vs inaccurate goal-kicks

Mean ± SD data for kinematic parameters for accurate and inaccurate goal-kicks are reported in **Table 6.2**. During the approach phase, a substantially straighter approach line (3 vs 12º, *most likely* large), with small differences in the length of the last step (1.42 vs 1.5 m, *likely* small) and COM velocity at kick-foot toe-off (3.3 vs 3.6 m, *possibly* small) were evident during accurate goal-kicks compared to inaccurate goal-kicks. During the kicking phase, accurate goal-kicks demonstrated substantially greater ankle plantar flexion (39 vs 30º, a *very likely* large), lower knee (64 vs 69º, *most likely* large) and hip (64 vs 69º, *most likely* large) flexion, with lower linear (foot speed, COM) and angular (ankle, knee and shank) velocities in the kick-leg at BC compared to inaccurate kicks. In addition, accurate goal-kicks demonstrated substantially lower ankle, knee and hip joint range of motion (ROM) in the in the kick-leg throughout the kicking phase (see **Table 6.2** and **Figure 6.4**). Support-leg characteristics differed between accurate and inaccurate goal-kicks; accurate kicks demonstrated lower maximum knee flexion at (43 vs 49º, *most likely* moderate), which was maintained through to BC (38 vs 43º, *likely* large) (see **Figure 6.4**). At the end of follow through, players finished with a straighter-leg line (2 vs 12º, *most likely* large), with greater ankle plantarflexion (26 vs 22º, *possibly* moderate decrease) during accurate goal-kicks compared to inaccurate goal-kicks.

Table 6.2. Kinematic means ± standard deviations (SD) for accurate (hit) and inaccurate (miss) goal-kicks, mean differences between goal-kicks (Hit-Miss), with 90% confidence limits (CL), standardised effect, with 90% CL, and the magnitude of the inference for each parameter. All parameters relate to the kick-leg unless stated.

Parameter	Accurate Mean ± SD	Inaccurate Mean ± SD	Mean Difference, 90% CL	Stand. Effect, 90%	Non-Clinical Inference
Approach phase					
Last step distance (m)	1.42 ± 0.26	1.52 ± 0.30	-0.10, 0.12	-0.36, 0.52	small↓****
Average COM velocity ($m.s^{-1}$)	1.9 ± 0.6	1.9 ± 0.4	-0.0, 0.2	-0.03, 0.23	trivial****
Max COM velocity ($m.s^{-1}$)	4.1 ± 1.5	4.2 ± 1.3	-0.1, 0.6	-0.07, 0.36	trivial***
COM velocity at kick-foot toe-off ($m.s^{-1}$)	3.3 ± 1.4	3.6 ± 1.7	-0.3, 0.7	-0.19, 0.22	small↓****
Approach angle (°)	3 ± 4	12 ± 3	-9, 2	-1.69, 0.21	large↓****
Kicking phase					
At Ball Contact					
Ankle plantar-flexion (°)	39 ± 10	30 ± 4	9, 4	1.20, 0.18	large↑***
Knee flexion (°)	64 ± 6	69 ± 6	-5, 2	-0.91, 0.21	mod↓****
Hip flexion (°)	35 ± 10	40 ± 8	-5, 4	-0.63, 0.36	mod**
Pelvic posterior tilt (°)	49 ± 14	48 ± 15	1, 7	0.06, 0.70	trivial+
Trunk posterior tilt (°)	2 ± 9	3 ± 11	-1, 5	-0.07, 0.86	trivial+
Shank angle (°)	-1 ± 10	-5 ± 9	4, 2	0.52, 0.27	mod↑**
Thigh angle (°)	57 ± 11	58 ± 10	-1, 2	-0.10, 0.19	trivial**
Foot speed ($m.s^{-1}$)	18.0 ± 1.8	19.4 ± 1.4	-1.4, 0.7	-0.89, 0.45	mod↓****
COM velocity ($m.s^{-1}$)	2.3 ± 0.4	2.7 ± 0.3	-0.4, 0.2	-1.20, 0.28	large↓*
Knee angular velocity (°/s)	1433 ± 218	1542 ± 202	-109, 93	-0.64, 0.32	mod↓*
Hip angular velocity (°/s)	56 ± 97	78 ± 100	-18, 45	-0.22, 0.42	small↓**
Shank angular velocity (°/s)	1647 ± 123	1723 ± 132	-76, 38	-0.63, 0.29	mod↓**
Thigh angular velocity (°/s)	136 ± 106	154 ± 113	-38, 37	-0.22, 0.19	small↓***
Ankle angular velocity (°/s)	345 ± 131	433 ± 120	-88, 48	-0.84, 0.45	mod↓ ***
Support-leg ankle angle (-plantar/ +dorsi flexion) (°)	-1 ± 7	1 ± 5	-2, 1	0.10, 0.90	trivial+
Support-leg knee flexion (°)	38 ± 5	48 ± 7	-10, 2	-1.21, 0.30	large↓**
Support-leg hip flexion (°)	15 ± 12	15 ± 11	0, 5	0.00, 0.76	trivial***

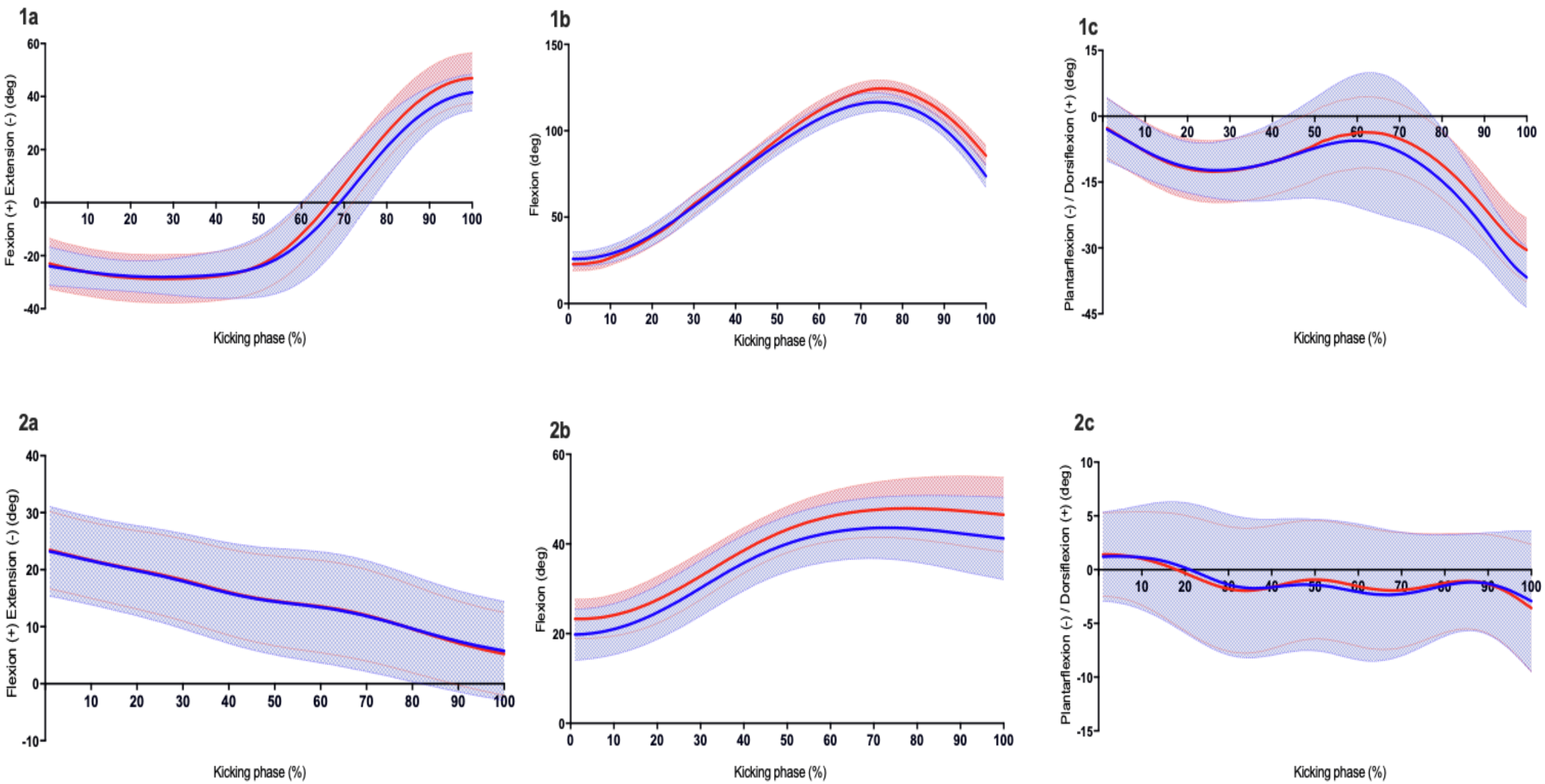
Direction of effect: ↑ positive, ↓ negative; **mod**: moderate
Symbols denote: * possibly, ** likely, *** very likely and **** most likely chance of the true effect was substantial, + true effect was unclear

Table 6.2. *Continued*

Parameter	Accurate Mean ± SD	Inaccurate Mean ± SD	Mean Difference, 90% CL	Stand. Effect, 90%	Inference
Kicking phase					
Support Heel Strike					
Support-leg ankle dorsiflexion (º)	20 ± 25	19 ± 11	1, 8	0.05, 0.10	trivial****
Support-leg knee flexion (º)	23 ± 6	25 ± 4	-2, 3	-0.40, 0.55	small↓**
Support-leg hip flexion (º)	30 ± 9	32 ± 11	-5, 4	-0.19, 0.21	trivial**
Maxima & Minima					
Maximum knee flexion (º)	116 ± 13	120 ± 14	-3, 6	-0.29, 0.36	small↓**
Maximum support-leg knee flexion (º)	43 ± 7	49 ± 7	-5, 3	-0.87, 0.28	mod↓****
Maximum hip extension (º)	29 ± 6	31 ± 6	-2, 3	-0.36, 0.25	small↓****
Range of Motion					
Ankle ROM (º)	32 ± 4	38 ± 8	-6, 2	-1.23, 0.12	large↓****
Knee ROM (º)	50 ± 7	54 ± 9	-4, 4	-0.61, 0.34	mod↓**
Hip ROM (º)	34 ± 9	40 ± 9	-6, 4	-0.69, 0.42	mod↓**
Pelvis ROM (º)	46 ± 14	48 ± 19	-2, 7	-0.11, 0.23	trivial***
Direction (vector path, º)					
Foot path angle at BC	0 ± 2	3 ± 4	-3, 1	-0.92, 0.19	mod↓****
Follow through phase					
Leg position at end of follow through(º)	2 ± 7	12 ± 9	-10, 3	-1.24, 0.20	large↓***
Ankle plantarflexion at end of follow through (º)	10 ± 10	9 ± 15	-6, 6	0.63, 0.23	mod↑***

Direction of effect: ↑ positive, ↓ negative; **mod**: moderate
Symbols denote: * possibly, ** likely, *** very likely and **** most likely chance of the true effect was substantial, + true effect was unclear

Figure 6.4. Group mean ± SD for sagittal hip (a), knee (b) and ankle (c) joint angles curves of the kick-leg (1) and support-leg (2) for accurate (blue line) and inaccurate (red line) goal-kicks during the kicking phase (kick leg toe-off: 0 %, to BC: 100%).



6.3.2. Relationship between technical parameters and accuracy.

The curve estimation analysis between technical parameters and accuracy is reported in **Table 6.3**. After choosing the most appropriate fit for each relationship, there were six strong (five linear and one quadratic) and eight moderate (seven quadratic and one cubic) relationships identified. For the remaining parameters, relationships were classified as low to trivial.

Table 6.3. The relationship between kinematic parameters and accuracy. Linear, quadratic and cubic curve estimations for each parameter (r^2 values (SEE)), with the chosen relationship and magnitude of relationship identified. All parameters relate to the kick-leg unless stated.

Parameter	Relationship 1st order	2nd order	3rd order	Chosen relationship	Intercept	Magnitude of relationship
Approach phase						
Last step distance (m)	-0.21 (0.1)	0.24 (0.1)	0.24 (0.1)	quadratic	$y = -0.0023x^2 + 0.0179x + 1.4686$	low
Average COM velocity (m.s^{-1})	-0.02 (0.5)	0.02 (0.4)	0.03 (0.4)	cubic	$y = -0.0022x^3 + 0.046x^2 - 0.1656x + 3.4175$	trivial
Max COM velocity (m.s^{-1})	-0.29 (0.4)	0.31 (0.4)	0.35 (0.4)	linear	$y = -0.0157x^3 + 0.2365x^2 + 0.0403x + 4.2724$	low
COM velocity at KFTO (m.s^{-1})	-0.27 (0.3)	0.31 (0.3)	0.39 (0.3)	cubic	$y = -0.0114x^3 + 0.1264x^2 + 0.716x + 3.4398$	low
Approach angle (º)	-0.83 (1.1)	0.82 (1.2)	0.63 (1.2)	linear	$y = 1.4178x + 0.43$	strong
Kicking phase						
At Ball Contact						
Ankle plantar-flexion (º)	0.62 (2.4)	0.67 (1.9)	0.65 (2.2)	quadratic	$y = 0.1515x^2 + 1.3959x - 41.911$	strong
Knee flexion (º)	-0.56 (2.7)	0.65 (2.3)	0.68 (2.1)	cubic	$y =-2.17x^3 + 0.1663x^2 + 1.6096x + 58.358$	mod
Hip flexion (º)	0.02 (5.4)	0.03 (4.8)	0.03 (4.6)	cubic	$y =0.0016x^3 - 0.0069x^2 + 0.0638x + 2.6678$	trivial
Pelvic posterior tilt (º)	0.01 (4.4)	0.03 (4.3)	0.16 (4.3)	cubic	$y =0.0386x^3 - 0.766x^2 + 3.5616x + 55.435$	trivial
Trunk posterior tilt (º)	0.18 (1.0)	0.18 (1.2)	0.15 (1.2)	linear	$y =0.1312x + 1.5981$	trivial
Shank angle (º)	-0.57 (4.8)	0.59 (4.8)	0.59 (4.8)	quadratic	$y =-0.0464x^2 - 0.0126x - 1.012$	mod
Thigh angle (º)	-0.25 (3.7)	0.25 (3.6)	0.22 (3.6)	quadratic	$y =-1.362x^2 + 1.4825x + 54.946$	low
Foot speed (m.s^{-1})	-0.83 (0.6)	0.80 (0.7)	0.81 (0.8)	linear	$y =-0.0518x + 18.283$	strong
COM velocity (m.s^{-1})	-0.33 (0.2)	0.35 (0.1)	0.38 (0.1)	cubic	$y =-0.002x^3 + 0.0307x^2 - 0.0687x + 2.3012$	low
Knee angular velocity (º/s)	-0.20 (67)	0.27 (67)	0.26 (68)	quadratic	$y = 0.3507x^2 - 16.266x + 1528$	low
Hip angular velocity (º/s)	-0.26 (28)	0.27 (27)	0.24 (27)	quadratic	$y = -0.236x^2 + 9.2787x + 122.58$	low
Shank angular velocity (º/s)	-0.52 (43)	0.53 (43)	0.53 (43)	quadratic	$y = -0.3967x^2 + 6.6706x + 1634.9$	mod
Thigh angular velocity (º/s)	-0.30 (32)	0.37 (32)	0.36 (32)	quadratic	$y = -0.7366x^2 + 9.0505x + 93.359$	low
Ankle angular velocity (º/s)	-0.63 (38)	0.67 (37)	0.67 (37)	quadratic	$y = -0.0898x^2 + 2.4336x - 0.6136$	mod
SL ankle angle (º)	0.09 (1.0)	0.09 (1.0)	0.08 (1.0)	cubic	$y = 0.0014x^3 - 0.0424x^2 + 0.293x - 0.0433$	trivial
SL knee flexion (º)	-0.64 (1.5)	0.72 (1.4)	0.72 (1.4)	quadratic	$y = -0.5339x^2 + 6.682x + 28.226$	mod
SL hip angle (º)	-0.28 (1.1)	0.37 (1.1)	0.37 (1.1)	cubic	$y = 0.0103x^3 + 0.265x^2 - 0.4593x - 36.939$	low

For linear relationships, a negative sign is added to denote a negative of relationship. **mod**: moderate; **SL**: support leg; **SEE**: standard error of the estimate; **COM**: centre of mass

Table 6.3. *Continued*

Parameter	Relationship			Chosen relationship	Intercept	Magnitude of relationship
	1st order	2nd order	3rd order			
At Support Heel Strike						
SL ankle dorsiflexion (º)	0.03 (1.9)	0.05 (1.9)	0.05 (1.9)	cubic	$y = -0.006x^3 - 0.005x^2 + 1.3992x + 12.896$	trivial
SL knee flexion (º)	-0.08 (1.5)	0.09 (1.5)	0.09 (1.5)	cubic	$y = -0.004x^3 + 0.044x^2 + 0.2686x + 18.927$	trivial
SL hip flexion (º)	-0.02 (0.8)	0.05 (0.8)	0.06 (0.8)	cubic	$y = -0.0166x^3 + 0.2095x^2 - 0.015x + 27.133$	trivial
Maxima & Minima						
Max knee flexion (º)	-0.21 (1.6)	0.27 (1.6)	0.29 (1.6)	cubic	$y = -0.0088x^3 + 0.1092x^2 + 0.1841x + 115.21$	low
Max SL knee flexion (º)	-0.34 (2.2)	0.60 (2.1)	0.60 (2.1)	quadratic	$y = -0.2753x^2 + 3.7763x + 29.233$	moderate
Max hip extension (º)	-0.19 (2.5)	0.22 (2.4)	0.33 (2.4)	cubic	$y = 0.0157x^3 - 0.3191x^2 + 1.2419x - 30.298$	low
Range of Motion						
Ankle ROM (º)	-0.43 (1.3)	0.56 (1.3)	0.56 (1.3)	quadratic	$y = -0.1594x^2 + 2.5691x + 28.164$	mod
Knee ROM (º)	-0.14 (2.3)	0.24 (2.3)	0.25 (2.3)	quadratic	$y = 0.0079x^3 - 0.2184x^2 + 1.8215x + 89.04$	low
Hip ROM (º)	-0.52 (2.4)	0.75 (2.3)	0.69(2.4)	quadratic	$y = -0.3165x^2 + 5.3642x + 26.296$	strong
Pelvis ROM (º)	-0.02 (3.0)	0.03 (3.1)	0.03(3.2)	cubic	$y = -0.016x^3 + 0.2964x^2 - 0.8621x + 36.517$	trivial
Direction (vector path, º)						
Foot path angle at BC	-0.92 (0.2)	0.89 (0.5)	0.84 (0.5)	linear	y = 0.5899x + 0.0155	strong
At the end of the Follow through phase						
Leg position(º)	-0.73 (1.7)	0.73 (1.8)	0.73 (1.8)	linear	$y = 56.67x + 2.491$	strong
Ankle plantarflexion (º)	-0.75 (2.4)	0.73 (2.5)	0.73 (2.5)	linear	$y = 1.6024x - 1.977$	strong

For linear relationships, a negative sign is added to denote the direction of the relationship. **mod**: moderate; **SL**: support leg; **SEE**: standard error of the estimate; **COM**: centre of mass

6.4. Discussion

The aims of this research were to investigate if kinematic differences exist between accurate and inaccurate goal-kicks on a group-basis, and examine the relationship between technical factors and goal-kicking accuracy. Findings in this research indicated that many factors influence goal-kicking accuracy in AF, ranging from technical errors in the players' approach line, support-leg mechanics, kick-leg swing motion, to the final position of the kicker during their follow through. In addition, a number of substantial linear and quadratic relationships were reported between technical parameters and accuracy.

6.4.1. The approach phase

The angle of a player's approach differed between accurate and inaccurate goal-kicks. A substantially straighter approach line (3 vs 12°, *most likely* large difference) was evident in accurate goal-kicks compared to inaccurate goal-kicks, supporting previous findings by Ball et al. (2002). Furthermore, a strong linear relationship ($r^2 = 0.83$) was reported with increasing approach angle, indicating that a straighter approach line was more beneficial for accurate goal-kicking in AF (**Figure 6.5**). These findings are in agreement with previous scientific (Baker & Ball, 2002; Ball et al., 2002) and coaching recommendations (Hosford & Meikle, 2007; Parkin et al., 1984). Interestingly, no kicks were missed when the approach angle was less than 4.7° (**Figure 6.5**), emphasising the benefit of players adopting a straighter line of approach. Adopting a straighter line of approach is suggested to increase the planarity of the goal-kick action, through limiting the rotation of the kick-leg around the vertical axis through the body (Alcock et al., 2012; Anderson & Dörge, 2011; Baker & Ball, 2002; Ball et al., 2002; Scurr & Hall, 2009). This in turn, would enable players to apply a more direct line of force to the ball in respect to the ball’s centre of mass (Baker & Ball, 1996), which according to the oblique impact theory directly influences the ball’s flight characteristics (spin qualities and flight path trajectory) (Holmes, 2008). Post-hoc analysis supported this concept by indicating a strong relationship between foot-path angle at BC (smaller foot-path angle reflects a more direct line of contact with the ball) and approach angle (r_2 = 0.77) (**Figure 6.5**). Theoretically, a more direct (less angled) striking force applied close to the ball’s centre of mass would propel the ball straight towards the target, with minimal medio-lateral spin (side spin) (Alcock et al., 2012; Asai et al., 2002; Peacock & Ball, 2017). As a result, this would reduce the lateral deviation of the ball’s flight trajectory from the centre of the target (Alcock et al., 2012; Baker & Ball, 1996), thus helping to achieve an accurate kick. Similar findings have been documented in soccer kicking, (Alcock et al., 2012), were a straighter ball flight trajectory (3.02 ± 0.36 º vs 7.35 ± 0.20º, $p < 0.001$) was achieved when a straighter line of approach was adopted by players (18.0 ± 7.3º) compared to a curved approach line. The authors suggested that alterations in the approach line directly influenced the contact point on the ball (i.e. direction of the application of force on the ball), which resulted in different the ball spin and flight path trajectories. This suggests that making adjustments to a player’s approach line may be important in determining the success of a goal-kick, through triggering modifications to other aspects of a player’s technique (such as kick-leg motion). Further examination of ball flight characteristics and ball spin is warranted to support these findings.

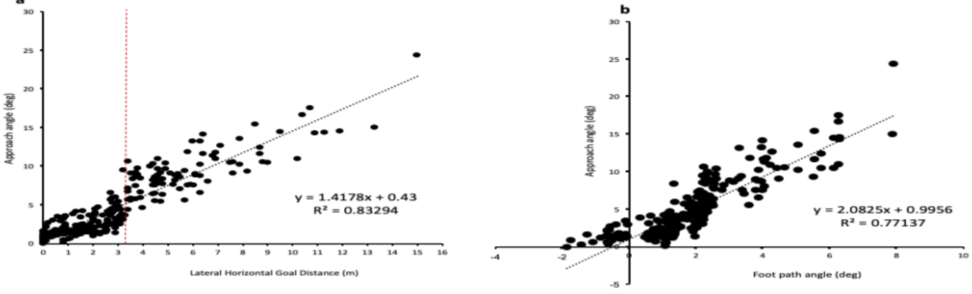


Figure 6.5. Relationship between (**a**) approach angle and accuracy (values to the right of the dashed indicate missed kicks) and (**b**) approach angle and foot-path angle).

6.4.2. The kicking phase (from kick foot toe off until ball contact)

Kick-leg mechanics

Accurate goal-kicking in AF requires increased control and regulation of the kick-leg motion during the kicking phase. Findings in this study indicated that accurate goal-kicks exhibited substantially less hip (34 vs 40°) and knee (34 vs 40°) ROM throughout the swing phase, with slower joint (knee: 1433 vs 1542 °/s; hip: 56 vs 78°/s) and segment (shank: 1647 vs 1723°/s; thigh: 136 vs 154°/s) angular velocities, compared to inaccurate goal-kicks. Similar findings have been reported when players kicked for accuracy in soccer (Button et al., 2005; Lees & Nolan, 2002; Ghiedi & Sadeghi, 2010; Katis et al., 2012) and rugby union (Sinclair et al., 2017). Constraining the number of joints acting in the system through reducing joint ROM and reducing the speed of the movement has been linked to increased control and regulation of the motion of the kicking limb, in an attempt to better position and orientate kicking limb for ball impact (Lees & Nolan, 2002; Lees et al., 2010). Theoretical literature would suggest that this strategy may be representative of the freezing of the redundant degrees of freedom (DOF) in a task-specific functional way (Bernstein, 1967; Berthouse & Lungarella, 2004; Caillou et al., 2002; Ko et al., 2003; Latash, 2008; Yang & Schol, 2005; Vereijken et al., 1992). In that, the nervous system may arrive at the desired movement solution by tightly controlling a specific task-relevant biomechanical variable (i.e., hip ROM) (Yang & Schol, 2005). In addition, the decreased joint and segment angular velocities may also be representative of the speed-accuracy trade-off, or Fitts's law (Fitts, 1954). This theory identifies an inverse relationship between the speed at which a skill can be performed and the accuracy that can be achieved (Fitts, 1954). Biomechanically, reductions in the speed of a movement is fundamentally linked to lower ROM (Parrington et al., 2015; Knudson, 2007). As a result, this trade-off may have prompted the changes in hip and knee ROM during accurate goal-kicks. Findings would indicate that players may be actively controlling the motion of the kick-leg, in an attempt to control the endpoint position of the foot for BC, to help improve accuracy.

Maintaining the movement of the hip within a specific range (20 - 39º) has advantages for goal-kicking accuracy. A strong quadratic relationship (r_2 = 0.75) was identified between hip ROM and accuracy (**Figure 6.6**). It is logical that increasing the ROM of the hip joint would lead to higher joint and angular velocities within the kick-leg (Knudson, 2007). Which according to the speed-accuracy trade-off (Fitts, 1954), would lead to decreased accuracy of the goal-kick. While insufficient ROM may constrain the movement of the kick-leg too much may negatively influence the final configuration of the kick-leg at ball impact. This would potentially result in a more proximal impact location (on the foot) between the ball and foot (Peacock & Ball, 2017), which would lead to undesirable alterations in the ball velocity and backspin, and consequently having a negative impact on kick accuracy (Peacock & Ball, 2018b, 2018c). Furthermore, examination of hip range of motion indicated that there was no association between changes in hip ROM and missing to the left or right of the target (**Figure 6.6).**

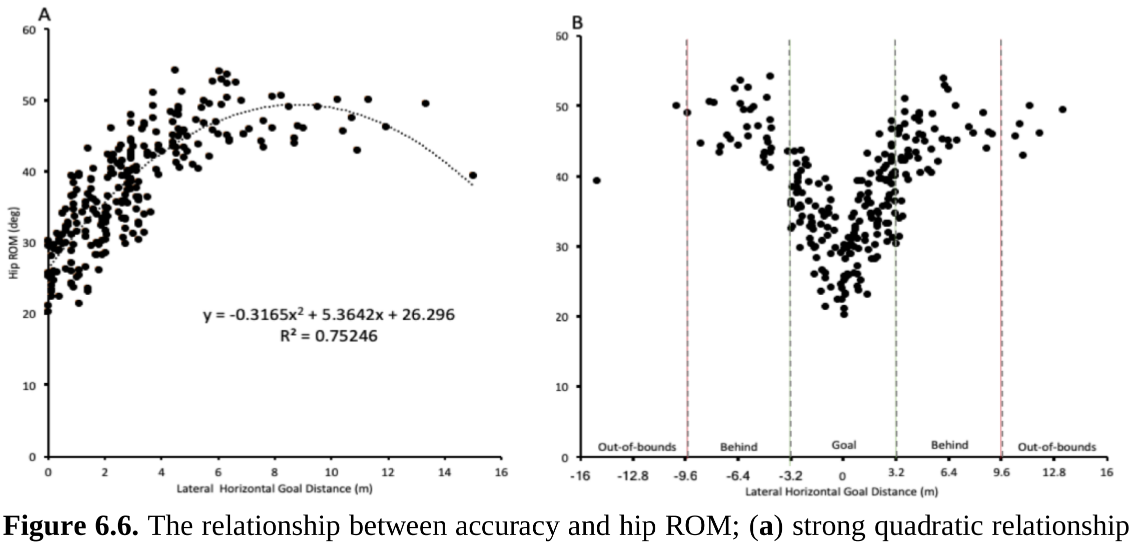


Figure 6.6. The relationship between accuracy and hip ROM; (**a**) strong quadratic relationship between hip ROM and accuracy, and (**b**) alterations in hip ROM in relation to left and right side of goals.

Adjustments to the kick-leg motion were more apparent during the final stage of the swing phase (60 - 100%). Finding indicated that the initial joint configuration of the hip, knee and ankle at the start of the kicking phase was not substantially different between accurate and inaccurate goal-kicks. Conversely, substantial alterations in joint motions occurred in the final phase (60 - 100%) of the movement (**Figure 6.4**), with players exhibiting a more extended posture (greater ankle plantarflexion, knee and hip extension in the kick-leg, with a more extended support-leg) at the BC in accurate goal-kicks. Alterations to kick-leg mechanics during the final stage of the swing phase (60 - 100%) has been previously linked to a motor control strategy to enhance kicking accuracy (Lees et al., 2010; Texieria et al., 1999). In the case of the goal-kick, it is logical to suggest that players may be making active adjustments to kick-leg mechanics in the final phase of the movement, to compensate for changes in ball drop characteristics which occurs around 20 - 40% of the movement. This has been suggested to be is an important feature of the concept of motor abundance and functional synergy (Latash et al., 2003); were if the contribution of one component (i.e. ball drop characteristics) at a particular time has a perturbing effect on an important performance variable (i.e. ball impact characteristics), other components are likely to modify their contributions to stabilise the desired performance outcome. This finding would suggest that kickers may be actively adjusting and controlling the motion of their kick-leg in the final phase of the motion according to ball drop position, in order to make good contact with the ball. Similar kinematic adjustments have been reported in other interceptive tasks, such as the tennis serve (Whiteside et al., 2013). The increased variability (as indicated by higher SD) in technical parameters at BC in accurate would provide support for the idea that players are making adjustments based on ball drop characteristics. A player's ability to control and drop the ball optimally, along with coordinating the interceptive task of striking the ball with the foot, may play a substantial role in the outcome of a goal-kick. Both ball orientation and the nature of impact between the ball and the foot have been considered as important factors for punt kicking with ovoid shaped balls (Ball, 2008, 2011; Peacock & Ball, 2018c). As accurate kicking is achieved by imparting an appropriate combination of flight characteristics on the ball (Peacock & Ball, 2018c), future research is warranted to examine the technique of controlling and dropping the ball, along with the interceptive task of striking the foot, as it may provide an additional insight and understanding of important factors which influence goal-kicking performance in AF.

Ankle and foot motion play a vital role in the success of a goal-kick. Players had substantially lower ankle ROM (32 vs 38º), lower foot speeds (18.0 vs 19.4 m.s-1), lower ankle angular velocity (607 vs 673 º/s), with higher ankle plantar flexion (39 vs 30º) at BC and a straighter foot-path at BC (0 vs 3º) in their accurate kicks compared to their inaccurate. In addition, strong linear relationships were reported between footspeed (r^2 = 0.75) and foot-path angle at BC (r^2 = 0.91), with a moderate quadratic relationship identified for ankle plantarflexion at BC (r^2 = 0.68) (**Figure 6.7**). No association between changes in these technical parameters and missing to the left or right of the target was identified. These adjustments in the distal segment may be indicative of an active strategy utilised by players to improve accuracy when kicking for goals.

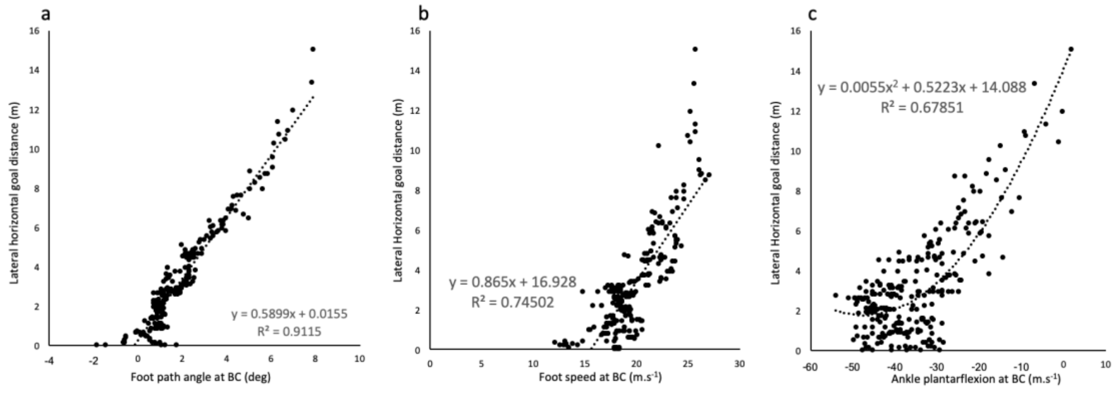


Figure 6.7. The relationship between accuracy and (**a**) footpath angle at BC, (**b**) foot speed at BC, (**c**) ankle plantarflexion at BC.

A number of possibilities exist for the ankle and foot strategy adopted by players during accurate goal-kicks. Firstly, decreased ankle ROM and angular velocity, along with slower foot speeds may be utilised to increase stabilisation and control of the foot in preparation for ball contact (Lees & Nolan, 2002). As previously discussed, this adjustment would represent a task dependent freezing of the redundant DOF, in order to attempt to stabilise the performance outcome (Berstein, 1967; Ko et al., 2003; Latash, 2008; Latash, 2012; Yang & Schol, 2012) and may be also representative of the speed-accuracy trade-off (Fitts, 1954). By impacting the ball, a player imparts a combination of flight characteristics which ultimately determine the outcome of the kick (Peacock & Ball, 2018b). Thus, controlling the motion of the foot so it is in an optimal position for impact, will enable players to impart the desired flight characteristics on the ball to achieve a successful outcome. Similar kinematic adjustments have been identified in soccer (Lees & Nolan, 2002; Gheidi et al., 2010) and rugby kicking (Sinclair et al., 2017), where accuracy was associated with lower ankle ROM and slower ankle and foot speeds. Similarly, findings have been reported in other striking tasks (i.e. handballing: Parrington et al., 2015; tennis serving: Knudson & Blackwell, 2005; ice hockey: Michaud- Paquette et al., 2009), where decreased joint ROM and velocities (linear and angular) of the distal segment have been associated with improved accuracy.

Secondly, increasing the rigidity within the ankle and foot segment has been associated with increased impact efficiency and accuracy through increasing the effective mass of the striking limb (Asami & Nolte, 1983; Ball et al., 2010; Peacock & Ball, 2018c; Plagenhoef, 1971; Sterzing & Hennig, 2008; Tol et al., 2002). This can be achieved through maintaining and increasing plantarflexion of the ankle joint prior to and through ball impact (Asami & Nolte, 1983; Ball, 2010; Kellis & Katis, 2007; Lees & Nolan, 1998; Peacock & Ball, 2017; Peacock & Ball, 2018c, 2017; Sterzing & Hennig, 2008;

Sterzing et al., 2009). It is also suggested that increased ankle joint plantarflexion enables players to reduce the uneven pressures across the anterior aspect of the foot (caused by bony prominences) enabling players to apply a more homogenous force to the ball to achieve a straighter ball flight trajectory (Peacock et al., 2017; Sterzing & Hennig, 2008; Hennig, 2011).

Lastly, players may be actively controlling the motion of the kick-foot to ensure a straighter line of force is applied to the ball. As previously discussed, a more direct line of contact (a smaller foot-angle at BC) would propel the ball straight towards the target with minimal medio-lateral spin. This provides biomechanical support the coaching cue "strike through the ball in the direction of the target" (Hosford & Meikle, 2007; Parkin et al; 1984). Alterations in foot and ankle mechanics appear to play an important role in accuracy. It may be that a combination of each of these adjustments in the distal segment (ankle and foot) is required to to improve accuracy when kicking for goal in AF. Further work is required to substantiate this strategy through examination of impact characteristics, to better understand the mechanism underlying the ankle and foot strategy.

Support-leg mechanics

Support-leg knee motion differed between accurate and inaccurate goal-kicks. During accurate goal-kicks, players demonstrated a more extended (less flexion) knee at SHS (23 vs 25°) that remained more extended during the stance phase until BC (38 vs 48°) compared to inaccurate goal-kicks (**Figure 6.4**), supporting previous findings in distance kicking (Ball, 2013). Ball (2003) suggested this could be indicating a stronger and more stable stance-leg during the kick-action. This explanation also shares similarity with the 'increased stability' suggestions in soccer instep kicking (Lees et al., 1998, 2010).

Increasing stability is suggested to be a fundamental prerequisite in the organisation of a skilled movement, in order to improve accuracy (Massion & Deat, 1991; Reed, 1989; Roberts, 1995). Greater stabilisation of the support-leg would provide the kicker with a stronger base of support to facilitate better control and regulation of the kick-leg motion during the kicking phase (Ball, 2013; Chew-bullock et al., 2012; Inoue et al., 2014; Lees et al., 1998, 2010; Putnam, 1991). Researchers have argued that the balance/stability of the support-leg is vital to kicking performance (Ball, 2013; Chew-bullock et al., 2012; Inoue et al., 2014; Lees et al., 1998, 2010). Thereby, these findings may also provide preliminary support for the importance of balance ability in goal-kicking performance in AF.

Maintaining the movement of the support-leg knee within a specific range (36 - 45°) may have advantages for accuracy. A moderate quadratic relationship (r^2 = 0.60) was identified between support-leg knee flexion and accuracy (**Figure 6.8**). Further examination identified there was a trend with support-leg knee flexion and missing to the right or left of goals (**Figure 6.8**). Players had a tendency to display lower knee flexion when they missed to the left of goals, while higher knee flexion was evident when players missed to the right of goals. One possible explanation for this may be related to alterations in swing plane characteristics (Alcock et al., 2012; Bezoids et al., 2018), as a result of the position achieved from the support-leg. Having a more extended position (less knee flexion) would potentially allow more rotation of the kick-leg around the vertical axis, resulting in a more curved movement path of the kick-leg. This would potentially result in a more lateral impact location, which in turn would cause a more medio-lateral spin on the ball (Peacock & Ball, 2017). As a result, this would cause the ball's flight path to deviate left of the target centre (Alcock et al., 2012; Baker & Ball, 2007; Knudson, 2007). Findings by Alcock et al. (2012) support this possibility as the authors documented a more curved ball flight path trajectory when the kicking-leg swing plane was steeper. Based on these findings, coaches working with kickers who have a tendency to miss to the left or right of the target, could aim at altering support-leg mechanics accordingly (either promoting an increase in knee flexion or decrease depending on the player's performance) as a potential avenue for improvement.

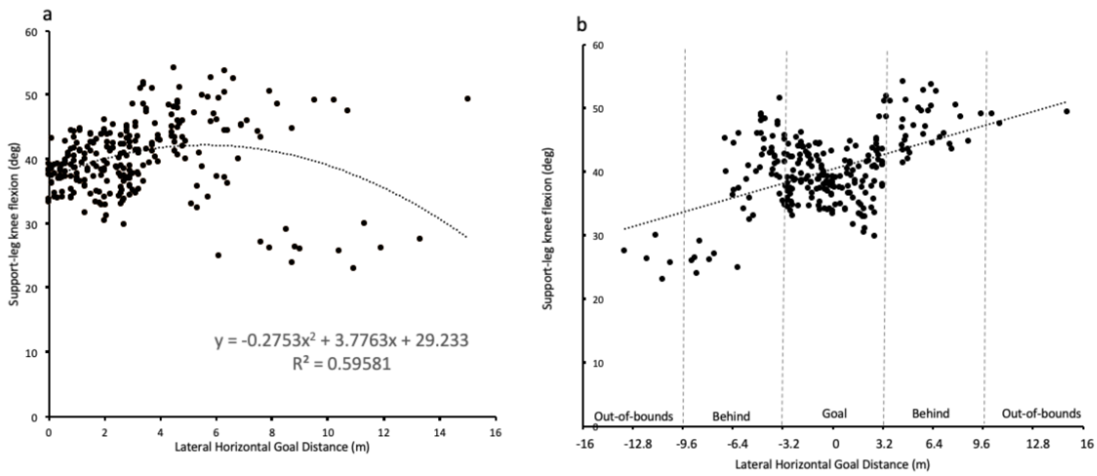


Figure 6.8. The relationship between accuracy and support-leg knee flexion; (**a**) a moderate quadratic relationship between support-leg knee flexion and accuracy, and (**b**) alterations in support-leg knee flexion in relation to left and right side of goals.

However, the findings in this study are in contrast to the suggestion that a more flexed support-leg is better for kicking accuracy in AF (Blair et al., 2017; Dicheria et al., 2006). A plausible reason for the conflicting findings may be directly related to the shorter distances used between the accuracy tasks (15 m: Dicheria et al., 2006; 20 m: Blair et al., 2017) compared to the distance (30 m) used in this study. Researchers have reported that when kicking distance increases, players are required to increase foot speed and ball speed accordingly, in order to meet the distance demand (Baker & Ball, 1996; Ball, 2008; Ball, 2011; Ball, 2013; Peacock & Ball, 2018b; Peacock et al., 2017). Lifting the whole-body upward through the motion of the support-leg (through knee extension) has been suggested to be an effective action to assist with maintaining a higher hip position, which in turn, helps generate faster foot speed's through achieving a more extended kick-leg (and hence a longer lever arm) during the swing phase without striking the ground (Augustus et al., 2016; Ball, 2013; Inoue et al., 2014). Furthermore, greater active contractions and extension of the support-leg musculature during the stance phase facilitates greater power flow across the pelvis and passive acceleration of the lower leg to maximise foot linear and angular velocities at BC (Augustus et al., 2016). This explanation is partly supported by the higher foot speed's (18.0 $m.s^{-1}$) reported in this study compared those reported from Blair et al. (2017) (13.2 $m.s^{-1}$). Another possible explanation may be that when kicking over shorter distances players might have purposely attempted to increase the relative target area by adopting a flatter ball flight trajectory to improve accuracy (Peacock et al., 2017). A lower ball flight trajectory would be achievable though adopting a more flexed kicking position (Peacock et al., 2017), which could be partly achieved through increased support-leg flexion. Conversely, when kicking at further distances from goals, achieving a higher ball flight trajectory (lofted kick) may be more beneficial to achieve the distance, as well as ensuring accuracy. This may not be surprising given that alterations in the task constraints (such as, the distance of the goal-kick) were found in Chapter 5 to trigger substantial differences in the way posture is organised to facilitate movement when achieving the same performance outcome (Davids et al., 2003; Davis & Burton, 1991; Gagen & Getchell, 2004). These findings may be indicative that variations in the task constraints leads to significant changes in the movement pattern required to complete the task, despite achieving the same performance outcome. It is possible that this represents a continuum of technique strategy, where at one end (short kicks for accuracy) a more flexed support leg is beneficial while at the other end (maximising distance) a more extended support leg is beneficial. In between, depends on how far the kick is required to travel. Examination of accurate goal-kicking technique over a range of distances would provide important information on how players adapt to different task constraints when achieving a stable performance outcome (such as an accurate kick). This is an important future direction for this work, as goal-kicks are typically performed over a range of distance from goals during a match.

6.4.3. The follow through phase

The motion of the kicker through the follow-through phase cannot directly influence the outcome of a goal-kicking as the ball is already in projectile motion, however, it is suggested to influence the motion path and the kinematics of the kick-leg prior to impact (Baker & Ball, 1996; Bezodis et al., 2017). Thereby, it can provide useful information regarding a player's goal-kicking performance. Finding in this study indicated that during accurate goal-kicks, players finished with their leg in-line towards the target (indicated by a smaller leg position angle: 2 ± 7º) with greater ankle plantarflexion (24 ± 10º), at the end of follow through. Conversely, player's had a tendency for the leg to swing across the mid-line of the body (12 ± 9º), with less ankle plantarflexion (18 ± 15º) in inaccurate kicks. These findings are in agreement with previous kicking literature in AF (Baker & Ball, 1996; Ball et al., 2002). Finishing with the toe pointing towards the goals is suggested to reflect a more planar swing motion of the kick-leg during the kicking phase (Baker & Ball, 1996). It is logical to assume that if a player applied a more direct line of force to the ball (through increasing the planarity of the kicking action) so that it propels straight towards the target, the kick-leg would follow in a similar motion path during the follow through. Post-hoc analysis supported this concept through reporting a strong relationship (r^2 = 0.61) between kick-leg position and foot-path angle at BC. In contrast, swinging the kick-leg across the mid-line of the body would indicate that kick-leg followed a curved path (greater rotation of the kick-leg around the vertical axis through the body) during the kicking phase. This would potentially be more detrimental to goal-kicking accuracy, as it would result in an angled force being applied to the ball, which in turn, would produce more medio-lateral spin on the ball, resulting in a curved ball flight trajectory away from the centre of the target (Alcock et al., 2010). In addition, higher ankle plantarflexion during the follow is suggested to provide an indication that players maintained a more rigid ankle through the kicking phase (Hosford & Meikle, 2007; Parkin et al., 1984). As maintaining and increasing plantarflexion of the ankle joint prior to and through ball impact has been linked to increasing the rigidity within the ankle and foot segment (Asami & Nolte, 1983; Ball et al., 2010; Peacock & Ball, 2018c; Plagenhoef, 1971; Sterzing & Hennig, 2008; Tol et al., 2002), to impact efficiency and accuracy (Asami & Nolte, 1983; Ball, 2010; Kellis & Katis, 2007; Lees & Nolan, 1998; Peacock & Ball, 2017; Peacock & Ball, 2018c, 2017; Sterzing & Hennig, 2008; Sterzing et al., 2009). The findings in this thesis provide scientific evidence to support the appropriateness and potential influence of the currently used coaching cue "finish with your toe pointing towards goals" (Hosford & Meikle, 2007; Parkin et al., 1984), thereby helping bridge the gap between biomechanical research and coaching practice. Interventions to improve kicking performance, through manipulating follow through characteristics has been identified as an area that warrants further investigation (Bezodis et al., 2018). Given the association with follow-through characteristics and the movements during the kicking phase documented in this thesis, examination of follow-through manipulations is an area worthy exploring.

6.4.3. Limitations and future directions

The investigation of joint kinematics was used to further advance the biomechanical understanding of factors which influence goal-kicking technique and accuracy in AF. Whilst the use of joint kinematics provided greater understanding of the motion of a kickers joints and segments, the underlying kinetics, along with the nature of the muscle activation patterns that can help explain how this motion is achieved (Ball, 2013; Lees et al., 2010; Katis et al., 2013). Attempting to link the kinematic factors identified in this thesis with the kinetic factors and muscle activation patterns is an important next step for future research, as this can help further understand the differences identified, to provide additional insight into how they might be improved.

This thesis chose to examine the direct mechanisms associated with accurate goal-kicking, however it is acknowledged that understanding how a player varies their technique may also help explain changes in goal-kicking accuracy (Peacock & Ball, 2018c). Literature has suggested that to achieve accurate end-point positions, skilled players do not consistently produce an 'ideal' technique (Glazier et al., 2015). Theoretical literature suggests that as a person becomes more skilled in a task, the constraints imposed on the DOF of the movement are gradually released and the movement becomes more fluid (Bernstein, 1967). In the context of football kicking, researchers have suggested that increased variability is used by players to adapt to different gameplay situations (such as fatigue, surface conditions and playing environment) (Ford & Sayers, 2015), which can be either functional or dysfunctional, depending on the event or phase of the kicking action (i.e. proximal segments, end-point position) (Peacock et al., 2018; Ford & Sayers, 2015). As a result, varying level of functional/dysfunctional variability (through using multiple technical solutions) would allow them to be more adaptable to changing game situations in order to maintain consistently in the outcome measure (i.e. accuracy) (Peacock et al., 2018). Initial examination of the standard deviations in this research would indicate that variability changes throughout the kicking phase and may have influenced kicking accuracy, however this warrants further investigation.

6.4.4. Coaching recommendations

Based on the current findings, a number of practical implications exist for the coaching of the goal-kicking skill:

1. The findings identified the importance of increasing the planarity of the goal-kicking action. Thereby, to improve performance, coaches should provide specific feedback to players regarding the motion path of the kick-leg. Emphasise the importance of a straight approach line and instructing players to “finish with their toe pointing towards goals” and “strike through the ball in the direction of the target” may be an effective instruction in order achieve straighter foot swing plane to increase the chances of a straighter kick.
2. It was also identified that the control and regulation of the joints within the kick-leg are important in accurate goal-kicking. Given that a lack of practice is believed to influence the control of the proximal joints, with less precise control and regulation resulting from reduced practice hours (Hore et al., 1996), it would be beneficial to increase the number of goal-kicks performed during practice.
3. Better kicking performance was achieved when players actively controlled the motion of the ankle/foot during the kicking phase. This can be achieved through maintaining and increasing plantarflexion of the ankle joint prior to ball impact. Use of the coaching cue ‘kick with a firm foot’ may be an effective instruction to encourage players to make the kick foot and ankle more rigid, to help improve impact efficiency (Hosford & Meikle, 2007; Parkin et al., 1984). Practically, this means that coaches can assess and analyse the foot/ankle motion to provide useful feedback to players regarding their kicking (Peacock & Ball, 2018c). Ball et al. (2010), suggested that players with low rigidity about the ankle should include strength training in order to improve this aspect of kicking.

4. Conditioning the support-leg to maintain an extended position may assist kickers attain a stronger base of support to facilitate a more controlled kick-leg motion. Ball (2013) suggested the use of task-specific movement, such as single-legged landing task, whilst maintaining a more extended knee (knee angle more than 36°) may assist in developing this strength using similar motor pattern. In addition, use of other dynamic and static tasks, such as single-leg hopping, swinging the kick-leg, lateral lunges with a knee drive may be effective in improving the strength in the support-leg.
5. Examination of inaccurate goal-kicks provided an indication of what technical errors player make when they miss the goals. These findings can also be used by coaches and practitioners to prompt modifications to a player's technique to reduce the presence of such undesirable technical factors.

6.5. Conclusion

Kinematic differences were identified between accurate and inaccurate goal-kicks on a group-basis. Accurate goal-kicks were associated with substantially lower kick-leg ankle, knee and hip ROM, a more direct foot path (0º vs 3º), substantially greater ankle plantar flexion (39º vs 30º) and lower knee flexion (63º vs 69º), with lower joint (knee) and segment (shank) velocities in the kick-leg at BC compared to inaccurate kicks. Support-leg characteristics differed between accurate and inaccurate kicks; accurate kicks demonstrated lower hip (28º vs 30º) and knee flexion (SHS: 23º vs 27º; BC: 38º vs 48º). In addition, players exhibited a substantially straighter approach line (6º vs 12º) and players finished with a straighter-leg line (8º vs 15º) with a greater plantar flexed ankle (26º vs 22º) during accurate kicks. In addition, a number of substantial linear and quadratic relationships were reported between technical parameters and accuracy.

6.6. Contribution of Chapter to the Aims of the Thesis

The specific aims of Chapter 6 were to compare and identify if kinematic differences exist between accurate and inaccurate goal-kicks, and examine the relationship between technical factors and goal-kicking accuracy. The findings of Chapter 6 contribute to answering the second main aim of this thesis, indicating that many factors influence goal-kicking accuracy in AF, ranging from technical errors in a player's approach, their support-leg configuration, kick-leg swing motions, through to their final position at the end of follow through. Further discussion of the technical factors associated with accurate goal-kicking can be found in Chapter 8 (**Section 8.2.** *pp 186 – 194)*. In this Chapter, several substantial kinematic differences between accurate and inaccurate kicks have been identified and discussed on a group-basis. However, in order to understand if these observed differences are consistent across individuals, an individual-based analysis is required, which will be explored in Chapter 7. In addition, further analysis of the results indicated that many individual specific differences were evident in the data set, resulting in some parameters being non-substantial on a group basis, however, on an individual level these may represent important performance factors. Understanding if individual-specific differences exist in goal-kicking is an important question to address. Therefore, Chapter 7 goal-kicking will explore kinematic differences between accurate and inaccurate goal-kicks on an individual level.

Chapter 7: Biomechanics of Accurate and Inaccurate Goal-Kicking in Australian Football: Individual-Based Analysis

7.1. Introduction

Individual-based analysis (evaluation of a problem within a single-subject) has been highlighted as an important component which should form part of a biomechanical analysis of a skilled movement (Ball & Best, 2012; Ball et al., 2003a, 2003b; Bates et al., 2004; Caster & Bates, 1995; Dufek et al., 1995). Whilst a group-based analysis can provide important information related to a skill, biomechanical investigations have shown that individual analyses can also detect important technical characteristics of a performance that might have been masked in the group-based analysis (Ball & Best, 2012; Ball et al., 2003a, 2003b; Bates & Stergiou, 1996; Dufek et al., 1995; James & Bates, 1997; Miller & Schwarz, 2018). For example, in golf, Ball & Best (2012) reported individual-specific relationships with centre of pressure parameters and club head velocity, with golfers returning different combinations of significant factors that were not evident on a group-basis (Ball & Best, 2007). Using only group-based analysis, these factors would not have been identified, and therefore not offered possible technical areas for improvement specific individuals.

Researchers have highlighted the need for the inclusion of an individual-based analysis when the examining technical aspects of punt kicking in AF (Ball, 2008, 2013; Ball & Blair, 2018; Ball et al., 2002; Blair et al., 2018). In an initial examination of kinematic differences between accurate and inaccurate goal-kicks in two junior AF kickers (Blair et al., 2017), individual differences were evident between players. Player one demonstrated significantly slower foot speeds (p = 0.04, d= 0.4) and shank angular velocities (p = 0.02, d = 0.6) during accurate goal-kicks, while an opposite relationship was evident in player two (higher foot speeds: p = 0.01, d = 1.2; higher shank angular velocities: p = 0.02, d = 0.9). The authors proposed that further work was required in a bigger sample to examine if individual strategies are characteristic of goal-kicking in AF. Individual-specific differences have also been reported in elite AF players when kicking for maximal distance (Ball, 2008) and between preferred and non-preferred leg kicks during a sub-maximal kicking task (Ball, 2008). These studies provide strong evidence for the existence of individual strategies in kicking in AF.

There is also evidence of individual-specific findings in rugby (Ball et al., 2013) and soccer kicking (Anderson & Dörge, 2011; Lees & Nolan, 1998). In rugby league, individual differences were found between four elite kickers when kicking towards goals (Ball et al., 2013). Amongst the group, preparation time (5 – 10 s), run-up (3 - 8 steps) and approach angle (20 - 41º) varied. Individual-specific patterns were also reported for support foot position and arm motion between successful and unsuccessful goal-kicks, however no clear patterns emerged between players. Based on these findings, Ball and colleagues (2013) stated goal-kicking technique was individual and it is clearly important to coach the skill on an individual basis. In soccer, Lees and Nolan (1998) reported individual differences between two professional soccer players when taking accurate kicks. These differences were evident in the speed of the movement (one player produced faster knee angular velocities, ankle and foot speeds under both conditions compared to the other player) and the orientation of the kick-leg at impact (one player was more upright in the sagittal plane but leaning more to the support-leg compared to the other player). These studies also provide an indication of the presence of individual patterns in kicking.

In other skilled movements, such as, pistol shooting (Ball et al., 2003b), golf swing (Ball & Best, 2012), javelin throwing (Morris et al., 1997), volley ball spike (Dufek & Zhang, 1996) and swimming (Tor, 2016), use of an individual-based analysis has been shown to provide important technical information that was not evident in a group-based analysis. In an elite sport example, Ball et al. (2003a) examined rifle shooters (n = 6 elite) on a group and an individual basis. While there were no significant relationships between body sway and performance on a group-basis, all shooters returned significant correlations when the relationships were examined on an individual basis (Ball et al., 2003a). The authors suggested individual-based analysis is most appropriate in terms of aiding improvements in performance for an individual, and should form part of performance-based biomechanical analysis (Ball & Best, 2012; Ball et al., 2003a, 2003b). These studies provide strong support for the existence of individual strategies across a range of skills.

Understanding if individual-specific differences exist in goal-kicking is an important question to address, as it will directly affect how the kicking skill should be coached. Therefore, the purpose of this research was to extend the findings in Chapter 6 and examine goal-kicking technique on individual-basis. The specific aims were to (1) compare and identify if kinematic differences exist between accurate and inaccurate goal-kicks, and (2) examine the relationship between technical factors and accuracy on an individual-basis.

7.2. Methodology

7.2.1. Experimental protocol and data analysis

The participants, testing procedure, experimental set-up and data analysis were consistent with the methodology reported in Chapter 6 (see **sections 6.2.1, 6.2.2, 6.2.3** and **6.2.4**, *pp. 126 - 130*).

7.2.2. Statistical analysis

Data were divided into two sets for subsequent analysis. The first data set was divided into accurate vs inaccurate goal-kicks for each player (see **Appendix D, Table 3,** *pp. 251*, for each player's accuracy scores). Subjects 3 and 15 were excluded from the hit vs miss analysis as they had successfully converted most of their goal-kicks with few missed shots. Individual differences between accurate and inaccurate goal-kicks was assessed using the general linear mixed-model procedure (Proc Mixed) in the Statistical Analysis System (SAS) studio (version 9.4, SAS 186 Institute, Cary NC). The fixed effects in the model were kick number (five levels, to estimate habituation effects), position (left, right and centre), and accuracy (two levels: Hit and Miss). The random effects, estimated as independent variances and allowing for negative variance, were subject identity (between-subject differences), kick position within subjects (within-subject differences between kick position), kick number within kick position (within-subjects changes between kicks) and residuals for position (pure measurement error). Low intra-class correlation co-efficients (ICC: <0.12) were reported for the residuals for position supported the grouping of these kicks in the analysis. All data showed no obvious non-uniformity of error, therefore all parameters were not log-transformed. Magnitudes of the effects (mean differences, SD) were evaluated by standardisation. Threshold values for assessing magnitudes of mean differences were: <0.19, trivial; 0.20 – 0.59, small;

0.60 – 1.1, moderate; 1.2 – 1.9, large; and >2.0, very large (Hopkins et al., 2009). Uncertainty in each effect was expressed as 90% confidence limits (CL) and as probabilities that the true effect was substantially positive and negative. The scale for interpreting the probabilities was: 25–75%, possible; 75–95%, likely; 95–99.5%, very likely; >99.5%, most likely.

To examine the relationship between the lateral horizontal distance from goal centre and each parameter, linear (first - order), quadratic (second - order) and cubic (third - order) polynomial curves were calculated in SAS studio. The choice of which curve fit best described the relationship (linear, second- or third-order polynomial) was based on r^2 values produced, standard error of the estimates (SEE), and residual plots were screened to confirm if the plotted relationship suited the data (Hopkins et al., 2009). Thresholds for interpreting a r^2 values were: <0.20, trivial; 0.21 – 0.49, low; 0.50 – 0.74, moderate; 0.75 – 0.92, strong; 0.92 – 0.98, very strong; and >0.99, extremely strong (Hopkins et al., 2009).

7.3. Results

7.3.1. Accurate vs inaccurate goal-kicks

The magnitude and direction of kinematic differences between accurate and inaccurate goal-kicks for each parameter and player are presented in **Table 7.1**[4]. Each player

[4] The mean ± SD data for kinematic parameters for accurate and inaccurate goal-kicks for each individual are reported in **Appendix E, Table 4 and Table 5**, *pp. 252-255*.

exhibited an individual-specific pattern across kinematic parameters with respect to the number of substantial kinematic differences (between 4 and 12) between accurate and inaccurate goal-kicks, and the magnitude (small, moderate, large and very large) and direction of these kinematic differences. The most prevalent substantial kinematic difference between goals-kicks (accurate and inaccurate) for individuals was foot path angle at BC, with all players returning a *most likely* large to *very likely* moderate substantial difference. The next most prevalent kinematic parameters were approach angle and hip ROM, with nine *most likely* large to very large substantial differences identified across players. The least prevalent kinematic parameters were average approach COM velocity, hip flexion at BC, hip and thigh angular velocity at BC, will all players returning a *most likely* to *unclear* small to trivial difference between accurate and inaccurate goal-kicks.

All players exhibited a smaller approach angle, greater kick-leg (KL) ankle plantarflexion at BC, a straighter foot-path angle at BC, higher ankle angular velocity at BC, lower KL hip and ankle ROM, lower support-leg (SL) knee flexion (at SHS, maximum and BC), with a straighter KL position and higher KL ankle plantarflexion at the end of follow in accurate goal-kicks compared to inaccurate goal-kicks. However, the magnitudes of these kinematic differences varied (from trivial to very large) between players. For the remaining parameters the direction and magnitude of kinematics differences between accurate and inaccurate goal-kicks varied between players, highlighting the individual nature of these technical parameters.

Table 7.1. The magnitude and inference for the difference between accurate (hit) and inaccurate (miss) goal-kicks each parameter and player. All parameters relate to the kick-leg unless stated.

Player	Parameter																														
	Last step distance	Avg approach COM velocity	Max approach COM velocity	COM velocity at KFTO	Approach angle	Ankle plantar-flexion at BC	Knee flexion at BC	Hip flexion at BC	Pelvic posterior tilt at BC	Trunk posterior tilt at BC	Shank angle at BC	Thigh angle at BC	Foot speed at BC	COM velocity at BC	Knee angular velocity at BC	Hip angular velocity at BC	Shank angular velocity at BC	Thigh angular velocity at BC	Ankle angular velocity at BC	SL knee flexion at BC	SL hip angle at BC	SL knee flexion at SHS	Max knee flexion	Max SL knee flexion	Max hip extension	Ankle ROM	Knee ROM	Hip ROM	Pelvis ROM	Foot path at BC	Leg position at FT	Ankle plantarflexion at FT
01	****	*	***	**	****	*	****	**	****	***	****	*	****	***	****	*	****	****	****	****	*	**	*	****	**	****	**	***	***	****	***	***
02	*	+	**	**	****	*	****	+	****	***	*	**	*	*	****	+	****	+	**	****	+	*	*	****	*	***	**	**	***	****	***	***
04	***	+	+	**	****	****	*	**	*	***	+	↑**	****	***	**	*	****	*	**	**	+	*	**	****	*	****	****	*	**	****	***	**
05	***	*	*	*	***	****	**	*	***	*	***	*	****	***	****	*	***	**	**	***	+	**	*	****	***	****	***	***	***	****	***	*
06	+	*	+	**	**	**	**	**	**	*	*	*	****	***	****	*	****	**	**	****	*	**	**	***	***	****	***	**	***	****	***	****
07	**	***	*	**	****	***	+	*	**	*	*	*	****	***	****	*	****	****	*	**	*	*	***	****	*	****	***	**	***	****	***	**
08	**	*	+	*	**	****	**	*	**	*	*	**	**	*	****	*	****	****	**	***	*	**	***	****	*	***	***	***	***	****	***	+
09	***	***	*	*	****	****	*	**	**	****	****	**	***	***	****	**	****	****	**	****	**	**	****	****	**	****	***	****	***	****	***	***
10	****	*	**	***	****	****	+	**	***	****	***	***	****	***	****	+	****	****	**	***	*	****	****	****	***	****	*	***	**	****	**	***
11	***	**	**	**	****	****	*	***	****	**	***	**	**	***	**	+	****	****	**	**	*	****	****	****	**	****	***	****	**	****	*	***
12	****	**	***	***	****	****	***	**	**	***	****	***	****	***	****	*	****	****	***	****	**	****	***	****	*	****	***	****	**	****	*	***
13	****	+	**	**	****	****	**	**	+	*	****	***	****	***	↑****	**	****	****	***	****	**	****	****	****	*	****	****	****	*	****	***	*
14	**	*	*	***	****	****	*	*	*	*	****	*	**	*	**	*	****	+	***	*	*	****	****	*	**	****	*	****	***	****	**	***
16	*	*	****	**	****	****	*	**	**	+	****	**	***	**	**	***	****	****	***	***	+	**	****	****	+	****	***	****	*	****	****	***
17	***	**	****	**	***	****	*	***	+	+	****	*	**	+	****	**	****	****	****	****	*	****	****	***	*	****	*	****	**	****	***	***
18	*	***	*	**	****	****	**	***	*	***	****	*	****	***	****	**	****	****	***	*	+	***	****	-*	**	****	**	****	****	****	***	**

Colours denote size of the effect: white-trivial, yellow-small, red-moderate, green-large, blue-very large. Shading denotes direction of effect: dark- positive, light-negative; Symbols denote: * possibly, ** likely, *** very likely and **** most likely chance of the true effect was substantial, + true effect was unclear. Abbreviations: **Max**: maximum; **Avg**: Average; **SL**: Support leg; **SHS:** Support leg heel strike; **BC**: Ball contact; **KFTO**: kick foot toe off

7.3.2. Relationship between technical parameters and accuracy

The magnitude and type (i.e. linear, quadratic and cubic) of relationships between kinematic parameters and accuracy for each individual are displayed in **Table 7.2**[5]. Each player exhibited an individual-specific profile, with respect to the number of substantial relationships between technical parameters and accuracy, the magnitude (low, moderate, strong and very strong), type and direction of relationships. Individual players returned between two and nine substantial relationships between technical parameters and accuracy after choosing the most appropriate fit, however the nature of these relationships varied.

[5] The individual r^2 values for each individual's relationship between kinematic parameters and accuracy is reported in **Appendix D, Table 6**, *pp. 256*.

Table 7.2. The magnitude and shape (linear, quadratic, cubic) of the relationship between each technical parameter and accuracy for each individual. All parameters relate to the kick-leg unless stated.

Player	Last step distance	Avg approach COM velocity	Max approach COM velocity	COM velocity at KFTO	Approach angle	Ankle plantar-flexion at BC	Knee flexion at BC	Hip flexion at BC	Pelvic posterior tilt at BC	Trunk posterior tilt at BC	Shank angle at BC	Thigh angle at BC	Foot speed at BC	COM velocity at BC	Knee angular velocity at BC	Hip angular velocity at BC	Shank angular velocity at BC	Thigh angular velocity at BC	Ankle angular velocity at BC	SL knee flexion at BC	SL hip angle at BC	SL knee flexion at SHS	Max knee flexion	Max SL knee flexion	Max hip extension	Ankle ROM	Knee ROM	Hip ROM	Pelvis ROM	Foot path at BC	Leg position at FT	Ankle plantarflexion at FT
01	-1	-	-1	-	-1	-1	-1	-	-1	-1	1	-	-1	-1	-1	-	-1	-	-1	2	-	-	-	2	2	2	-1	2	-1	-1	-1	-1
02	-	-	-	-1	-1	2	-1	-	-1	-1	-	-1	2	-1	2	1	2	-	2	2	-	-	-	2	-	2	2	1	2	-1	-1	-1
04	2	-	-	-	-1	1	-	2	-	-1	-	-1	-1	-	-1	-	-1	-	-1	2	-	-	-1	1	-	2	2	1	2	-1	-1	2
05	-	-1	-1	-1	-1	1	2	-	-1	-1	1	-	2	2	2	-	1	1	1	2	-	-	1	2	2	-1	-1	1	-1	-1	-1	-
06	-	-	-	-	-1	1	2	-	-	-	2	-	2	3	3	2	3	2	2	-	-	-	-	-	-	2	-1	2	2	-1	-1	-1
07	2/3	-1	-1	-	-1	1	-	-	-1	-1	-	-	2	2	3	-	3	3	1	2	-	1	1	1	2	-1	-1	1	2	-1	-1	2
08	-	-	-1	-	-1	2	-	-	-1	-1	-	-1	-1	3	-1	-	-1	3	1	2	-	1	1	2	-	2	2	2	-	-1	-1	-
09	2	-	-	-	-1	1	-	-1	-	-1	-	-1	-1	-1	-	2	-	1	1	2	1	1	-	2	-1	2	2	-	2	-1	-1	-1
10	-1	-1	-1	-1	-1	3	2	-	-	-	2	-1	2	2	2	2	2	-	1	2	-	1	1	1	-	-1	-	-1	2	-1	-	2
11	2	-	-1	-1	-1	-1	-	2	3	-1	2	2	-1	-1	2	-1	-	2	-1	2	-	1	-	2	2	2	2	2	-	-1	-	2
12	2	-1	2	2	-1	-1	-1	-	-	-1	-1	-	2	3	3	-1	3	1	1	2	-	-	1	2	-1	2	-1	-1	-1	-1	-	-1
13	2	-	-	-1	-1	-1	-	-1	-	-1	1	-1	-1	-1	3	-1	-	-1	2	2	1	1	-1	2	-	-1	2	-1	-	-1	-1	-
14	-	-	-	-1	-1	2	-	-	-	-	2	2	-1	-1	2	-	2	-	2	-	1	1	-1	-	-1	-1	-	-1	-1	-1	-1	-1
16	-1	-	2	-	-1	2	2	-	-1	-	-	-	-1	-1	-1	2	-1	-1	2	2	1	1	-1	2	-	2	2	2	-	-1	-1	-1
17	-1	-	2	-	-1	-1	2	-1	-	-	1	-1	-1	-1	-1	-	-1	-	-1	2	1	1	-1	2	2	-1	-	2	-1	-1	-1	-1
18	2	-	-	2	-1	2	2	-	2	-	2	-	2	2	1	-	-	-	-1	-		1	-1	-	2	-1	2	-1	2	-1	-1	2

Colours denote size of the effect: ☐ trivial, ☐ small, ☐ moderate, ☐ strong, ☐ very strong. Numbers denote the shape of the relationship: 1 linear, 2 quadratic, 3 cubic. Abbreviations: **Max**: maximum; **Avg**: Average; **SL**: Support leg; **SHS:** Support leg heel strike; **BC**: Ball contact; **KFTO**: kick foot toe off. For linear relationships, a negative sign is added to denote a negative of relationship.

7.4. Discussion

The purpose of this research was to investigate if individuals utilise different movement patterns to achieve an accurate goal-kick in AF. All players exhibited substantial kinematic differences between accurate and accurate goal-kicks, however these were individual-specific. The individual-specific differences ranged from the type and number of substantial kinematic differences between accurate and inaccurate goal-kicks, the magnitude (i.e. trivial, small, moderate, large, very large) and direction (i.e. increase or decrease) of these kinematic differences. In addition, each player demonstrated substantial relationships between technical parameters and accuracy, however these were also individual-specific, with the number, strength (i.e. low, moderate, strong, very strong) and type (i.e. linear, quadratic and cubic) of relationships varying between players. To highlight this individuality in goal-kicking in AF, the results of four players (1, 2, 6, 12) will be discussed.

For player 1, ten substantially large to very large (*most likely* to *very likely*) kinematic differences were reported between accurate and inaccurate goal-kicks. Accurate goal-kicks exhibited a lower maximum approach COM velocity, a smaller approach angle, less KL knee flexion at BC, lower foot speed at BC, lower COM velocity at BC, lower KL shank angular velocity at BC, less SL knee flexion (maximum and at BC), a smaller foot-path angle at BC and a straighter leg position at the end of follow through. In addition, there were four substantially strong negative linear relationships identified; approach angle (r_2 = -0.87), foot speed at BC (r_2 = -0.79), shank angular velocity at BC (r_2 = -0.76) and foot path angle at BC (r_2 = -0.87). As discussed in Chapter 5, a straighter approach line and smaller-foot path angle at BC would help increase the planarity of the foot swing motion, to allow players to apply a more direct (less angled) striking force to the ball (Baker & Ball, 1996). This in turn, would propel the ball with a straighter ball flight trajectory towards the target centre (Alcock et al., 2012; Baker & Ball, 1996; Knudson, 2007). Furthermore, the decreased linear and angular velocities may be representative of the speed-accuracy trade-off (Fitts's law: Fitts, 1954), where the player has reduced the speed of the movement to effectively improve accuracy. Consequently, for this player, a combination of increasing the planarity of foot swing motion and reducing the speed of the kick-leg movement, appear beneficial for improving goal-kicking accuracy. The results for player 1 are in agreement with the findings from the group-based analysis in Chapter 6.

For player 2, five substantially large to very large (*most likely* to *very likely*) kinematic differences were reported between accurate and inaccurate goal-kicks. Accurate goal-kicks exhibited a smaller approach angle, less posterior tilt at BC, less support-leg knee flexion at BC, less pelvis ROM and a smaller foot path angle at BC compared to accurate goal-kicks. In addition, there were three substantially large quadratic relationships identified; support-leg knee flexion at BC ($r^2 = 0.89$), maximum support-leg knee flexion ($r^2 = 0.80$) and pelvis ROM ($r^2 = 0.76$). A more extended support-leg has been suggested to indicate a stronger and more stable base of support (Ball, 2003), which in-turn would facilitate better control and regulation of the kick-leg motion during the kicking phase (Ball, 2013; Chew-bullock et al., 2012; Inoue et al., 2014; Lees et al., 1998, 2010; Putnam, 1991). The strong quadratic relationship identified for support-leg knee flexion indicated that maintaining the movement of the knee within a flexion range of 30 - 39° (from maximum to BC) has advantages for accuracy. Findings also indicated that player 2 may be utilising control from the pelvis to control the dynamics of the kick-leg (Lees & Nolan, 2002; Lees et al., 2010). Lees and Nolan (2002) suggested that constraining the movement of the pelvis is suggested to facilitate increased control and regulation of the motion of the kicking limb, in an attempt to better position and orientate kicking limb for ball impact. This may be linked to the Bernstein's theory (Bernstein, 1967) of freezing of degrees of freedom (DOF). In this case, player 2 reduced the involvement of the pelvis to help control and perform the movement successfully. This adjustment was not evident in the group-based analysis in Chapter 7.

For player 6, three substantially large (*most likely* to *very likely*) kinematic differences were reported between accurate and inaccurate goal-kicks. Accurate goal-kicks exhibited greater ankle plantar flexion at BC, a smaller foot-path angle at BC and greater ankle plantar flexion at the end of follow through. In addition, there were three substantially strong quadratic (ankle plantar flexion at BC: $r^2 = 0.90$; footspeed at BC: $r^2 = 0.78$; ankle ROM: $r^2 = 0.85$) and one negative linear (foot path angle at BC: $r^2 = 0.89$) relationship identified. For this player, it is apparent that ankle and foot mechanics are important in achieving an accurate goal-kick. As discussed in Chapter 6, constraining the ROM of the ankle and reducing foot speed has been linked to increased stabilisation and control of the foot in preparation for BC (linked to freezing of the redundant DOF; Bernstein, 1967; Latash, 2008; Yang & Schol, 2005), whilst maintaining and increasing ankle plantarflexion is suggested help increase impact efficiency (Asami & Nolte, 1983; Ball, 2010; Kellis & Katis, 2007; Lees & Nolan, 1998; Peacock & Ball, 2017, 2018c; Peacock et al., 2017; Sterzing & Hennig, 2008; Sterzing et al., 2009). This would enable player 6 to impart the desired flight characteristics on the ball, to achieve a successful outcome. For these parameters, the strong quadratic relationships indicated maintaining the movement of the ankle and the speed of the foot within specific ranges (ankle plantar flexion at BC: 33 - 38º; footspeed at BC: 16 - 17.5 $m.s^{-1}$; ankle ROM: 42 - 45º) has advantages for goal-kicking accuracy. The results for player 6 are in agreement with the findings from the group-based analysis in Chapter 6.

For player 12, ten substantially large (*most likely* to *very likely*) kinematic differences were reported between accurate and inaccurate goal-kicks. Accurate goal-kicks exhibited a longer last step, higher COM velocity at KFTO, a smaller approach angle, greater ankle plantar flexion at BC, faster foot speed at BC, higher COM velocity at BC, lower maximum support-leg knee flexion, lower ankle ROM, higher hip ROM and a smaller foot path angle at BC. In addition, four substantially strong linear relationships (approach angle: $r_2 = -0.87$; ankle plantar flexion at BC: $r_2 = -0.75$; hip ROM: $r_2 = 0.84$; foot path angle at BC: $r_2 = -0.79$) and three substantially strong quadratic relationships (foot speed at BC: $r_2 = 0.79$; COM velocity at BC: $r_2 = 0.81$; shank angular velocity at BC: $r_2 = 0.76$) were identified for player 12. Similar to player 1, a straighter approach line and smaller-foot path angle at BC would increase the planarity of the kicking motion to allow players to apply a more direct (less angled) striking force to the ball to achieve a straighter ball flight trajectory (Baker & Ball, 1996). However, in contrast to player 1, increasing the speed of the movement (as indicated by faster linear and angular velocities) was more beneficial for accuracy. The majority of results for player 6 are in contrast with the findings from the group-based analysis in Chapter 6.

The group-based analysis in Chapter 6 did not account for each individual's technical strengths and weaknesses in the skill. When examining specific technical parameters, how players regulated the speed of the movement to improve goal-kicking accuracy differed between individuals. For the majority of players (1, 2, 4, 6, 8, 11, 14, 16, 17, 18), accurate goal-kicks exhibited substantially slower linear (COM, footspeed) and angular (ankle, shank and knee) velocities at BC compared to inaccurate goal-kicks. This may be representative of the speed-accuracy trade-off (Fitts, 1954), which specifies an inverse relationship between the speed at which a skill can be performed and the accuracy that can be achieved (Fitts, 1954). In this instance, these players may have sacrificed the speed of the goal-kicking action to allow for the detection and correction of errors, in order to improve the accuracy of the kick. The presence of this trade-off was identified in the group-based analysis in Chapter 6. However, this was in contrast to players 7, 5, 10 and 12, who demonstrated faster linear (COM, footspeed) and angular (ankle, shank and knee) velocities at BC in the kick-leg. In addition, during the approach phase these players had a longer last step and a faster approach velocity (higher average and maximum COM velocity and higher COM at kick-foot toe-off). The ability to perform more accurately at higher velocities may be explained by the impulse-variability theory (Urbin et al., 2011). In contrast to the speed-accuracy trade-off, the impulse-variability describes a curvilinear relationship between kinematic variability and force production (Urbin et al., 2011). Where an increase in kinematic stability is achieved with increased force production (higher velocities), which has been suggested to translate to greater spatial accuracy in a task (Urbin et al., 2011). The presence of this theory may supported through the lower SD in technical parameters in accurate goal-kicks (indicating more consistent movements) compared to inaccurate goal-kicks, along with the quadratic relationship reported for foot speed, COM velocity and shank angular velocity at BC in these players. The existence of this concept (impulse-variability theory) was not identified in the group-based analysis in Chapter 6. The existence of both individual strategies have previously been documented during accurate goal-kicking AF (Blair et al., 2017) and in accurate instep kicking in soccer (Lees & Nolan, 2002).

Accurate goal-kicking requires increased control and regulation of the kicking-limb, however the control mechanism of this movement is also individual. In agreement with the findings from the group-based analysis, nine players (8, 10, 11, 12, 13, 14, 16, 17, 18) exhibited substantially lower hip ROM during accurate goal-kicks compared to inaccurate goal-kicks. In contrast, players 2, 4 and 9 demonstrated substantially lower pelvis ROM (2: 31 vs 46°; 4: 35 vs 47°*;* 9: 30 vs 37°) and knee (2: 51 vs 58°; 4: 48 vs 61°*;* 9: 43 vs 48°) in accurate goal-kicks compared to inaccurate goal-kicks. As constraining the number of joints acting in the system through reducing joint ROM has been linked to increased control and regulation of the motion of the kicking limb (Lees & Nolan, 2002; Lees et al., 2010), this suggests some players made more use of the hip to control the movement, whilst other utilised contributions from the pelvis and knee. The contribution for the pelvis was not evident on a group-basis (no substantial effect of pelvis ROM between accurate and inaccurate goal kicks: 46 vs 48°, *very likely* trivial). A potential reason for these different movement patterns could be related the variable nature of the ball drop aspect of the goal-kicking action in AF. This aspect of the task means that subtle variations in foot position may be required to make good contact with the ball in response to the variable nature of the ball drop characteristics (Ball, 2011). It has been suggested that having greater control of the kick-leg movement from the hip rather than the knee/ pelvis would allow for greater DOF to be utilised to achieve this more variable foot positioning (Ball, 2011). Given that the accuracy percentage of goal-kicks (< 60%) was lower in the players that utilised control from the hip, this could be indicating a less consistent ball drop amongst these players, so the need to adjust the path of the foot/ kick-leg would be higher (Ball, 2011). Future research is warranted to examine the technique of controlling and dropping the ball, as it may provide an additional insight and understanding of important factors which influence goal-kicking performance in AF.

The existence of the knee-thigh angular velocity continuum was evident in the group of AF players tested in this study (**Figure 7.1**). Findings indicated that knee angular velocity and thigh angular velocity at BC were inversely related, and each player utilised a slightly different combination of knee and thigh angular as indicated along the continuum, supporting previous findings in AF kicking (Ball, 2008, 2011; Blair & Ball, 2018). At one end of continuum, players utilise a knee strategy (larger knee angular velocities, with smaller thigh angular velocities at BC). For example, during accurate goal-kicks player 9 exhibited a relatively high knee angular velocity (1802 ± 128°/s), with a smaller thigh angular velocity (-61 ± 15°/s) at BC. While, at the other end the continuum, players utilised a thigh strategy (larger thigh angular velocities, with smaller knee angular velocities at BC. For example, during accurate goal-kicks player 18 exhibited a relatively low knee angular velocity (1145 ± 422), with a higher thigh angular velocity (422 ± 38) at BC. Despite observing technical differences between the knee and thigh strategy, a similar performance was produced (accurate goal-kick). Further analysis indicated that similar relationships were identified for accurate (r_2 = 0.45) and inaccurate (r_2 = 0.55) goal-kicks when all kicks were analysed together. However, the relationships identified between accurate and inaccurate goal-kicks were not as strong as those reported by Ball (2008) (r_2 = 0.90, p<0.001). This might be explained by the differences in tasks between the two studies (Ball, 2011). It was suggested by Ball (2011), that slightly different combinations of knee and thigh angular velocity could be combined when a sub-maximal task is performed, like the goal-kick in this study, conversely, when kicking for maximal distance individuals are more likely to maximise this relationship. This possibly is supported by the slightly different combinations of knee and thigh angular velocity between accurate and inaccurate goal-kicks for each individual. These findings have important implications for the physical training of players, as the dependent on their position on the continuum (more knee strategy or thigh strategy) will require different conditioning recommendations to suit the movement patterns. For example, knee strategy kickers rely on active transfer from the knee extensors to perform the kick, whilst thigh strategy kickers might rely more on transfer hip flexors (Ball, 2008).

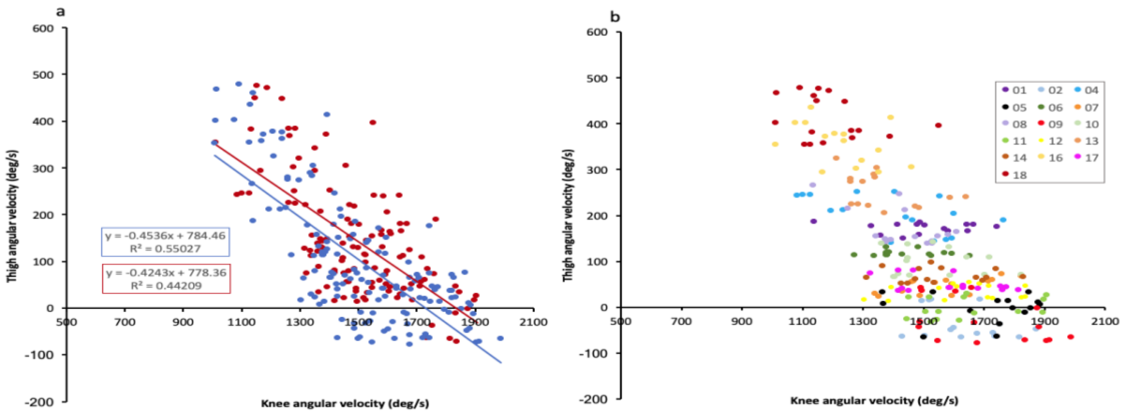


Figure 7.1. The relationship between knee and thigh angular velocity for continuum for; a) accurate (blue) and inaccurate (red) goal-kicks across all players and, b) on an individual basis.

Important technical characteristics associated with accurate goal-kicking on a group basis was also evident on an individual basis. In accurate goal-kicks, all players exhibited a straighter approach line, less KL joint (ankle and hip) ROM, less maximum SL knee flexion during the kicking phase, with greater KL ankle plantarflexion, lower KL ankle angular velocity, less SL knee flexion and a smaller KL foot-path angle at BC compared to inaccurate goal-kicks. In addition, all players finished with their leg pointing towards goals, with higher ankle plantarflexion at the end of follow through in accurate goal-kicks. For the majority of players ($\geq$ 12 players), these differences ranged from substantially *very large* to substantially *small*. Furthermore, the nature of the relationships between these technical parameters and accuracy identified in this study were also similar to the results from the group-based analysis (Chapter 5). As previously discussed in Chapter 5, these adjustments may be indicative of several strategies utilised by players to improve accuracy. Firstly, players may be actively controlling the motion of the kick-leg through constraining the number of joints (freezing of redundant DOF; Bernstein, 1967; Berthouse & Lungarella, 2004; Caillou et al., 2002; Ko et al., 2003; Latash, 2008; Yang & Schol, 2005; Vereijken et al., 1992) acting in the system, in an attempt to better position and orientate the foot for ball impact (Lees & Nolan, 2002; Lees et al., 2010). Secondly, players may be controlling the swing plane characteristics of the kick-leg/ foot (increasing the planarity of the motion), in order to apply a more direct (less angled) striking force to the ball's centre of mass (Baker & Ball, 1996). This in turn, would propel the ball with a straighter ball flight trajectory towards the target centre (Alcock et al., 2012; Asai et al., 2002; Baker & Ball, 1996; Knudson, 2007; Peacock & Ball, 2017), thus helping to achieve an accurate goal-kick. Thirdly, players may be trying to increase the rigidity within the ankle and foot segment through maintaining and increasing ankle plantarflexion (Asami & Nolte, 1983; Ball, 2010; Kellis & Katis, 2007; Lees & Nolan, 1998; Peacock & Ball, 2017, 2018c Peacock et al., 2017; Sterzing & Hennig, 2008; Sterzing et al., 2009). This is suggested to improve impact efficiency and accuracy, through increasing the effective mass of the striking limb (Asami & Nolte, 1983; Ball et al., 2010; Peacock & Ball, 2018c, Plagenhoef, 1971; Sterzing & Hennig, 2008; Tol et al., 2002). Lastly, players may be adjusting support-leg motion in order to achieve a stronger base of support to help improve stability during the kick (Ball, 2013; Lees et al., 1998, 2010). This would facilitate better control and regulation of the kick-leg motion during the kicking phase (Ball, 2013; Chew-bullock et al., 2012; Inoue et al., 2014; Lees et al., 1998, 2010; Putnam, 1991). Given that these finding were evident on both a group and individual basis indicates these technical adjustments/strategies are clearly important for accuracy when kicking for goals in AF.

7.4.1. Coaching and research implications

The identification of individual-specific differences has important practical implications for the coaching of the goal-kicking skill in AF. Given that joints and segments are used differently for players, training exercises need be tailored to the individual. For example, thigh strategy kickers might rely more on the hip flexors, while knee strategy kickers rely on the knee extensors when kicking for goals (Ball, 2008). Similarly, players that utilise greater pelvis and knee control might rely more on the contributing musculature around these segments/ joints, while players that utilise more control from the hip would have different strength qualities and requirements from the musculature around the hip. As such, consideration should be given to exercises that specifically target improving strength within the different muscles. Practically, this means that coaches need to evaluate their players' goal-kicking technique to determine which strategy they utilise, to appropriately target their training. In addition, findings from the group-based analysis would suggest that a slower movement is beneficial for accuracy, however, the individual-based analysis revealed this could be detrimental to the goal-kicking in performance for specific individuals. For individuals that benefit from the speed accuracy trade-off, coaches could emphasis the accuracy component of the kick which has been shown to decrease the speed of a movement (Peacock et al., 2017). Conditioning and technical drills that promote faster foot speeds and shank angular velocities, might be useful methods of training for individuals that benefit from increasing the speed of the movement. Findings in this study indicated that when implementing technical refinements in applied coaching practice, coaching recommendations need to be tailored to the individual, as providing one 'ideal' kicking technique model may not appropriate for all players in AF.

The results of this study indicate that individual differences needed to be recognised in biomechanical research. Use of the individual-based analysis provided an additional and important insight into goal-kicking performance in AF. Whilst certain findings confirmed the results from the group-based analysis in Chapter 5, the individual-based analysis detected important technical information for specific individuals, which was masked in the group-based analysis (such as, the contributions from the pelvis). Using only a group-based analysis, these technical factors would not have been identified, and therefore not offered possible technical areas for improvement for these specific players. This study highlights the need for an individual-based analysis to be utilised in conjunction with a group-based analysis in the examination of kicking kinematics in AF.

7.5. Conclusion

Individuals utilise different movement patterns when kicking for goals in AF. Findings indicated that all players exhibited substantial technical differences between accurate and accurate goal-kicks, however these were individual-specific. The individual-specific differences ranged from the type and number of substantial kinematic differences between accurate and inaccurate goal-kicks, the magnitude (i.e. trivial, small, moderate, large, very large) and direction (i.e. increase or decrease) of these kinematic differences, and the number, strength (i.e. low, moderate, strong, very strong) and type (i.e. linear, quadratic and cubic) of relationships between accuracy and technical parameters. Results from the individual-based analysis supported the findings from the group-based analysis in Chapter 5; all players exhibited a more extended support-leg, lower joint (ankle and hip) ROM in accurate goal-kicks compared to inaccurate goal-kicks. In addition, all players exhibited a straighter approach line, a smaller foot-path angle and finished with their kick-leg in-line towards the target. However, the individual-based analysis also identified important technical information that was not evident on a group-basis. For example, individual patterns were evident in terms of the speed of movement (i.e. accurate goal-kicks were characterised by substantially faster linear (COM, footspeed) and angular (shank and knee) velocities at BC for players 5, 7, 10 and 12, where an inverse trend was evident in the remaining players). Using only a group-based analysis, these factors would not have been identified, and therefore would be considered as possible technical aspects to improve goal-kicking accuracy for these individual players. Findings from the individual-based analysis highlighted the individual nature of goal-kicking in AF, suggesting it is clearly important to coach this skill on an individual basis.

7.6. Contribution of Chapter to the Aims of the Thesis

Chapter 7 explored if individual differences exist between accurate and inaccurate goal-kicks on an individual basis. This was driven by recommendations from previous kicking literature (i.e. authors have stated that an individual-based analysis is needed in the analysis of goal-kicking (Ball & Blair, 2018; Ball et al., 2002; Blair et al., 2018)), as well as the findings from Chapter 6. The findings of Chapter 7 contributed to answering the second main aim of this thesis, all players demonstrated substantial kinematic differences between accurate and inaccurate goal-kicks, along with substantial relationships between kinematic parameters and accuracy, but these were individual-specific. Further discussion of the implications of individual differences in goal-kicking can be found in Chapter 8 (**Section 8.2.** *pp 194 - 196*). In addition, further discussion on the implications of group and individual based analysis can be found in Chapter 8 (**Section 8.2.3** *pp. 207 - 211*). A combination of both the group (Chapter 6) and individual-based (Chapter 7) analysis provided a more thorough and comprehensive understanding of technical factors which influence goal-kicking technique in AF, to answer the second main aim of this thesis.

Chapter 8: General Discussion

Goal-kicking is an important skill in Australian Football (AF), which accounts for approximately 62% of points scored during a match (Anderson et al., 2018). However, despite its importance, the key technical characteristics underpinning the goal-kicking skill are not well understood. Following a review of the literature in Chapter 2, it was identified there is clear scope for biomechanical research to investigate goal-kicking technique and identify technical factors associated with accuracy. The general aims of this thesis were to; 1) validate a methodological approach to enable quantification of goal-kicking technique in a field environment, and 2) examine goal-kicking technique and identify technical factors associated with accuracy.

8.1. Application of an inertial measurement system

Following a comprehensive validation of the Xsens inertial measurement system (IMS) in Chapter's 3 and 4, the application of the IMS offered several advantages for the examination of goal-kicking technique in AF. Firstly, the IMS enabled an in-field examination of goal-kicking performance. This facilitated the assessment of accuracy under more realistic conditions, as players were able to kick towards their usual target (goals), which is often a restricted in a laboratory testing environment. Furthermore, this meant that two accuracy criteria measures (1: hit vs miss; 2: lateral horizontal distance) could be employed, to provide both a discrete and continuous measure of performance. Specifically, the use of the lateral distance measure enabled assessment of accuracy over a wider margin (lateral distance: > 19.2 m), which was able to provide more information about the magnitude and direction of the error associated with missing the target (Ball & Ball, 2018). Secondly, the IMS permitted analysis of the complete goal-kicking action (i.e. approach phase, kicking phase and follow-through phase), which is often limited with the use of camera-based motion analysis systems (MAS), as a player's approach during a goal-kick in AF can range from 2 - 20 steps (Baker & Ball, 1996). This provided a more comprehensive understanding of the biomechanical characteristics of accurate goal-kicking, as important technical factors were identified from each phase. Furthermore, this allowed direct links between technical factors in each phase to be determined (for example, approach angle had a strong relationship with foot path angle at BC). Lastly, the use of the IMS enabled the examination of technique across different angles and distances from goals in Chapter 5, to determine how task constraints influence goal-kicking performance in AF. Substantial technical differences were reported between goal-kicks taken at 30 m and 40 m, highlighting the importance of considering the position of shot when making technical refinements in coaching practice. If a camera-based motion analysis system (MAS) had have been utilised in this thesis, examining this aspect would not have been feasible and these differences in techniques would not have been identified. Subsequently, the important understanding of how task constraints influence goal-kicking in AF would have been overlooked. Thereby, the use of the IMS in thesis was able to provide a more ecologically valid measurement of goal-kicking technique, to provide a more comprehensive understanding of the key technical factors associated with goal-kicking performance in AF.

The use of IMS can help advance the current body of biomechanical knowledge in football kicking and across other sports. Up until now, the majority of biomechanical investigations have been conducted in a laboratory environment, with the need for more in-field testing highlighted as an important next step in football research (Nunome et al., 2017; Baktash et al., 2009; Blair et al., 2017) and in others areas (Chambers et al., 2015; Dinu et al., 2016; Reenalda et al., 2016) The validation and application of the IMS in this thesis demonstrated the suitability of utilising these systems for the assessment of kicking technique in the training environment. Other potential applications of IMS in football research include; exploring the other football actions (such as ball stopping, goal-keeping skills and ball throwing skills: Numone et al., 2017), long-term monitoring or intervention studies in kicking (Ball, 2007; Lees et al., 2010), and examination of kicking technique during game/drills within training (Cust et al., 2018). In addition, findings from this thesis also broaden the scope of IMS applications in other sport biomechanical research. Chapters 3 and 4 build upon previous IMS validations, indicating these systems maintain good concurrent validity when measuring at higher velocities (linear velocities of up 20.4 $m.s^{-1}$ and angular velocities of 1834 °/s validated) and across joints that undergo a larger ROM (greater knee ROM; 130º flexion/extension, 18º abduction/ adduction, 27º internal/external rotation validated). Findings from this thesis may therefore be generalisable across other movement tasks were high-velocity movements exist, such as in sprinting (knee angular velocities (flexion/extension) of up to 1400 °/s: Slawinski et al., 2010). Future research is warranted to explore the validity of IMS in quantifying movements that involve long axis rotations, such as during throwing (Humeral angular velocities of up to 1600 °/s reported: Seroyer et al., 2010), to extend the applications of IMS.

However, the limitations of the IMS should also be considered. Firstly, the use of the IMS is currently limited to the analysis of the kicker. As a result, this meant that the ball drop mechanics could not be tracked in this thesis. Development and integration of inertial sensors into footballs (such as, Adidas intelligent ball and the AFL smart ball) have been made in an attempt to provide real-time tracking of ball mechanics and the ball flight trajectory (Li et al., 2016; Weizman & Fuss, 2015). However, alterations to performance have been reported. Unpublished research at Victoria University in Melbourne, reported differences between a player's technique, impact characteristics and ball performance between the Sheerin football and the Sheerin smart ball (McNicol, 2016). As a result, smart balls are currently ruled out of elite competition. Thereby, camera-based systems, such as a digital video camera, along with ball flight prediction algorithms (Atack et al., 2018) may still offer an alternative solution for providing this type of assessment. One reason for not implementing these resources in this thesis, was that the advantage of utilising an IMS was to reduce the complexity of the test set-up to facilitate analysis in an elite environment, where time frames are limited. The addition of camera-based systems to adequately capture ball drop mechanics and ball flight trajectory would have increased the complexity and set-up time of the biomechanical analysis, requiring extra resources and time. In addition, testing was conducted on training pitches where power sources were limited, therefore extra generators would have had to be sourced. Given the importance of the ball-drop, future research is warranted to examine the technique of controlling and dropping the ball, along with the interceptive task of striking the foot, as this may provide an additional insight and understanding of important factors which influence goal-kicking performance in AF. Thereby, exploring if alternative methods can be utilised, along with the IMS to easily capture this may be needed. This can also have implications across other sports that utilise equipment, such as in hockey (stick), tennis (racket) or golf (club), where additional consideration should be given to tracking the equipment.

Secondly, the findings in Chapter 4 indicated that the performance of the IMS was reduced when measuring frontal and transverse joint kinematics. These differences have been attributed to slight variations between the Xsens MVN biomechanical model and the ISB biomechanical model (Lu & Zhang, 2014; Robert-Lachaine et al., 2017; Zhang et al., 2013). Realignment and post-processing techniques have been suggested as solution to improve the output of frontal and transverse joint kinematics (Lu & Zhang, 2014; Robert-Lachaine et al., 2017; Zhang et al., 2013), however they require lengthy set-up and post-processing techniques, diminishing some of the benefits of the use of IMS, such as real-time feedback. As the AF goal-kicking action is a more linear movement, the majority of important technical characteristics associated with performance occur in the sagittal plane, indicating these systems are appropriate for the assessment of AF goal-kicking performance. However, for other movements that involve a rotational aspect, such as in soccer instep kicking or rugby goal-kicking, may require realignment and post-processing techniques to appropriately treat data to ensure valid outcomes are determined. Interestingly, findings in Chapter 4 also indicated that the IMS performs better when measuring segment kinematics (pelvis) compared to joint kinematics (ankle, knee and hip) (across all axis). It was suggested that this could also be due to the calculation of pelvis kinematics in relation to a global (fixed) reference, rather than using an angle between to segments. As a result, the measurement is only influenced by movement around one segments axis (pelvis) rather than taking into consideration the anatomical frames and kinematical constraints from a proximal segment. This suggests the IMS may also perform better when measuring foot, shank and thigh segment kinematics, enabling a valid measure of a rotational movement, however further work is warranted to support this assertion.

Lastly, analysis of impact characteristics is not yet possible with the Xsens IMS. The accelerometers in the Xsens IMS have a ± 16 g (160 m.s^{-2}) range, which has previously been shown to saturate during the ball impact phase (Ellens et al., 2017). The authors suggested a range of ± 200 g was needed to facilitate measurement through the ball impact phase. This can have implications for the use of IMS in other sports where impacts occur, such as tennis serving, baseball hitting and golf. Development of accelerometers have led to the higher ranges, which may be expected to be included in IMS in future hardware updates.

8.2. Biomechanical considerations in goal-kicking accuracy

8.2.1. Biomechanics of goal-kicking accuracy

Following a review of scientific literature in Chapter 2, a deterministic model was constructed to guide the initial understanding of the potential technical factors underpinning accurate goal-kicking technique in AF (see **Chapter 2**, **Section 2.2.3**, **Figure 2.4,** *pp. 25*). A deterministic model approach was used as it provides a strong theoretical basis when determining and examining the importance of key technical parameters that influence the outcome of a movement task (Bartlett, 1999; Chow & Knudson, 2011; Hay & Reid, 1988). Using accuracy as the dependent performance variable, the key independent variables in **Figure 2.4** were evaluated in Chapters 5, 6 and 7. Based on the findings in this thesis, the proposed deterministic model has been updated (**Figure 8.1**).

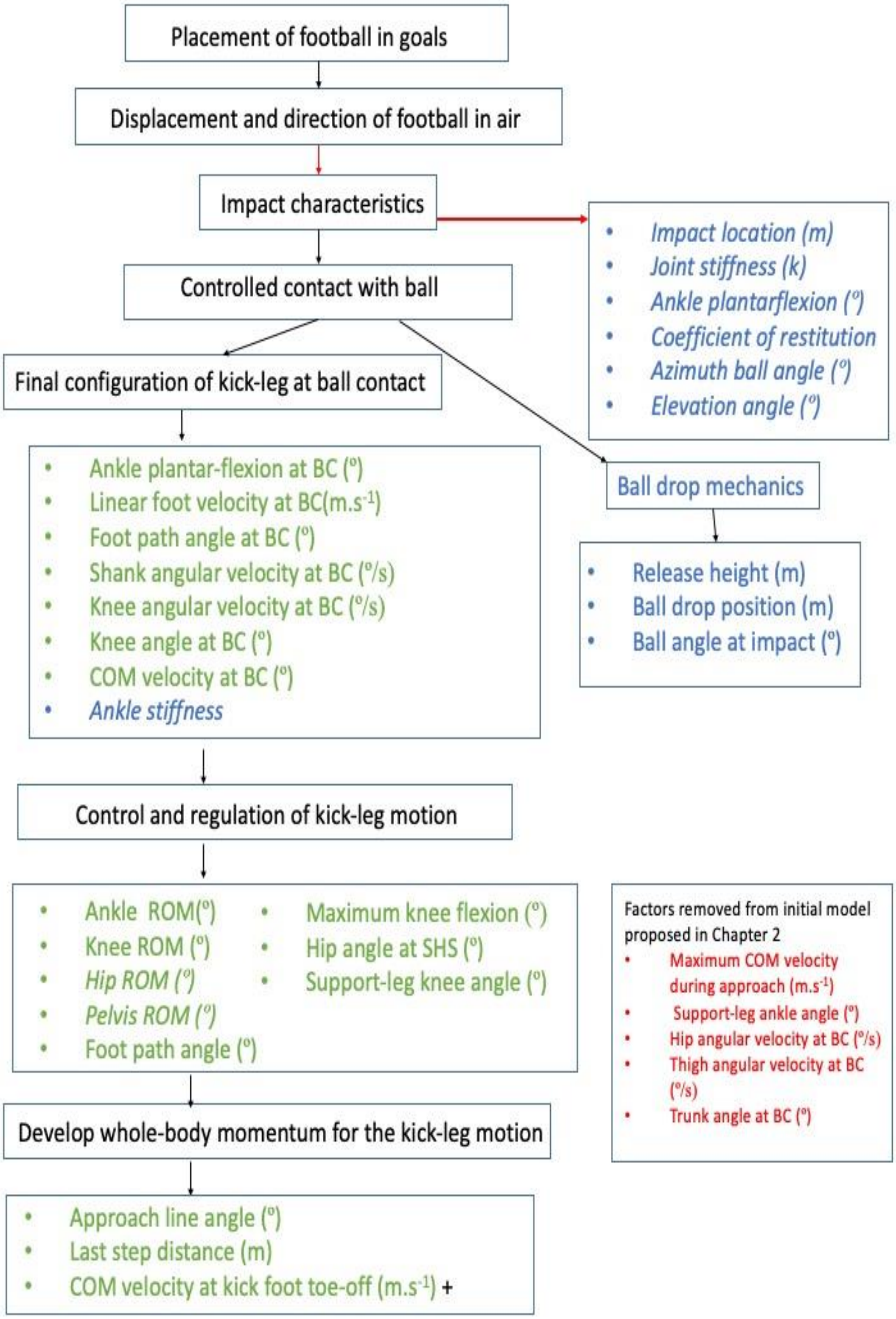


Figure 8.1. Deterministic model of important technical factors associated accurate goal-kicking in Australian Football. Green text indicates important technical parameter as identified in this thesis. + denotes important technical parameter only when distance from goals is altered. Blue text indicates a potentially important technical factor but has not been investigated yet as it was outside the scope of this thesis. Red text indicates factors removed from the deterministic model proposed in Chapter 2 based on the results of this thesis.

A detailed analysis of goal-kicking technique was facilitated by dividing the movement into three key phases: approach phase, kicking phase and follow through phase. Examination of accurate goal-kicks enabled the identification of key technical factors associated with accuracy, to further develop the theoretical understanding of what a ‘perfect’ goal-kick resembles in AF. Furthermore, examination of inaccurate goal-kicks enabled the identification of what technical errors are made when players miss the goals (Numone et al., 2017). Findings in this thesis expanded upon the limited biomechanical understanding of the underlying technical factors which influence goal-kicking in AF. A range of important technical factors across each phase of the movement (approach phase, kicking phase and follow through phase) were highlighted to influence goal-kicking performance:

8.2.1.1. The approach phase

The angle of a player’s approach influences goal-kicking performance in AF. Accurate goal-kicks exhibited a substantially smaller approach angle line compared to inaccurate goal-kicks when examined on a group (Chapter 6) and individual-basis (Chapter 7). Furthermore, a strong negative linear relationship (r_2 = -0.83) was reported between accuracy and approach angle, indicating that a straighter approach line was beneficial for accurate goal-kicking, supporting previous scientific (Baker & Ball, 2002; Ball et al., 2002) and coaching recommendations (Hosford & Meikle, 2007; Parkin et al., 1984). Adopting a straighter approach line is suggested to help increase the planarity of the kick action, through limiting the rotation of the kick-leg around the vertical axis through the body (Alcock et al., 2012; Anderson & Dörge, 2011; Baker & Ball, 2002; Ball et al., 2002). Increasing the planarity of the kicking action allows players apply a more direct line of force to the ball (Baker & Ball, 1996), which according to the oblique impact theory directly influences the ball spin and flight path trajectory (Holmes, 2008). Theoretically, a more direct (less angled) striking force applied to the ball would propel the ball towards the target with minimal medio-lateral spin (Peacock & Ball, 2017), reducing the deviation of the ball flight path from the centre of the target (Alcock et al., 2012; Baker & Ball, 1996; Knudson, 2007). As a result, adopting a straighter line may be an effective strategy used by players to help assist in attaining an accurate goal-kick in AF.

8.2.1.2. The kicking phase (from kick foot toe off until ball contact)

Accurate goal-kicking requires increased control and regulation of the proximal-to-distal sequencing of the kick-leg. When examined on a group-basis (Chapter 6), accurate goal-kicks were characterised by less joint (hip) range of motion (ROM), and slower angular joint (knee) and segment (shank) velocities. Similar findings were evident in the individual-based analysis, with 12 out of 18 players demonstrating this pattern. The remaining players appeared to utilise more control from the pelvis. Similar findings have been reported during accurate kicking in soccer (Lees & Nolan, 2012; Gheidi et al., 2010) and rugby (Sinclair et al., 2017). Constraining the number of joints acting in the system through reducing joint ROM and reducing speed has been linked to increased control and regulation of the motion of the kicking limb, in an attempt to better position and orientate kicking limb for ball impact (Lees & Nolan, 2002; Lees et al., 2010). Theoretical literature would suggest that this may be representative of the freezing of the redundant degrees of freedom (DOF) in a task-specific functional way (Berthouse & Lungarella 2004; Caillou et al. 2002; Ko et al., 2003; Latash, 2008; Yang & Schol, 2005; Vereijken et al., 1992). However, it may also be representative of the speed-accuracy trade-off, or Fitt' law (Fitts, 1954). Biomechanically, reductions in the speed of a movement is fundamentally linked to lower ROM (Parrington et al., 2015; Knudson, 2007). As a result, this trade-off may have prompted the changes in hip and knee ROM during accurate goal-kicks. These findings would indicate that players may be actively controlling the motion of the kick-leg, specifically within the proximal limbs/joints, in an attempt to control the endpoint position of the foot for BC, to help improve accuracy.

Experimental literature has also identified the use of reduced ROM, along with slower velocities in the proximal joints as a more effective strategy to improve accuracy in other interceptive tasks, such as, tennis (Elliott et al., 2003; Göktepe et al., 2009; Knudson & Blackwell, 2005; Saviano, 2003; Whiteside et al., 2013), AF handballing (Parrington et al., 2015), baseball hitting (Katsumata, 2007), ice hockey shooting (Michaud-Paquette et al., 2009) and during other skilled movements when an accuracy demand was placed on individuals (Dupuy et al., 2000; Kudo et al., 2000). Furthermore, theoretical literature has identified the use of reduced ROM and slower movement speed as an effective strategy to improve accuracy in a skilled movement (Button & Summers., 2002; Knudson, 2007; Newall, 1986; Schmidt et al., 1979). This would indicate that this movement strategy is potentially a general feature of tasks where an accuracy constraint is placed on individuals.

How players configure their kick foot/ankle is important for accurate goal-kicking in AF. Accurate goal-kicks were associated with lower ROM (ankle), lower linear (foot) and angular (ankle) velocities, higher ankle plantar flexion, along with a straighter foot-path at BC. A number of possibilities for these adjustments where identified in Chapter 6; 1) decreased ankle ROM and angular velocity, along with slower foot speeds may be utilised to increase stabilisation and control of the foot in preparation for BC, 2) maintaining and increasing plantarflexion of the ankle may help increase the rigidity within the foot segment to improve impact efficiency, and 3) a more direct line of contact with the ball (evident through a smaller foot-angle at BC) would facilitate a straighter ball flight trajectory towards the centre of goals through limiting medio-lateral spin of the ball. Given the strong relationships (r_2 = > 0.52) identified between each of these technical parameters and accuracy, would suggest that a combination of each of these adjustments may be needed in the distal segment (ankle and foot) in order to achieve an accurate goal-kick. Similar adjustments of the distal segment/ endpoint have been identified in other striking tasks (i.e. handballing: Parrington et al., 2015, tennis serving: Elliott et al., 2003; Göktepe et al., 2009; Knudson & Blackwell, 2005; Whiteside et al., 2013). Thereby, the regulation and control of distal segment in a striking task plays a vital role in the success of a skill as it directly influences the ball flight characteristics.

As impact location cannot be predetermined during the goal-kick (due to the variable nature of the ball drop), compensatory adjustments may also play a vital role in the success of a goal-kick. Finding in this thesis indicated that the initial joint configuration of the hip, knee and ankle at the start of the kicking phase was not substantially different between accurate and inaccurate goal-kicks, while substantial alterations in joint motions occurred in the final phase (60 - 100%) of the movement. In the case of the goal-kick, it is logical to suggest that players may be making active adjustments to kick-leg mechanics in the final phase of the movement, to compensate for changes in ball drop characteristics which occurs around 20 - 40% of the movement. This has been suggested to be is an important feature of the concept of motor abundance and functional synergy (Latash et al., 2003); where if the contribution of one component (i.e. ball drop characteristics) at a particular time has a perturbing effect on an important performance variable (i.e. ball impact characteristics), other components are likely to modify their contributions to stabilise the desired performance outcome. However, as the ball movement was not measured in this thesis, future research is needed to support this assertion.

Support-leg knee mechanics play an important role in the success of a goal kick in AF. Findings in Chapter 6 and 7, indicated that during accurate goal-kicks players exhibited a more extended (less flexion) knee at SHS (23 vs 25°) that remained more extended during the stance phase until BC (38 vs 48°) compared to inaccurate goal-kicks. Researchers have suggested this adjustment is representative of a stronger and more stable stance-leg during the kick-action (Ball, 2013; Inoue et al., 2014; Lees et al., 1998; Lees et al., 2010). Theoretically, greater stabilisation of the support-leg would provide the kicker with a stronger base of support to facilitate better control and regulation of the kick-leg motion during the kicking phase (Chew-bullock et al., 2012; Ball, 2013; Inoue et al., 2014; Lees et al., 1998; Lees et al., 2010; Putnam, 1991). Researchers have argued that the balance/stability of the support-leg is vital to kicking performance (Chew-bullock et al., 2012; Ball, 2013; Inoue et al., 2014; Lees et al., 1998; Lees et al., 2010). Findings in this research suggest that decreasing support-leg knee flexion may be used as an effective strategy to stabilise the kickers during the kicking action, in order to improve accuracy.

Increasing stability is suggested to be a fundamental prerequisite in the organisation of a skilled movement in order to improving accuracy (Gibson & Pick, 2000; Massion & Deat, 1991; Reed, 1989; Rochat & Bullinger, 1994). Kinematic adjustments of the posture of supporting limb(s) have been reported in other sports, such as golf (Wells et al., 2009), pistol shooting (Ball et al., 2003a), archery (Mason & Pelgrim et al., 1986) and baseball pitching (Marsh et al., 2004) in an attempt to stabilise the performer to improve accuracy. Findings in this thesis may provide preliminary support for the importance of balance ability in goal-kicking performance in AF.

8.2.1.3. The Follow Through phase

Kick-leg mechanics during the follow-through phase provided useful information regarding a player's goal-kicking performance. Findings in this thesis indicated that technical differences exist between accurate and inaccurate goal-kicks; during accurate goal-kicks players finished with the kick-leg pointing towards goals, with higher ankle plantarflexion compared to inaccurate goal-kicks in both the group and individual analysis. These adjustments were in agreement with previous goal-kicking literature (Ball et al., 2002). The motion of the kicker through the follow-through phase cannot directly influence goal-kicking performance (as the ball is already in projectile motion), however, it can provide an indication of what happened prior to BC. For example, finishing with the leg pointing towards the goals is suggested to reflect a more planar swing motion of the kick-leg during the kicking phase (Baker & Ball, 1996). Post-hoc analysis supported this concept through reporting a moderate relationship (r_2 = 0.61) between kick-leg position and foot-path angle at BC. The findings in this thesis provide scientific evidence to support the appropriateness of the currently used coaching cue "finish with your toe pointing towards goals" as potentially an effective manipulation (Hosford & Meikle, 2007; Parkin et al., 1984), to have a direct impact on goal-kicking performance. Thereby, these finding help bridge the gap between biomechanical research and coaching practice. Interventions to improve kicking performance, through manipulating follow-through characteristics has been identified as an area that warrants further investigation (Bezodis et al., 2018). Given the strong association with follow-through characteristics and the movements during the kicking phase documented in this thesis, examination of follow-through manipulations is an area worthy exploring.

The findings in this thesis may have important implications for other sports where a follow-through exists, such as, golf swing, tennis serve, baseball batting, basketball shooting. Commonly, when investigating the biomechanics of a skill, the motion of the performer during the follow-through is not of primary interest as it cannot directly influence the performance outcome. The follow-through is often seen as only a release mechanism at the end of the movement to dissipate the energy build from the movements in the previous phase (Knudson, 2007). However, evidence in this thesis would suggest that the follow-through would provide an interesting avenue for further examination, as it may provide a means to effectively adjust the movements during the previous phases. Howard et al. (2015) demonstrated that experimental manipulations of the follow-through could be useful when learning variations of simple motor skills such as grasping an object or reaching a target. Interestingly, the authors highlighted that use of a consistent follow-through motion can reduce interference in a movement, helping achieve a more consistent movement solution. Thereby, the follow-through in a skilled movement can potentially provide important information regarding performance and offer a potential avenue for improvement.

8.2.2. Individual-specific findings

Individual technical differences exist when players kick for goals in AF. These differences ranged from the type (i.e. specific technical parameter) and number of substantial kinematic differences between accurate and inaccurate goal-kicks, along with the magnitude (i.e. trivial, small, moderate, large, very large) and direction (i.e. increase or decrease) of these kinematic differences between players. Furthermore, all players demonstrated at least two substantial relationships between technical parameters and accuracy, however these were also individual-specific. It was evident that player used different combinations of technical factors to achieve the same performance outcome. Findings highlighted the individual nature of goal-kicking in AF, suggesting it is clearly important to coach this skill on an individual basis rather than applying a theoretical ‘perfect kick’ model across all players.

Difference movement patterns were evident amongst players when kicking for goals in AF. For example, how players controlled and regulated the motion of kicking-limb during the goal-kicks, differed between players. The majority of players constrained the movement of the hip (lower hip ROM) to increase control and regulation of the motion of the kicking limb, whilst other players utilised contributions from the pelvis and knee. Consequently, this would require greater strength in the contributing musculature. As such, consideration should be given to exercises in training that directly target the muscles for these individual players. In addition, the speed of the goal-kicking action differed between individuals. For the majority of players, it was evident that they may have sacrificed the speed of the goal-kicking action (substantially slower linear and velocities at BC in the kick-leg in accurate goal-kicks compared to inaccurate goal-kicks) to allow for the detection and correction of errors, in order to improve the accuracy of the kick, which is representative of the speed-accuracy trade-off (Fitts, 1954). However, this was in contrast to players 7, 5, 10 and 12, who demonstrated a faster kick-leg movement (faster linear (COM, footspeed) and angular (ankle, shank and knee) velocities) during the kicking phase in accurate goal-kicks. The ability to perform more accurately at higher velocities was explained through the impulse-variability theory (Urbin et al., 2011); where an increase in kinematic stability is achieved with increased force production (higher velocities), which has been suggested to translate to greater spatial accuracy in a task. Coaches need to be cognisant of these different strategies, as different coaching cues may be needed for the different players. One strategy to determine which group players fall into would be to perform a simple 2 D analysis (sagittal plane) of their current goal-kicking technique.

The existence of the knee-thigh angular velocity continuum was also evident in the group of 18 AF players tested in this thesis. At one end of continuum, players utilised a knee strategy (larger knee angular velocities, with smaller thigh angular velocities at BC). For example, during accurate goal-kicks player 9 exhibited a relatively high knee angular velocity (1749 ± 187°/s), with a smaller thigh angular velocity (82 ± 15°/s) at BC. At the other end the continuum, players exhibited utilised a thigh strategy (larger thigh angular velocities, with smaller knee angular velocities at BC. For example, during accurate goal-kicks player 1 exhibited a relatively low knee angular velocity (1145 ± 422), with a larger thigh angular velocity (422 ± 38) at BC. Whilst technical differences existed between the thigh strategy and knee strategy kickers, no substantial differences in accuracy were reported, indicating that a similar performance was produced at either end of the continuum, supporting previous findings in AF kicking (Ball, 2008, 2011; Blair & Ball, 2018). These findings have important implications for the physical training of players, as the different strategies (knee and thigh) will require different conditioning recommendations to suit the movement patterns. For example, knee strategy kickers rely on the knee extensors to perform the kick, whilst thigh strategy kickers might rely more on the hip flexors (Ball, 2008). Consequently, the findings in thesis identified that coaching recommendations need to be tailored to the individual in order to aid improvement in goal-kicking performance.

The findings in this thesis extend the current biomechanical understanding of the presence of individual differences within a skilled performance (Ball & Best, 2012; Ball et al., 2003a, 2003b; Bates & Stergiou, 1996; Bates et al., 2004; Caster & Bates, 1995; Dufek & Zhang, 1996; Dufek et al., 1995; James & Bates, 1997; Miller & Schwarz, 2018; Morris et al., 1997). Biomechanical research is commonly conducted on a group-basis to answer a given research question, without the consideration of an individual's athlete's performance. Supporting previous research (Ball & Best, 2012; Ball et al., 2003a, 2003b; Bates & Stergiou, 1996; Bates et al., 2004; Caster & Bates, 1995; Dufek & Zhang, 1996; Dufek et al., 1995; James & Bates, 1997; Miller & Schwarz, 2018; Morris et al., 1997), the findings in this thesis also clearly demonstrate the need to examine the technical aspects of a skill on an individual level, as well as across the group.

8.2.3. Exploration of task constraints in goal-kicking

Modifying the task constraints of the goal-kick in AF, can influence the technique players utilise to achieve a consistent performance outcome (successful kick). Findings in Chapter 5 indicated that increasing the distance of the shot by 10 m led to substantial changes in goal-kicking technique in AF. A substantially faster approach (higher max COM velocity), with higher linear (foot and COM) velocities, angular velocities (shank and knee) and larger joint (hip and knee) ROM of the kick-leg were evident when players kicked at 40 m from the goals posts. These findings were in agreement with Baker and Ball (1996) who reported alterations in punt kicking technique with increasing distance. Theoretically, increased linear and angular velocities allow more momentum to be generated and transferred from the leg to the ball, which would lead to increased ball velocity (Ball, 2008). This would indicate that at further distances players were attempting to move the ball faster (more maximally) toward the target, which is a necessary adjustment when kicking distance increases (Baker & Ball, 1996; Ball, 2008; Ball, 2013; De Witt et al., 2012; Kellis & Katis, 2007; Peacock & Ball, 2018c; Peacock et al., 2017; Lees et al., 2010; Sinclair et al., 2014; Zhang et al., 2012). These changes in technique support the constraint-led approach to motor control, which postulates that alterations to the constraints under which a task is performed leads to significant changes in the movement pattern required to complete the task (Davids et al., 2008; Renshaw et al., 2010). However, it is worthy to note that this thesis examined accurate kicks only, and it is unknown if players' may have scarified the speed of a kick to achieve greater accuracy; a phenomenon described as the speed-accuracy trade-off (inverse relationship between the speed at which a skill can be performed and the accuracy that can be achieved: Fitts, 1954). Further examination of accurate and inaccurate goal-kicks at each distance would determine if faster speeds are maintained or whether too much speed is detrimental to accuracy.

Altering the angle of the goal-kick (from 0º (directly in-front of goals) to 45º to the left or right) had no substantial influence on technique. Theoretically, the only apparent change that players have to contend with is a reduction in the angle of opportunity/relative width of the goal-line available (13.20 to 10.15°/6.4 m to 6.35 m) (Galbraith & Lockwood, 2010). As a result, the same technique would be required to place the ball directly in the centre of the goal, however, it would require players to be more consistent in their goal-kicking technique, as they have less margin for error (smaller target). The idea of a more consistent technique was reflected through lower standard deviations across technical parameters in goal-kicks taken at a 45°. Conversely, when the distance of the kick increases to 40 m, players have to contend with a slightly bigger decrease in the angle of opportunity/relative width of the goal-line (13.20° to 7.38°: 6.4 m to 6.34 m), along with need for the ball to travel further (10 m). As a result, players also need to be more consistent in their goal-kicking technique (as they have less margin for error) but also need to apply more force to the ball to meet the distance requirement. In contrary to intuition, being straight in-front of goal (in the central corridor) does not necessarily equate to a better goal scoring opportunity for players (Anderson et al., 2018; Galbraith & Lockwood, 2010). Findings in this thesis would indicate that kicks taken at 40 metres directly in-front of goals pose a greater technical difficulty opposed to 30 metre kicks taken at an angle. Findings in thesis have enhanced both the theoretical and practical understanding of the goal-kicking movement in the presence of game-specific task constraints.

This thesis provided an insight into the effect of altering task constraints (distance and angle from goals) on goal-kicking technique and performance in AF. Within a competitive performance environment, players also need to successfully adapt to numerous other fluctuating constraints such as, task constraints (changes in fatigue), environmental constraints (wind, rain, crowd noise, and the stadium where the match is contested), personal constraints (anxiety, decision-making skills) and contextual factors (e.g. score margin and time remaining) (Anderson et al., 2018; Nel, 2013; Quarrie & Hopkins, 2015). Biomechanical theorists have suggested that a skilled movement is a result of the complex interactions between the task goal, performer, contextual and environmental constraints (Davids et al., 2003; Davis & Burton, 1991; Gagen & Getchell, 2004). Given that specific task constraints influence theoretical frameworks such as, the dynamical systems theory (Davids et al., 2005; Davids et al., 2003) may offer a useful framework to investigate how technique is affected by the interaction of constraints (such as, the task, morphological and environmental constraints). The dynamical systems theory is an interdisciplinary framework, that can explain how functional patterns of movement emerge to satisfy competing and cooperating tasks, informational and environmental constraints (e.g., Newell, 1986). Davids et al., (2005) suggested that manipulating key task constraints can direct the learners' search for effective coordination solutions and to achieve functional and unique coordination solutions to achieve a specific task goal. These applications could provide useful insights into processes of motor skill acquisition and tactical development of players and their goal-kicking ability. Therefore, application of the dynamical systems theory may provide an interesting avenue for further investigation in goal-kicking research to study the interaction of constraints on individuals in goal-kicking.

The findings from thesis have important scientific implications. As kinematic differences were shown to occur for specific task constraints, the findings indicate that researchers need to consider the influence of task constraints on a skilled movement when designing and implementing a biomechanical investigation. Often researchers aim to gain an understanding of what an 'ideal' technique resembles to better inform coaching practice. However, if task constraints affect the technique of a skill, such as identified in goal-kicking, this will directly influence how the skill should be coached. As a result, researchers need to be aware of what setting best represents the competition environment and the conditions of the task when investigating the key technical parameters associated with a skill.

8.3. Methodological considerations

Several important methodological considerations arose from the experimental chapters in this thesis, specifically regarding the assessment of goal-kicking technique and the factors that influence performance. These included; the measurement of accuracy, the cohort of participant used, the use of a group and an individual-based analysis approach, measurement of performance in an applied context and the use of magnitude-based inferences (MBI) to provide statistical comparisons between accurate and inaccurate goal-kicks.

8.3.1. Measurement of Accuracy

Kicking accuracy in football has been defined as the ability to kick a ball to a specific target (Finnoff et al., 2002). A goal-kick in AF is recorded as an accurate kick when the ball passes through the two inner large goal posts (no vertical limitation of where the ball can pass through the posts), whilst anything outside of this is regarded as an inaccurate goal-kick (**Figure 8.2**). Different criterion measures have been utilised in scientific literature to access kicking accuracy across the football codes; hit (accurate) vs miss (inaccurate) (Blair et al., 2017; Dicheria et al., 2006; Gheidi & Sadeghi, 2010; Katis et al., 2013; Lees & Nolan, 2002; Sinclair et al., 2017), sub-divisions of a target (Ball et al., 2002; Chew-Bullock et al., 2012; Finnoff et al., 2002), distance from the centre of a target (Bezodis et al., 2007; Izovska et al., 2016) and use of bull-eye target (Hunter et al., 2018). Each method poses advantages and limitations, which can influence the conclusions made from a set of experimental data (Finnoff et al., 2002; Hancock et al., 1995). In this thesis, accuracy was assessed using a combination of two criterion measures: hit vs miss and a radial distance measure (lateral horizontal distance from the centre of a target).

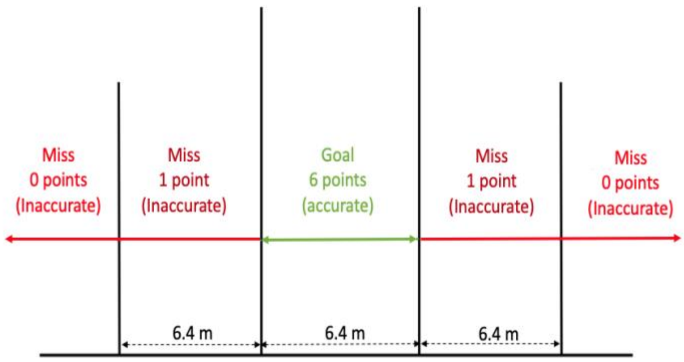


Figure 8.2. Definition of an accurate and inaccurate goal-kick in AF.

At a broad level, the use of the hit vis miss method represents a true performance measure which corresponds to how goal-kicks are classified in competition. The advantage of this method is that provides a discrete measure of performance which permits the data set to be split into two distinct groups. This enabled statistical comparisons to made between accurate and inaccurate goal-kicks, to elucidate important technical factors associated with goal-kicking performance on a group and individual level. For example, in Chapter 5, it was identified that less support-leg knee flexion is an important technical adjustment evident in accurate goal-kicks. Such kinematic information is crucial to coaches and practitioners when attempting to develop coaching programmes aimed at improving goal-kicking performance. Importantly, this method also identified what technical errors are made when players miss the goals. For example, inaccurate goal-kicks was associated with substantially less ankle plantar flexion at ball impact. This also provides important information that can be used by coaches and practitioners to inform or develop coaching cues to prompt modifications to a player's technique to reduce the presence of such undesirable technical factors. Given that discrete kinematics are often used as the primary information by coaches and players in their evaluation of technique, use of the hit vs miss provides a direct method that coaches and players can easily relate to and utilise (Ball & Blair, 2018; Finnoff et al., 2002; Phillips et al., 2012), highlighting the practical significance of the hit vs miss method, and its corresponding findings.

The weakness of the hit vs miss method, however, is its limited resolution of performance measurement. As kicks are classified into two distinct groups it does not convey information about the magnitude of the error of the shot (Ball & Ball, 2018; Hancock et al., 1995). For example, kicks that miss by a small margin of error are grouped with kicks that miss by a large margin of error. Similarly, kicks that are scored directly in the centre of the goals are grouped with kicks that pass just inside the post. As a result, goal-kicks are classified over a wide margin (for example, 6.4 m in accurate goal-kicks) which consequently, decreases the sensitivity of the measure. This could potentially mask important technical information associated with accurate or inaccurate goal-kicking. Another potential issue that arises is when kicks that pass either side of the post are classified in different categories, where only slightly different ball flight characteristics and/or technical differences may occur. This can then skew the results in the corresponding category, as these kicks are averaged with other kicks that may have completely different technical characteristics as they missed by a greater margin (eg: kicks that miss by 6 m vs 0.1 m). However, despite the weaknesses in this method, it is extremely important that it is the first avenue of examination taken, as this is what players and coaches will expect to see and can most easily understand (Ball & Blair, 2018).

The use of a radial distance method provides a continuous measure of performance which can increase the resolution of the analysis. As players aim for the middle of the goal, any deviation from this can effectively represent an error. This method uses the centre of the goal as the 'target' and measures the lateral horizontal distance (note: unlike the other football codes, there is no elevation (height) constraint on where the ball needs to pass in AF goal-kicking) from this point (**Figure 8.3**) to provides a continuous performance measure which can provide more information about the magnitude and direction of the error associated with missing the target (Ball & Blair, 2018). As a result, the error margins of the position of the shot can be determined for any given shooting position, providing finer detailed associated with kicking accuracy. In addition, this approach can increase the statistical power and allow for regression-based statistics to be employed (Ball & Ball, 2018; Hancock et al., 1995) to explore the strength of the association between specific technical parameters and accuracy. In this thesis, a number of substantial linear, quadratic and cubic relationships were identified in both the group and individual based analysis which provided more detail on how these factors were influenced by accuracy. Furthermore, the radial distance method was able to provide more specific information related to goal-kicking performance that could not be provided by the hit vs miss comparison. For example, in Chapter 5, the hit vs miss comparison identified that less support-leg knee flexion is an important technical aspect in accurate goal-kicks. A quadratic relationship was then identified in the radial distance analysis for support-leg knee flexion at BC; where accurate kicks were associated with a knee flexion range of 36 - 45°, with either side of this range associated missed goal-kicks on a group-basis. This indicated that too much and/or not enough knee flexion was associated with errors in goal-kicking, which was not apparent in the hit vs miss comparison. Further examination of this aspect, identified that knee flexion less than 36° was associated with goal-kicks missed to the left of goals, whilst knee flexion greater than 45° was associated with missed kicks to the right of the goals. Based on these findings, coaches working with kickers who have a tendency to miss to the left or right of the target, could aim at altering support-leg mechanics as a potential avenue for improvement. This can provide an athlete more solutions to a performance (i.e. if they work within this range) compared to targeting a discrete measure for performance. Consequently, the use of the radial distance method can provide finer detail on the complexity of a skill, providing a more in-depth understanding important technical characteristics associated with accuracy.

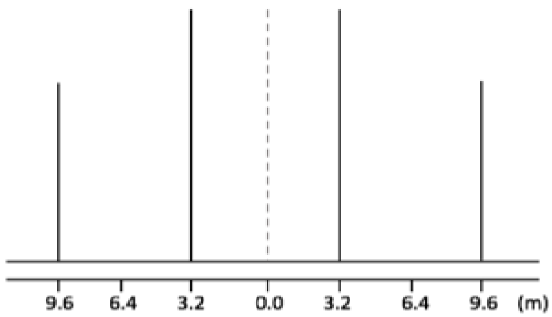


Figure 8.3. Definition of the radial distance method used for the goal-kick in AF.

The weakness of the radial distance method, however, is that it is not directly related to the game-based performance measure. Despite the potential value associated with the lateral distance method, it can increase the complexity of the biomechanical findings, which makes it not readily understood by coaches and athletes outside of the biomechanical discipline. For example, various linear, quadratic and cubic relationships were identified for the different parameters and individuals. In an attempt to address this, researchers need to translate the complexity of the results from these types of analyses into easily useable language and/or coaching cues that coaches and athletes can easily relate to. For example, for a non-scientific audience the identification of a strong quadratic relationship between support-leg knee flexion and accuracy is difficult to understand and put into practice. Conversely, indicating that this means there is an optimal range that players can perform within to benefit accuracy makes the findings more easily understood and useable for coaches and athletes. Despite the complexity of this method, it can provide a more in-depth understanding of a skill it can give an athlete more solutions to a performance compared to targeting a discrete measure for performance.

A combination of the hit vs miss and radial distance measures of accuracy offered a more thorough and useful investigation of technical factors which influence goal-kicking accuracy in AF. From a scientific perspective, this provides finer detail on the complexity of the skill, to provide a more in-depth understanding of the biomechanical characteristics associated with goal-kicking performance. From an applied perspective, this provides coaches, practitioners and players with specific kinematic information that can be used to help improve goal-kicking across all levels. Thus, a combination of both methods is recommended for future investigations examining the technical aspects of kicking accuracy.

8.3.2. Selection of skilled participants: Game demands vs playing level

The participants in this thesis were selected based on their game-demands (i.e. participant that regularly perform goal-kicks during a match) rather than playing level, as players who compete at a higher level, such as elite, do not necessarily represent a higher skilled cohort of goal-kickers (Bezodis et al., 2018). Elite AF players typically possess a abroad set of multi-dimensional performance qualities, such as, high physiological performance attributes (i.e. running endurance, strength, speed, and agility), a proficient technical skill set that broadly encapsulates different aspects of ball disposal (i.e. kicking and/or handballing under varying environmental and game contexts), possession (i.e. marking, ball pick up, bouncing the ball) and checking skills (i.e. tackling and bumping), along with perceptual components (Haycraft et al., 2017; Robertson et al., 2015a; Woods et al., 2015; Woods et al., 2016; Young et al., 2010). However, research has indicated that elite AF players demonstrate varying levels of proficiency within each of these components, depending on their involvement in an AF game (Young et al., 2010). For instance, forwards have been reported to exhibit higher levels of kicking proficiency due to their involvement in more contests/ball disposals (i.e. taking goal-kicks, kicks to players) during a game (Young et al., 2010) compared to other playing positions such as, defenders. Analysis of the 2018 AFL season indicated similar findings, with forwards demonstrating higher kicking accuracy compared to other playing positions (**Table 8.1**). This provides support for the assertion that all elite AF players do not represent a higher skilled cohort of goal-kickers. Furthermore, a player competing at a lower playing level (such as, amateur or sub-elite) who performs goal-kicks on a regular basis may have high technical goal-kicking proficiency, but may not have the other desirable attributes to become an elite performer (Bezodis et al., 2018). This would indicate that there is also value in recruiting players outside of an elite population as they can potentially represent a higher skilled cohort of goal-kickers. Thereby, when examining the technical aspects of a skill, representing players on game-demands may therefore have greater importance than directly recruiting players based on playing level, especially when trying to elucidate technical factors associated with performance. A similar argument could also apply to other skills across the football codes, such as tackling, or more broadly to skills in other team sports.

Table 8.1 Example of changes in goal-kicking accuracy in elite AFL players. Data taken from Champion Data statistics of the 2018 AFL season.

Player	AFL Club	Playing position	Goal-kicking accuracy %
Jake Barret	Brisbane Lions	Forward	100%
Aidyn Johnson	Port Adelaide	Forward	85.7%
Tom McDonald	Melbourne	Forward	68.8%
Alex Bullen	Melbourne	Midfielder	54%
Tom Mitchell	Hawthorn	Midfielder	41.9%
Josh Kelly	Western Sydney	Midfielder	32.3%
Taylor Duryea	Hawthorn	Defender	9.1%
Ryan Burton	Hawthorn	Defender	0%

8.3.3. Group and individual-based analysis

Two analysis approaches were used in this thesis: 1) group-based analysis (evaluation of a problem across a group of subjects), and 2) individual-based analysis (evaluation of a problem within a single-subject) (Bates et al., 2004). Adopting a combination of both a group and individual-based analysis approach has been recommended for biomechanical research when examining the technical aspects of a skilled movement to ensure all important information is extracted (Ball & Best, 2012; Ball et al., 2003a; Ball et al., 2003b). In this thesis, a group-based analysis approach was firstly used to identify key technical differences between accurate and inaccurate goal-kicks in a sample of 18 elite AF players, followed by an individual-based analysis to provide a more specific analysis of technique changes between accurate and inaccurate kicks on an individual level.

Use of a group-based analysis in Chapter 6 provided important technical information related to accurate goal-kicking technique that was not evident in the individual-based analysis in Chapter 7. For example, substantially less support-leg knee flexion (38 vs 43, *likely* large) was associated with accurate goal-kicking when examined on a group-basis, however in the individual-based analysis there was no substantial effect of support-leg knee flexion reported for players 14 (48 vs 50, *possibly* trivial) and 18 (48 vs 48, *possibly* trivial). Compared to the others, players 14 and 18 demonstrated lower kicking accuracy and had the largest values produced for knee flexion at BC in their accurate goal-kicks. Given the link identified (in this thesis and the literature (Ball, 2013)) between support-leg knee extension and kicking performance, it might be useful for these players to seek to increase knee extension throughout the kicking phase, as a potential modification to improve their goal-kicking accuracy. Using only individual-based data, this possibility would not have been detected. The findings from Chapter 6 were useful in characterising goal-kicking technique to help establish an evidence base to better define the key technical factors that are associated with goal-kicking performance and develop a general understanding of what a 'good' goal-kicking technique resembles. Given the advantages of the group-based approach (i.e. provides a larger sample to control for inter-subject variability to provide adequate statistical power), the results can be generalised to the greater population (Bates et al., 1994; Vincent, 2012) and used to objectively guide development programmes designed to improve goal-kicking performance across a range of levels. However, it is important to consider that the results may not apply to all individuals.

Use of an individual-based analysis in Chapter 7 provided important information that was not evident in the group-based analysis in Chapter 6. For example, players 2, 4 and 9 demonstrated substantially lower pelvis and knee ROM in accurate kicks compared to inaccurate kicks (2: 31 vs 46°; 4: 35 vs 47°; 9: 30 vs 37°), whilst there was no substantial effect of pelvis ROM on a group basis (46 vs 48°, *very likely* trivial). Findings indicated that players 2, 4 and 9 may be constraining the movement of the pelvis to facilitate control and regulation of the motion of the kicking limb rather than control initiated from the hip (which was identified as important on a group basis). For these players, it may be important to implement more conditioning work around the pelvis and knee rather than the hip for improvements in goal-kicking performance. Using only a group-based analysis, these factors would not have been identified. This has been identified as a weakness of a group statistical design, where 50% of the individuals in an analysis reside in the opposite end of the distribution compared to the other 50% of individuals, and therefore may not respond favourably (Bates et al., 2004). Consequently, data observed "on average" across a sample using a group-based analysis may provide a misleading information on what is true for certain players, masking important individual performance factors (Ball & Best, 2012; Ball et al., 2003a; Ball et al., 2003b; Bates et al., 2004). Thereby, individual-based analysis is needed to account for individual variations in technique to provide a more targeted approach to performance improvement.

Some conflicting findings were found between the group-based analysis in Chapter 6 and the individual-based analysis in Chapter 7. For example, four players (5, 7, 10, 12) demonstrated substantially higher linear (foot) and angular velocities (shank) in accurate goal-kicks compared to inaccurate goal-kicks. Conversely, in the group-based analysis an opposite substantial relationship was reported; accurate goal-kicks demonstrated substantially lower linear (foot) and angular velocities (shank) compared to inaccurate goal-kicks. Findings from the group-based analysis would suggest that a slower movement is beneficial for accuracy when kicking for goal in AF. While, for players 5, 7, 10 and 12, the individual-based analysis revealed this could be detrimental to their performance. Consequently, conclusions from the group-based analysis should be treated with caution. Whilst the group-based analysis provides a general understanding of what a ‘good’ technique resembles, implications arise when findings from only this analysis is used by coaches and practitioners to objectively guide and inform training sessions aimed at improving a skill. Inappropriate coaching cues or recommendations could be given to a player, which could ultimately impact their skill development and performance. From a scientific perspective, this increases the complexity of the research design, as both a group and individual-based analysis is needed to provide a more comprehensive understanding of a skill. In addition, researchers should be cautious when prescribing specific coaching recommendations from only a group-based analysis, as this could be detrimental to specific individuals. Often coaching staff and practitioners refer to current research to inform coaching practice, therefore acknowledgement of the presence of individual-specific findings needs to be reported in group-based analysis research, if the study is not accompanied by an individual-based analysis. From a practical perspective, this means that coaches and practitioners need to evaluate their players’ technique on an individual-level, to ensure training and coaching recommendations are appropriately tailored to an individual when targeting improvement in performance. Consequently, when implementing technical refinements in applied coaching practice, coaching recommendations need to be tailored to the individual, as providing one ‘ideal’ kicking technique model may not appropriate for all players in AF.

In conclusion, the combination of both a group and individual-based analysis provided a more thorough understanding of the technical factors which influence goal-kicking technique and performance within and between players in AF. Findings in this thesis support the recommendation by Ball et al. (2003a) and Ball & Best, (2012) that a combination of both approaches (group and individual-based analysis) is appropriate to extract all important information related to a skill. Furthermore, findings in Chapter 6 and 7 provide additional evidence supporting the inclusion of both a group and individual-based analysis for biomechanical research applications in kicking.

8.3.4. In-field analysis of performance

Providing a biomechanical analysis of goal-kicking in an applied context was a strength of the kicking experimental chapters in this thesis (Chapters 5, 6 and 7). Use of the IMS approach was able to obtain a more ecological valid representation of goal-kicking performance through having players kick towards their usual target, which is often limited in a laboratory data collection. In addition, all players wore appropriate attire (boots that they currently used at training and in game situations they currently use at training and in game situations), which is often restricted when testing in a laboratory environment (players are often required to wear boots without cleats or studs). As a result, this meant the protocol was more representative of in-game situations, providing a more ecological valid measure of goal-kicking technique.

A limitation of an in-field analysis is the inability to control for varying external environmental factors, such as weather conditions (rain, wind, light, temperature, etc) and degrading ground conditions. Whilst testing was conducted on low wind and dry, varying levels of wind could have potentially impacted the ball flight characteristics of the goal-kick (i.e. wind advantage). Furthermore, whilst data was collected over the period of two sessions, degrading of grounds may have occurred between the start and end of the season. Conducting a biomechanical analysis in a controlled laboratory environment can be used to eliminate the effects of external environmental factors. However, a laboratory data collection rarely allows players to perform a skill under realistic conditions (such as kicking towards their goal target) and often does not permit analysis of skills across a range of contexts, which was found to have important implications for the goal-kicking skill. However, it is worth noting, that laboratory assessments are still valued in biomechanical research as they provide a controlled environment to enable a more comprehensive examination of technique, through facilitating the ability to run a full biomechanical analysis (collection of simultaneous 3D kinematics, joint kinetics, electromyography and plantar pressure).

8.3.5. The use of Magnitude-based Inferences

Another strength of the experimental chapters in this thesis was that participants are sampled from elite and sub-elite population and represented a high skill level. However, reliance on an elite cohort/ higher skilled players resulted in a relatively lower small sample size due to the availability and access to the players. This is a common difficulty across the sport science discipline, where researchers are often not able to obtain an adequate sample sizes (as defined by G*power analysis), meaning their study may not have sufficient statistical power to detect a true effect and consequently, any inferences about the results should be treated with caution (Hopkins, 2006). This is a specific problem in traditional inferential statistics, such as null-hypothesis significance testing (NHST), where a reduction in sample size exposes researchers to falsely concluding that there are no significant differences (Type II error) when in-fact a real change in performance occurred, or concluding that a significant difference exists when it does not (Type I error) (Batterham & Hopkins, 2006; Hopkins & Batterham, 2016; Hopkins et al., 2009, 1999). Motivated by the limitations of NHST, Magnitude-based inferences (MBI) was introduced to detect meaningful performance changes in relatively small sample sizes (Hopkins et al., 2009, 1999). Due to the advantages of MBI, it was the inferential statistical approach adopted in each experimental chapter in thesis.

Magnitude-based inferences enable researchers to make inferences about the importance of an effect (true value statistic) between two groups, taking into account the uncertainty in its magnitude (Batterham & Hopkins, 2006; Hopkins et al., 1999; Smith & Hopkins, 2011; Hopkins et al., 2018a). Confidence limits (CL) are calculated to represent the likely range in which the true value would fall, and when considered alongside an outcome statistic (such as a difference in means or an effect size), it can be assessed in relation to values that are considered to be substantial (smallest worthwhile change) (Batterham & Hopkins, 2006). A qualitative probabilistic non-clinical magnitude-based inference is then made about its usefulness, which is based on the probabilities that the true effect was substantially positive, negative or trivial (**Figure 8.4**) (Batterham & Hopkins, 2006; Hopkins et al., 2009; Hopkins et al., 1999). Sample sizes that give acceptable precision with 90% CL are based on an α-level of 0.5% (Type I error: using an effect as beneficial when real-world application is harmful) and a β-level of 25% (Type II error: not using an effect that in real-world application is beneficial) (Hopkins & Batterham, 2016). The acceptable rates for each type of error are decided and set by the researcher in advance of the study (Hopkins et al., 1999). This is in contrast to NHST, where the α-level is set by the researcher, though the β-level is affected by the statistical power of a test which is dependent on the sample size (Hopkins & Batterham, 2016; Hopkins et al., 1999). Consequently, when a reduction in sample size is met, researchers are exposed to inflation of Type 2 (β-level) errors, resulting in falsely (false positives) concluding that there are no significant differences, when in-fact a substantial change (true effect) in performance was evident (Batterham & Hopkins, 2006; Hopkins & Batterham, 2016; Hopkins et al., 2009). Error rates with MBI have been found to be comparable to those reported in NHST studies, indicating the potential for publication bias is negligible within smaller sample studies using MBI (Batterham & Hopkins, 2006).

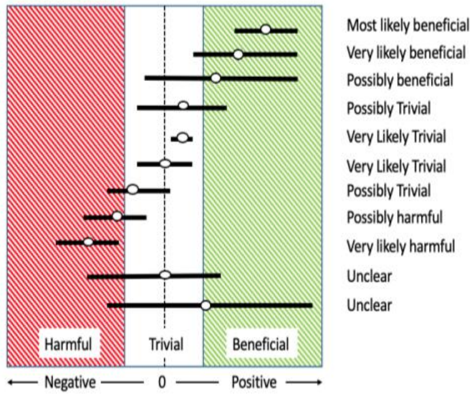


Figure 8.4. The three-level scale of magnitudes that inferences are qualified with the likelihood that the true value is harmful/trivial/beneficial.

The use of MBI in thesis enabled differences to be objectively identified between two measurement systems (IMS and MAS: Chapters 3 and 4), different goal-kicking positions (Chapter 5) and accurate and inaccurate goal-kicks (Chapters 6 and 7). Use of thresholds and probabilities enabled more informative inferential assertions about the effect magnitude detected in each experimental study. For example, there is a *mostly likely* large increase in approach angle associated with inaccurate goal-kicks (Chapter 6), there is a *mostly likely* large effect of foot speed on goal-kicking performance for player 7 (Chapter 7), a *likely* small measurement error exists between the IMS and MAS minimum kick-leg knee angle (Chapter 4). The application of MBI also enabled the identification of possibly beneficial changes in performance which may be worthy of implementation to aid improvements in goal-kicking performance. For example, a *possibly* substantial (moderate effect) increase in COM velocity at BC was associated with accurate goal-kicks. Whilst other technical factors had more of a substantial (*most likely* large effect) impact on performance, findings indicated that alterations in COM velocity may also *possibly* offer a potential avenue for improvement in goal-kicking performance. Consequently, the use of MBI has also been suggested to provide a more meaningful statistical approach to aid real-world decision-making in applied sport (Hopkins & Batterham, 2016; Mengersen et al., 2016; van Schaik & Weston, 2016).

Despite some debate on the use of MBI (Sainani, 2018; Welsh & Knight, 2015), MBI has been shown to produce comparable results to other inferential statistical approaches (such as, fully Bayesian statistical approach) (Hopkins & Batterham, 2016; Mengersen et al., 2016; van Schaik & Weston, 2016). For example, in a re-analysis of data from a typical study of sports performance (i.e. small sample size) which used a fully Bayesian statistical approach, the authors found that using the MBI the outcomes were consistent with those obtained a fully Bayesian statistical approach (Mengersen et al., 2016). As a result, MBI is being increasingly used in sport science research (eg. Bezodis et al., 2018; Blair et al., 2018; Carling et al., 2018; Colyer et al., 2018; Coutinho et al., 2018; Dello et al., 2018; Luteberget et al., 2018; Floria et al., 2018; Schaefer et al., 2018; Warren et al., 2018; Vickery et al., 2018) and research using this approach has been published in many leading sport science journals (e.g. Journal of Biomechanics, Sport Biomechanics, Journal of Sport Science, Journal of Science and Medicine in Sport, Medicine and Science in Sports and exercise, Human Movement Science). Thereby, MBI is currently accepted as a practically meaningful statistical approach in the sport science discipline.

8.4. Limitations & Future Directions

Chapter 3 and 4

- It could be argued that a limitation of the validation studies in this thesis, was their failure to assess the performance of the IMS in a field-based setting, as this is the most ecologically valid environment. However, it is important to have a valid and reliable measure to compare with, in this case having the controlled laboratory conditions, which is widely used in football research, maximises the validity of the MAS measures (Windolf et al., 2008).

- The validity of kinematic data measured by the Xsens IMS was assessed up until the instant prior to BC, to avoid issues of smoothing through foot-ball impact (Knudson & Bahamonde, 2001; Numone et al., 2018). It is unknown if the validity of the IMS is maintained when measuring movement through a collision, such as during foot-ball impact, where higher frequencies exist (outside of the validated frequencies in this thesis). As foot-ball impact characteristics have important implications for the outcome of a kick (Peacock & Ball, 2018a, 2018b), determining the validity of kinematic data measured from the IMS during this collision would extend the potential research applications of the IMS in kicking, as well as in other skills were collisions exist, such as a tennis serve.

Chapter 5, 6 and 7

- Whilst a number of important technical differences were identified between accurate and inaccurate kicks, these may not account all the potential factors which influence goal-kicking accuracy in AF. With the distinct aspect of releasing the ball from the hand during the punt kick, this adds an additional task constraint, which may influence the accuracy of the shot at goal. The ovoid shape of the ball means that different impact points on the balls circumference would influence the spin about the balls long or short axis (Ball, 2008; Peacock & Ball, 2018b), consequently altering the ball flight characteristics and outcome. A player's ability to control and drop the ball optimally, along with co-ordinating the interceptive task of striking the ball with the foot, may play a substantial role in the outcome of a goal-kick. Both ball orientation and the nature of foot-to-ball impact have been considered as important factors for punt kicking performance (Ball, 2008; Ball, 2011a; Peacock & Ball, 2018c). As accurate kicking is achieved by imparting an appropriate combination of flight characteristics on the ball (Peacock & Ball, 2018c), future research is warranted to examine the technique of controlling and dropping the ball, along with the interceptive task of striking the foot, as this may provide an additional insight and understanding of important factors which influence goal-kicking performance in AF.

- In this thesis, goal-kicking technique was examined under a non-fatigued state, which enabled an examination of technique under 'ideal' conditions. However, fatigue has been shown to be detrimental to kicking performance in AF (Coventry et al., 2015) and across the football codes (Apriantono et al., 2006; Kellis et al., 2006; Lyons et al., 2006). Given the high physical demands placed on AF players during a game, it is logical to assume they would be required to perform goal-kicks under varying levels of fatigue. Thereby, future research is warranted to understand how fatigue affects the goal-kicking skill.

8.5. Practical Applications

The practical applications of this thesis are:

1. The Xsens IMS may be used to validity quantify kicking biomechanics in an applied environment, to provide objective information to support coaching practice.
2. The findings from Chapter 5 may be useful for informing the design of training programs aimed at improving goal-kicking performance. Typically, players are coached to execute goal-kicks in a consistent manner irrespective of pitch location (Bezodis et al., 2018; Hosford & Meikle, 2007). However, findings in thesis indicated that adjustments in goal-kicking technique are required at different distances. Consequently, Coaches may need to instruct players to adjust goal-kicking technique

according to the location of the shot. In an attempt to address this, coaches could employ goal-kicking drills across a range of positions to simulate relevant situations experienced in competitive environments. This would guide players through a range of potential movement solutions. This would also highlight to coaches and practitioners on the specific constraints which pose greatest difficulty for players (i.e. a specific kicking position that results in greatest inaccuracy), thereby offering areas to work on. The incorporation of specific constraints within practice has been suggested to better prepare athletes for the competition settings, through developing more "game-smart" players (Davids et al., 2008; Renshaw et al., 2010).

3. Given that goal-kicking success was reported to change dependent on pitch location, the findings in this thesis could be used to inform in-game decision making strategies. Encouraging players to run the ball wider along the wing to kick closer to the goal, may increase the probability of scoring a goal, rather than directing the ball through the centre corridor (the middle of the ground) and kicking from further out.
4. Using the results from Chapter 6 and 7, a number of theoretical guidelines were established for what an 'ideal' goal-kicking technique in AF resembles and a number of coaching recommendations were identified. These recommendations can be used by coaches to guide development programmes designed to improve goal-kicking performance at all levels.
5. Examination of inaccurate goal-kicks provided an indication of what technical errors player make when they miss the goals. These findings also have important implications as they provide information that can be used by coaches and practitioners to inform or develop coaching cues to prompt modifications to a player's technique to reduce the presence of such undesirable technical factors.

6. Examination of goal-kicking technique on an individual-basis highlighted that players utilise different movement strategies when kicking for goal. These findings have important implications for the physical training of players, as the different strategies (knee and thigh; pelvis and hip) will require different conditioning recommendations to suit the movement patterns.

8.6. Summary of Findings

The aims of Chapters 3 and 4 were to examine the concurrent validity of the Xsens IMS for quantifying lower extremity joint and segment kinematics in comparison to a Vicon motion analysis system (MAS) during kicking in AF, soccer, and the rugby codes. Trivial to small mean differences were reported between the IMS and MAS across all lower extremity discrete (0.2 – 5.8 %) and time-series (0.1 – 10.1 %) parameters. Additionally, low levels of measurement error (discrete parameters: 0.1 – 5.8 %; time-series parameters: 0.1 – 7.9 %) were found between the IMS and MAS. Findings indicated good concurrent validity between the Xsens IMS and Vicon MAS when quantifying important technical parameters associated with kicking performance, advocating the use of IMS for quantifying goal-kicking kinematics in Chapters 5, 6 and 7.

The aim of Chapter 5 was to examine the effect of altering kicking position goal-kicking technique in AF. Goal-kicking technique changed depending on the location of the shot of the pitch. When the distance of the goal-kick increased (30 m to 40 m), players demonstrated substantially greater kick-leg ROM (knee and hip), lower support-leg knee flexion (37 vs 43°), with higher linear and angular velocities evident in the kick-leg (higher centre of mass (COM) velocity: 2.7 vs 2.4 $m.s^{-1}$; higher knee angular velocity: 1632 vs 1459°/s; higher shank angular velocity: 1736 vs 1643°/s; linear foot velocity:

18.0 vs 19.9 m.s^{-1}). In addition, substantial differences were reported during the approach phase in 40 m kicks compared to 30 m kicks (moderately longer last step: 1.55 vs 1.42 m; higher max COM velocity: 5.9 vs 4.2 m.s^{-1}). Altering the angle of the goal-kick from goals had no substantial influence on goal-kicking technique (kinematic comparisons classified as *most likely* to *likely* trivial/small). Findings suggest that players may be required to adjust goal-kicking technique dependent on the location of the kick to achieve a successful outcome.

The general aim of Chapter 6 was to examine goal-kicking technique and identify key technical factors associated with accuracy. Eighteen AF players performed 15 x 30 m goal-kicks in-front of goals and kinematics differences between accurate and inaccurate goal-kicks were examined on a group-basis. During the approach phase, players exhibited a substantially straighter approach line (6 vs 12º), with smaller differences evident in the length of the last step (1.42 vs 1.5 m) and COM velocity at kick-foot toe-off (3.3 vs 3.6 m) during their accurate kicks compared to inaccurate kicks. During the kicking phase, accurate goal-kicks were associated with substantially lower ankle, knee and hip joint range of motion (ROM), a more direct foot path (0º vs 3º) substantially greater ankle plantar flexion (39 vs 30º) and lower knee flexion (63 vs 69º), with lower joint and segment velocities in the kick-leg at BC compared to inaccurate kicks. Support-leg characteristics differed between accurate and inaccurate kicks; accurate kicks demonstrated lower hip (28 vs 30º) and knee flexion (SHS: 23 vs 27º; BC: 38 vs 48º). At the end of follow through, players finished with a straighter-leg line (8 vs 15º), with a greater plantar flexed ankle (26 vs 22º) during accurate kicks. In addition, a number of substantial linear and quadratic relationships were identified between technical parameters and accuracy. Findings in this chapter indicated that many factors influence goal-kicking accuracy in AF, ranging from technical errors from the players' approach, support-leg characteristics, kick-leg swing motion to final follow-through position.

The general aim of Chapter 7 was to identify if kinematic differences exist between accurate and inaccurate goal-kicks on an individual-basis. Findings indicated that all players exhibited substantial technical differences between accurate and accurate goal-kicks, however these were individual-specific. The individual-specific differences ranged from the type and number of substantial kinematic differences between accurate and inaccurate goal-kicks, the magnitude (i.e. trivial, small, moderate, large, very large) and direction (i.e. increase or decrease) of these kinematic differences, and the number, strength (i.e. low, moderate, strong, very strong) and type (i.e. linear, quadratic and cubic) of relationships between accuracy and technical parameters. Results from the individual-based analysis supported the findings from the group-based analysis in Chapter 5; all players exhibited more extended support-leg, lower joint (ankle and hip) ROM in accurate goal-kicks compared to inaccurate goal-kicks. In addition, all players exhibited a straighter approach line, a smaller foot-path angle and finished with their kick-leg in-line towards the target. However, the individual-based analysis also identified important technical information that was not evident on a group-basis. For example, individual patterns were evident in terms of the speed of movement (i.e. accurate goal-kicks were characterised by substantially faster linear (COM, footspeed) and angular (shank and knee) velocities at BC for players 5, 7, 10 and 12, while an inverse trend was evident in the remaining players). Using only a group-based analysis, these factors would not have been identified, and therefore would be considered as possible technical aspects to improve goal-kicking accuracy for these individual players.

8.7. Conclusions

The overall conclusions of this thesis are:

- The Xsens IMS provides acceptable levels of concurrent validity in measuring discrete and time-series kicking kinematics compared to Vicon MAS. Thereby, the Xsens IMS is suitable for quantifying kicking kinematics in AF.
- Modifying the task constraints of the goal-kick in AF, can influence the technique players utilise to achieve a consistent performance outcome (successful kick). Players alter goal-kicking technique when the distance from goals increases.
- Technical differences exist between accurate and inaccurate goal-kicks on a group-basis. Findings in this thesis indicated many factors influence goal-kicking accuracy ranging from errors from the players' approach, support-leg characteristics, kick-leg swing motion and follow through position.
- All players exhibited substantial technical differences between accurate and accurate goal-kicks, however these were individual-specific. Findings from the individual-based analysis highlighted the individual nature of goal-kicking in AF and suggest it is clearly important to coach this skill on an individual basis.
- A combination of both group and individual-based analysis is needed in the examination of goal-kicking in AF.

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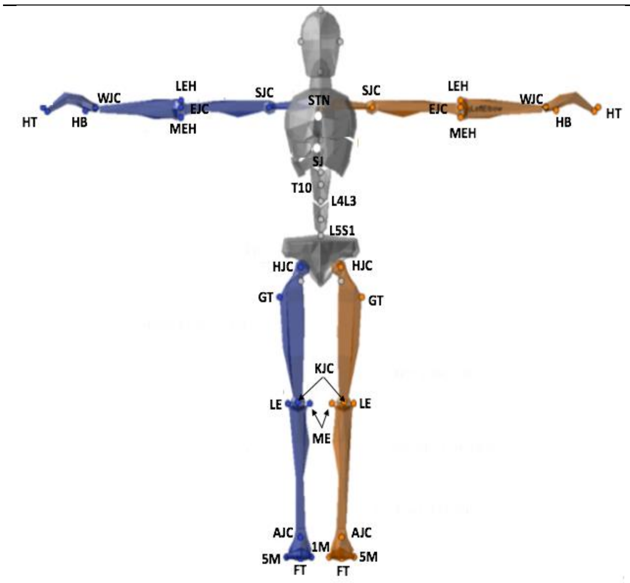
Appendix A: Model Abbreviations

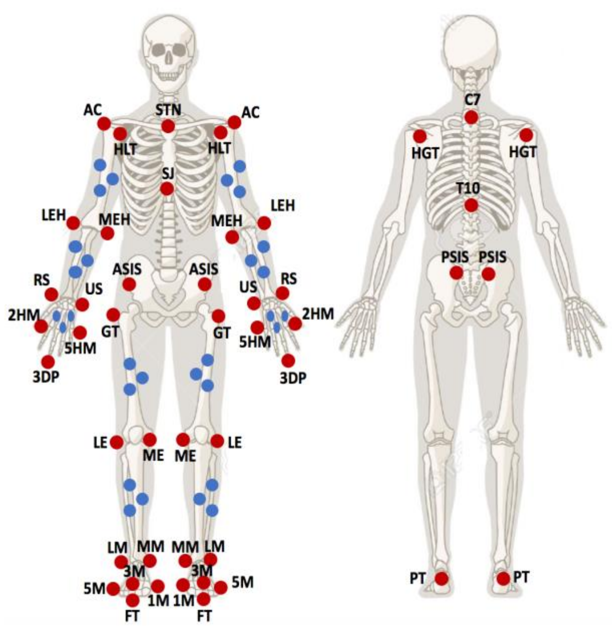
Xsens Biomechanical Model



Abbrev	Definition
FT	Tip of foot
1M	First metatarsal head
5M	Fifth metatarsal head
AJC	Ankle joint centre
LE	Lateral femoral epicondyle
ME	Medial femoral epicondyle
KJC	Knee joint centre
GT	Femoral greater trochanter
HJC	Hip joint centre
L5S1	Lumbosacral joint 10
L4L3	Lumbar spine 3
T10	Thoracic vertebrae 10
SJ	Sternum xiphisternal joint
STN	Sternum
SJC	Shoulder joint centre
EJC	Elbow joint centre
LEH	Humerus lateral epicondyle
MEH	Humerus medial epicondyle
WJC	Wrist joint centre
HB	Ball of the hand
HT	Tip of the hand

Vicon Biomechanical Model

3M



Abbrev	Definition
PT	posterior heel
FT	tip of foot
1M	first metatarsal head
3M	third metatarsal head
5M	fifth metatarsal head
LM	lateral malleoli
MM	Medial malleoli
ME	Medial femoral epicondyle
LE	lateral femoral epicondyle
GT	femoral greater trochanter
ASIS	anterior superior iliac spines
PSIS	posterior superior iliac spines
T10	thoracic vertebrae 10
SJ	sternum xiphisternal joint
C7	Cervical Vertebrae 7
STN	sternum
AC	acromion
HLT	humerus lesser tubercle
HGT	humerus greater tubercle
LEH	lateral epicondyle of humerus
MEH	epicondyle of the humerus
RS	radius-styloid process
US	ulna-styloid process
HM	medial head of Metacarpal
3DP	tip of the third distal phalanx

Appendix B: Participant Characteristics

Table 1: Participant characteristics for study 1 (chapter 3) and study 2 (chapter 4).

Player	Sport	Playing Level	Kicking foot	Age (years)	Height (cm)	Mass (kg)	Leg length (cm)
01	Australian Football	Amateur	Right	20	183	80	98
02	Australian Football	Amateur	Right	21	170	77	89
03	Australian Football	Amateur	Right	19	185	81	96
04	Australian Football	Amateur	Right	19	183	76	96
05	Australian Football	Amateur	Right	20	170	81	91
06	Australian Football	Amateur	Left	25	180	83	90
07	Australian Football	Amateur	Right	21	181	78	93
08	Australian Football	Amateur	Right	19	182	78	94
09	Australian Football	Semi-Professional	Left	19	184	79	96
10	Australian Football	Amateur	Right	26	177	83	90
11	Soccer	Amateur	Left	29	189	85	96
12	Soccer	Semi-Professional	Left	27	184	79	93
13	Soccer	Amateur	Right	26	181	76	93
14	Soccer	Amateur	Right	24	183	82	91
15	Soccer	Amateur	Right	21	173	68	85
16	Soccer	Amateur	Right	21	183	74	98
17	Soccer	Amateur	Right	21	182	80	92
18	Soccer	Amateur	Right	20	178	69	95
19	Soccer	Semi-Professional	Right	22	166	73	87
20	Soccer	Amateur	Left	25	181	82	90
21	Rugby league	Semi-Professional	Right	26	182	84	91
22	Rugby league	Semi-Professional	Right	23	180	86	90
23	Rugby league	Amateur	Right	22	183	81	93
24	Rugby league	Amateur	Right	19	187	81	93
25	Rugby league	Amateur	Right	21	189	81	91
26	Rugby Union	Amateur	Right	23	184	82	85
27	Rugby Union	Amateur	Right	22	181	83	98
28	Rugby Union	Amateur	Right	25	180	79	92
29	Rugby Union	Amateur	Right	23	175	83	96
30	Rugby Union	Amateur	Right	24	192	98	109

Table 2: Participant characteristics for study 3 (chapter 5), study 4 (chapter 6), and study 5 (chapter 7).

Player	Playing level	Kicking foot	**Age** (years)	**Height** (cm)	**Mass** (kg)	Leg length (cm)	Goals (%)
01	Sub-elite (school)	Right	17	187	65	102	66
02	Sub-elite (school)	Right	17	185	67	97	61
03	Elite (academy)	Right	17	184	69	98	27
04	Sub-elite (school)	Right	17	188	76	96	47
05	Sub-elite (school)	Right	18	189	87	99	43
06	Elite (club)	Right	18	175	65	91	60
07	Elite (academy)	Right	17	183	68	95	56
08	Elite (academy)	Right	18	177	69	97	54
09	Elite (academy)	Right	17	186	73	99	56
10	Elite (academy)	Right	17	180	63	95	40
11	Elite (club)	Right	17	186	65	97	62
12	Sub-elite (club)	Right	17	178	74	97	49
13	Sub-elite (club)	Right	18	197	81	94	67
14	Sub-elite (club)	Right	18	187	78	104	50
15	Elite (academy)	Right	17	183	81	99	79
16	Elite (academy)	Right	18	190	78	107	57
17	Elite (academy)	Right	18	178	77	92	53
18	Elite (academy)	Right	18	188	79	92	45

Appendix C: Participant Information and Consent Forms

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate

You are invited to participate in a research project entitled: *Use of wearable technology for kick performance assessment in males across the football codes: A validation study.*

This project is being conducted by a student researcher Stephanie Blair as part of a PhD study at Victoria University under the supervision of Dr Kevin Ball, Dr Grant Duthie and Dr Sam Robertson.

Project explanation

The primary aim of the research is to examine if wearable technologies can accurately measure kick performance. The performance of the Xsens movement system (wearable technologies) will be assessed against a gold standard measurement (Vicon camera system) currently used in Biomechanics. The specific objectives are to identify any differences in the values recorded by both systems for joint and segment speeds and timing variables.

What will I be asked to do?

Participants involved in the study will be required wear a black suit (similar to training clothes) over their clothing and have biomechanical markers placed on the pelvis, trunk, and on both legs and feet, and both arms and hands. You will be required to wear runners.

The markers used in the study are small, non-invasive portable reflective markers that are placed on the skin. It will take approximately 20-30 minutes to put all markers on the body and the research will talk you through each location. This procedure is common in sports biomechanics testing. During the testing procedure only the research team will be present.

You will then perform a 5 min bike ride, 5 min warm up jog around the oval with several stretches and 12 practice kicks on each side of the body to avoid injury and familiarise yourself with the task ahead. After sufficiently warming up you will be asked to perform under the four conditions depending on your football code (Australian Football, rugby union, rugby league and soccer:

Australian football	**Rugby union and league**	**Soccer**
20m “on the run” kicks	place kicks towards a 20m goal.	Instep kicks towards a 12 m goal
maximal kicks for distance.	place kicks towards a 40 m goal.	Instep kicks towards a 12 m goal
set shot kicks towards 20m goals.	maximal kicks for distance.	Instep maximal kicks for distance.
set shot kicks towards 40m goals.	drop kicks towards a 40 m goal.	Instep kicks towards a 20 m target

Once all testing has been completed you can remove the suit with the markers attached, taking approximately 1-2 minutes.

What will I gain from participating?

You will have volunteered your time in the interest of research, helping to improve the way me measure and evaluate kick performance in biomechanical research. You will be reimbursed for parking to participate in the study and will be provided with feedback to enable you to adjust and/or improve your kicking action on request. You will be notified on future studies in this area, if interested.

How will the information I give be used?

Access to your own biomechanical data and results is available on request after processing (2-3 weeks post testing). You may choose to pass your data on to your coach if you wish. All data that will be used in future publications will be unidentifiable. Researchers will have access to the data only for data analyses and discussion of results. Results from this study can provide useful information to be incorporated into future research. Your unidentified results may be included in a PhD thesis, published in journals or presented at conferences.

What are the potential risks of participating in this study?

There is no physical risk greater than your football training but you will be asked to undergo a sufficient warm up before testing to avoid injury. The kicking tasks are no different to those that you would perform at a regular training session.

There may a feeling of nervousness or anxiety towards having markers placed on the certain locations of the body. Markers will be placed from least intrusive (ankle) to most (hip) to allow you time to become accustomed to the marker placement procedure. You will be asked constantly, but if at any point you are uncomfortable with the procedures, participation can be ceased without consequence or any obligation to continue. Also, you may request to have only male or female research members place markers on your body. You will be asked to wear runners and the fitted suit, but for some it may not be too different to what you generally wear to training. You will be asked if you are comfortable with the procedure. The lab will be closed off to public access with only the research team inside, no other participants will be present. If you need or want to discuss any issues, we will provide a registered psychologist (details at bottom of page) to you free of charge.

Your participation in this study is voluntary and you are able to stop and have a rest or withdraw from the study for any reason, without consequence or obligation for you to participate and/or finish the study. Please bring runners, football/tight fittings shorts or skins and a sports crop top and singlet to wear during testing.

Who is conducting the study?

Stephanie Blair	Dr Kevin Ball
Student PhD Researcher	Chief Investigator
Victoria University	Victoria University
P: 0450253266	P: 9919 1119
E: stephanie.blair@ vu.edu.au	E: kevin.ball@vu.edu.au

Register Psychologist

Associate Professor, Daryl Marchant
Sport Psychology & Sport Coaching
Victoria University
P: 9919 4035
E: Daryl.Marchant@vu.edu.au

Any queries about your participation in this project may be directed to the Principal Researcher listed above. If you have any queries or complaints about the way you have been treated, you may contact the Ethics and Biosafety Coordinator, Victoria University Human Research Ethics Committee, Victoria University, PO Box 14428, Melbourne, VIC, 8001 phone (03) 9919 4148.

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

INFORMATION FOR PARTICIPANTS

We would like to invite you to be a part of a study that is exploring whether wearable technologies can be used to accurately measure kick performance across the football codes (Australian football, rugby Union, rugby league and soccer).

The researched is titled: Use of wearable technology for kick performance assessment in males across the football codes: A validation study.

CERTIFICATION BY SUBJECT

I____(full name)

of____(address)

Certify that I am at least 18 years old and that I am voluntarily giving my consent to participate in the study investigating if wearable technologies can be used to validly measure kick performance across the football codes. The study will be conducted at the Victoria University Biomechanics lab Footscray Park Campus, Ballarat Rd Footscray, by Dr Kevin Ball and Stephanie Blair.

I certify that the objectives of the study, together with any risks and safeguards associated with the procedures listed below to be carried out in the research, have been fully explained to me by:

Ms Stephanie Blair

and that I freely consent to participate in the following procedures:

- Perform a warm up 5 min bike riding jogging for 5 minutes, several leg stretches/ swings and up to 12 familiarisation football kicks on each leg.
- I will wear a measurement suit and allow researchers to physically palpate anatomical landmarks on the lower limbs, trunk and upper extremities, placing markers and sport tape on each leg, the pelvis, trunk, both arms and hands on the outside of the suit in order to collect data. Please note, access to the laboratory during testing will only be made available to the research team and the participant.
- Perform a total of 20 kicks over 4 conditions (specific to my football code___________) whilst being recorded by the Xsens Motion Capture system and Vicon camera system.

I certify that I have had the opportunity to have any questions answered and I understand that I can withdraw from this study at any time and that this withdrawal will not jeopardise me in any way.

Following from this study, we expect to continue our research into the aspects of kicking. These include technical comparisons between men and women, further analysis into pelvic motion and knee flexion comparisons between other sports and comparisons to sub-elite and underage groups. All data is partially de-identified, which means it is only identifiable through a participant code.

I allow researchers to use all of my data in future research ☐

I do not allow researchers to use all of my data in future research ☐

If no, do you allow the researchers to use 3D data? ☐

Please indicate if you had a lower extremity injury in the past three months or any injury that may affect your participation in the study:

Yes, I have had a lower extremity injury in the past three months ☐
If yes, what was the injury:

Yes, I have had an injury that may affect my participation ☐

If yes, what was the injury:

No, I am not injured or have not sustained a lower extremity injury in the past three months ☐

I have been informed that the information I provide will be kept confidential, and all data files will be kept in a locked filing cabinet or on password protected computers for (five years under the information/ethics protection act).

Signed: ____________________________________

Date:

Any queries about your participation in this project may be directed to the researcher

Stephanie Blair
Student PhD Researcher
Victoria University
P: 0450253266
E: stephanie.blair@ vu.edu.au

Dr Kevin Ball
Chief Investigator
Victoria University
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Register Psychologist

Associate Professor, Daryl Marchant
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If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001, email Researchethics@vu.edu.au or phone (03) 9919 4781 or 4461.

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate

You are invited to participate in a research project entitled "Benchmarking Talent Development in the Australian Football League (AFL) System".

This project is being conducted by a research team from Victoria University's Institute of Sports, Exercise and Active Living, including Professor Damian Farrow, Assoc Prof. Daryl Marchant, Dr. Kevin Ball, Dr. Jason Berry, Dr. Sam Robertson, and Dr. Paul Larkin.

Project explanation

Talent selection and identification in Australian Football is based on numerous factors during a player's development, with the Australian Football League (AFL) investing significant resources into the detection and development of athletes. The current talent identification approach uses numerous measures, with the central premise to identify and select the most promising young athletes with the potential to become a senior elite athlete. This however raises questions regarding the most effective and efficient use of resources to ensure optimal talent selection, development, retention, and ultimately successful athletic performance. Despite a vast body of research examining technical, tactical, physical and psychological aspects of developing and elite Australian Football players, to date, researchers have failed to track and evaluate these capabilities within the AFL talent pathway from U12 through to senior AFL competition. Therefore, the aim of this research is to understand talent development to guide the evolution of the AFL Talent Pathway.

What will I be asked to do?

You will be required to complete a range of measures designed to provide an overview of Australian Football talent development. All tasks are common Australian Football performance measures and not outside the usual club or AFL testing procedures. These tasks will include technical, tactical, physical, psychological and playing history measures.
Technical: You will complete two Australian football specific kicking tests. The first is based on a typical Australian Football Kicking Drill, used at the AFL Draft Combine, which requires you to complete 20 kicks of differing distances and angles on an Australian Football oval. During the drill you will be required to wear a movement tracking suit (similar to wearing fitted shirts and shorts; Skins) which tracks the movement of the body during the kicking motion. The second test is a game-based assessment where you will participate in a 6v6 small-sided game which will consist of 4x3minute quarters. The game will be video recorded and coded for each kick you complete. Finally, your in-game performance will be measured using a GPS/accelerometer (which collects running speed and distances covered) mounted in a fitted singlet. You will be required to wear this device during 3-5 games within the first 3 months of your football season.
Tactical: You will be asked to complete a computer-based decision-making test, which is currently administered in the AFL academy program. The activity presents short video clips of AFL playing situations on a computer screen which then freeze at a critical time point. You will select the most appropriate decision by clicking the computer mouse on the player you wish to kick to. The test takes approximately 20 minutes to complete, with decision-making accuracy expressed as a percentage relative to the correct responses as identified by a panel of expert AFL coaches.

Physical: You will be asked to provide your previous results, or complete a number of physical tests currently used at the AFL Draft Combine. These tests include: 20 m sprint, 6 x 30 m repeat sprint, AFL planned agility, running vertical jump, countermovement jump, and 20 m multi-stage fitness test (Beep Test) and the athletic ability assessment movement screen (e.g., chin-up, push-up, overhead squat). Anthropometric measures which include measurements of height, body mass, and body fat percentage (skinfold measure) will also be recorded.
Psychological: You will be required to complete several online psychological questionnaires including the Self-Regulated Learning Questionnaire and the Role Strain Questionnaire for Junior athletes. Both questionnaires will take between 15-20 minutes to complete and attempt to link learning and school performance to sporting performance.
Playing History: You will complete the online developmental history of athletes questionnaire (DHAQ), which takes approximately 30-60min to complete and provides information about the activities and background of players during their development. In addition, you will be asked to complete a Training diary, where you will record your monthly training load.
All of your data will be pooled with other participant data and analysed for reporting.

What will I gain from participating?

By participating in this study you will contribute to a larger AFL project that will provide an overview of performance benchmarks within the AFL talent development from under 12's through to senior elite. The information collected will allow for a greater understanding of the different performance factors that different players experience as they transition through AFL development pathways. Furthermore, this research will provide practical guidelines for coaches, players, recruiters, club personnel, and talent development practitioners relating to the typical physical and match performance patterns that can be used to shape talent development priorities of individual players at significant stages within the Australian football participation pathway. A specific benefit you will receive is an individualised player analysis and report on strengths and weaknesses in key performance factors. You will not be paid as part of your participation in this project.

How will the information I give be used?

The data collected will be used to model the relationships between the measured variables and each level of the Australian Football participation pathway. This will allow for developing players to be classified to the appropriate level of the Australian Football participation pathway based on their technical, tactical, physical, psychological and playing history characteristics. The findings will primarily benefit the AFL by allowing for more specific talent development and player retention. Whilst results of comparisons between all the performance variables using data obtained from multiple clubs will be published in scientific journals, personal information will not be disclosed and all data will be coded to prevent identification of team and/or specific player information. Specifically, only analysis undertaken at the group (skill, age) level will be used in any scientific publications emanating from this project, which will protect against the information being an advantage for other Australian Football clubs.

What are the potential risks of participating in this project?

The associated risks of this project are low as the technical, tactical, and physical testing will be conducted using methods which form part of the AFL Draft Combine, and therefore none of the aspects of the project are outside what you would normally perform in either training or a game of Australian Football. Obviously the technical testing (kicking) does involve minor risks of physical injury similar to those that may occur in the regular game itself. In addition, while it is stressed that this research project is about individual responses and performance across the technical, tactical, physical, psychological measures, you will have the option of completing all elements of the testing measures individually if they so choose. If you do not wish to participate in this study there will be no ramifications for withdrawal from the research project. Nor will findings from the study have any influence on current or future squad selections.

How will this project be conducted?

All testing sessions will be conducted by the research team including student investigators with support from research assistants. Participants will be assessed during separate testing sessions (i.e., technical, tactical, and physical) that will be allocated to each group identified (i.e., national and state level clubs, TAC clubs, school academies, and local clubs). During the technical and physical testing sessions participant performance will be videoed and coded according to the specific measure. The psychological and playing history questionnaires will be administered online to participants from district clubs and above prior to their attendance at the testing sessions. Training diaries will be provided to the participants following the testing and will be asked to complete them on a weekly basis in their own time. All results will be stored securely at the Institute of Sport, Exercise and Active Living (ISEAL), Victoria University. Analysis of the data will be undertaken by the Research team and student investigators with relevant findings reported to the AFL and ISEAL at Victoria University.

Who is conducting the study?

The study is conducted by personnel from the Institute of Sport, Exercise and Active Living (ISEAL) at Victoria University in association with the Australian Football League.

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Any queries about your participation in this project may be directed to the Chief Investigator or Student Investigator listed above. If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001, email researchethics@vu.edu.au or phone (03) 9919 4781 or 4461.

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

Benchmarking Talent Development in the AFL system

INFORMATION TO PARTICIPANTS:
We would like to invite you to be a part of a study exploring the technical skill performance, psychological, physiological and socio-cultural influences on Australian football players at key development stages of the AFL participation pathway (under 12's through to senior elite AFL). The primary purpose of the project is to understand at developmental stage can key performance components, such as technical, tactical, physical, psychological and playing history, be identified to potentially discriminate between elite and sub-elite players. The results of the study will provide a greater understanding of the AFL talent development pathway and the key influences on Australian football player development.

CERTIFICATION BY SUBJECT

I, ___________________________________

of ____

certify that I am at least 18 years old* and that I am voluntarily giving my consent to participate in the study being conducted through Victoria University by: Prof. Damian Farrow, Assoc Prof. Daryl Marchant, Dr. Kevin Ball, Dr. Jason Berry, Dr. Sam Robertson, and Dr. Paul Larkin.

I certify that the objectives of the study, together with any risks and safeguards associated with the procedures listed hereunder to be carried out in the research, have been fully explained to me by the research team and that I freely consent to participation involving the below mentioned procedures (please tick the procedures for which you are providing consent):

☐ **Retrospective Measures**

Allow access to physical performance test information from AFL Draft Combine databases.

☐ **Technical Measures**

Drill and Game-based kicking assessments.

In-game performance video recorded and coded using common Australian Football performance coding.

☐ **Tactical Measures**

Complete a computer-based test of game-specific decision-making.

☐ **Physical Measures**

AFL Draft Combine fitness and performance tests including, anthropometric and physical measures.

Allow access to results from AFL Draft combine and/or club testing measures.

☐ **Psychological Measures**

Complete questionnaires to understand links between psychological constructs and sport performance.

☐ **Playing History Measures**

Online questionnaires designed to understand my sporting developmental history.

Use a training dairy to monitor current training load.

☐ **All of the above**

I certify that I have had the opportunity to have any questions answered and that I understand that I can withdraw from this study at any time and that this withdrawal will not jeopardise (i.e., will not affect current training or selection) me in any way.

I have been informed that the information I provide will be kept confidential.

Signed: ____________________________

Date: ____/____/____

Any queries about your participation in this project may be directed to the researcher:

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Victoria University & Australian Institute of Sport
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If you have any queries or complaints about the way you have been treated, you may contact the Ethics Secretary, Victoria University Human Research Ethics Committee, Office for Research, Victoria University, PO Box 14428, Melbourne, VIC, 8001, email Researchethics@vu.edu.au or phone (03) 9919 4781 or 4461

Appendix D: Study 4 (Chapter 6) & 5 (Chapter 7) Accuracy Scores

Table 3: Accurate and inaccurate kick number for each player in study 3 and 4.

Player	Accurate	Inaccurate
01	9	6
02	11	4
03	15	0
04	11	4
05	8	7
06	7	8
07	8	7
08	9	6
09	10	5
10	7	8
11	9	6
12	6	9
13	7	8
14	9	6
15	14	1
16	8	7
17	6	9
18	9	6

Appendix E: Individual-Based Analysis Results

Table 4: Kinematic means ± standard deviations (SD) for accurate (hit) and inaccurate (miss) goal-kicks for players 1- 9 (excl. 3). Data is reported accurate, inaccurate

	Player							
Parameter	1	2	4	5	6	7	8	9
Approach phase								
Last step distance	1.09±0.25,1.34±0.27	1.15±0.29,1.62±0.34	1.66±0.27,1.86±0.28	1.19±0.28,1.18±0.41	1.41±0.33,1.37±0.53	1.36±0.24,1.46±0.14	1.29±0.31,1.28±0.34	1.39±0.26,1.81±0.34
Avg COM vel	1.3±1.0, 2.0±0.3	1.7±1.1, 2.1±0.3	1.3±0.3, 1.5±0.4	1.6±0.3, 1.9±0.3	1.6±0.7, 1.6±0.3	1.3±0.3, 2.1±0.3	1.9±0.8,2 .1±0.3	1.8±0.5, 3.6±0.6
Max COM vel	1.8±1.1, 4.1±1.1	2.1±1.2, 4.3±1.1	4.9±3.1, 5.0±1.3	4.2±2.9, 2.5±1.2	4.5±1.2, 4.6±1.3	3.4±1.2, 3.1±1.3	4.6±1.1, 5.0±1.2	3.5±0.5, 4.2±1.3
KFTO COM vel	1.3±1.0, 2.0±0.3	1.7±1.1, 2.1±0.3	1.3±0.3, 1.5±0.4	1.6±0.3, 1.9±0.3	1.6±0.7, 1.6±0.3	1.3±0.3, 2.1±0.3	1.9±0.8, 2.1±0.3	3.3±1.2, 3.3±1.5
Approach angle	2±5, 13±2	2±0, 10±4	2±3, 14±4	2±8, 7±3	4±7, 7±2	5±4, 17±3	3±1, 17±4	2±3, 16±3
Kicking phase								
At Ball Contact								
Ankle angle	37±4, 35±1	20±6, 19±11	22±12, 17±11	24±6, 35±5	36±4, 38±5	38±1, 44±12	55±7, 47±13	56±8, 24±2
Knee angle	62±5, 74±7	60±5 ,73±5	72±10, 72±5	60±7, 63±5	73±6, 74±5	72±5, 73±8	59±5, 59±7	57±6, 63±7
Hip angle	35±14, 39±15	34±4, 40±11	34±12, 38±14	35±14, 38±15	34±9, 41±13	29±11, 31±12	31±17, 30±11	29±10, 38±11
Pelvis angle	40±11, 55±14	40±9, 54±14	49±9, 49±14	42±10, 51±13	47±14, 50±11	47±14, 52±11	46±14, 51±12	54±13, 50±10
Trunk angle	-1±4, 1±2	5±3, 3±2	3±4, 5±2	9±7, 3±10	2±3, 1±13	-1±2, 2±12	3±7, 5±4	2±2,7 ±4
Shank angle	-2±13, -8±13	-3±13, -8±13	-5±13, -2±13	4±9, -6±10	-4±7, -4±3	-2±3, -1±14	-1±9, 1±7	-4±3, 1±6
Thigh angle	70±14, 69±4	64±15, 69±5	70±16, 65±8	60±10, 60±8	53±17, 55±6	49±21, 52±7	42±22, 47±6	53±19, 53±7
Foot speed	18.5±1.2, 24.8±1.2	18.5±1.2, 18.2±3.4	18.5±1.2, 23.7±3.4	20.4±1.2, 17.6±3.5	16.0±0.8, 19.3±2.5	19.9±0.2, 17.0±1.0	19.7±1.2, 23.5±1.1	19.9±1.1, 20.3±1.1
COM velocity	2.2±0.3, 3.0±0.2	3.4±0.3, 3.0±0.3	2.2±0.3, 2.8±0.3	1.6±0.2, 3.6±0.1	1.9±0.3, 3.7±0.4	2.0±0.2, 3.9±0.4	2.2±0.2, 1.7 ±0.4	1.8±0.1, 2.6±0.2
Knee angular vel	1381±229,1742±188	1387±182,1634±188	1396±228,1462±186	1479±183,1270±185	1428±195,1570±168	1379±184,1703±173	1431±226,1707±174	1076±182,1404±182
Hip angular vel	54±9, 96±86	35±126, 73±129	67±90, 32±83	44±40, 83±81	54±67, 86±9	135±126, 173±129	67±90, 83± 32	44±40, 83±81
Shank angular vel	1903±109,1666±134	1722±98, 1625±129	1726±126,1596±110	1693±119,1666±150	1545±127,1631±133	1843±130,1616±126	1704±123, 1848±61	1542±231,1743±23
Thigh angular vel	70±60, 114±90	116±161, 132±139	209±143, 109±240	65±21, 97±236	60±47, 160±31	99±36, 134±27	153±52,173±20	96±74,167±43,
Ankle angular vel	303±103, 428±107	310±106, 427±100	358±102, 427±114	362±106, 396±121	353±110, 393±115	369±96, 397±140	356±119, 398±138	364±87, 434±141
SL knee angle	40±4, 46±5	32±6, 44±6	41±5, 42±5	33±7, 39±7	38±5, 46±7	46±4, 48±9	42±5, 47±10	32±6, 41±3
SL hip angle	50±4, 48±2	31±6, 32±2	32±6, 32±4	32±6, 33±6	31±7, 34±5	30±8, 30±3	31±6, 31±3	29±3, 32±5
Support Heel Strike								
SL knee angle	22±3, 23±3	20±5, 21±5	16±9, 17±9	26±4, 27±4	33±5, 34±4	33±6,34±6	25±3, 26±3	20±1, 21±3

*Abbreviations: **Avg:** average; **max**: maximum; **COM**: centre of mass; **vel**: velocity; **KFTO**: kick-foot toe off; **SL:** support-leg*

Table 4: *Continued*

Parameter	Player 1	2	4	5	6	7	8	9
Kicking phase								
Max knee angle	123±6, 122±1	124±8, 122±1	121±6, 122±1	119±6, 119±1	124±5,126±3	123±6, 115±3	123±7, 116±1	110±7, 125±1
Max SL knee angle	40±8, 49±4	35±8, 46±4	39±4, 46±4	39±4, 48±4	42±4, 45±4	43±3, 51±3	43±4, 57±3	39±6, 46±3
Max hip angle	26±6, 28±6	27±7, 28±6	22±5, 21±6	24±5, 25±6	27±5, 30±6	28±6, 32±5	32±6, 39±5	36±4, 31±8
Ankle ROM	28±4, 31±4	25±7,27 ±8	24±4, 35±7	36±4, 47±5	44±2, 47±3	36±2, 46±3	34±9, 41±4	27±10, 30±8
Knee ROM	48±13,53±7	51±7,58±5	46±3,61±3	53±6,56±3	51±3,54±4	50±6,58±8	42±6,52±7	43±5,48±4
Hip ROM	31±9, 36±4	33±7, 40±8	40±4, 34±7	34±4, 31±4	34±4, 37±5	35±4, 36±5	33±8, 38±3	27±8, 38±3
Pelvis ROM	34±2, 30±6	31±4, 56±5	36±8, 47±2	38±4, 32±7	45±4, 35±13	35±7, 47±10	44±9, 36±10	31±3, 37±3
Foot path	0±1, 3±1	0±1, 2±1	1±1, 2±1	0±1, 3±1	0±1, 3±1	0±1, 3±1	1±1,3±1	1±1, 3±1
Follow through phase								
Leg position	2±2, 13±7	1±5, 13±3	6±5, 14±2	6±4, 11±2	2±2, 11±2	3±5, 9±7	6±5, 10±4	6±5, 8±2
Ankle angle	20±7, 18±6	26±5, 19±6	25±10, 22±6	23±12, 23±8	16±12, 19±14	27±11, 21±15	20±11, 21±15	24±10, 9±6

Abbreviations: ***Avg:*** *average;* ***max****: maximum;* ***COM****: centre of mass;* ***vel****: velocity;* ***KFTO****: kick-foot toe off;* ***SL:*** *support-leg*

Table 5: Kinematic means ± standard deviations (SD) for accurate (hit) and inaccurate (miss) goal-kicks for players 10-18 (excl. 15). Data is reported accurate, inaccurate

	Player							
Parameter	10	11	12	13	14	16	17	18
Approach phase								
Last step distance	1.40±0.31,1.71±0.29	1.12±0.28,1.60±0.27	2.00±0.18,1.35±0.34	1.64±0.32,1.95±0.28	1.89±0.29,1.78±0.20	1.43±0.16,1.63±.26	1.26±0.28,1.36±.33	1.34±0.29,1.36±0.32
Avg COM vel	1.9±0.8, 2.0±0.4	1.6±0.2,1.7±0.3	1.1±1.0, 2.5±0.3	1.5±0.3, 1.7±0.4	1.7±0.3, 2.1±0.3	2.0±0.3, 2.0±0.3	2.0±0.2, 2.0±0.5	2.0±0.9, 2.0±0.4
Max COM vel	4.1±1.6,3.6±1.3	4.0±1.6, 3.2±1.2	5.1±1.9, 5.8±1.8	4.1±1.9, 5.2±1.3	5.4±1.6, 5.4±1.5	5.0±0.2, 6.3±1.3	4.7±1.3, 5.7±1.2	2.9±1.7, 3.9±1.3
KFTO COM vel	4.0±1.2, 3.1±0.2	3.0±1.5, 3.7±0.2	3.4±1.2, 3.3±0.2	3.3±1.3, 3.5±0.2	2.9±1.3, 3.6±0.2	2.9±1.3, 3.7±0.2	3.1±1.2, 3.7±0.2	3.7±1.1, 4.3±0.2
Approach angle	2±5, 9±2	1±2, 12±10	3±1, 13±5	4±5, 16±3	4±2, 11±9	5±5, 8±5	5±9, 11±6	4±9, 14±3
Kicking phase								
At Ball Contact								
Ankle angle	57±3, 25±2	39±15, 29±1	41±2, 28±11	59±4, 30±2	34±13, 27±1	30±15, 27±5	35±13, 25±5	41±13, 38±11
Knee angle	71±7, 70±7	53±7, 69±6	66±2, 68±7	57±8, 68±9	56±9, 67±10	65±3, 71±5	67±9, 66±9	67±3, 71±9
Hip angle	32±5, 34±12	31±9, 34±15	30±10, 33±18	30±2, 36±9	39±11, 46±10	50±15, 52±10	48±13, 57±11	42±739±10
Pelvis angle	54±4, 50±10	49±7, 49±11	51±5, 50±11	47±9, 38±5	52±12, 52±5	49±10, 39±4	50±10, 49±8	51±10, 39±9
Trunk angle	-5±3, 3±4	6±6, 3±5	4±2, 6±4	-2±6, 7±6	4±3, 4±3	1±5, -1±13	3±4, 4±6	3±9, 1±3
Shank angle	1±2, -6±8	-4±8, 3±8	2±7, 5±11	-3±1, -13±3	-4±3, -11±3	-3±6, -11±3	-1±8, -14±4	-2±4, -10±3
Thigh angle	67±7, 62±1	69±6, 64±2	62±3, 68±5	53±4, 44±5	55±4, 49±7	58±4, 58±7	51±2, 58±7	49±4, 49±6
Foot speed	20.3±3.3, 18.0±1.1	19.0±2.6, 20.4±1.2	20.6±1.2, 18.1±3.6	17.1±3.2, 20.6±1.3	16.8±1.7, 20.7±1.4	17.8±1.8, 17.9±1.4	16.4±1.5, 18.1±2.3	17.3±1.7, 18.0±2.3
COM velocity	2.0±0.1, 2.4±0.1	1.9±0.3, 2.2±0.1	2.3±0.4, 1.8±0.1	1.8±0.5, 2.6±0.1	3.8±0.5, 2.4±0.1	2.6±0.5, 2.5±0.3	2.5±0.6, 2.5±0.6	2.9±0.3, 2.3±0.7
Knee angular vel	1564±177,1030±238	1745±238,1866±184	1668±141,1531±233	1589±128,1625±231	1417±122,1505±230	1310±211,1422±13	1429±162,1316±20	1342±196,1824±214
Hip angular vel	74±74, 24±40	71±40, 78±60	70±60,54±98	105±49, 112±68	114±91, 140±67	66±87, 85±96	122±90, 136±99	74±86,98±99
Shank angular vel	1905±70,1618±236,	1768±186,1798±119	1847±64,1725±118	1705±117,1704±146	1510±155,1680±39,	1633±134,1725±15	1391±39,1480±102	1413±84,1433±122
Thigh angular vel	149±78, 127±100	90±29, 96±83,	132±108, 93±143,	174±89, 183±116	95±128, 135±116	106±103, 116±131	265±141, 248±18	139±234, 122±48
Ankle angular vel	361±108432±116	366±110, 436±120	359±111, 400±133	317±108, 401±98	314±114, 398±109	322±110, 498±87	335±111, 468±70	333±107, 450±96
SL knee angle	40±6, 44±4	40±4, 43±4	43±5, 51±3	40±4, 45±3	38±4, 40±6	45±4, 48±5	40±1, 46±5	30±1, 40±5
SL hip angle	53±4, 52±4,	46±3, 46±2	44±3, 49±3	38±7, 45±7	45±5, 41±10	28±5, 26±4	28±3, 26±3	23±4, 23±5
Support Heel Strike								
SL knee angle	22±3, 23±3	20±5, 21±5	16±9, 17±9	26±4, 27±4	33±5, 34±4	33±6,34±6	25±3, 26±3	20±1, 21±3

Abbreviations: ***Avg:*** *average;* ***max****: maximum;* ***COM****: centre of mass;* ***vel****: velocity;* ***KFTO****: kick-foot toe off;* ***SL:*** *support-leg*

Table 5: *Continued*

	Player							
Parameter	10	11	12	13	14	16	17	18
Kicking phase								
Max knee angle	107±5,121±4	109±11, 123±10	113±12, 119±11	109±7, 122±8	109±7, 120±7	116±6, 120±9	117±6, 123±9	107±6, 123±11
Max SL knee angle	32±3, 44±2	52±3, 56±2	54±2, 51±2	47±2, 51±3	51±2, 51±5	43±1, 47±6	48±3, 51±5	51±5, 51±6
Max hip angle	33±6, 31±5	31±6, 36±5	34±5, 33±5	37±5, 37±4	34±4, 37±5	33±5, 32±6	31±5, 32±5	36±6, 34±6
Ankle ROM	26±2, 39±7	24±3, 40±4	26±5, 37±9	37±3, 43±5	31±2, 37±33	34±5, 41±3	32±4, 28±6	35±7, 31±6
Knee ROM	50±5, 44±5	49±5, 39±6	42±6, 60±4	57±3, 52±4	45±4, 45±7	47±5, 51±7	53±5, 54±10	53±6, 56±8
Hip ROM	27±5, 40±6	35±4, 44±6	29±4, 40±7	25±2, 42±6	29±3, 37±9	32±2, 64±8	32±3, 51±9	27±3, 45±7
Pelvis ROM	48±2, 53±13	45±14, 51±12	50±2, 53±22	50±3, 54±8	43±4, 47±8	46±4, 49±21	54±5, 51±19	44±8, 47±8
Foot path	1±1, 3±1	1±2, 4±2	2±1, 3±1	1±1, 3±3	1±1, 2±1	1±3, 2±1	2±1, 2±2	1±2, 3±1
Follow through phase								
Leg position	6±6, 6±4	4±6, 5±4	4±4, 6±6	1±3, 6±4	3±5, 5±4	1±5, 8±3	3±5, 8±7	2±4, 9±2
Ankle angle	20±9, 13±11	29±8, 13±12	18±13, 11±12	27±12, 27±13	23±14, 9±12	34±10, 19±10	28±8, 21±12	31±7, 15±12

*Abbreviations: **Avg:** average; **max**: maximum; **COM**: centre of mass; **vel**: velocity; **KFTO**: kick-foot toe off; **SL:** support-leg*

Table 6. The r_2 values for each relationship between each technical parameter and accuracy for each individual. All parameters relate to the kick-leg unless stated.

Player	Parameter																														
	Last step distance	Avg approach COM velocity	Max approach COM velocity	COM velocity at KFTO	Approach angle	Ankle plantar-flexion at BC	Knee flexion at BC	Hip flexion at BC	Pelvic posterior tilt at BC	Trunk posterior tilt at BC	Shank angle at BC	Thigh angle at BC	Foot speed at BC	COM velocity at BC	Knee angular velocity at BC	Hip angular velocity at BC	Shank angular velocity at BC	Thigh angular velocity at BC	Ankle angular velocity at BC	SL knee flexion at BC	SL hip angle at BC	SL knee flexion at SHS	Max knee flexion	Max SL knee flexion	Max hip extension	Ankle ROM	Knee ROM	Hip ROM	Pelvis ROM	Foot path at BC	Leg position at FT	Ankle plantarflexion at FT
01	.23	.17	.23	.19	.86	.73	.33	.11	.12	.36	.18	.09	.85	.55	.72	.08	.81	.11	.22	.63	.11	.14	.07	.50	.20	.44	.48	.53	.32	.87	.70	.64
02	.10	.04	.00	.24	.62	.52	.39	.09	.27	.67	.03	.00	.62	.32	.23	.30	.32	.00	.33	.89	.15	.05	.11	.80	.03	.32	.89	.43	.76	.56	.68	.65
04	.24	.09	.00	.01	.75	.79	.01	.39	.04	.33	.09	.01	.75	.09	.43	.01	.34	.01	.35	.65	.13	09	.23	.65	.07	.78	.92	.33	.86	.66	.67	.44
05	.17	.11	.18	.33	.66	.88	.36	.01	.29	.69	.61	.18	.66	.72	.78	.08	.75	.05	.28	.63	.08	.08	.67	.68	.21	.56	.41	.57	.56	.46	.56	.02
06	.12	.07	.14	.10	.49	.90	.23	.19	.09	.19	.38	.18	.78	.56	.71	.52	.73	.49	.52	0.1	.01	.04	.13	.06	.05	.81	.29	.71	.48	.89	.36	.58
07	.33	.18	.25	.03	.34	.68	.09	.17	.25	.45	.18	.05	.34	.38	.65	.10	.64	.30	.21	.78	.10	.00	.10	.72	.09	.77	.26	.75	.33	.79	.68	.34
08	.02	.18	.22	.08	.78	.65	.12	.01	.35	.34	.08	.22	.48	.35	.59	.11	.65	.21	.23	.80	.09	.01	.67	.83	.21	.76	.33	.72	.04	.83	.52	.01
09	.61	.19	.09	.00	.82	.87	.04	.21	.05	.54	.09	.29	.22	.27	.12	.31	.01	.41	.36	.75	.07	.21	.53	.75	.18	.34	.58	.19	.56	.70	.35	.87
10	.55	.10	.08	.52	.75	.76	.45	.04	.09	.19	.30	.58	.75	.76	.87	.21	.17	.01	.48	.72	.00	.11	.01	.71	.28	.65	.57	.43	.68	.81	.12	.31
11	.32	.03	.01	.23	.82	.75	.09	.03	.67	.21	.33	.61	.72	.65	.04	.23	.78	.23	.45	.79	.00	.15	.61	.81	.27	.53	.32	.55	.34	.79	.08	.01
12	.52	.11	.24	.53	.78	.75	.34	.13	.17	.33	.46	.11	.79	.81	.72	.45	.76	.28	.31	.55	.03	.01	.22	.51	.23	.21	.19	.84	.13	.92	.05	.34
13	.21	.17	.09	.30	.62	.84	.18	.29	.05	.45	.27	.27	.82	.34	.78	.33	.03	.36	.01	.65	.14	.23	.33	.73	.03	.87	.28	.64	.01	.79	.48	.06
14	.01	.19	.18	.27	.32	.67	.12	.07	.02	.12	.78	.65	.32	.37	.74	.43	.65	.11	.11	.67	.13	.25	.43	.01	.04	.82	.18	.69	.33	.82	.32	.56
16	.21	.09	.55	.05	.45	.65	.22	.03	.03	.03	.09	.08	.45	.25	.56	.33	.69	.31	.14	.11	.08	.21	.41	.86	.00	.73	.51	.78	.21	.65	.45	.55
17	.36	.04	.53	.11	.50	.75	.43	.21	.04	.01	.24	.64	.60	.35	.67	.32	.59	.01	.21	.56	.00	.32	.62	.83	.21	.31	.01	.69	.21	.69	.62	.43
18	.23	.13	.04	.21	.82	.79	.23	.00	.08	.09	.23	.13	.42	.71	.91	.01	.05	.03	.22	.11	.07	.19	.73	.17	.20	.50	.33	.57	.01	.71	.78	.34

Abbreviations: **Max**: maximum; **Avg**: Average; **SL**: Support leg; **SHS:** Support leg heel strike; **BC**: Ball contact; **KFTO**: kick foot toe off