THE RELATIONSHIP BETWEEN FOOT-BALL IMPACT AND KICK OUTCOME IN FOOTBALL KICKING

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Abstract

Across the football codes, kicking is the main skill used to score goals and pass between team members. Kicking with high ball velocity and high accuracy is required to kick to targets at far distances or reach a submaximal target in less time. The impact phase is the most important component of the kicking action: it is the only time a player forcefully contacts the ball to produce the flight path. Ensuring high impact efficiency and the appropriate combination of flight characteristics are imparted onto the ball during foot-ball impact is important for successful kicking. The aim of this thesis was to determine how foot-ball impact characteristics influences impact efficiency, ankle plantarflexion, ball flight characteristics and kicking accuracy. By using a mechanical kicking machine to systematically explore impact characteristics and performing an intra-individual analysis of human kickers, high-speed-video analysis of foot-ball impact found impact characteristics influenced impact efficiency, ankle plantarflexion, ball flight characteristics, and kicking accuracy. Increasing ankle joint stiffness, impact locations on the foot closer to the ankle joint, altering foot-ball angle and reducing foot velocity each increased impact efficiency. These results supported the coaching cue 'maintaining a firm ankle' during impact as effective at increasing impact efficiency. The impact location between the foot and ball across the medial-lateral direction, foot-ball angle and foot trajectory were each identified as influential to ball flight characteristics and/ or kicking accuracy. The oblique impact theory applied to the duration of impact provided a theoretical framework underpinning how each impact characteristic influenced ball flight characteristics. More consistent performing players produced less kick-to-kick variability in their impact characteristics, while lower kick accuracy was due to errors produced in the combination of impact characteristics. In conclusion, foot-ball impact characteristics were influential to impact efficiency, ankle plantarflexion, ball flight characteristics, and kicking accuracy.

Student declaration

I, James Peacock, declare that the PhD thesis entitled *The relationship between foot-ball impact with kick outcome in football kicking* is no more than 100,000 words in length including quotes and exclusive of 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: 02/03/2018

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Chapter 1: Introduction

Kicking is the defining skill of the football codes. In each of the football codes, kicking is one of the most common modes of disposal used to score goals, to pass to fellow team members, and to clear the ball from defensive pressure. The execution of the kicking skill varies between and within each football code due to the constraints imposed during gameplay, but the fundamental movement pattern of the skill is consistent: players swing their striking limb forward, impact the ball with their foot, and impart a combination of ball flight characteristics.

There are two demands that players must meet for kicks to be successful within gameplay: high accuracy and high ball velocity. High kicking accuracy is required to successfully score goals/ points and pass to fellow team members, and is achieved by imparting a combination of flight characteristics that ensures the ball passes within a set area of space such as the goal posts or within receiving distance of the desired team member when passing. Kicking with a higher ball velocity will provide more opportunities to pass and score, as targets that are further in distance from the kicker can be reached. Kicking with a high ball velocity when passing and scoring at submaximal distances is also desirable within gameplay: with a higher ball velocity and a reduced elevation angle, the ball will travel a set distance in a shorter time, limiting the opportunity for opposition players to intercept the ball. The ability to kick with both high ball velocity and high accuracy is desirable for skilled players of all football codes, and understanding how players attain these two characteristics is important for performance.

Most biomechanical research of football kicking has explored how players attain a high ball velocity. Foot velocity has consistently been identified as an important factor toward final ball velocity and the ultimate kick distance (Andersen, Dörge, & Thomsen, 1999; Ball, 2008a; Dørge, Andersen, Sørensen, & Simonsen, 2002; Ishii, Yanagiya, Naito, Katamoto, & Maruyama, 2012; Nunome, Lake, Georgakis, & Stergioulas, 2006b). Researchers have consequently identified the factors that influence foot velocity, whereby the coordination pattern can be summarised as a proximal-distal sequence. The final step length, the magnitude of hip extension at the top of the back swing, the knee extension muscular work during the forward swing, and the knee extension angular velocity just prior to impact are each important components in producing a high foot velocity (Ball, 2011; Dørge, et al., 2002; Nunome, Asai, Ikegami, & Sakurai, 2002; Nunome, Ikegami, Kozakai, Apriantono, & Sano, 2006a). The importance of foot velocity toward ball velocity also has theoretical support: the conservation of momentum combined with the coefficient of restitution (Equation 1.1), a theoretical equation representing the collision between foot and ball, identifies foot velocity and impact efficiency measures of foot-ball speed ratio, effective mass and coefficient of restitution will determine final ball velocity.

$$v_b = \left(\frac{1+e}{1+m_b/m_f}\right)\cdot u_f + \left(\frac{e-m_b/m_f}{1+m_b/m_f}\right)\cdot u_b \qquad \text{Equation 1.1}$$

Where v_b = ball velocity after it leaves the foot, e = coefficient of restitution, m_b = ball mass, m_f = foot mass, u_f = initial foot velocity, u_b = initial ball velocity.

Impacting the ball efficiently is required to impart a high ball velocity for a given foot velocity. While a player can alter their biomechanics to increase foot velocity, it is important they impact the ball appropriately to ensure efficient transfer of energy. Foot-ball impact lasts approximately 7-16 ms between different kicking styles (Ball, 2010; Peacock, Ball, & Taylor, 2017a; Shinkai, Nunome, Isokawa, & Ikegami, 2009; Shinkai, Nunome, Suito, Inoue, & Ikegami, 2013; Tsaousidis & Zatsiorsky, 1996), and energy is transferred from foot to ball (Shinkai, et al., 2013) over three-fourths of this time (Peacock, et al., 2017a; Shinkai, et al., 2009). Kick factors considered important to impact efficiency include impact location on the foot (Asai, Carré, Akatsuka, & Haake, 2002; Ishii, Yanagiya, Naito, Katamoto, & Maruyama, 2009; Ishii, et al., 2012), the physical mass of the striking limb (Amos & Morag, 2002; Andersen, et al., 1999; Moschini & Smith, 2012; Shinkai, et al., 2013), and the magnitude of ankle plantarflexion during impact (Asami & Nolte, 1983; Kellis & Katis, 2007; Lees & Nolan, 1998; Peacock, et al., 2017a; Sterzing, Kroiher, & Hennig, 2009).

The knowledge of how foot-ball impact characteristics influence impact efficiency is limited, and conflicting results have been identified. Most notable, conflicting results exist to the effectiveness of reducing ankle plantarflexion during impact to increase impact efficiency, a commonly used coaching cue (Nunome, Ball, & Shinkai, 2014). While several studies have suggested reducing ankle plantarflexion increases impact efficiency or ball velocity (Ball, Smith, & MacMahon, 2010; Kellis & Katis, 2007; Lees & Nolan, 1998; Peacock, et al., 2017a; Sterzing, et al., 2009), these suggestions were not supported by statistically significant results or they were not original papers. Further, several studies have identified no associated between reduced ankle plantarflexion and increased impact efficiency (Shinkai, et al., 2013) or ball velocity (Nunome, et al., 2006b). Research is needed to understand how effective this coaching cue is at improving kick performance.

Further, how players control the magnitude of ankle plantarflexion is not understood. Increasing the stiffness of the ankle joint has been suggested as a strategy to reduce the magnitude of ankle plantarflexion (Peacock, et al., 2017a; Sterzing, et al., 2009), and distal impact locations on the foot have been qualitatively observed to produce larger magnitudes of ankle and foot plantarflexion (Asami & Nolte, 1983). However, these studies each relied on qualitative observations. Ishii, et al. (2012) identified an optimal relationship between impact location on the foot across the proximal-distal direction with impact efficiency, and this relationship may be associated with ankle plantarflexion. Theoretically, the resulting ankle motion will be a sum of the internal and external torques applied to the ankle joint: an external plantarflexion torque greater than the internal dorsiflexion torque will theoretically produce ankle plantarflexion. As players impact distally on their foot, the external torque will be increased, causing large magnitudes of ankle plantarflexion and possibly reducing impact efficiency. Supporting this hypothesis, Ishii, et al. (2012) identified impact efficiency decreased with distal impact locations distally on the foot from a location approximately 1 cm from the foot centre of mass toward the toe. However, this must be explored. Moreover, the influence of each impact characteristic on impact efficiency and ankle plantarflexion requires further analysis, and the effectiveness of reducing the magnitude of ankle plantarflexion to improve impact efficiency, a commonly used coaching cue (Nunome, et al., 2014), must be determined.

One issue that exists with analysing the foot-ball impact phase is the number of impact characteristics that can influence energy transfer. The physical mass of the performer and foot velocity just prior to impact are both known to influence impact efficiency and ball velocity (Andersen, et al., 1999; Shinkai, et al., 2013), and the studies exploring the relationship between reduced ankle plantarflexion and impact efficiency were performed on a group level where differences in the physical mass and foot velocity existed (Asami & Nolte, 1983; Nunome, et al., 2006b; Peacock, et al., 2017a; Shinkai, et al., 2013). Thus, the values observed for ball velocity and impact efficiency likely weren't solely due to the changes in ankle motion, but a multitude of impact characteristics. This highlights a key issue that exists in the research of foot-ball impact: confounding impact characteristics. Kick outcome measures are known to be influenced by several impact characteristics, and the only way to identify the true effect of one impact characteristic on kick outcome is when all impact characteristics other than that being analysed are held constant. It is impossible to systematically explore the influence of individual impact characteristics with human kickers due to the variability they produce between kicks. But, the number of confounding characteristics can be reduced by performing an intra-individual analysis. An intra-individual analysis removes anatomical differences and individual techniques, and task specific strategies can also be eliminated by analysing a singular task. Or, alternatively, a systematic exploration of individual impact characteristics can be performed by using a mechanical kicking machine designed to replicate the impact of human kickers. Thus, exploring the relationship between foot-ball impact with kick outcome should ensure methods that reduce or eliminate the influence of confounding impact characteristics are used.

More research is also required to understand how foot-ball impact influences kicking accuracy. In addition to transferring energy from foot to ball, successful kicking requires impacting the ball to impart an appropriate combination of ball flight characteristics that enables the ball to reach the desired target. One study has explored how foot-ball impact directly influences kicking accuracy, where Hennig and colleagues identified different footwear designs influenced a measurement of kicking accuracy (Hennig, Althoff, & Hoemme, 2009). In subsequent articles discussing their work, the authors suggested the pressure distribution across the anterior aspect of the foot was the primary factor influencing kicking accuracy (Hennig, 2011). However, accurate kicking is theoretically achieved by imparting a combination of ball flight characteristics that enables the ball to travel on an appropriate flight path that will reach the desired target. Foot-ball impact will not directly influence kicking accuracy, rather, foot-ball impact directly influences the ball flight characteristics. The relationship between impact characteristics and ball flight characteristics had only been partially explored. Changes to the medial-lateral impact location on the foot produced a trade-off between ball speed and ball spin in soccer instep kicking (Asai, et al., 2002), an increased foot velocity translated to an increased ball velocity (Andersen, et al., 1999), and altering the proximal-distal impact location and the attack angle of the foot influenced ball velocity and ball spin (Ishii, et al., 2009). While both ball velocity and spin are components of the ball flight characteristics, it is unknown how impact characteristics influence ball flight trajectory (azimuth and elevation angles). Further, it is also not known how ball orientation of an ellipsoidal ball, the ball used in rugby and Australian football, influences ball flight characteristics. Research is required to determine the theoretical link between foot-ball impact characteristics and ball flight characteristics.

The overall aim of this thesis was to explore the relationship between foot-ball impact and kick outcome. Specifically, two areas are identified that require further analysis: the influence of foot-ball impact characteristics on impact efficiency and ankle motion, and the influence of foot-ball impact characteristics on ball flight characteristics and kicking accuracy. A key issue with analysing foot-ball impact is the influence of confounding impact characteristics, and two specific methodologies were chosen to address this issue. Firstly, a systematic exploration of impact characteristics with a kicking machine was performed to determine the theoretical link between individual impact characteristics (i.e. impact location, joint rigidity) and kick outcome measures of impact efficiency, ankle plantarflexion, and ball flight characteristics. The second chosen methodology was an intra-individual analysis of a submaximal accuracy task. The intra-individual analysis of a singular task was chosen to eliminate the influence of individual anatomical differences, individual techniques, and task specific strategies. The aim of the intra-individual analysis was to also identify how foot-ball impact characteristics influenced impact efficiency, ankle plantarflexion, and ball flight characteristics.

1.1. Aims

The overall aim of the thesis was to explore the relationship between foot-ball impact characteristics and kick outcome. Two areas were identified for more research to be performed:

Aim 1: Determine how foot-ball impact characteristics influence impact efficiency (foot-ball speed ratio, coefficient of restitution, and effective mass) and ankle plantarflexion.

Aim 2: Determine how foot-ball impact characteristics influence ball flight characteristics and kicking accuracy.

Each aim was answered by performing a systematic exploration of impact characteristics with a mechanical kicking machine, followed by an intra-individual analysis of human kickers. The specific aims of the thesis were to:

Study 1: Validate a mechanical kicking machine with a rigid ankle designed to replicate the foot-ball impact phase of a human kicker (aim 1 and 2).

Study 2: Perform a systematic exploration of impact characteristics using a mechanical kicking machine with a rigid ankle and an ellipsoidal ball, to determine the influence of proximal-distal impact location, medial-lateral impact location, foot-ball angle about the x-axis, ball flight trajectory, ball spin, ball velocity; and determine the influence of foot velocity on ball flight trajectory, ball spin, ball velocity, and impact efficiency measures of foot-ball speed ratio and coefficient of restitution (aim 1 and 2).

Study 3 and 4 both featured systematic exploration of impact characteristics using the mechanical kicking machine to explore the influence of ankle motion on impact efficiency. Study 3 first identified if ankle motion was influential to ball velocity and impact efficiency. Study 4 focused on the practical implications of the finding in Study 3 by exploring different strategies players could use to reduce ankle motion and improve kicking performance.

> Study 3: Validate the ankle motion of a non-rigid ankle joint on the mechanical kicking machine designed to replicate a human kicker, and perform a comparison of a rigid ankle and a non-rigid ankle to determine if impact efficiency and ball velocity differ (aim 1).
>
> Study 4: Perform a systematic exploration of impact characteristics using a mechanical kicking machine with a non-rigid ankle to determine the influence of joint stiffness, proximal-distal impact location and foot velocity on impact efficiency, ball velocity and ankle plantarflexion (aim 1).

Study 5 and 6 featured an intra-individual analysis of ten players (the same player cohort) performing the same task (30 meter drop punt kick to target). Study 5 and 6 were split as they each answered different aims of the thesis and used a different analysis procedure. Study 5 solely determined the influence of impact location on impact efficiency and azimuth ball flight angle. These results were then used to discuss the philosophical question of whether a sweet spot exists on the foot. Study 6 explored how all impact characteristics, not just impact location, influenced kicking accuracy. Study 6 also discussed how human movement variability influenced kicking accuracy.

> Study 5: Perform an intra-individual analysis on human kickers to identify the relationship between proximal-distal impact location on the foot and ankle plantar/dorsal flexion, foot-ball speed ratio, coefficient of restitution, and effective mass (aim 1), and to identify the relationship between medial-lateral impact location on the foot and azimuth ball flight trajectory (aim 2).

Study 6: Perform an intra-individual analysis on human kickers to identify the relationship between ball flight characteristics and a measurement of kicking accuracy for a submaximal accuracy task, to identify the relationship between impact characteristics and ball flight characteristics influential to kicking accuracy, and to identify if variability in foot-ball impact characteristics is functional or non-functional (aim 2).

1.2. Thesis structure

Aim 1: Determine how foot-ball impact characteristics influence impact efficiency measures (foot-ball speed ratio, coefficient of restitution, and effective mass) and ankle plantarflexion

Chapter 2.1: Literature review

Chapter 3: Study 1 – The impact phase of drop punt kicking: validation and experimental data of a mechanical kicking limb

Chapter 4: Study 2 – The relationship between foot-ball impact and flight characteristics in punt kicking

Chapter 5: Study 3 – The influence of joint rigidity on impact efficiency and ball velocity in football kicking

Chapter 6: Study 4 – Strategies to improve impact efficiency in football kicking

Chapter 7: Study 5 – Is there a sweet spot on the foot in kicking?

Chapter 9: Study 7 – The contact area between foot and ball during impact

Chapter 10.1 (General discussion): How do foot-ball impact characteristics influence impact efficiency and ankle plantarflexion.

Aim 2: Determine how foot-ball impact characteristics influence ball flight characteristics and kicking accuracy.

Chapter 2.2: Literature review

Chapter 3: Study 1 – The impact phase of drop punt kicking: validation and experimental data of a mechanical kicking limbChapter 3

Chapter 4: Study 2 – The relationship between foot-ball impact and flight characteristics in punt kicking

Chapter 7: Study 5 – Is there a sweet spot on the foot in kicking?

Chapter 8: Study 6 – Kick impact characteristics of accurate football kicking

Chapter 9: Study 7 – The contact area between the foot and ball during impact

Chapter 10.2 (General discussion): How do foot-ball impact characteristics influence ball flight characteristics and kicking accuracy

Chapter 2: Literature review

The two themes within this thesis are the production of ball velocity and the factors that influence kicking accuracy. The end goal of reducing the magnitude of ankle plantarflexion during impact is to ultimately increase final ball velocity by increasing impact efficiency. The first section in the literature review, “The generation of ball velocity”, will discuss the previous literature that has focused on producing ball velocity: foot velocity; the transfer of energy from foot to ball; and impact efficiency. The second section of the literature review will cover the key research football kicking accuracy.

2.1. The generation of ball velocity

2.1.1 Theoretical framework

The conservation of momentum combined with the coefficient of restitution indicates the final ball velocity will be determined from the initial foot velocity and impact efficiency measures of foot-ball speed ratio, effective mass and the coefficient of restitution. Because the foot is a non-rigid body and comprises rotational and linear movement, the physical mass of the foot and entire striking limb does not represent the mass component that is effective to the collision. This was observed by Shinkai, et al. (2013) in their analysis of 51 soccer players: the physical mass of the foot contributed approximately 84% of the effective mass used in the collision. The mass that is effective to the collision, namely the effective mass, can be calculated from the conservation of momentum using the initial and final foot and ball velocities, and the mass of the ball (Shinkai, et al., 2013). Energy is lost during the collision between foot and ball due to hysteresis. Coefficient of restitution quantifies the magnitude of elastic energy that is retained during the collision. During foot and ball collision, both the foot, ankle and ball deform. Elastic energy is stored in this process and is subsequently released during its reformation. The influence of foot-ball impact characteristics can be assessed using impact efficiency measures of foot-ball speed ratio, coefficient of restitution and effective mass as performance measures.

The conservation of momentum combined with the coefficient of restitution relies on the assumption that energy is transferred solely between foot and ball during impact. In the context of football kicking, it has been suggested that additional force is applied to the system of the foot and ball during impact due to muscular force. Muscular force is one source of energy that has been discussed as potentially being added during impact. Tsaousidis and Zatsiorsky (1996), analysing the soccer toe kick, argued the conservation did not validly represent the impact of foot-ball due to three reasons:

1. The large contact distance.
2. The magnitude of ball velocity at maximal deformation being greater than 50% of final ball velocity.
3. The non-reduction in foot velocity during ball reformation.

Ball (2008b) also suggested muscular force could be applied during impact of drop punt kicking, because the magnitude of change in shank angle during impact (18 ± 3°), work done on the ball (271 ± 36 J) and contact distance (24 ± 6 cm) were also large enough for muscular force to be applied at the hip and/ or knee joints during impact.

Muscular force also may not be applied during impact, where the increase in ball velocity is solely due to energy/ momentum transferred from the foot to the ball. The first argument by Tsaousidis and Zatsiorsky (1996) comprised the magnitude of distance the foot and ball travelled together during foot-ball impact was substantial and muscular force was applied during impact. However, it has been identified that muscular force is not applied immediately prior to impact. Nunome, et al. (2006a) identified the quadriceps were unable to apply a concentric force during the final 10% of leg acceleration phase prior to impact. This lack of ability to produce muscular force was thought to be caused from the angular velocity exceeding the inherent force-velocity relationship of the quadriceps. During phase 4 of impact (see section 2.1.2.2 for further explanation of four impact phases), Peacock, et al. (2017a) identified foot velocity to increase 0.5 ± 0.7 m/s. This increase in velocity could be due to two possibilities: the application of muscular force, or, elastic energy stored in the structure of the knee and/ or ankle due to the large force applied during impact was released. Regardless of what contributed to the increase in foot velocity, this increase did occur during phase 4 of impact where ball velocity did not increase, and thus this release of energy was not influential to ball velocity. The contact time (~16 ms) observed by Tsaousidis and Zatsiorsky (1996) was also substantially larger than that observed for drop punt, soccer instep, and rugby kicking (7 – 13 ms) (Ball, 2010; Peacock, et al., 2017a; Shinkai, et al., 2009). Further, it has been suggested the motion of the foot and ball during impact is passive. Nunome, et al. (2006b) suggested ankle motion was passive during impact, and the foot-ball interaction was determined solely from the initial conditions of impact, i.e. foot speed just prior to impact, and therefore not muscular force. Thus, while the foot and ball do travel a distance together over a certain time, this does not mean muscular force is applied. Further, the ability to apply muscular force may not exist until the angular velocity of the knee has decreased partway through impact, and it is likely this does not contribute to ball velocity.

Tsaousidis and Zatsiorsky (1996) identified a non-reduction in foot velocity during ball reformation. Subsequent studies analysing foot-ball impact have observed dissimilar results. It has been observed in most studies that the transfer of energy from foot to ball during impact is characterised by a reduction in foot velocity with any increase in ball velocity (Ball, Ingleton, Peacock, & Nunome, 2013; Peacock, et al., 2017a; Shinkai, et al., 2009). These results indicate that kinetic energy of the foot is transferred into kinetic energy of the ball, where the addition of muscular force alone does not contribute to the kinetic energy of the ball. Shinkai, et al. (2009) suggested the different observations (mainly about the non-reduction of foot velocity during phase 3 of impact) may have been due to different methodologies and the style of kick analysed: Tsaousidis and Zatsiorsky (1996) analysed the soccer toe kick and measured the kinematics of the foot and ball using a method that assumed no deformation of the foot segment and no angular motion of the ball. Deformation of the foot and angular motion of the ball are important factors that have been assessed in several studies (Asami & Nolte, 1983; Ishii, et al., 2009). Therefore, the results of Tsaousidis and Zatsiorsky (1996) for the soccer toe kick appear as an anomaly to what has been identified in several studies analysing foot-ball impact of drop punt and soccer instep kicking.

Some of the evidence used by Tsaousidis and Zatsiorsky (1996) to indicate muscular force was applied during impact have been observed in collisions where additional energy is not added to the system. One of the key points (point 3) of the argument by Tsaousidis and Zatsiorsky (1996) was the magnitude of ball velocity being greater than 50% than the final velocity at the point of maximal deformation. However, other analyses of impact where no additional energy is added to the collision have also observed this pattern (Cross, 1999), indicating this occurrence is not specific to muscular force being applied during impact. The magnitude of final ball velocity at the point of maximal deformation for any non-elastic collision is always greater than 50% of final ball velocity due to hysteresis.

Tsaousidis and Zatsiorsky (1996) argued the conservation of momentum did not validly represent the impact of football kicking due to the magnitude of muscular force applied during impact. However, the arguments used by Tsaousidis and Zatsiorsky (1996) do not prove the conversation of momentum combine with the coefficient of restitution does not validly represent the impact of football kicking. There are several irregularities identified between the results of Tsaousidis and Zatsiorsky (1996) with other analyses, where arguments 1 and 2 are do not definitely prove the theory is not valid. Secondly, the magnitude of ball velocity at maximum ball deformation being greater than 50% is due to hysteresis. Therefore, the addition of coefficient of restitution to the conservation of momentum can accommodate this factor to more validly represent foot-ball impact. Therefore, the conservation of momentum and the coefficient of restitution can be used as a theoretical framework to analyse foot-ball impact.

2.1.2 Foot velocity

2.1.2.1 Contribution of foot velocity toward ball velocity

Foot velocity is an important factor toward final ball velocity, and altering foot velocity is one mechanism that players use to control ball velocity and kick distance. The association between higher foot velocity and higher ball velocity has been identified through multiple study designs: regression analyses, comparisons of different performers and theoretical equations (Andersen, et al., 1999; Ball, et al., 2010; De Witt & Hinrichs, 2012; Shinkai, et al., 2013). Furthermore, comparisons of different kicking tasks by the same player have identified changes in foot velocity with changes in kick distance and ball velocity (Peacock, et al., 2017a), indicating that players can use different foot velocities for different kick distances/ tasks.

2.1.2.2 Four phases of impact

Because foot velocity prior to impact is an important factor, analysis of the interaction between foot velocity and ball velocity is warranted. The impact phase lasts approximately 8-12 ms in duration over a distance of approximately 20-30 cm for both instep and drop punt kicking, depending on the distance kicked (Ball, 2008a; Peacock, et al., 2017a; Shinkai, et al., 2009). Shinkai, et al. (2009) identified four phases during foot-ball impact of the soccer instep kick, based on the profile of foot velocity, ball velocity, and ball deformation. Using the criteria set out by Shinkai, et al. (2009) to identify the phases during impact, Peacock, et al. (2017a) identified a similar general pattern of foot and ball velocity in the drop punt kick; indicating the transfer of energy from foot to ball was not influenced by the different kicking style and ball shape.

Phase 1 and 2 of impact were characterised by ball deformation. Phase 1 lasted approximately 22% of impact duration, and was characterised by an increase in ball deformation and reduction in foot velocity. Depending on how ball velocity was calculated, differences existed on its motion during the phase due to the large degree of ball deformation. Shinkai, et al. (2009) developed a method to predict the centre of gravity of the ball during impact by including ball deformation data, and compared its velocity with that of the undeformed geometric centre of the ball. During phase 1, the centre of gravity of the ball increased velocity immediately. The increase in velocity of the geometric centre of the ball was delayed, due to deformation. Phase 2 of impact lasted approximately 20% of impact duration, and was characterised by further increase in ball deformation and ball velocity, and further reduction in foot velocity. The beginning of this phase can be most easily identified from the velocity of the geometric centre of the ball. At approximately 20% of impact duration, the beginning of phase 2, the velocity of the geometric centre of the ball began to increase. During phases 1 and 2, velocity of the geometric centre of the ball was less than the velocity of the centre of gravity of the ball because the centre of gravity is moving within the geometric shell of the ball. This has implications for the calculation of further parameters from ball velocity, such as instantaneous force for example, which could be under or overstated if calculated from the geometric centre of the ball.

Phase 3 and 4 of impact are characterised by ball reformation. Phase 3 began at approximately 45% of impact duration, and lasted approximately 33% of impact duration. The onset of this phase was defined by the point of maximal deformation, coinciding with the crossover of foot and ball velocity, where ball velocity remained higher than foot velocity for the remainder of impact. During the phase, ball velocity continued to increase, foot velocity continued to decrease, and the ball began reforming. Phase 4 of impact began at approximately 75% of impact duration. Interestingly, this phase was identified by a plateau in the increase in ball velocity and reduction in foot velocity as the ball continued to reform fully. Because ball velocity had little increase during phase 4, a player has only three-fourths of visually identified ball contact to effectually accelerate the ball (Shinkai, et al., 2009).

Two notable differences existed in the profile of impact for the drop punt kick compared to the soccer instep kick. Firstly, ball velocity was non-zero at the beginning of impact for the drop punt kick. This was due to the ball being dropped from the hand prior to being impacted by the foot. Secondly, foot velocity increased by 0.5 m/s in phase 4. Peacock, et al. (2017a) identified two factors that may explain this increase in foot velocity: muscular force may have been applied during foot-ball impact, where it was not until phase 4 where ball velocity plateaued that the increase in foot velocity appeared; or, elastic energy stored in the soft-tissue structures surrounding the foot and/ or knee was released, thus increasing the linear velocity of the foot.

2.1.2.3 An alternate profile of impact

During foot-ball impact of the less popular soccer toe-kick, Tsaousidis and Zatsiorsky (1996) identified three phases, rather than four. During deformation, phases 1 and 2 were similar to those identified by Shinkai, et al. (2009) and Peacock, et al. (2017a). Ball reformation, however, was not split into two phases but was treated as one phase (phase 3). Interestingly, there was no reduction in foot velocity during this phase, but it can be identified approximately midway through that ball velocity began to plateau. Shinkai, et al. (2009) noted this discrepancy may have been due to two factors: firstly, the particular point of the foot to calculate velocity was not identified; and secondly, Tsaousidis and Zatsiorsky (1996) assumed no deformation of the toe part of the foot that penetrated into the ball.

2.1.2.4 Ball deformation and reformation

The point of maximum deformation occurs at the crossover point of foot and ball velocity (Shinkai, et al., 2009). The timing of these events is logical; when the foot is in contact with the ball but is travelling faster, the ball must be deforming. When ball velocity is greater than foot velocity, the ball is travelling away from the foot, and thus the ball must be reforming. Shinkai, et al. (2009) reported a maximum deformation of 6.2 ± 0.6 cm for instep kicking, Ishii, et al. (2012) reported maximum ball deformation was between the range of 2.9 to 6.5 cm.

2.1.2.5 Force applied between foot and ball

Quantifying the magnitude of peak force between foot and ball can improve our understanding of injury risk associated with excessive football kicking: anterior ankle impingement syndrome. Tol, Slim, van Soest, and van Dijk (2002) tested two hypotheses that were developed to explain the occurrence of anterior ankle impingement syndrome: (i) hyper-ankle plantarflexion; (ii) the magnitude and location of force applied to the ankle joint. By analysing 150 kicks from 15 elite soccer players, the authors identified hyper-ankle plantarflexion occurred only in the minority of kicks, therefore the magnitude and location of force applied to the foot and ankle was likely the main cause of the condition.

Measuring the average force applied to the ball can easily be obtained by the change in ball velocity, contact time and ball mass (Peacock, et al., 2017a; Shinkai, et al., 2009; Tol, et al., 2002). Average force differs between kick distances (Ball, 2008b; Peacock, et al., 2017a), whereby the increased foot velocity was the considered cause of greater average force (Peacock, et al., 2017a). Greater average force has also been identified in senior compared to junior players (Ball, et al., 2010), and between the preferred compared to the non-preferred limb (Smith, Ball, & MacMahon, 2009) (calculated post-hoc by the author of the present thesis).

Several authors have identified the maximum force applied between foot and ball. Shinkai, et al. (2009) reported a maximum deformation of 6.2 ± 0.6 cm for instep kicking, and at this event calculated a peak force of 2926 ± 509 N. Ishii, et al. (2012) developed a method to calculate instantaneous force during foot-ball impact from ball deformation, but did not report peak values. Tol, et al. (2002) estimated peak force during impact by multiplying average force (calculated from the change in ball velocity, contact time and ball mass) by $\pi/2$, assuming the force profile followed a half sine-wave. Shinkai, et al. (2009) identified this method severely underestimated the true magnitude of peak force applied during impact: Tol, et al. (2002) estimated peak force to be 1610 N, approximately 1.6 times the average force of 1025 N; whereas Shinkai, et al. (2009) measured a peak force of 2926 N, approximately 2.1 times the average force of 1403 N. As Shinkai, et al. (2009) identified the method by Tol, et al. (2002) underestimated their measured magnitude of peak force, Iga, Nunome, Sano, Sato, and Ikegami (2017) set to explore the validity of measuring impact force using the various methods in the literature using a force plate as a criterion for validation. They developed a new method to measure force, citing increased accuracy compared to the previous methods, and future work is looking to utilise this method in football kicking actions.

2.1.3 Impact efficiency

Impacting the ball efficiently, whereby the maximum ball velocity is attained for a given foot velocity, is desirable for players. As identified from the energy transfer principles, impact efficiency, as measured from foot-ball speed ratio, will be determined by the effective mass of the striking limb and the coefficient of restitution for the collision. Several foot-ball impact characteristics have been identified to influence impact efficiency (foot-ball speed ratio), effective mass and coefficient of restitution.

2.1.3.1 Impact location

Moving impact location distally on the foot will theoretically increase ball velocity linearly. Andersen, et al. (1999) rearranged an equation combining the conservation of angular momentum, conservation of momentum, and coefficient of restitution to predict ball velocity, and found it to be in good agreement with their experimental data. From this equation, an increase in the distance between the knee and impact location on the foot/ ball centre will increase ball velocity. Ball velocity increases because distance between the rotating knee and the impact location increases with a distal impact location, thus translating to a higher velocity of the impacting point.

An alternative theoretical relationship identifies an optimal relationship exists between proximal-distal impact location with ball velocity. Analysing side and instep kicking techniques, Ishii, et al. (2009) and Ishii, et al. (2012) identified an optimal impact location for each kick within their theoretical equations based upon the impact dynamic theory. This equation predicts ball velocity was maximum with an impact location approximately 1 cm toward the toe for instep kicking, and approximately 3.5 cm toward the heel for the side kick. Validation of their models identified good agreement with the experimental data: absolute differences existed with experimental data and the model, however, the relationships between impact location with ball velocity were consistent. To facilitate changes in impact location for the instep kick, they altered the height of the ball above the ground by using a cardboard tee. Although this might violate ecological validity, this constraint yielded a produced a large range of impact locations (0.16 m) across the dorsal aspect of the foot.

A finite element analysis identified changes to impact location in the medial-lateral direction from the foot centre of mass decreases ball velocity, but increases ball spin. Asai, et al. (2002) compared the offset distance, calculated from the distance between foot-ball impact and the centre of the ball, and identified ball velocity was maximal with an offset distance of 0 cm, where the impact location passed through the centre of the ball. There was a trade-off between ball velocity and spin rate. Ball velocity decreased when the offset distance increased in either direction (positive or negative), while the spin rate increased.

2.1.3.2 Physical mass

Increasing the physical mass of the shoe, such as by adding masses to the foot, increases the effective mass of the foot. This might appear to be an effective strategy to increase ball velocity, given Nunome, et al. (2006a) identified players were unable to apply force through the quadriceps just prior to impact as the knee extension velocity was too great for the muscles to contract. The results of Nunome, et al. (2006a) identify the increase in knee extension velocity was limited by the capability muscle contractile velocity, thereby increasing the mass would mean a lower velocity is required for the constant momentum. However, Amos and Morag (2002) and Moschini and Smith (2012) both identified increasing the physical mass resulted in no change to final ball velocity, as the momentum of the limb remained constant as the effective mass increased but foot velocity decreased. This does indicate, however, that because ball velocity was constant but foot velocity reduced, that increases to effective mass will increase foot-ball speed ratio.

A greater physical mass of the performer translates to a greater foot-ball speed ratio. Shinkai, et al. (2013) identified in a cross-sectional analysis of 51 junior to senior players that ball velocity increased with player age. Two factors caused the increased ball velocity: higher foot velocities and higher physical masses. This indicates that despite higher leg masses they also increased foot velocity, likely due to greater strength levels. Interestingly, the physical mass of the players also correlated with impact efficiency measures. The sum of the shoe and foot mass corresponded to 84.0 ± 9.6% of their effective mass. Further, effective mass correlated positively with foot-ball speed ratio ($r = 0.89$). This indicates increases to effective mass, through physical mass, will increase foot-ball speed ratio.

2.1.3.3 Reducing the magnitude of foot and ankle plantarflexion during impact

During foot-ball impact, the ankle joint is forced into passive plantarflexion (Nunome, et al., 2014; Nunome, et al., 2006b; Peacock, 2013; Peacock, et al., 2017a; Shinkai, et al., 2009; Shinkai, et al., 2013). Analysis within the foot-ball impact phase identified three general patterns of ankle motion to exist within both drop punt and instep kicking (Peacock, 2013; Shinkai, et al., 2009): (1) distinct plantarflexion through the entire duration of impact; (2) initial dorsiflexion for the first fourth-to-third of impact duration, followed by distinct plantarflexion; (3) dorsiflexion through the entire duration of impact. Both Shinkai, et al. (2009) and Peacock (2013) identified most players produced pattern number two, and only one player who produced a unique technique displayed pattern three.

The foot metatarsophalangeal and ankle joint motion have been identified as an important factor toward producing ball velocity (Asami & Nolte, 1983; Ball, et al., 2010; Peacock, 2013; Peacock, et al., 2017a; Plagenhoef, 1971; Sterzing, et al., 2009). Asami and Nolte (1983) first identified a relationship between foot and ankle plantarflexion with ball velocity. In an analysis of six players, including one international player, 19 kicks were analysed and correlations were identified for ankle plantarflexion ($r = -0.409$;) and foot plantarflexion ($r = -0.805$). Post-hoc analysis by the author of this thesis identified the correlation between ankle plantarflexion with ball velocity was $p = 0.08$, and the correlation between foot plantarflexion with ball velocity was $p < 0.001$. These results first introduced the concept that increasing rigidity, to reduce the magnitude of foot and ankle plantarflexion, was beneficial to ball velocity. Qualitative analysis by Asami and Nolte (1983) identified impacting distally on the metatarsus and/ or phalanges produced the large foot plantarflexion. Shinkai, et al. (2013) performed a cross-sectional analysis on the impact characteristics of 51 junior to senior players. Despite identifying a non-significant correlation between change in ankle plantarflexion with foot-ball speed ratio ($r = -0.36$), post-hoc partial correlation analysis by the author of this thesis identified a significant relationship, partial to effective mass ($r = -0.79$; $p < 0.0001$). This partial correlation is warranted, because the physical mass of the performer is known to increase foot-ball speed ratio (Amos & Morag, 2002). Therefore, strategies to reduce foot and ankle motion during impact appear to be beneficial to final ball velocity.

Relying on anatomical structures at the end of the ankle and foot plantarflexion range of motion increases their rigidity. This strategy is considered effective at improving impact efficiency due to a reduced ankle plantarflexion during impact. Sterzing, et al. (2009) compared maximal ball velocity kicking between several shoe types, barefoot and with a sock, and stated "kicking barefoot provided superior collision biomechanics", due to a greater magnitude of ankle and foot plantarflexion adopted at the beginning of impact. Peacock, et al. (2017a) identified, despite a greater force applied to the foot, that maximal kicks produced significantly less ankle plantarflexion during impact because they adopted a more plantarflexed position at the beginning of impact. As the foot and ankle are forced into plantarflexion during foot-ball impact, the stiffness within the foot and ankle joint increases as the soft tissue structures are stretched and the hard tissue structures come in direct contact.

A players strength may also improve a player's ability to maintain ankle and foot position during impact. Ball, et al. (2010) compared the impact characteristics of senior to junior Australian football players. Despite a larger force applied to the foot for the senior players, they produced a significantly smaller magnitude of change in ankle plantarflexion during impact. Due to the higher levels of strength within the senior players, the authors suggested increasing muscular strength may be an effective strategy to increase rigidity in the foot and ankle segment, but did throw caution to this mechanism as other impact characteristics such as foot-ball orientation may have also caused this difference. Further, senior players are also likely to have greater body mass, also increasing foot-ball speed ratio in the senior players.

The conservation of momentum combined with the coefficient of restitution can provide two mechanisms to explain how energy transfer between foot and ball might be influenced by ankle and foot motion during impact (Equation 2.1): effective mass and coefficient of restitution. In their literature review, Lees and Nolan (1998) introduced the conservation of momentum theory combined with the coefficient of restitution to describe the impact between foot and ball. They stated the effective mass is the mass equivalent of the striking object (foot and shank) that is made more rigid from muscle activation, and the coefficient of restitution relates to the firmness of the foot due to foot plantarflexion. In another review of the literature, Kellis and Katis (2007) state less deformation in the foot translates to higher coefficient of restitution. Similarly, Sterzing, et al. (2009) stated greater change in ankle plantarflexion during impact resulted in more energy dissipation, which can be interpreted as reduces to the coefficient of restitution. These three studies, despite using several different terms, have used the concepts of energy transfer to describe how reduced ankle and foot motion influences ball velocity: effective mass and coefficient of restitution. The effective mass, as introduced by Kellis and Katis (2007) and Lees and Nolan (1998), appears to be influenced by change in ankle plantarflexion during impact. Whereas coefficient of restitution is influenced by change in foot plantarflexion during impact (Kellis & Katis, 2007; Lees & Nolan, 1998) and change in ankle plantarflexion (Sterzing, et al., 2009).

$$v_b = \left(\frac{1+e}{1+m_b/m_f}\right)\cdot u_f + \left(\frac{e-m_b/m_f}{1+m_b/m_f}\right)\cdot u_b \qquad \text{Equation 2.1}$$

Where v_b = ball velocity after it leaves the foot, e = coefficient of restitution, m_b = ball mass, m_f = foot mass, u_f = initial foot velocity, u_b = initial ball velocity.

Several other studies have identified differences in coefficient of restitution between kicking groups, identifying the mechanical properties and the motion of the foot and ankle during impact are influential to final ball velocity. Andersen and colleagues have identified several circumstances where coefficient of restitution has differed (Andersen, et al., 1999; Andersen, Kristensen, & Sorensen, 2005, 2008; Dørge, et al., 2002). In their first study (Andersen, et al., 1999), they identified coefficient of restitution varied within a group of athletes, whereby the mechanical properties of the shoe, foot and ankle joint were suggested to probably contribute to the differing values. A comparison of preferred and non-preferred kicking limbs identified coefficient of restitution differed, and stated a small difference in the extension and stiffness of the foot and ankle may alter the coefficient of restitution (Dørge, et al., 2002). They also performed a series of studies comparing the toe and instep style of kicks (Andersen, et al., 2005, 2008). The key difference between the toe and instep kicks is the impact location on the foot: the toe kick impacts the ball with a notably smaller contact area compared to the instep kick. To determine the differences in kicking dynamics between the two techniques, they first performed a systematic comparison with a pendulum with two impacting surfaces of different areas: a smaller contact area to represent the toe kick; and a larger contact area to represent the instep kick. The results identified a smaller contact area produced higher coefficient of restitution values, suggesting the toe kick would produce an improved ball velocity. However, subsequent comparisons between the toe and instep kick styles with human players identified this performance advantage reduced at moderate-high foot velocities (> 15 m/s), where they speculated the stiffness in the foot and ankle diminished. This suggests that foot and ankle motion again may be detrimental to kicking performance.

The effectiveness of reducing the magnitude of ankle and foot plantarflexion during impact is not fully understood. The literature presented thus far indicates there is a positive relationship between foot and ankle motion during impact with a sound theory describing the interaction. However, several studies have also identified non-significant and conflicting results in the relationship between change in ankle plantarflexion with ball velocity. Nunome, et al. (2006b) identified an athlete that produced a relatively high ball velocity also demonstrated substantial change in ankle plantarflexion during impact in respect to the analysed group. Despite identifying a significant difference in ankle plantarflexion during impact between two tasks, Peacock, et al. (2017a) identified no significant difference in foot-ball speed ratio. Shinkai, et al. (2013) identified a non-significant relationship between change in ankle angle with foot-ball speed ratio in a group of 51 players. While subsequent post-hoc partial correlations with effective mass by the author of the present thesis suggests this relationship is significant, effective mass might also be dependent on ankle motion (Lees & Nolan, 1998), thus this result should be taken with caution. Despite identifying a significant difference in change in ankle plantarflexion during impact, Ball, et al. (2010) identified a non-significant difference ($p = 0.02$; $d = 0.7$) in foot-ball speed ratio. While the p-value was less than 0.05, this was non-significant due to Bonferroni adjustment. Further, given foot-ball speed ratio is influenced by the physical mass of a performer, this observed difference might also be due to the physical mass changing between the senior and junior players, not ankle motion.

To further confuse the influence of foot and ankle motion on impact efficiency during impact, the previous studies that promoted a clear relationship between foot and ankle motion with ball velocity each have their limitations. In fact, the only result that provides a statistically significant relationship between ankle motion with foot-ball speed ratio is the post-hoc partial correlation of Shinkai, et al. (2013) performed by the author of this thesis, which should be taken with caution. Lees and Nolan (1998) and Kellis and Katis (2007) introduced the concepts of effective mass and coefficient of restitution, and how each are influenced by ankle and foot motion during impact. However, these claims were not based on any data as they were not original papers. Despite Sterzing, et al. (2009) discussing the magnitude of foot and ankle plantarflexion at the beginning of and during impact in their comparison of barefoot to shod kicking, they did not quantitatively measure foot and ankle motion. Rather, they performed a qualitative analysis on one individual within the group, and inferred that this result was consistent for all players within the group. Furthermore, the statistical results do not support their claims that ball velocity was higher in the barefoot over shod conditions, which is the foundation of their link between foot and ankle motion with ball velocity. The authors performed an ANOVA analysis between the groups: however, firstly, the ANOVA at the group level was non-significant ($p = 0.05$); and secondly, they did not perform any post-hoc analyses to identify direct differences between the barefoot with any shod conditions. Rather, they stated “there was a strong trend toward higher ball velocity in the barefoot condition”. While Asami and Nolte (1983) did identify a significant relationship between foot plantarflexion with ball velocity, foot velocity was also identified as a key determinant of ball velocity ($r = 0.738$), where the analysis of ankle and foot motion must be made with impact efficient measure of foot-ball speed ratio, or energy transfer mechanisms of coefficient of restitution and effective mass. It is possible foot velocity caused the greater final ball velocity and greater change in plantarflexion during impact. Thus, there is no empirical evidence supporting the relationship between foot and ankle motion with impact efficiency, possibly explaining why several researchers have identified dissimilar results (Nunome, et al., 2006b).

2.1.4 Summary of factors influential to ball velocity

Currently, the only strategy that players can use to increase ball velocity that has statistical and theoretical support is through an increased foot velocity. However, the type of the relationship (i.e. linear, non-linear) is not yet fully understood, and this has implications for future analyses. Although Peacock, et al. (2017a) identified foot-ball speed ratio was non-significant between the two kicking tasks, they argued that the greater foot velocity in the maximal distance kick confounded the results, where reducing reduced ankle plantarflexion was beneficial to foot-ball speed ratio. They argued that foot-ball speed ratio would decrease with an increasing foot velocity, assuming all other characteristics were held equal. This suggests the relationship between foot velocity with ball velocity was non-linear, rather, the increase in ball velocity diminished with increases in foot velocity. This has implications for future comparisons. If impact efficiency measures are dependent on foot speed, then comparisons of different conditions, such as different footwear designs, must take this information into consideration to understand where differences might exist.

No study has identified the relationship between impact location with ball velocity under kicking conditions. The studies that have analysed the relationship between impact location with ball velocity have used theoretical equations (Andersen, et al., 1999; Asai, et al., 2002; Ishii, et al., 2009, 2012). Further, conflicting relationships exist within the validated models that predict ball velocity from impact location. Due to difficulties with measuring impact location between the foot and ball, no study has explored this relationship using experiment data. Therefore, a methodology must be developed to calculate impact location in three-dimensional space to further understand if and why impact location influences ball velocity.

Lastly, it is widely established in the scientific literature that reducing change in plantarflexion of the foot and ankle during impact will translate to an increased ball velocity. However, critical analysis of the literature identified there is no empirical evidence supporting this theory (Asami & Nolte, 1983; Peacock, et al., 2017a; Sterzing, et al., 2009), or, several authors have introduced the concepts in literature reviews without evidence supporting their claims (Kellis & Katis, 2007; Lees & Nolan, 1998). Further, several studies have identified no relationship between reducing change in ankle plantarflexion with increased ball velocity, stating the relationship requires an appropriate analysis (Nunome, et al., 2006b; Shinkai, et al., 2013). More research is required to understand if and why ankle and/ or foot motion is influential to impact efficiency and/ or ball velocity, where the influence of confounding impact characteristics is either eliminated or controlled for.

2.2. Kicking accuracy

2.2.1 Theoretical framework

2.2.1.1 Measurements of kicking accuracy

In gameplay, a successful shot at goal occurs when the ball successfully passes through the space bounded by the goal posts. When passing, a kick can be classified as successful if the desired team member receives the ball. There are levels of success for passing, whereby passing to a team member without deviating from a specific path on the field enabling them to continue attacking or move into an attacking position can be considered the ultimate form of success. However, there are times when a pass will still be successful despite this occurring: a fellow team member can deviate from their specific path on the field and receive the ball; or, if the pass is not received by the desired target but is received by a different team member. For all conditions, though, a player will select a specific target whereby the success of this outcome is dictated by the distance the ball travels from this target in relation to the context of the game. Thus, there are levels of accuracy that differentiate the outcome of the kick to be successful or unsuccessful, such as travelling within the goal posts when scoring or within reach of a fellow team member when passing.

The measurement of kicking accuracy can be reduced to a two-dimensional coordinate within the vertical and horizontal planes perpendicular to the direction of the kick. In the vertical plane, the accuracy outcome of a kick can be reduced to a two-dimensional coordinate comprising the horizontal and vertical distances from the target. In the horizontal plane, the accuracy outcome can also be reduced to a two-dimensional coordinate comprising the perpendicular and parallel distances. Depending on the desired outcome of the kick, either of the planes are a more suitable measurement plane. When scoring and passing, the vertical plane is often most representative given the orientation of both players and goals on the field (Figure 2.1).

Figure 2.1: Measurements of kicking accuracy as a two-dimensional coordinate in the vertical plane when scoring (A) and passing (B) in different codes of football. The direction of the coordinates is represented by the red arrows.

Other studies assessing football kicking accuracy and sports that demand high end-point accuracy have taken other approaches to measuring kicking accuracy and/ or identify factors associated with accuracy. Rather than splitting the end-point position into a two-dimensional coordinate, the resultant distance from the desired target can be measured (Hennig, et al., 2009).

This can reduce complexity of the subsequent analysis because only one performance outcome is determined. But, the ability to identify direct mechanisms is often reduced because of the scalar nature of measurement. For example, two kicks that miss the target by both 1 m on the left and 1 m on the right will travel on distinctly different flight paths despite both displaying an accuracy measurement of 1 m. Defining boundaries of successful and unsuccessful outcomes have also been employed (Atack, Trewartha, & Bezodis, 2017; Dichiera, et al., 2006; Phillips, Portus, Davids, & Renshaw, 2012), enabling the option of group analysis to be performed. This measurement does have a real-world context because the outcome of kicking often comes down to the ball passing within a boundary, such as the goal posts. However, this method again limits the opportunity for mechanisms to be identified because continuous measures are not employed. Further, kicks that may be characterised by a small difference in the real world may be classed as different outcomes. For example, two kicks that pass immediately either side of the goal posts, while only differentiating by a small distance such as 10 cm, will be classed as different outcomes.

To reach a specific target, the ball must travel on a necessary flight path once the ball leaves contact with the foot. During this flight path, the ball is in projectile motion and there is nothing a player can do to alter its path. In addition to gravity, aerodynamic forces (including drag force, lift force and buoyancy) are applied to the ball (Goff, 2013). Because there are several forces applied to the ball, there are multiple combinations of flight characteristics that will enable a specific target to be reached. For example, a lower elevation angle but higher ball velocity can reach the same target. Mechanically, to kick toward a specific target, a player will impart a combination of ball flight characteristics by impacting the ball with their foot. Thus, to identify how foot-ball impact influences kicking accuracy, taking the approach of foot-ball impact – ball flight characteristics – kicking accuracy measurement will enable the direct mechanisms to be outlined. This was the theoretical framework chosen for this thesis to determine how kicking accuracy is influenced by foot-ball impact characteristics.

2.2.2 The ball flight path

Ball flight characteristics can be defined by the magnitude of ball velocity (m/s), azimuth and elevation trajectories, ball orientation in the X, Y and Z axes, and ball angular velocity (spin) in the X, Y and Z axes (Figure 2.2).

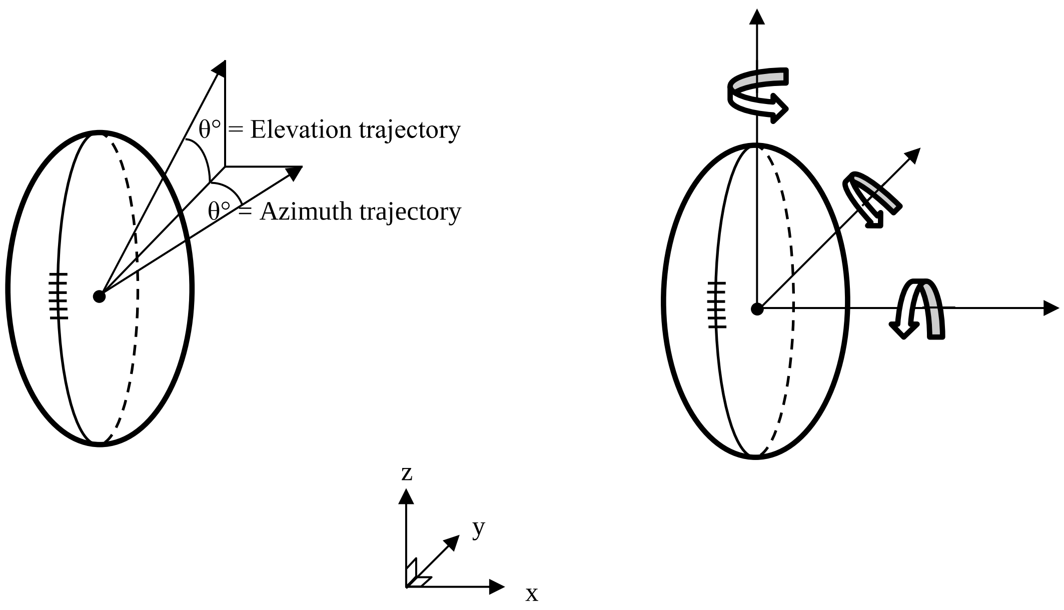

Figure 2.2: Ball flight characteristics

Gravity and aerodynamic forces of drag and lift are applied to the ball as it travels through air as a projectile (Goff, 2013). Carré, Asai, Akatsuka, and Haake (2002) performed a systematic exploration of ball flight spin characteristics to calculate the drag and lift coefficients for the spherical soccer ball, where it was identified a back-spin will produce a positive lift force onto the ball and greater velocity increases the drag force. For non-spherical balls, such as the ellipsoidal rugby league and Australian football balls, the orientation of the ball also influences the aerodynamic forces on the ball (Alam, Subic, Watkins, & Smits, 2009). No work has been performed on a spinning ellipsoidal shaped football, thus we can only speculate, based on the results of Alam, et al. (2009) and Carré, et al. (2002), that an ellipsoidal ball slightly tilted with back-spin will produce a lift force pushing the ball off plane. This is likely why players perform the drop punt kick most frequently in Australian football; the back-spin imparted onto the ball produces a stable flight path.

Several studies have developed mathematical models to predict the flight path and outcome of football kicks. Atack, Trewartha, and Bezodis (2015) developed a mathematical model to determine the success of rugby union place kicking toward goal from 22.0 m. This model included initial ball flight characteristics from eight trials, ball mass, ball size and spin coefficients from a previous study (Djamovski, Rosette, Chowdhury, Alam, & Steiner, 2012). Carré, et al. (2002) more extensively developed a mathematical model predicting the flight path of the spherical soccer ball. A cannon fired the ball at various velocities and spin rates, where two cameras captured the initial velocity, elevation angle and the flight path over 10 meters. The values of coefficient of drag and lift were calculated for each trial, and mathematical modelling was applied to determine the relationship between ball angular velocity with coefficient of lift, and ball linear velocity with coefficient of drag.

2.2.2.1 Optimising ball flight characteristics to increase the likelihood of successful kicking

Following on from developing the relationships between flight characteristics with aerodynamic forces, Carré, et al. (2002) explored the predicament players face when performing a free-kick at goal. Under the hypothetical situation of taking a free-kick 18 m from goal with a ball velocity of 25 m/s, the shortest time period of 0.9 s for the ball to reach the top corner of the goal is with no spin imparted onto the ball. A player might instead choose to impart a spin onto the ball, which would result in a reduction in ball linear velocity (due to a trade-off between ball linear velocity and ball angular velocity). With adjusting the flight characteristics to ensure the ball will reach the target, the flight time would increase to 1.6 s. It might seem obvious to perform Kick A with no ball spin because the shortest flight time will ensue, where the goal keeper would need to react and intercept the ball with the least time period. However, applying the ball curve might give the impression to the goal keeper that the ball will miss the goal, thus they may delay their attempt or choose not to make an attempt at intercepting the ball. The authors noted that an experienced player would be able to impart a high ball linear and angular velocities.

Peacock, et al. (2017a) identified elite players altered the ball flight characteristics in a comparison of a maximal distance kick to an accuracy based task. For the accuracy based task, the players kicked toward a sports training mannequin 20m away. Comparatively, the ball travelled approximately 60 m in the maximal distance task. Rather than reducing ball velocity from 28.1 m/s in the maximal distance kick to one-third to merely reach the required distance, players reduced ball velocity by 21% down to 22.1 m/s and lowered elevation flight trajectory from 30° to 15° to ensure the ball would intercept the target. This change in ball flight characteristics, a lower elevation angle but increased ball velocity, was discussed to benefit the chance of success for the task: the relative target area is increased with a lower ball flight trajectory. Because the target was aligned vertically, the relative target area (the perpendicular distance of the target relative to the ball flight trajectory) is increased with a lower elevation angle. This process is similarly discussed in basketball shooting, whereby an increased elevation increases the relative area of the horizontal hoop. Additionally, a lower elevation angle and higher ball velocity will travel a constant distance but in a shorter time period. Given the players were elite, ensuring the ball is received by team members when passing in the shortest time period is a strong demand within gameplay because a longer flight time can increase the opportunity for opposition players to intercept the ball. This strategy may be engrained in their ability to kick toward targets.

2.2.3 The relationship between foot-ball impact characteristics with ball flight characteristics

Understanding how players impart the combination of ball flight characteristics onto the ball is important to develop coaching cues for accurate kicking. In the first of the two-paper series investigating the trade-off between ball velocity and ball spin, Asai, et al. (2002) identified players can alter the magnitude of ball velocity and ball spin by changing the medial-lateral impact location between the foot and ball. Thus, foot and ball impact location influences ball spin and ball velocity. An impact location through the centre of the ball imparts a maximum ball velocity with no ball spin, and ball velocity decreases and ball spin increases as impact location is moved either direction from the centre. Thus, an optimal relationship exists between impact location with ball velocity, and an inversed optimal relationship exists with ball spin. Peacock (2013), which is the original thesis that Peacock, et al. (2017a) was developed from, discussed possible mechanisms of how the players imparted the differing ball flight characteristics between the maximal distance kick and 20 m accuracy task. Ball flight trajectory reduced from 30° in the maximal distance kick to 15° in the 20 m accuracy task. Foot angle, as measured in the global coordinate system, was aligned closer to the vertical by 15° in the accuracy task, and the change in ankle plantarflexion during impact was greater in the accuracy task, both were factors suggested to translate to the differing elevation ball flight trajectory.

Ishii and colleagues developed two mathematical models to predict ball velocity and ball spin for the soccer instep kick and soccer sidestep kick (Ishii, et al., 2009, 2012). For the soccer instep kick, impact location across the proximal-distal direction of the foot was treated as the independent variable, where ball velocity, standardised to foot velocity (foot-ball speed ratio), followed an optimal relationship with a maximum velocity at approximately 1 cm from their defined foot centre of mass in the proximal direction. For the soccer sidestep kick, attack angle (comprising foot trajectory and foot angle) and impact location across the proximal-distal direction on the medial surface of the foot were treated as the independent variables. Foot-ball speed ratio was identified to be maximum with an impact location 5 cm to the heel from the foot centre of mass with an attack angle of approximately 10 degrees. Ball spin was maximum with the opposite combination of impact characteristics: an impact location approximately 7 cm from the foot centre of mass in the distal direction with an attack angle of 30 degrees. Both of these models were developed based upon the impact dynamic theory, comprising the angular and linear impulse-momentum relationship and coefficient of restitution, and were validated using experimental data from players.

2.2.4 Other factors influencing kicking accuracy

By measuring kicking accuracy and treating it as a dependent variable, several more factors have been identified to be associated with kicking accuracy: kinematic and kinetic patterns during the forward leg swing, and footwear designs. Both the kinematic and kinetic patterns and footwear designs are important factors for the execution of the kicking skill, thus it is warranted to identify how they influence kicking accuracy. However, by analysing the direct relationship between kinematic and kinetic patterns and footwear designs with kicking accuracy, key information, such as ball flight characteristics and impact characteristics, can be missed, possibly confounding the influence of several factors identified through this project design. Further, the direct mechanisms influencing kicking accuracy cannot be identified, rather, only associations are generated. Regardless, important information about factors influencing kicking accuracy can be identified.

2.2.4.1 Kinematic and kinetic patterns

Two studies have identified how kinematic and kinetic patterns are associated with kicking accuracy by comparing less accurate to more accurate kickers (Atack, et al., 2017; Dichiera, et al., 2006). Atack, et al. (2017) identified rugby place kickers who executed a kick that travelled less than 32 m and to the left of the goals relied more on the tension arc – the relative pelvis-thorax rotation – compared to those that travelled over 32 m in distance, suggesting reliance on this tension arc may be associated with reduced accuracy. Dichiera, et al. (2006) split 10 elite players performing the drop punt kick into accurate (N = 5) or inaccurate (N = 5) kicking groups based on the performance of 20 kicks, and subsequently compared sagittal plane kinematics. Hip flexion of both support and striking limbs, greater knee flexion in the support limb, and anterior pelvic tilt differed between the groups at certain events during the execution of the skill. The key finding of this study was in the support limb: they identified lowering the body centre of mass, by greater knee flexion in the support limb, may be associated with improved kicking accuracy by increasing the stability of the player.

2.2.4.2 Footwear designs

Footwear designs that promote a more homogenous surface between the foot and ball to reduce pressure peaks have been stated to be the primary factor of accurate kicking (Hennig, 2011, 2014; Hennig & Althoff, 2018; Hennig & Sterzing, 2010). The accuracy of kicking with five different footwear designs and with barefoot to a target 10m in distance was compared, where it was identified that kicking barefoot produced the least accurate outcome (Hennig, et al., 2009). The authors stated subsequent testing with a pressure sensor attached to the impact area across the dorsal aspect of the foot identified reduced peak pressures in the shoe that yielded higher accuracy, whereby they suggested large pressure gradients across the foot-ball surface caused by anatomical structures (bony prominences) could be the reason explaining these results. To further test this theory, the authors stated that adding padding between the length of the first metatarsal and the longitudinal arch and between the gaps of the phalanges further reduced the pressure peaks across the foot and improved accuracy.

Hennig, et al. (2009), however, did not report the results or statistics to support their claim that pressure differed between the two accurate and less accurate footwear designs, nor any results or statistics on the pressure differences and kicking accuracy between the padding and non-padding conditions. Over several review papers and book chapters discussing their work (Hennig, 2011, 2014; Hennig & Althoff, 2013, 2018; Hennig & Sterzing, 2010), the authors released fragments of the results from the initial study (Hennig, et al., 2009) to support these additional claims – the difference in peak pressure gradients between the shoes producing more and less accuracy (Hennig, 2011; Hennig & Althoff, 2018) and the differences in accuracy incurred from added padding onto the shoe (Hennig & Althoff, 2018). However, the results do not clearly identify accuracy was improved from a more homogenous pressure distribution between the foot and ball.

Between the accurate and less accurate footwear designs, it was stated the pressure for the accurate footwear was more homogenously distributed (Hennig, et al., 2009). In the subsequent studies, it was stated the location of the centre of pressure differed to be medial and proximal in the more accurate footwear design, and the pressure differences between adjacent transducers was just under 20% more in the less accurate shoe (Hennig, 2011; Hennig & Althoff, 2018). However, standard deviation was not presented, nor was a statistical analysis performed. Thus, the generalisability of this result between individuals that would exhibit differing kicking techniques and foot shapes is somewhat limited.

The effectiveness of additional padding to improve accuracy may also not be as effective as originally stated, because the influence of padding produced a non-significant influence on kicking accuracy. It was stated in the original study that adding padding reduced the high-pressure differences gradients across the foot improved shooting accuracy. However, the influence of padding in comparison to the non-padding kicking conditions, as released in a subsequent book chapter (Hennig & Althoff, 2018), produced non-significant difference in kicking accuracy ($p = 0.11$) and non-significant difference in kicking precision ($p = 0.12$). No mean and standard deviations for kicking accuracy nor kicking precision were reported, rather, the authors stated there was a trend toward improved performance when kicking with padding (Hennig & Althoff, 2018). Again, the non-significant result questions the generalisability to a greater population and the overall effectiveness of the intervention.

From these results, and despite not testing any other mechanism, the authors state the homogeneity of pressure between the shoe upper and the ball is the primary factor that influences kicking accuracy (Hennig, 2011, 2014; Hennig & Althoff, 2018; Hennig & Sterzing, 2010). The design of the footwear to reduce the lower the pressure differences across the dorsal aspect of the foot does appear to influence accuracy, however, this theory does not explain some important instances of kicking accuracy: why players produce a percentage breakdown of accurate and inaccurate kicks within the one task. When performing repetitions of a singular task, and depending on the complexity of the task, even elite players produce an undesired percentage breakdown of accurate and inaccurate kicks. This is evident in the literature of football kicking: Dichiera, et al. (2006) identified out of ten elite Australian football players the highest percentage of accuracy attained was 75% and the lowest at 20%. The complexity of the task will influence the percentage breakdown – but, it is important here that within an individual task no player was able to produce 100% consistency. Between kicks within the task, the structure of the footwear, the structure of the players foot, and therefore the homogeneity of the pressure distribution across the anterior surface of the foot is consistent. But, the accuracy differed between tasks. Thus, the homogeneity of the pressure distribution, as stated by Hennig as being the primary factor influencing kicking accuracy, cannot explain this aspect of kicking accuracy, and therefore cannot be the primary factor influencing kicking accuracy.

2.2.5 Summary of factors influencing kicking accuracy

The path of ball travel is governed by the laws of physics, and several authors have estimated the flight path and outcome of a kick from the initial ball flight characteristics using these (Atack, et al., 2015; Carré, et al., 2002). To kick accurately, players must have knowledge (not necessarily explicit knowledge) of the forces applied to the ball during flight. Players can and do exploit these ball flight laws to increase the chance of success for a task (Asai, et al., 2002; Peacock, et al., 2017a).

Each foot-ball impact characteristic influences ball flight characteristics, but this relationship has only been partially explored (Asai, et al., 2002; Ishii, et al., 2009, 2012; Peacock, 2013). Key factors such as impact location on the foot is only known to influence a few ball flight characteristics, only because the full extent of the relationship has not been explored. Further, for kicking codes that feature a non-spherical ball, such as rugby and Australian football, the influence of ball orientation is also likely influential and should be explored.

Several researchers have attempted to identify factors that influence kicking accuracy (Atack, et al., 2017; Dichiera, et al., 2006; Hennig, et al., 2009). However, systematic approaches to identify the direct mechanisms influencing accuracy were not employed. Statements such as ‘the primary factor’ has been used, despite testing any other factor. Further, this factor does not explain all instances of accurate and inaccurate kicking. Most importantly, it is not known why players produce a breakdown of accurate and inaccurate kicks. Ultimately, all football coaches should improve the breakdown of accurate and inaccurate kicks produced by their players, which can only be determined once the mechanisms determining kicking accuracy have been established.

2.3. Methodological approaches to analysing foot-ball impact

2.3.1 Analysis of human kickers

The analysis of football kicking has primarily been performed by taking observations of a group and attributing differences in technique to the changes in performance outcomes. This approach of analysing groups, however, may have concealed how certain impact characteristics influence the outcome of the task. Previous group analyses have included comparisons between different conditions and player cohorts (such as senior and junior players, preferred and non-preferred limbs, different kicking tasks, and comparisons of footwear designs) and analyses between individuals within a group (Asami & Nolte, 1983; Ball, et al., 2010; Nunome, et al., 2006b; Peacock, et al., 2017a; Shinkai, et al., 2009; Shinkai, et al., 2013; Smith, et al., 2009; Sterzing & Hennig, 2008). The limitations of a group analysis are (1) the inability to assess changes in technique of one individual and (2) anatomical and technique differences between players might also conceal differences in performance. For example, as mentioned previously, the observed difference in foot-ball speed ratio between the junior and senior players by Ball, et al. (2010) was likely not due to solely the difference in change in ankle plantarflexion, but also the physical mass as this is known to influence impact efficiency (Andersen, et al., 1999).

The limitations of group analyses, however, do not encompass all possible analysis approaches of human kickers. Experiments can alternatively be designed to make comparisons within an individual, such as testing a player to perform multiple repetitions of a singular task. Single-subject designs are still limited as the results from one individual cannot be inferred to a larger group. However, this limitation can be eliminated by performing the individual analysis across several participants and drawing conclusions from a group. This approach does require a larger amount of work (as the number of overall trials analysed is greater), however, is appropriate when the research question necessitates it. In football kicking, where the changes in impact efficiency are influenced by the physical size of different players and the technique of an individual, requires this methodological approach.

2.3.2 Mechanical kicking machines

Mechanical kicking machines have also been employed to explore how foot-ball impact influences kick outcome measures (Flemmer & Flemmer, 2015; Fraser, Harland, Donovan, & O'Shea, 2012). Mechanical kicking machines, and further extended to mechanical tests such as ball drops, have been shown to produce far more stable outcomes than testing human kickers directly (Flemmer & Flemmer, 2015). The ability to produce stable executions enables the ability to directly assess the influence of one parameter on outcome measures. For example, Holmes (2008) identified impacting the ball on the point and the belly produced a different coefficient of restitution.

Attempts have also been made to isolate the influence of an individual parameter with human kickers, where (Ishii, et al., 2012) used a cone to elevate a soccer ball off the ground to assist in testing impact location across the proximal-distal direction. A similar strategy could also be employed to test the influence of ball angle in rugby place kicking, by placing the ball at different angles on the supporting tee. However, in kicking codes where the ball is not stationary prior to impact (such as drop punt kicking), it is not possible to precisely control these conditions at the beginning of impact. Furthermore, a consideration for all human kicking, is that an individual may alter their technique based on these conditions at the beginning of impact. Highlighting this, Ishii, et al. (2012) included normalised ball velocity, not ball velocity, in their mathematical model likely because players varied their foot velocity under different kick conditions. The dynamical behaviour of humans provide difficulty in determining the influence of one individual factor.

2.3.3 Theoretical models & computer simulations

Theoretical models and computer simulations have also been used to determine the influence of individual impact characteristics on outcome measures. Several theoretical models to predict ball velocity have been developed and validated for soccer kicking (Andersen, et al., 1999; Ishii, et al., 2009, 2012). Finite element analysis, a computer simulation approach, was used to determine how impact location across the medial lateral direction of the foot influenced ball spin and ball speed in soccer kicking (Asai, et al., 2002). These theoretical models and computer simulations were all found to produce ‘agreeable’ results to the collected experimental data, enabling further analysis of the developed methods to predict how performance can be improved through manipulating individual components constructing the model. Importantly, the ‘agreeability’ of the results was subjectively determined.

Future work is required before the adaption of a theoretical model is applied to kicking a non-spherical ball. A common thread of these theoretical models and simulations is the shape of the ball used: the spherical soccer ball. Given the angle of an ellipsoidal ball has been shown to influence coefficient of restitution (Holmes, 2008), this provides a level of complexity for developing a model for an ellipsoidal ball. The inclusion of the ellipsoidal ball requires an expansion of a new theoretical model – such as the oblique impact theory – to accommodate the influence of ball angle. However, it is not yet known if the oblique impact theory is applicable to football kicking. Furthermore, rather than developing a theoretical model which predicts the outcome, a more robust approach is to experimentally assess an individual parameter by using a mechanical kicking machine.

Chapter 3: Study 1 - The impact phase of drop punt kicking: validation and experimental data of a mechanical kicking limb

This chapter was presented at the 34th International Conference of Biomechanics in Sport (2016) and has undergone the peer review process.

Abstract: The purpose of this study was to validate a mechanical kicking limb and analyse changes in foot speed on impact characteristics of drop punt kicking. Foot speed was recorded as 9.1 – 21.2 m/s, and covered a range of kick distances. Ball speed (13.0 – 29.7 m/s), contact distance (10.7 – 20.2 cm) and contact time (14.75 – 11.75 ms) were comparable to drop punt kicking. Impact efficiency (F:B ratio = 1.37 – 1.48, coefficient of restitution = 0.66 – 0.79) were high, caused by near perfect rigidity in the design of the limb. Overall, the limb was found to be a valid representation of a human performer. Foot speed displayed significant relationships with ball speed (r = 0.998), contact time (r = -0.89), contact distance (r = 0.99) and F:B ratio (r = -0.694). The relationship between foot speed and COR (-0.347) was not significant.

3.1. Introduction

The human limbs (hands, feet) are frequently used among ball sports to strike the ball at a specific location directing it onto a desired flight path (i.e. volleyball ‘spike’, football ‘kick’). Across the football codes, the execution of the entire kicking skill differs due to the shape of the ball used and the constraints of performing each kick. For example, a spherical ball is kicked off the ground in soccer and an ellipsoidal ball is dropped from the hand prior to impact in drop punt kicking.

Impact phase research has, for the most part, yielded similar results but with some notable exceptions. Despite the different executions of the skills, four phases through the impact phase have been identified with similar patterns reported in soccer and drop punt kicking (Peacock, et al., 2017a; Shinkai, et al., 2009). On the other hand, relationships between some impact characteristics have not been consistent across the codes. An increase in foot speed has been linked to decreased contact time in soccer kicking (Nunome, et al., 2014). For drop punt kicking, this relationship has been similarly found in one comparison of kicking tasks (Peacock, 2013), but has not been found in other comparisons (Ball, 2008b; Ball, et al., 2010; Smith, et al., 2009). Further, foot to ball speed ratio (F:B ratio) is considered a good measure of impact efficiency and a medium, positive relationship has been identified with ankle rigidity (Shinkai, et al., 2013). It is somewhat expected F:B ratio and ankle rigidity are linked due to relationships between increased rigidity and ball speed in another soccer kicking study (Asami & Nolte, 1983). For drop punt kicking however, comparisons of kicking groups found the measure to not differ significantly when rigidity was increased (Ball, et al., 2010; Peacock, 2013).

Mechanical testing is an important addition to analyse the impact phase. An increased variability is expected between kicking trials of performer-based studies, particularly in drop punt kicking due to the execution in the skill where the ellipsoidal ball is dropped from the hand prior to impacting the foot. Mechanical testing will allow for the isolation of specific variables so a methodical exploration is made available if found to be valid, and thus should be used in conjunction with performer-based studies. The aim of the present study was to validate a mechanical kicking limb by using previous literature and analyse changes in foot speed on impact characteristics during punt kicking.

3.2. Methods

A mechanical kicking limb performed punt kicks using a standard AF ball (Sherrin ‘Match Ball’, inflation: 69 kPa). Limb construction was based off information found in the literature, including just the shank and foot segments rotating about a fixed point representing the knee. These lower limb segments were found to be most influential during the impact phase, and so the thigh was not included (Andersen, et al., 1999; Ball, 2008a). The shank was constructed from a metal frame, with length (0.455 m) and mass (5.8 kg) similar to a typical AF player (height = 1.85m, mass = 85kg) (Winter, 1990). The shape of the impacting object has been identified to influence impact characteristics (Andersen, et al., 2008), so to obtain the correct foot impacting area, impact location on the ball and relative foot-to-ball angle, a human foot was scanned and printed as a rigid body whilst in a plantar-flexed position (Peacock, 2013) and attached to the shank (further details on limb construction can be found in Section 4.2.).

The limb was validated by using the results found in the literature of AF and soccer kicking and a range of foot speeds were generated while keeping all other impact characteristics constant across the kicking trials. Three reflective markers were attached to both foot and ball. Data points were tracked at 4,000 Hz from three high speed video cameras (Photron SA3 and MC2, Photron Inc., USA) and reproduced in 3d using ProAnalyst (Xcitex Inc., USA) and Visual3d software (C-Motion Inc., USA). A low pass Butterworth filter of 280Hz smoothed all data (Peacock, 2013). Impact characteristics were calculated using Matlab software (The Mathworks Inc., USA). Pearson’s correlation calculated the relationship between foot speed with impact characteristics.

The centre of the foot and ball were treated as a virtual landmark based off their tracking markers (Peacock, et al., 2017a). Using these virtual landmarks, foot and ball speed were averaged over five frames before and after impact. F:B ratio and coefficient of restitution (COR) were computed using these measures (Andersen, et al., 1999; Peacock, et al., 2017a). Contact time was visually identified using from one of the high speed video cameras located perpendicular to impact (Peacock, et al., 2017a; Shinkai, et al., 2009). Contact distance was measured by the distance the centre of the ball travelled from contact to release (Ball, 2008b). Effective mass was calculated using conservation of momentum equations (Shinkai, et al., 2013).

3.3. Results

The mechanical limb generated a range of foot speeds between 9.1 to 21.2 m/s. Ball speed was 13.0 – 29.7 m/s, and correlated significantly with foot speed (r = 0.998, Figure 3.1A). Contact distance was 10.7 – 20.2 cm and correlated significantly with foot speed (r = 0.990). Contact time was 14.75 – 11.75 ms, and correlated significantly with foot speed (r = -0.890). Foot to ball speed ratio (Figure 1B) was 1.48 – 1.39 and correlated significantly with foot speed (r = -0.694). Though not significant, COR (0.75 – 0.67) displayed a moderate relationship with foot speed (Figure 3.1B, r = -0.347). Effective mass was calculated to be 2.29 ± 0.19 kg across the kicking trials.

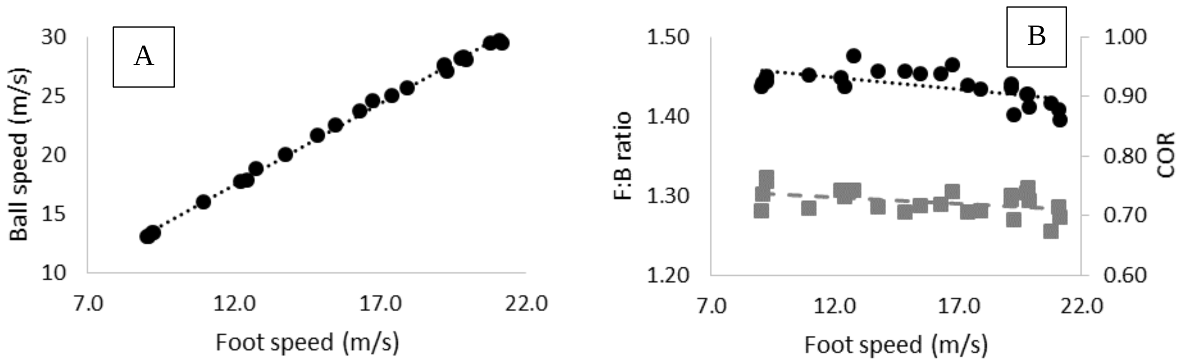

Figure 3.1: Correlations between foot speed with ball speed (A), F:B ratio (B, black round ticks, primary axis) and COR (B, grey square ticks, secondary axis).

3.4. Discussion

The foot speeds recorded are similar to performers' kicks of varying distance. The foot speed of drop punt kicking has ranged from 17.7 m/s for 20m kicks and 22.1 m/s for maximal distance (Peacock, 2013). The 17.7 m/s recorded for 20m kicks in Peacock (2013) were also considered high for the kick distance, due to a task specific strategy by the elite performers to maximise accuracy. The foot speeds of the present study (9.1 to 21.2 m/s) are therefore considered representative of kicks ranging in distance from 10 to 60 m (maximal distance), and the limb was successfully designed to cover a range of kick distances.

The impact characteristics indicate the mechanical limb was a very close representation of a human performer during the impact phase. Ball speed, contact time, contact distance and effective mass were similar to those recorded in AF (Table 3.1), however, F:B ratio was slightly higher. In soccer kicking where performers had a calculated effective mass comparable to that of the present study, F:B ratio was found to be in the range of 1.37 – 1.53 (Shinkai, 2013). These values are very similar to that of the present study, and indicate the mechanical limb was almost a perfect representation of the impact phase with only F:B ratio being slightly higher.

Table 3.1: **Summary of impact characteristics across the literature of AF kicking.**

Study	Ball speed (m/s)	Contact distance (cm)	Contact time (ms)	Effective mass (kg)	F:B ratio
Present study	13.0–29.7	10.7–20.2	14.75–11.75	2.29 ± 0.19	1.48–1.39
Peacock (2013)	22.1 ± 1.1	20.3 ± 2.4	13.2 ± 1.4	2.39 ± N/A	1.25 ± 0.04
Peacock (2013)	28.1 ± 2.5	22.8 ± 2.9	12.1 ± 1.3	2.04 ± N/A	1.28 ± 0.06
Smith et al. (2009)	32.6 ± 4.4	22 ± 2	11.53 ± 1.25	N/A	1.23 ± 0.11

The slightly higher value of F:B ratio is considered to be due to two factors of the limb's design. Firstly, there was no rotational displacement about the ankle and; secondly, there was no shoe attached to the foot. This indicates the limb represented near perfect rigidity throughout the impact phase. Future designs should consider implementing reduced rigidity about the ankle and foot, to analyse ankle motion strategies (Peacock, 2013).

Foot speed correlated almost perfectly with ball speed and contact distance. Previous comparisons of kick distances have displayed ball speed and contact distance to increase with foot speed (Ball, 2008b; Peacock, 2013). As expected, this shows increases in foot speed should be made by players to increase ball speed if they are able to keep all other impact characteristics constant. The increased contact distance was possibly caused by greater deformation of the ball, but, this was not measured. As noted by Nunome, et al. (2014), a method to calculate the deformation of an ellipsoidal shaped ball should be developed to substantiate this claim.

Impact efficiency, as indicated by F:B ratio, decreased as foot speed increased. Contrasts exist in the literature of F:B ratio in comparisons of drop punt kicking. Though ankle rigidity was not analysed in this study, the studies by Ball, et al. (2010) and Peacock (2013) reported a significantly larger foot speed in the conditions of increased ankle rigidity, and thus a two-fold effect may have taken place: increased foot speed would have decreased F:B ratio, but an increased ankle rigidity may have increased F:B ratio. To confirm this hypothesis, future studies should analyse the link between ankle rigidity and impact efficiency while variability in foot speed is minimised.

Although not significant, the relationship between foot speed and COR was negative with a medium effect. A previous analysis using a pendulum to analyse the impact of soccer kicking reported COR decreased with increases in pendulum speed (Andersen, et al., 2008). Further, this negative relationship between foot speeds and COR is found in other impacts of sporting codes (Cross, 2013). This literature suggests a negative relationship between foot speed and COR should exist, however the cause behind the non-significance of this relationship could not be explained by the results calculated. Possibilities may include the aging effect of the ball or variances in manually placing the ball on the kicking tee between trials, however further work is required.

Contact time decreased as foot speed increased, a similar mechanism to soccer kicking (Nunome, et al., 2014). This has been previously identified in a comparison of accuracy and maximal distance drop punt kicks (Peacock, 2013), however, dissimilar results have been reported in other comparisons (Ball, 2008b; Ball, et al., 2010; Smith, et al., 2009). The exact reasoning behind the mixed results of drop punt kicking is beyond the scope of this study, but a high variability can exist between trials and possibly influenced these previous studies. The results of the present study and Peacock (2013) indicate the relationship between foot speed and contact time is not specific to just soccer kicking, but also punt kicking. This also highlights the need to conduct more mechanical testing due to the ability to investigate individual parameters.

3.5. Conclusions

This study successfully validated a mechanical kicking limb and analysed the change in foot speed on impact characteristics. The design of the limb was found to be a very close representation of a human performer during drop punt kicks of various distances, and future designs should consider implementing reduced rigidity about the ankle and foot to decrease impact efficiency. Foot speed was found to produce relationships with the measured impact characteristics, excluding COR.

3.6. Acknowledgements

The authors would like to thank: Mick Küsel (Küsel Designs) for his work in the development and construction of the mechanical limb and; Caleb Brockwell and Brandon Defina for their assistance throughout the study.

3.7. Contribution of individual chapter to overall thesis

Each aim answered in the present chapter contributed toward the overall thesis. Aim 1, of validating the mechanical kicking machine, identified the mechanical kicking machine represented the human limb. The mechanical kicking machine was used again in Chapter 4, 5, 6 and 9. Aim 2, of performing a systematic exploration of foot speed, identified the efficaciousness of performing a systematic exploration of impact characteristics with the mechanical kicking machine. The high correlations found between foot speed and ball speed, contact distance and contact time (each above a correlation of $r = 0.88$) support the ability to perform a systematic exploration of impact characteristics with the mechanical kicking machine. The methodology of performing a systematic exploration with the mechanical kicking machine was used in Chapter 4, 5 and 6.

Chapter 4: Study 2 - The relationship between foot-ball impact and flight characteristics in punt kicking

This chapter has been published in Sports Engineering, Volume 20, Issue 3, pp 221-230 and has undergone the peer-review process. The published version of the manuscript is in Appendix B.

Abstract: In football kicking, a player imparts the initial flight characteristics by impacting the ball with their foot. Imparting the correct combination of flight characteristics is the basis of a successful kick. However, examination of the relationship between foot-ball impact with flight characteristics for a non-spherical ball, the ball shape in Australian football and rugby, has been limited to ball velocity. Consequently, little is known of the relationship with other flight characteristics of ball trajectory and spin. The aim of this study was to determine the relationship between impact and initial ball flight characteristics. A mechanical limb, designed to replicate the impact phase of Australian football, performed punt kicks. Four impact characteristics were systematically examined to determine their influence on flight characteristics: foot velocity, medial-lateral impact location, proximal-distal impact location and ball orientation. This study identified each flight characteristic (ball velocity, elevation angle, azimuth angle and spin rate) was influenced by multiple impact characteristics (foot velocity, ball orientation and/ or impact location). For example, elevation angle was increased by foot velocity, relative foot-ball orientation and proximal-distal impact location on the foot. Foot velocity had the largest influence on ball velocity (linear slope = 1.43). Medial-lateral impact location had the largest influence on azimuth angle (linear slope = 2.73). Ball orientation had the largest influence on elevation angle and back-spin rate, both measures were sine dependent (elevation angle curve amplitude = 19.4°; back-spin

rate curve amplitude = 2754°/s). Players must control all impact characteristics to successfully kick to their desired destination.

4.1. Introduction

Impact forms one of many fundamental skills for ball sports. Across the football codes, kicking is considered one of the most important skills of the game (Ball, 2008a). Players impart ball flight characteristics by impacting the ball with their foot to achieve a desirable outcome, such as scoring goals and passing the ball to fellow team members. There are multiple combinations of flight characteristics that can achieve the same outcome for a kick. For example, a consistent flight distance can be achieved by increasing the velocity and decreasing the trajectory (assuming the trajectory is below the optimum angle based off the projection height).

Within gameplay however, there are specific flight characteristics that can increase the chance of success for a kick. Impacting the ball at a higher velocity can enable shots at goal to be taken from further distances and reduce the likelihood of interception from opposition by decreasing flight time. Players can actively alter ball velocity and kick distance by changing impact characteristics. The most notable mechanism for players to change ball velocity is to control foot velocity before contact. The relationship between foot velocity and ball velocity has been identified in several experiment designs (Ball, 2008a; Ball, et al., 2010; Peacock, et al., 2017a; Smith, et al., 2009). Players can also increase ball velocity by increasing rigidity within the ankle joint and foot segment (Ball, et al., 2010; Peacock, et al., 2017a; Sterzing & Hennig, 2008), and altering footwear characteristics such as mass and stiffness (Amos & Morag, 2002; Hennig & Sterzing, 2010; Sterzing & Hennig, 2008).

While ball velocity is an important characteristic in gameplay situations, a player must control all flight characteristics to reach a desired destination. The flight path, and therefore the destination, is influenced by the initial trajectory, spin direction and spin rate due to their influence on aerodynamic properties of air resistance and lift force (Alam, et al., 2009; Carré, et al., 2002; Goff, 2013). Furthermore, players can purposely impart a spin as the curve of a ball in flight can open the angle of goal and avoid interception from the opposition. When impacting a spherical ball (such as soccer), spin qualities are influenced by impact characteristics of foot velocity, the distance between the ball centre and the line of force applied to the ball, attack angle of the foot and the coefficient of friction between the foot and the ball (Asai, et al., 2002; Ishii, et al., 2009).

For football codes that use a non-spherical ball, such as Australian Football (AF) and rugby league (RL) that feature an ellipsoidal shape ball, little experimental data exists for impact characteristics influential to flight characteristics other than the relationship between foot and ball velocity (Ball, 2010; Peacock, et al., 2017a). Studies have analysed impact characteristics (Ball, et al., 2010; Peacock, et al., 2017a; Smith, et al., 2009), initial flight characteristics (Holmes, 2008; Holmes, Jones, Harland, & Petzing, 2006), and aerodynamics (Alam, et al., 2009). For example, Holmes (Holmes, 2008; Holmes, et al., 2006) identified the initial flight characteristics of rugby kicking such as ball velocity and spin rate. But, these studies analysing kicking with the ellipsoidal ball did not determine the relationship between foot-ball impact characteristics with kick outcome or the initial flight characteristics. Thus, it is not known how players control the flight path, and therefore the destination it reaches.

Oblique impact theory suggests spin qualities and flight trajectories are influenced by the line of force application in respect to the ball centre of mass (Holmes, 2008). The findings of spherical balls likely exist in kicking of an ellipsoidal ball. But, some of the most common types of kicks used in AF and RL, drop punt and place kicking, are distinctly characterised by back-spin about the short axis. The application of force (magntiude, direction, and point of application) with respect to ball orientation, to obtain the back-spin, have different dynamics to that of kicking a spherical ball. Therefore, the relationship between impact and flight of kicking an ellipsoidal ball compared to a spherical ball will be different.

The aim of this study was to determine the relationship between impact and initial flight characteristics featuring an AF ball (ellipsoidal shape). The impact characteristics of foot velocity, medial-lateral impact location, proximal-distal impact location, and ball orientation were systematically explored. Their relationship with initial flight characteristics of ball velocity, trajectory (azimuth angle and elevation), and spin rate was determined.

4.2. Methods

A mechanical kicking limb performed drop punt kicks with a standard Australian Football (AF) ball ('Match Ball', Sherrin, Australia) inflated to the Australian Football League recommended pressure (69 kPa). The mechanical limb was developed to provide the ability to systematically explore the effect of one impact characteristic on the outcome of the foot-ball interaction without the influence of other characteristics. The striking limb comprised the shank and foot (Figure 4.1) because previous studies had identified these to be influential during the collision (Andersen, et al., 1999; Ball, 2008a; Ball, 2008b). Designed to replicate a typical AF player, the shank was of metal construction comprising of two outer plates with a length of 0.455 m between the proximal and distal joints (based on an AF player's average height = 1.85 m, and using anthropometric data from Winter (1990) (Winter, 1990)). At the proximal end of the shank, the 'knee joint' was modelled as a freely rotating axis to mimic flexion and extension. For the foot segment, the foot and bottom part of the shank on the right side of a human that was 1.78 m tall were three-dimensionally scanned whilst in a plantar-flexed position (the position adopted during the kick) and printed as a three-dimensional object made of ABS plastic. To achieve the appropriate length of the foot, the size of the scanned image was scaled up by the ratio of 1.85:1.78 based on the height of the person (1.78 m) and a typical AF player (1.85 m). The use of a human foot was important as the shape of the contacting surface with the ball will influence impact (Andersen, et al., 2005, 2008) and subsequent ball flight (Figure 4.2). For the purposes of this study, the 'ankle joint' was locked so no movement occurred at the ankle and metatarsophalangeal joints. These two segments were joined at the distal end of the shank with two plates fixed to the medial and lateral sides of the foot, and designed so that no contact between these plates and the ball occurred.

Figure 4.1: **The mechanical limb**

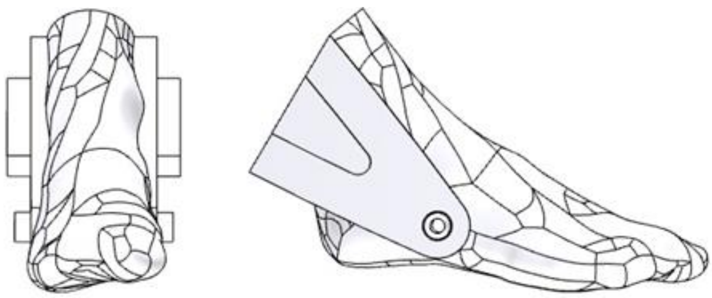

Figure 4.2: **Foot segment attached at the distal point of shank**

The rotating limb segment was powered by a counterweight via a pulley system that was connected by the frame supporting the limb. Different foot velocity at ball contact were produced by manipulating the starting point of the limb. The pulley system was designed for the counterweights to cease applying torque to the rotating limb immediately before contact. For each kicking trial, the ball was positioned on a kicking tee (Moose Kicking Tee Pty Ltd, Australia) that was placed on a platform built into the frame. The tee allowed for a straight swing through of the leg, typical of AF kicks (Ball, 2011), without any contact being made between the foot and the tee. Adjustments could be made to the impact location moving the tee on the platform (for medial-lateral), or adjusting the height of the platform in relation to the foot (proximal-distal). Because the foot was rigid in construction, the orientation of the foot was unable to change and therefore only ball orientation about the x-axis (see Figure 4.3 for ball orientation calculation) was required to calculate relative foot-to-ball angle in the sagittal plane. Ball orientation about the x-axis was adjusted by altering the position of the ball on the tee.

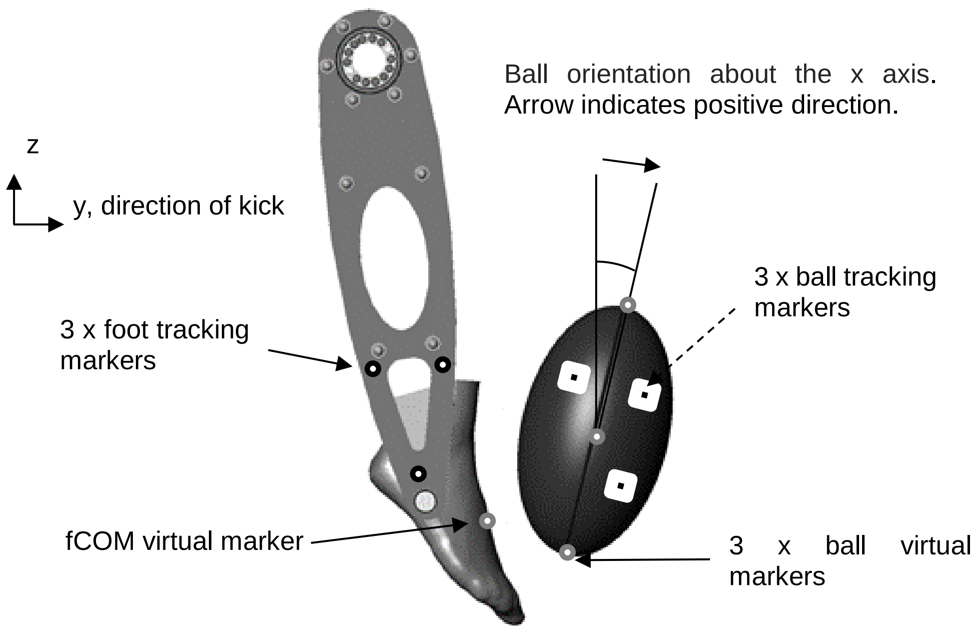

Figure 4.3: **Reflective and virtual markers attached to the limb and ball**

To analyse the impact phase, three high speed video cameras (Photron SA3 and MC2, Photron Inc., CA USA) were synchronised, and recorded each trial at 4,000 Hz. Ball contact and ball release were visually identified from the camera placed directly perpendicular to the direction of the kick, and each video trial was cut down to 20 frames before and after impact. Three tracking points were attached to the limb using 12.7 mm retro-reflective spherical markers (B & L Engineering, CA, USA). Three tracking points were attached to the ball using a square piece of reflective tape (25 x 25 mm) with a black circular sticker (radius = 8 mm) fixed to the middle (3M Scotchlite 7610 reflective tape, 3M©, MN USA). These points were tracked in ProAnalyst software (Xcitex Inc., MA USA) to generate three-dimensional coordinates with a root mean square error of 0.9 mm. Calibration involved digitising 32 known points within a space of 0.12 x 0.45 x 0.3 m, which covered the entire capture field.

Visual3d software (C-Motion Inc., MD USA) reproduced virtual landmarks from a pre-recorded static capture of the foot centre of mass (fCOM) based off three tracking markers attached to the limb, and the ball geometric centre (bGC), top point of the ball and bottom point of the ball from three tracking markers attached to the ball (Figure 4.3). All data were smoothed with a low-pass, 2nd order Butterworth filter with a cut-off frequency of 280 Hz (Nunome, et al., 2006b; Peacock, et al., 2017a). The fCOM was found at the midpoint between the lateral malleolus and the head of the first metatarsal (Winter, 1990), however because the lateral malleolus was not visible due to the construction of the limb, this point was approximated on the dorsal surface of the foot (see Figure 3 for approximate location), and remained consistent throughout the analysis. The bGC was calculated from the average position between two markers attached to the top and bottom points of the ball captured during under static setting.

Impact and ball flight characteristics were calculated in Matlab software (The Mathworks Inc., USA) (Figure 4.4). Foot and ball velocity were calculated from the first derivative of the fCOM and bGC positional data averaged over five frames before and after contact. Impact location in the medial-lateral direction was defined as the distance between the fCOM and bGC, with positive values indicating a lateral displacement from the fCOM. Impact location in the proximal-distal direction was defined as the distance between the bottom point of the ball and the fCOM along the anterior surface of the foot, with positive values indicating a distal displacement from the fCOM. Relative foot-to-ball angle was not calculated because the shape of the foot varied pending on the area of impact on the foot. Rather, ball orientation about the x axis was calculated and used as an indication of the relative foot-to-ball angle in the sagittal plane. Ball orientation was calculated in the sagittal plane (Figure 4.3). Azimuth and angle of elevation were calculated as the average of five frames after release from the foot (Figure 4.4). Back-spin rate was calculated about the global x-axis. Foot-to-ball speed ratio, $F{:}B_{ratio}$, was calculated from

$$F{:}B_{ratio} = \frac{v_{bGC}}{u_{fCOM}} \qquad \text{Equation 4.1}$$

where, v was the final velocity u was the initial velocity. The coefficient of restitution, *CoR*, was calculated from

$$CoR = \frac{v_{bGC} - v_{fCOM}}{u_{fCOM}} \qquad \text{Equation 4.2}$$

Both foot-to-ball speed ratio and coefficient of restitution were used as measures of impact efficiency, because foot-to-ball speed ratio has been used as a measure of impact efficiency for the impact of AF kicking (Ball, et al., 2010; Peacock, et al., 2017a; Smith, et al., 2009), and the coefficient of restitution quantifies the amount of energy lost during a collision and can therefore also be considered a measure of efficiency.

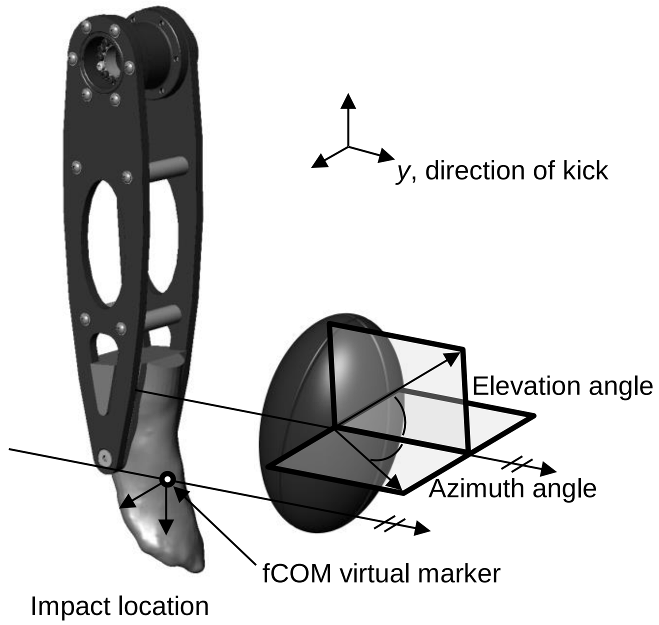

Figure 4.4: **Orthogonal reference system, approximate location of fCOM virtual marker and parameter calculation of impact location on the foot, elevation angle and azimuth angle. Arrows and angles represent positive directions.**

The study examined foot velocity, medial-lateral impact location, proximal-distal impact location, and relative foot-ball orientation in the sagittal plane. Each input measure was analysed independently, where all remaining inputs were held constant. The baseline setting comprised a foot velocity of 16.7 m/s, impact location in the medial-lateral direction of -1.15 cm from the foot centre of mass, impact location in the proximal-distal direction of 2.61 cm from the foot centre of mass and ball orientation in the x-axis of 47.4°. Five trials were captured at this baseline setting and used across all data sets. Kicks were performed in four datasets with all parameters held constant within each dataset with the exception of the parameter of interest. For data set 1 (21 trials), foot velocity was varied from 9.1 – 21.2 m/s. For dataset 2 (17 trials), impact location in the medial-lateral direction was analysed using a range of positions between -3.55 – 0.84 cm across the foot centre of mass. For dataset 3 (17 trials), impact location in the proximal-distal direction was analysed over a range of positions between -5.70 – 7.30 cm across the foot centre of mass. For dataset 4 (28 trials), ball orientation about the x axis was analysed using a range of positions between -11.6° to 85.3°.

A curve fitting procedure was used to identify the relationship between each impact characteristic with each flight characteristic. The choice of curve fitted to the data was based on two criteria: literature indicating previously identified relationships and theoretical models. Visual inspection of plotted data and residual plots were screened to confirm if the plotted relationship suited the data, and outliers were screened during this process. Linear relationships were fitted to the systematic exploration of foot velocity. Linear relationships were fitted to the relationship between medial-lateral impact location and azimuth angle and elevation angle, and second order regressions were fitted to the relationship between medial-lateral impact location and ball velocity and ball-spin rate. The choice of second order regression was based upon the oblique impact theory. Linear relationships were fitted to the relationship between proximal-distal impact location and ball flight characteristics, due to the linear increase in velocity of the impact location with distal impact locations. For the exploration of ball orientation, a second order regression was fitted to the relationship with ball velocity, a linear regression was fitted to the relationship with azimuth angle, and a sine wave was fitted to the relationship for elevation angle and back-spin rate due to the angular nature of ball orientation.

4.3. Results

Five outliers were removed from the foot velocity data set, thought to be due to a break-in process of the ball and were removed from the remainder of the analysis. Foot velocity was influential to all initial flight characteristics (Figure 4.5). Ball velocity (Figure 4.5: A), elevation angle (Figure 4.5: C) and back-spin rate (Figure 4.5: D) increased linearly with foot velocity. Azimuth angle decreased linearly with foot velocity (Figure 4.5: B). Impact efficiency measures of foot-to-ball speed ratio and coefficient of restitution both decreased linearly with foot velocity (Figure 4.5: E-F).

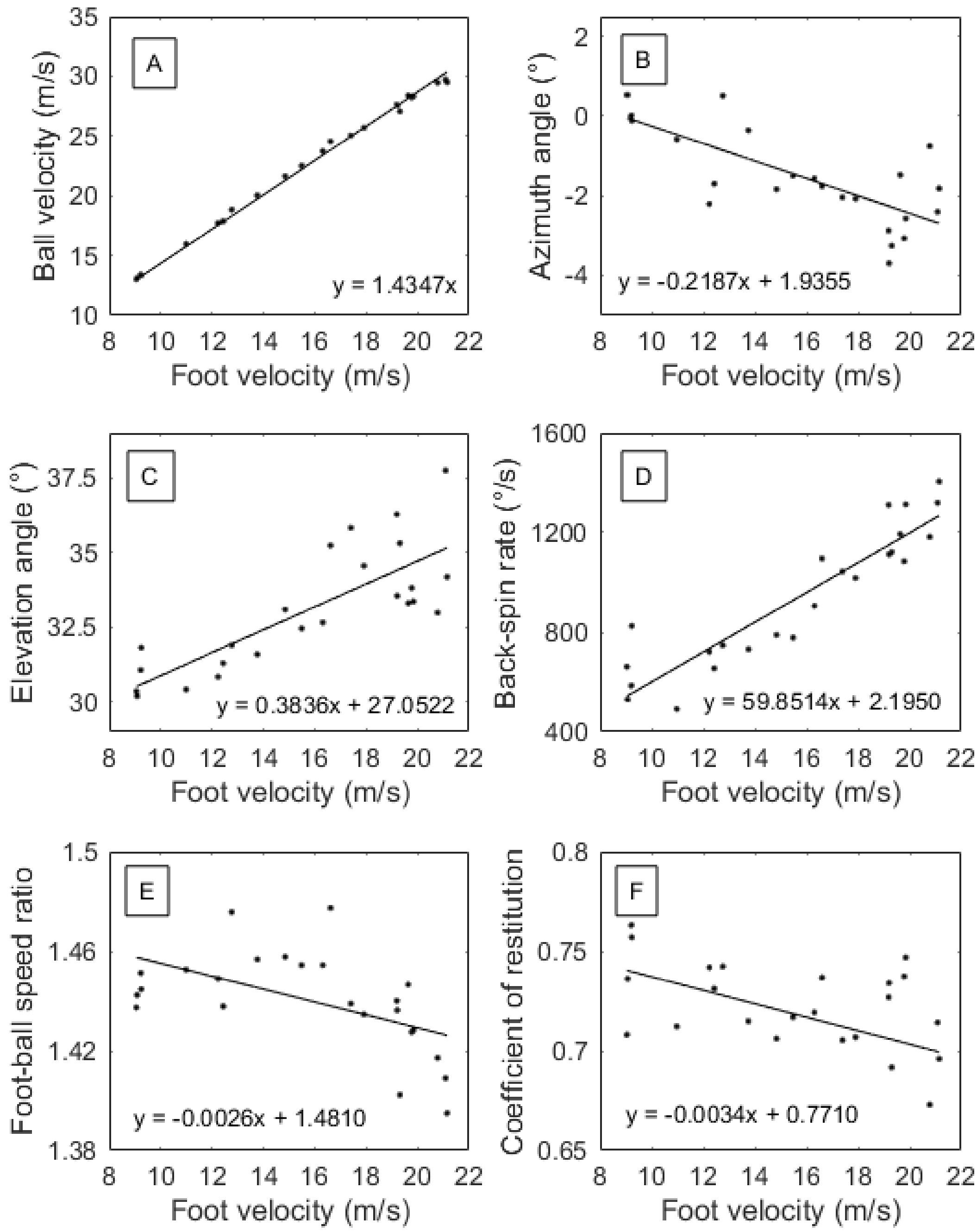

Figure 4.5: **The relationships between foot velocity with ball velocity (A), azimuth angle (B), elevation angle (C), back-spin rate (D), foot-ball speed ratio (E), and the coefficient of restitution (F).**

Medial-lateral impact location was influential to ball velocity, azimuth angle and back-spin rate (Figure 4.6). Optimal relationships were identified between medial-lateral impact location with ball velocity (Figure 4.6: A) and back-spin rate (Figure 4.6: C). Maximums were identified at a medial-lateral impact location approximately -0.5 cm from the foot centre, however, the dependence of ball velocity on impact location was low. Azimuth angle increased linearly with impact location across the medial-lateral direction (Figure 4.6: B). Elevation angle increased linearly with impact location across the medial-lateral direction (Figure 4.6: D), but the magnitude of the slope was small suggesting low dependence.

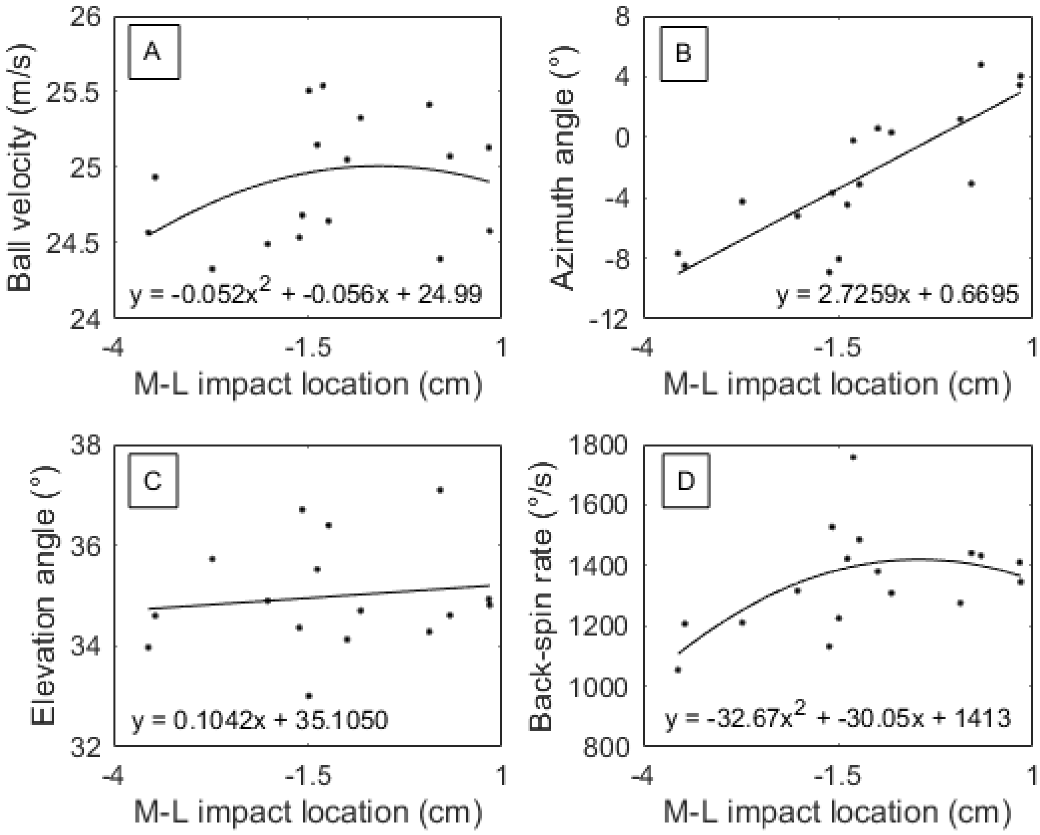

Figure 4.6: **The relationships between impact location across the medial-lateral direction with ball velocity (A), azimuth angle (B), elevation angle (C), and back-spin rate (D).**

Proximal-distal impact location was influential to ball velocity (Figure 4.7: A), elevation angle (Figure 4.7: C) and spin rate (Figure 4.7: D), and all increased linearly with impact location across the distal direction. A linear curve was fitted to proximal-distal impact location with azimuth angle (Figure 4.7: B), and the magnitude of slope was small suggesting low dependence.

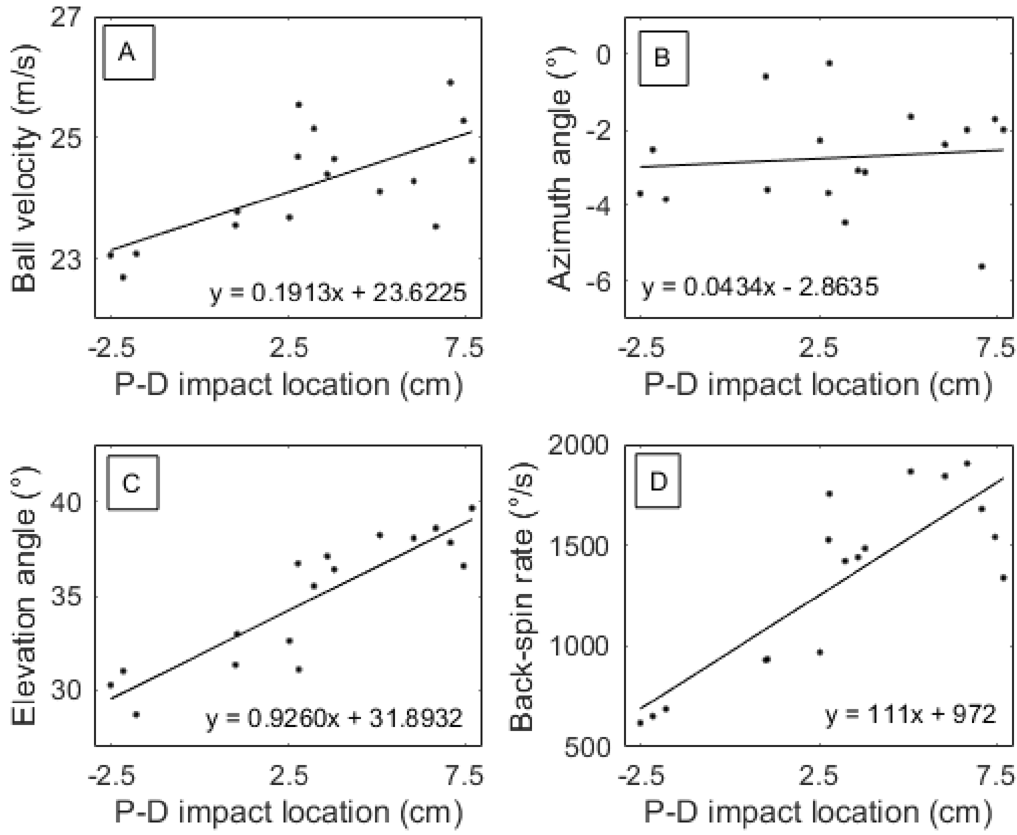

Figure 4.7: **The relationships between impact location across the proximal-distal direction with ball velocity (A), azimuth angle (B), elevation angle (C), and back-spin rate (D).**

Ball orientation about the x-axis was influential to ball velocity, elevation angle and spin rate (Figure 4.8). An optimal relationship was identified between ball orientation with ball velocity (Figure 4.8: A), with a maximum identified at an orientation of approximately 43°. Sine curves were fitted to the relationships between ball orientation with elevation angle (Figure 4.8: C) and back-spin rate (Figure 4.8: D). A linear curve was fitted to the relationship between ball orientation with azimuth angle (Figure 4.8: B), but the magnitude of slope was small suggesting low dependence.

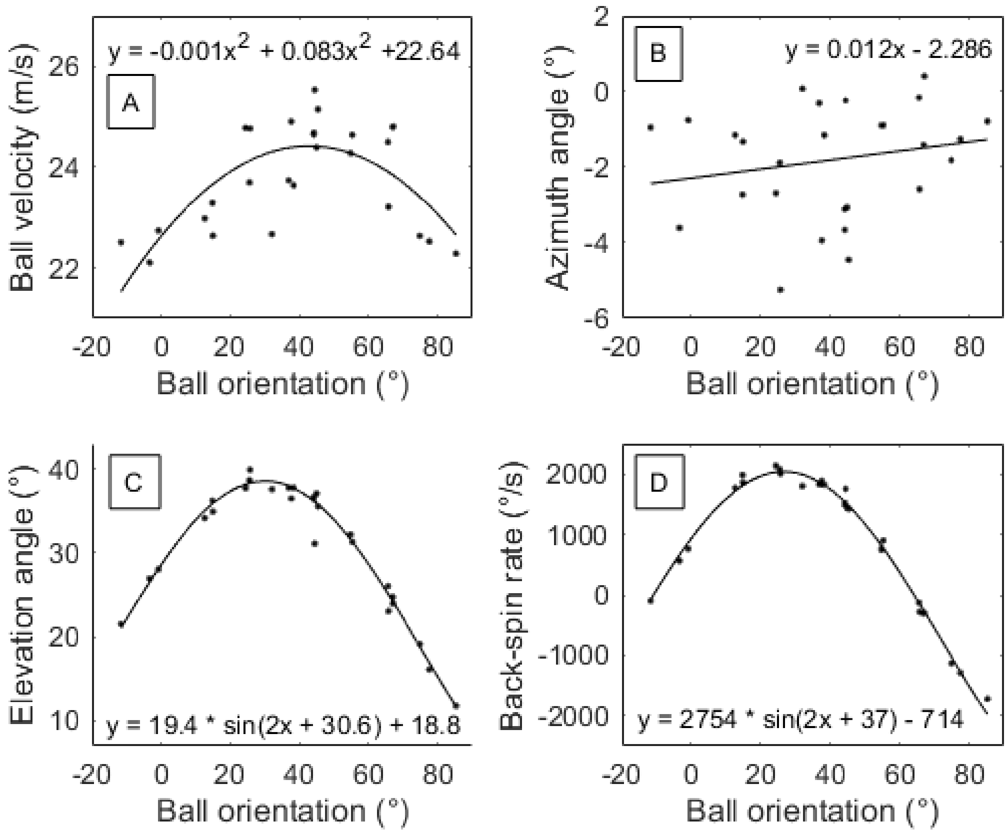

Figure 4.8: **The relationships between ball orientation about the x-axis with ball velocity (A), azimuth angle (B), elevation angle (C), and back-spin rate (D).**

4.4. Discussion

A player must control flight characteristics for a kick to be successful. To date, little is known of the relationship between foot-ball impact with all flight characteristics, the phase of kicking when a player imparts the flight characteristics. Therefore, the aim of this study was to determine the relationship between impact and ball flight characteristics through systematic exploration.

4.4.1 Foot velocity

Ball velocity increased linearly with foot velocity (Figure 4.5: A). This linear relationship was comparable to previous results (Andersen, et al., 1999; De Witt & Hinrichs, 2012; Kellis & Katis, 2007). Andersen & colleagues (Andersen, et al., 1999) developed a model to predict ball velocity from the angular momentum of the leg and coefficient of restitution, which indicated ball velocity increased linearly with foot velocity. They found the results of soccer instep kicking fitted the model appropriately. Similarly, group comparisons have identified increases in foot velocity translated to increases in ball velocity (Peacock, et al., 2017a).

Foot velocity negatively influenced impact efficiency (Figure 4.5: E-F), but, the magnitude of reduction had little overall effect on the relationship between foot velocity with ball velocity. Negative linear relationships were identified between foot velocity with foot-ball speed ratio and coefficient of restitution, a similar finding to previous analyses of inelastic objects in collisions (Cross, 2013). Foot-ball speed ratio represents the slope of the linear relationship between foot and ball velocity. Because foot-ball speed ratio was not constant, the relationship between foot and ball velocity was not linear. Post-hoc curve fitting between foot velocity and ball velocity with a power curve to represent the negative slope of foot-ball speed ratio also fit the data well (equation: $y = 1.599x^{0.962}$). But, a comparison of the power and linear curves over the range of foot velocity that a player can produce (up to 26.5 m/s (Ball, 2011)) revealed a minimal difference between the two curves (Figure 4.9). The linear curve adequately described the dependence of ball velocity on foot velocity for the range of values a player can produce.

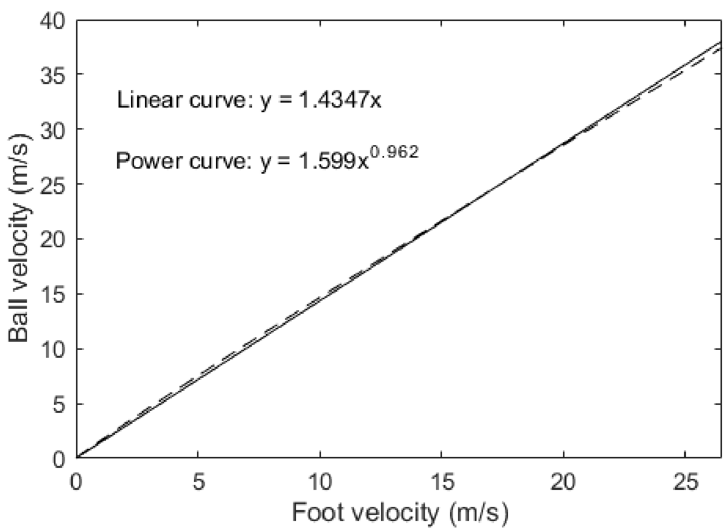

Figure 4.9: **Post-hoc analysis of the relationship between foot velocity with ball velocity. The solid line represents the linear curve, and the dashed line represents the power curve.**

Back-spin rate increased linearly with foot velocity (Figure 4.5: D). The increase in back-spin rate was caused from a combination of the magnitude of force applied to the ball and the ellipsoidal shape of the ball with its orientation on the foot. The oblique impact theory indicates spin generated during impact is created from a result of the moment that is applied to the ball when the force vector does not pass through the centre of mass of the ball, and is proportionate to the product of the magnitude of the force and the moment arm (Holmes, 2008). Across the foot velocity dataset, the magnitude of force increased with foot velocity, increasing the moment applied to the ball.

Foot velocity influenced the trajectory of ball flight (Figure 4.5: B-C), but each flight component was influenced by different factors associated with an increased foot velocity. Elevation angle increased linearly with foot velocity, due to a greater elevation trajectory of the foot during foot-ball contact. The contact distance between foot and ball increased linearly with foot velocity (post-hoc analysis; linear relationship; $r^2 = 0.989$). As the foot was at the beginning of the upward arc as it rotated about the knee, the elevation angle of the foot increased with the increased contact distance. Azimuth angle decreased linearly with foot velocity, due to the nonhomogeneous geometric properties of the foot. The trajectory of the ball in the azimuth direction was determined solely by the geometric surface of the foot across the medial-lateral direction. Oblique impact theory indicates the trajectory of the foot and the angle of foot surface impacting the ball changes the angle of the force vector applied to the ball. The trajectory of the foot was held constant for the present study and therefore was not influential. When foot velocity increased, the surface impacting the ball changed. This was due to a two-step process. Firstly, an increased foot velocity meant a greater area of the ball covered the foot. Secondly, because the surface of the foot was asymmetrical about the proximal-distal axis, the force direction applied to the ball across the azimuth dimension was speed dependent. This supports previous work that has suggested designing footwear with a more symmetrical surface will be beneficial to a more consistent ball flight, also associated with kicking accuracy (Hennig, 2011). A shoe was not included in the present analysis due to the current design iteration of the mechanical kicking machine used in the present study.

4.4.2 Impact location

Ball velocity and back-spin rate increased linearly as impact location moved distally (Figure 4.7: A & D). The linear velocity of the impacting point increased as the impact location was moved distally, increasing the force applied to the ball. However, continuing to move the impact location distally has limitations. Firstly, there is an endpoint where if the impact location was moved beyond the length of the foot, the ball would be partially or not impacted at all. Secondly, a limitation of the analysis was that the ankle joint was fixed. Plantar flexion during impact of AF kicking has been reported to range from 2.2° to 7.2° depending on the task (Ball, et al., 2010; Peacock, et al., 2017a), and an increased ankle plantarflexion during impact has been associated with decreased impact efficiency (Lees & Nolan, 1998). Furthermore, these studies analysed kicks that were struck ‘well’. An impact towards the toe, while contacting the foot on an aspect that is moving faster, will result in a greater moment arm tending to force the foot into plantar flexion reducing the performance advantage may be lost. Future work should implement reduced rigidity about the ankle when analysing impact location to determine the influence of changes in rigidity on kick outcome.

Ball velocity and back-spin rate were maximum with a medial-lateral impact location of 0.5 cm from the foot centre (Figure 4.6: A & D). The results of Asai and colleagues (Asai, et al., 2002) indicated an optimal relationship existed between impact location across the medial-lateral direction with ball velocity in instep soccer kicking, and a similar mechanism was expected to occur with back-spin rate. The results of the present study however, identified little reduction in ball velocity and a moderate reduction in back-spin rate when impact location was moved either medially or laterally from -0.5 cm from the foot centre. Asai and colleagues (Asai, et al., 2002) observed a much greater reduction in ball velocity, reducing from 26.0 m/s to 0 m/s when impact location was moved medially 16 cm, and to 6.2 m/s when moved laterally 16 cm. This reduction occurred because of the distance the impact location was moved. The change in impact location from foot centre for the present study was only -3.6 cm to 0.8 cm from the foot centre of mass in the medial-lateral direction. Further changes of impact location from foot centre were limited by the ball supporting the tee, because moving the impact location further would have resulted in the foot impacting the tee and not impacting the ball cleanly, thus altering the impact conditions.

Moving impact location laterally increased azimuth angle linearly and had no influence on elevation angle (Figure 4.6: B & C). These relationships can be explained by the shape of the foot; as the impact location was moved laterally, the surface angle of the foot changed pointing from the medial to lateral direction, which in-turn altered the ball flight trajectory to move from the medial to lateral direction. Moving the impact location laterally had no effect on elevation angle, because there was no change in the shape of the foot surface across this direction. Post-hoc analysis revealed that angular velocity about the y-axis of the ball was linearly dependent upon impact location across the medial-lateral direction, considered also to be due to change in angle of the foot surface. This supports accuracy may be enhanced through footwear designs that promote a more symmetrical surface.

Moving impact location distally increased elevation angle linearly and had no influence on azimuth angle (Figure 4.7: B & C). The relationship between elevation angle with change in the impact location in the proximal-distal direction was not due to the shape of the foot, but due to the higher linear velocity at the impacting point. As the impact location was moved distally, a higher linear velocity of the impacting point was applied to the ball, influencing the force vector applied to the ball. Moving the impact location distally had no effect on azimuth angle because there was no change in the surface angle of the foot.

4.4.3 Ball orientation about the x-axis

Ball orientation about the x-axis influenced back-spin rate and elevation angle (Figure 4.8: C & D). The sine curve fit the data well, outlining the dependence of these flight characteristics on ball orientation about the x-axis. Holmes (Holmes, 2008) performed a ball drop test to determine the influence of ball orientation on flight parameters, tested between the range of 0° to 90°. Their results identified a sine dependence was likely to be present over a change in ball orientation about the x-axis of 0° to 180°. We hypothesise the amplitude of both sine waves, and the vertical midpoint of the elevation angle sine wave were dependent on the velocity and elevation trajectory of the foot prior to impact. This is supported by the previous analysis of foot velocity, where it was identified under a constant ball orientation, increasing foot velocity resulted in an increase to ball velocity and elevation angle.

Ball velocity was maximum at a ball orientation about the x-axis of approximately 43° (Figure 4.8: A). Holmes (Holmes, 2008) performed a bounce test and identified the coefficient of restitution for an Australian Football ball was greater at the point compared to the centre. The results of the present study support this finding, where ball velocity was greater when impacted at the point (ball orientation of 65° = ball velocity of 24 m/s) compared to the centre (ball orientation of -25° = ball velocity of 20 m/s). However, ball velocity was even higher when impacted at 43°, the maximum ball velocity of 24.4 m/s.

4.5. Conclusion

This study systematically explored four impact characteristics of kicking an ellipsoidal shaped ball to determine the relationship with initial flight characteristics. Each flight characteristic was influenced by multiple impact characteristics. Ball velocity increased linearly with foot velocity and proximal-distal impact location. Impacting the ball 0.5cm medially from the foot centre, or with a ball orientation about the x-axis of 43° produced the highest ball velocity. Azimuth angle increased linearly with foot speed and with medial-lateral impact location. Elevation angle increased linearly with foot velocity and proximal-distal impact location. The relationship between elevation angle with ball orientation about the x-axis followed a sine curve, over the period of 180°. Back-spin rate increased linearly with foot velocity and proximal-distal impact location. The relationship between back-spin rate with ball orientation about the x-axis also followed a sine curve over the period of 180°.

4.6. Contribution of individual chapter to overall thesis

Chapter 4 contributed toward the overall thesis by further exploring how individual foot-ball impact characteristics influence ball flight characteristics. As identified in Chapter 3, the mechanical kicking machine was identified to validly replicate the human limb and could be used to perform a systematic exploration of individual foot-ball impact characteristics. The mechanical kicking machine was used to perform the systematic exploration of individual foot-ball impact characteristics. The number of foot-ball impact characteristics systematically examined, and the number of ball flight characteristics assessed increased from Chapter 3. Foot velocity, impact location and ball orientation were each examined and treated as independent variables. Ball velocity, ball flight trajectory and ball spin, the chosen ball flight characteristics, were measured and treated as dependent variables. The results from these systematic examinations contributed to answering aims 1 and 2 of the overall thesis. Specifically, aim 1 was to identify how foot-ball impact influenced impact efficiency. It was identified foot velocity, ball angle, and impact location each influenced impact efficiency. Further discussion on how this chapter contributes to aim 1 can be found in section 10.1. Aim 2 was to identify how foot-ball impact influenced ball flight characteristics and kicking accuracy. It was identified foot velocity, ball orientation and impact location each influenced ball flight characteristics. Further explanation of how this chapter contributed to aim 2 can be found in section 10.2. One design feature of the limb was that it featured a rigid ankle (i.e. no ankle motion). Ankle motion is an important factor influencing kicking (Nunome, et al., 2006b; Peacock, et al., 2017a), and Chapters 5 and 6 explored the influence of ankle motion via systematic exploration of impact characteristics with the mechanical kicking machine.

Chapter 5: Study 3 - The influence of joint rigidity on impact efficiency and ball velocity in football kicking

This chapter has been published in Journal of Biomechanics (in press) and has undergone the peer-review process. The published version of the manuscript is presented in Appendix C.

Abstract: Executing any skill with efficiency is important for performance. In football kicking, conflicting and non-significant results have existed between reducing ankle plantarflexion during foot-ball contact with impact efficiency, making it unclear as to its importance as a coaching instruction. The aims of this study were to first validate a mechanical kicking machine with a non-rigid ankle, and secondly compare a rigid to a non-rigid ankle during the impact phase of football kicking. Measures of foot-ball contact for ten trials per ankle configuration were calculated from data recorded at 4,000Hz and compared. The non-rigid ankle was characterised by initial dorsiflexion followed by plantarflexion for the remainder of impact, and based on similarities to punt and instep kicking, was considered valid. Impact efficiency (foot-to-ball speed ratio) was greater for the rigid ankle (rigid = 1.16 ± 0.02; non-rigid = 1.10 ± 0.01; $p < 0.001$). The rigid ankle was characterised by significantly greater effective mass and significantly less energy losses. Increasing rigidity allowed a greater portion of mass from the shank to be used during the collision. As the ankle remained in plantarflexion at impact end, stored elastic energy was not converted to ball velocity and was considered lost. Increasing rigidity is beneficial for increasing impact efficiency, and therefore ball velocity.

5.1. Introduction

Many ball sports involve a performer accelerating the ball by impacting it with a distal body segment or piece of equipment. The outcome of this collision can be quantified by its initial flight characteristics, such as velocity, spin and trajectory, because they all influence the flight path of a projectile (Goff, 2013). Attaining a high ball velocity is a desirable characteristic for performance, enabling the ball to travel further or to reach a target in a shorter time. In game situations, this can reduce the possibility of interception from the opposition and provide more opportunities for scoring from further distances. The velocity of the distal body segment (Kellis & Katis, 2007; Lees & Nolan, 1998) or piece of equipment (Cross, 2011) immediately prior to the collision is an important component for final ball velocity. However, the ability to produce a high velocity can be limited by a players' physical capacity, so impacting the ball with a higher efficiency will generate a higher ball velocity for a given striking velocity.

In football kicking, where the foot impacts the ball, the ankle is passively plantar-flexed during the collision due to the high forces and short impact duration of approximately 10 ms (Shinkai, et al., 2009). A reduction in the forced plantarflexion has been associated with an increase in ball velocity (Asami & Nolte, 1983; Peacock, et al., 2017a), by improving impact efficiency from an increase in the effective mass (Kellis & Katis, 2007; Lees & Nolan, 1998). Furthermore, it can also be considered that when the ankle remains in plantarflexion at the end of impact, elastic energy stored within the joint is not converted to ball velocity and can therefore be considered lost, and might cause a further reduction in impact efficiency. The relationship between impact efficiency with effective mass and energy losses also has theoretical support; the conservation of momentum combined with the coefficient of restitution (Equation 5.1) indicates impact efficiency (foot-to-ball speed ratio) and ball velocity would be improved from an increase in either the effective mass or coefficient of restitution.

$$v_b = \left(\frac{1+e}{1+m_b/m_f}\right)\cdot u_f + \left(\frac{e-m_b/m_f}{1+m_b/m_f}\right)\cdot u_b \qquad \text{Equation 5.1}$$

Where v_b = ball velocity after it leaves the foot, e = coefficient of restitution, m_b = ball mass, m_f = foot mass, u_f = initial foot velocity, u_b = initial ball velocity.

While some studies have identified a reduction in the forced plantarflexion to be beneficial to kick performance, there are some that have observed non-significant findings with small effect sizes or individual players questioning the association. Peacock, et al. (2017a) identified a significantly different magnitude of plantar-flexion between distance and accuracy kicks but impact efficiency was non-significant with a small effect, indicating a reduction in forced plantarflexion may not be associated with impact efficiency. Furthermore, Nunome, et al. (2006b) identified a player that produced a relatively high ball velocity also displayed a relatively high plantar-flexion, again questioning the association of reduced plantar-flexion with impact efficiency. Further to support no association between reduced plantarflexion with impact efficiency, Shinkai, et al. (2013) stated that when the ball mostly impacted the foot on the centre of mass, ball impact was most likely assumed to be a collision between the foot and ball, and therefore motion of the ankle does not influence the outcome. This questions the coaching instruction of attaining a firm ankle for kicking performance, and more generally the influence of joint rigidity in sporting skills when attaining high ball velocity. Therefore, the aim of this study was to determine the influence of plantarflexion during foot-ball impact on impact efficiency and ball velocity.

To determine the influence of plantarflexion during foot-ball impact on impact efficiency, a mechanical kicking machine with a rigid and a non-rigid ankle configuration was used. Kicking is a dynamic skill where many characteristics can influence the outcome of a kick, therefore, a methodology to control other impact characteristics, such as a mechanical kicking machine, was warranted. The rigid setting of the mechanical kicking machine has already been validated (Peacock & Ball, 2016), but not the non-rigid configuration. The first aim of the study was to validate the ankle motion of the non-rigid ankle configuration. The second aim was to compare the rigid and non-rigid ankle configurations.

5.2. Methods

5.2.1 Mechanical kicking machine with adjustable ankle rigidity

A mechanical kicking machine performed trials with an Australian football (AF) ball (‘Sherrin Match Ball’, Russell Corporation, Scoresby, Australia; mass = 0.456 kg, inflation = manufacturers recommendation and league requirement of 69 kPa) (Figure 5.1A). To replicate drop punt kicking of elite AF players, the kick leg was constructed to match the length and mass of the shank and foot, and foot shape of an AF player (height: 1.85m; mass = 85kg). This mechanical kicking machine was used previously with a rigid foot segment and was found to be a valid representation of drop punt kicking (Peacock & Ball, 2016).

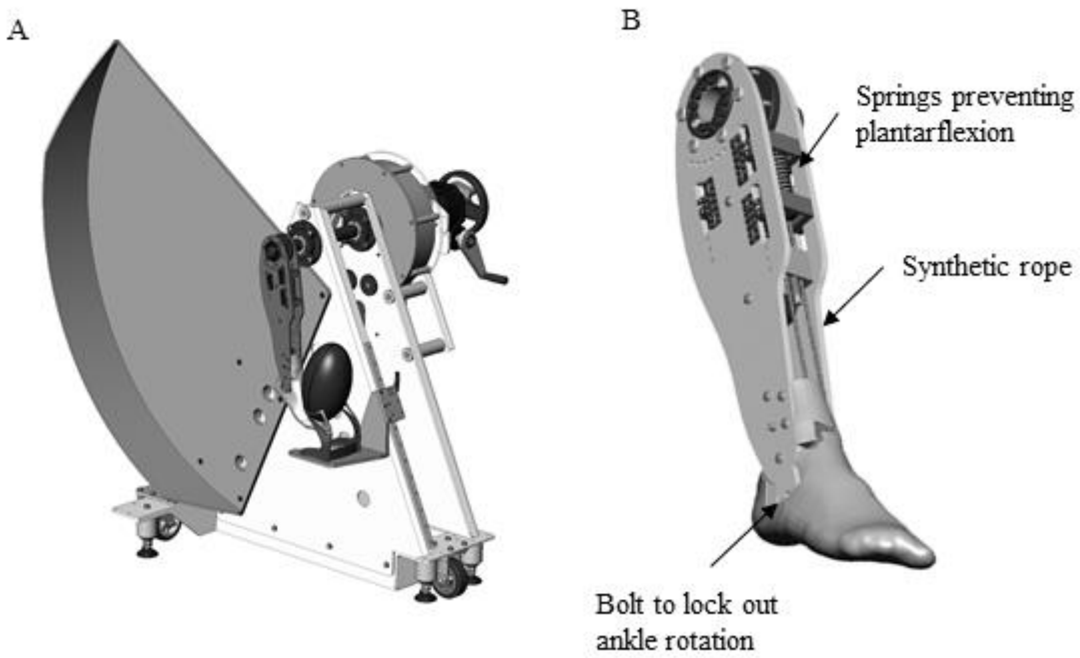

Figure 5.1: A) The mechanical kicking limb. B) Ankle rotation design with controlled rigidity via spring mechanism.

To analyse the influence of ankle rigidity on impact efficiency, a spring mechanism resisting plantarflexion was added to the previously validated mechanical kicking machine (Figure 5.1A). The spring mechanism was considered appropriate to represent the ankle motion during impact, as both the spring and human ankle during impact are passive (Shinkai, et al., 2009), where it is considered the initial conditions at the start of impact determine the phase (Nunome, et al., 2006b). The leg configuration (Figure 5.1B) comprised two segments: a shank and a foot segment. The shank segment was constructed of two metal plates (length = 0.455 m; mass = 4.2 kg) that attached to the trigger mechanism of the kicking machine (leg and trigger mass = 21.15 kg). While the mass of the trigger was high, it contributed little to the moment of inertia because it was close to the axis of rotation. The foot segment was attached to the distal end of the shank segment and plantar/dorsal ankle rotation occurred via two bearings. Because the shape of the impacting surface influences the interaction (Andersen, et al., 2005, 2008), and because the impacting area during drop punt kicking covers the bottom part of the shank (Nunome, et al., 2014), the bottom part of the shank and entire foot of a human was 3d scanned and integrated into the limb design. The foot segment was constructed by a 3d printer, made of ABS plastic with a weight of 1.09 kg. It was assumed the foot acted as a rigid body during impact. A football boot (Adidas Kaiser 5; mass = 0.364 kg) was placed on the foot segment. Overall, the moment of inertia of the entire kick leg was estimated to be 0.71 kg.m^2. It was assumed each body were rigid during impact, the only motion was rotation about the knee and ankle joints.

By setting the ankle to be either rigid or non-rigid at the start of impact, this enabled a direct comparison to determine the influence of ankle rigidity while all other impact characteristics were held constant (foot speed, impact location, ball orientation, moment of inertia, etc.). The rigid ankle was obtained by locking out rotation of the foot segment by inserting a bolt between shank and foot segments (see insert of Figure 5.1B). The non-rigid ankle was obtained by synthetic rope representing connective tissue and two springs representing elastic tissue within the joint. The synthetic rope stemmed from the foot segment and passed across the anterior side of the ankle joint, before connecting to two springs just below the knee joint (Figure 5.1B). The torque preventing plantarflexion could be calculated by multiplying spring stiffness by the radius of 40 mm (the displacement between the ankle axis of rotation and the contact point of the tendon across the anterior aspect of the joint). It was assumed the synthetic rope did not stretch while the ankle was forced into plantarflexion, enabling the linear deformation of the spring to be calculated from the ankle plantar/dorsal flexion motion. To determine if the non-rigid ankle validly represented ankle motion of human performers, the ankle motion of the mechanical limb was compared to previous literature.

5.2.2 The initial conditions of impact for the comparison of ankle rigidity

The imposed initial conditions of impact were a foot velocity prior of 16.4 ± 0.2 m/s across all trials, and spring force at the ankle joint of 950 N for the non-rigid setting (yielding a torque preventing plantarflexion of 38 N.m). The angle of the rigid ankle was set at 155.6°, and the angle of the non-rigid ankle was set at 156.8°. Impact location was set to impact the foot approximately at its centre of mass. Pilot testing identified this setting to obtain a change in ankle angle of approximately 8° plantarflexion, a similar value obtained in both AF (7.2 ± 2.2°) and soccer (7.1 ± 5.8°) performer studies where the foot was passively plantarflexed during impact (Peacock et al., 2017; Shinkai et al., 2009). Ten trials were recorded for each setting on the same testing session using the same ball, and to minimise the possibility of order effects (given the ball can 'soften') five trials were completed under the rigid setting, followed by 10 trials under the non-rigid setting, and five final trials under the rigid setting.

5.2.3 Data collection

Two-dimensional sagittal plane data were measured through high-speed video camera (Photron SA3, Photron Inc., USA, 4,000 Hz, resolution 768 x 512 pixels) zoomed in to include just the kicking area. Tracking markers (12.9 mm spherical and 8 mm flat) on the limb and ball were tracked from 20 frames before ball contact to 20 frames after the ball had left the boot (identified visually from the video) using ProAnalyst software (Xcitex Inc., Woburn MA, USA). To eliminate movement of the boot influencing foot and ankle data, the foot tracking marker was attached directly to the fifth metatarsal by cutting a hole in the boot and tapping a thread into the foot. This marker was also occluded for approximately 10 frames through the middle of the tracking stage as it passed through the tee supporting the ball, and these points were interpolated within the tracking software. The interpolation feature was considered suitable because there was no change in direction of the marker during this period.

5.2.4 Data analysis and parameter calculation

Raw X and Y coordinates were exported to Visual3d software (C-Motion Inc., Germantown MD, USA) to be analysed with a custom-made pipeline. Firstly, four virtual markers were derived from the three tracking markers of the foot using the method from (Peacock et al., 2017). These virtual markers were on the anterior aspect of the foot, and were found at the top of the shank segment (ShT), bottom of the shank segment (ShB), centre of the foot (FC) and bottom of the foot (FB) (Figure 5.2). All parameters were calculated within Visual3d and Microsoft Excel (Microsoft Corporation, Redmond WA, USA) software from the measured X-Y coordinate data. Foot and ball velocity were calculated from the first derivative of X-Y coordinate data, and were smoothed with a low-pass Butterworth filter at a cut-off frequency of 170 Hz. The choice of cut-off filter was based upon three criteria: discrete Fourier Transform analysis looking at different cut-offs between 10 to 400 Hz, visual inspection of the signals at different cut-offs and previous literature (Nunome et al., 2006; Peacock et al., 2017; Shinkai et al., 2009). Initial and final velocity of foot and ball were averaged over five frames.

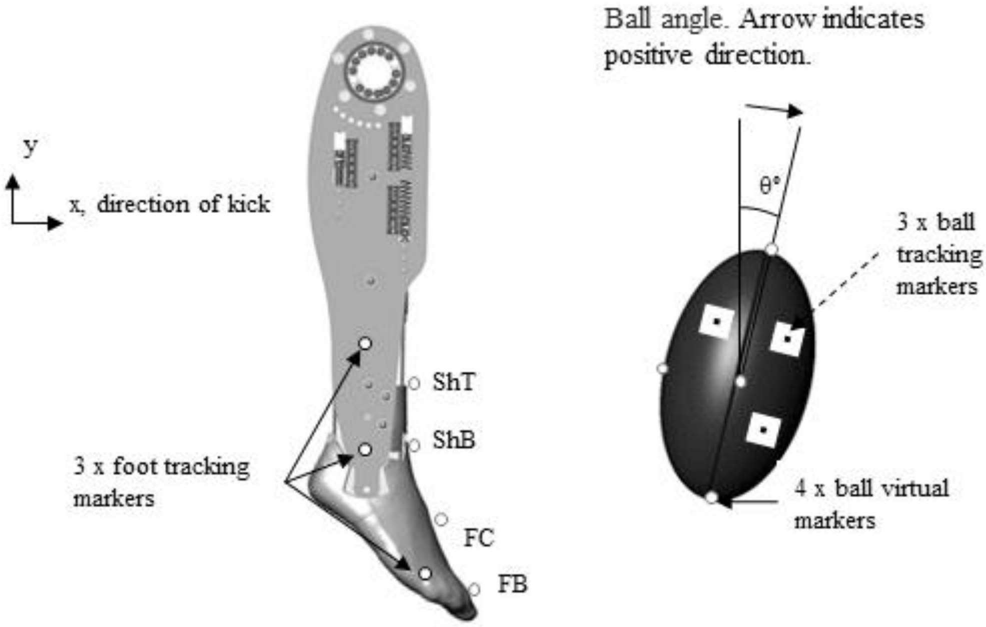

Figure 5.2: Orthogonal reference and tracking and virtual markers of the limb and ball. Virtual markers are represented by the grey outline of the circular markers.

The energy sources of interest were the kinetic energy of the ball and the elastic energy stored in the springs preventing plantarflexion of the ankle. Linear kinetic energy of the ball was quantified from its mass and linear velocity (Equation 5.2). Rotational energy was quantified from the angular velocity and moment of inertia (Equation 5.3 and Equation 5.4). Energy stored in the spring mechanism preventing plantarflexion was quantified from its deformation (Equation 5.5 and Equation 5.6). The sum of ball and ankle energy included translational and rotational kinetic energy and the energy stored within the spring mechanism (although not applicable to the rigid ankle).

$$Ball_{KE,Translational}\ (J) = {}^{1}/_{2} \cdot m_b \cdot {v_b}^2 \qquad \text{Equation 5.2}$$

$$Ball_{KE,Rotational}\ (J) = {}^{1}\!/_{2} \cdot I_b \cdot {\omega_b}^2$$ Equation 5.3

Where I_b = Inertia of the ball, calculated from Equation 5.4; ω = angular velocity.

$$I_b = \frac{m({R_a}^2 + {R_b}^2)}{5}$$ Equation 5.4

Where R_a = the short radius of the ball; R_b = the long radius of the ball

$$d = \left(D_i + \frac{\Delta AA}{180} \cdot \pi \cdot R_t\right)$$ Equation 5.5

Where d = spring deformation; D_i = initial spring deformation (m), ΔAA = change in ankle angle (degrees), R_t = radius of tendon across ankle joint (m).

$$Ankle_{EE}\ (J) = {}^{1}\!/_{2} \cdot k \cdot d^2$$ Equation 5.6

Where k = spring stiffness; d = spring deformation, as calculated from the limb settings and change in ankle angle.

Impact efficiency measures of foot-to-ball speed ratio, coefficient of restitution and effective mass are presented in Equation 5.7, Equation 5.8, Equation 5.9.

$$F\!:B\ Ratio = \frac{v_b}{u_f}$$ Equation 5.7

$$COR = \frac{v_f - v_b}{u_f} \qquad \text{Equation 5.8}$$

$$EM\ (kg) = \frac{m_b \cdot (v_b - u_b)}{v_f - u_f} \qquad \text{Equation 5.9}$$

5.2.5 Statistical analysis

A two-tailed, two-sampled equal variance T-test was performed and effect sizes were calculated. The P-value was set at 0.05 to indicate significance and effect sizes were defined as: $d < 0.2$ = none, $d < 0.5$ = small, $d < 0.8$ = medium and $d > 0.8$ = large (Cohen, 1988). A Holm's correction was applied to reduce the likelihood of type 1 statistical errors (Holm, 1979).

5.3. Results

5.3.1 Validation of mechanical limb segment

The non-rigid ankle was in dorsi-flexion for the first 31% of impact duration, followed by distinct plantar-flexion for the remainder of impact (Figure 5.3). The total change in ankle angle between ball contact and ball release was 8.2 ± 0.7° and the total impact duration was 10.7 ± 0.3 ms.

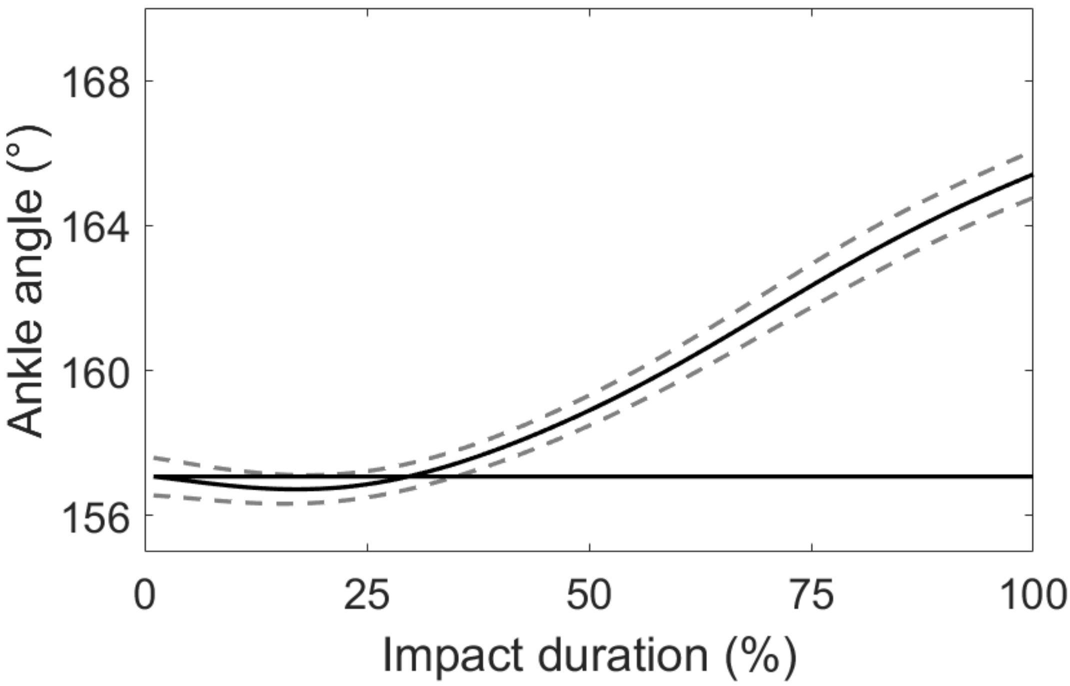

Figure 5.3: Non-rigid ankle motion through impact (± standard deviation). The flat black line represents ankle angle at impact start, plotted throughout the duration of impact as a reference to the change in angle during impact.

5.3.2 Comparison of ankle rigidity settings

Foot to ball speed ratio, ball velocity and translational kinetic energy of the ball were significantly greater under the rigid ankle (Table 5.1). The effective mass of the striking limb was greater under the rigid ankle; effective mass as calculated through the conservation of momentum was greater for the rigid ankle, and although the elastic energy in the ankle for the rigid setting was naught, the sum of ball kinetic energy and ankle elastic energy were equal under the rigid and non-rigid ankle settings despite a smaller reduction in foot velocity under the rigid ankle. Energy losses during the collision were significantly greater under the non-rigid ankle; coefficient of restitution was greater under the rigid ankle and 6.3 ± 0.6 J of elastic energy was stored in the spring mechanism at the end of impact as the ankle remained in plantarflexion.

Table 5.1: Kick impact characteristics.

	Rigid	Non-rigid	*T-test*	Holm's Corrected P-value threshold	Effect size *Value (Cohen's d)*	 *Classification*
Foot to ball speed ratio	1.16 ± 0.01	1.11 ± 0.01	$p < 0.001$*	*0.007*	*1.79*	*Large*
Ball velocity (m/s)	19.0 ± 0.3	18.3 ± 0.2	$p < 0.001$*	*0.013*	*1.61*	*Large*
Translational kinetic energy of ball (J)	82.3 ± 2.5	76.7 ± 1.5	$p < 0.001$*	*0.017*	*1.60*	*Large*
Effective mass (kg)	2.1 ± 0.1	1.7 ± 0.1	$p < 0.001$*	*0.008*	*1.72*	*Large*
Σ ball kinetic and ankle elastic energy (J)	88.6 ± 2.5	89.1 ± 1.3	$p = 0.32$	*0.050*	*0.22*	*Small*
Reduction in foot velocity (m/s)	4.1 ± 0.2	4.8 ± 0.3	$p < 0.001$*	*0.010*	*1.63*	*Large*
Coefficient of restitution	0.42 ± 0.01	0.40 ± 0.02	$p = 0.01$*	*0.025*	*0.96*	*Large*
Change in ankle angle (°)	-	8.3 ± 0.7	-	-	-	*N/A*
Energy stored in ankle (J)	-	6.3 ± 0.6	-	-	-	*N/A*

**denotes significance*

5.4. Discussion

5.4.1 Validation of non-rigid ankle limb configuration

Kicking is a dynamic skill where many impact characteristics, if not accounted for, can influence the outcome of a kick. Therefore, to determine the influence of one characteristic on kick outcome, specifically ankle plantarflexion for the present study, a mechanical kicking machine with the ability to control ankle motion was developed. The first aim of the present study was to validate the non-rigid ankle motion by comparing to previous research.

The passive motion of the non-rigid ankle was representative of human ankle motion during drop punt and instep soccer kicking based on similar motion of the ankle during impact, overall change in ankle plantarflexion, and contact time. The ankle was in dorsiflexion for the first 31% of impact duration, followed by distinct plantarflexion for the remainder. This ankle movement pattern was similar to both drop punt and instep kicking, where both Peacock, et al. (2017a) and Shinkai, et al. (2009) identified the majority of analysed players within the tested groups produced a similar pattern. The overall change in ankle plantarflexion was 8.2 ± 0.7°, a comparable value to both drop punt kicking (7.2 ± 2.2°) and soccer instep kicking (7.1 ± 5.8°) (Peacock, et al., 2017a; Shinkai, et al., 2009). Further, the overall contact time (10.7 ± 0.3 ms) was consistent with human kicking values of both the drop punt (13.2 ± 2.2 ms) and soccer instep (9.0 ± 0.4 ms) kicks (Peacock, et al., 2017a; Shinkai, et al., 2009). Based on these similarities, it can be concluded the ankle motion of the mechanical kicking machine validly represented human football kicking. This result supports ankle motion during impact as being passive, as the ankle motion was validly replicated by a spring mechanism that was passive in motion.

5.4.2 Comparison of rigid to non-rigid ankle

During impact the ankle is forced into passive plantar-flexion due to the high forces and short time of the interaction (Shinkai, et al., 2009). Contrasting results exist as to whether impact efficiency is improved when reducing this plantarflexion. Therefore, the aim of this study was to compare a rigid and a non-rigid ankle while all other impact characteristics were held constant.

The key results were that impact efficiency was greater under the rigid ankle, due to an increase in effective mass and decrease in energy losses.

A more rigid ankle increases the effective mass of the striking limb compared to a less rigid ankle, where a greater portion of mass from the shank is included in the collision. The higher effective mass for the rigid ankle was evidenced by two mechanisms: firstly, effective mass as calculated through the conservation of momentum was greater for the rigid ankle; secondly, the sum of ball kinetic energy and elastic energy stored in the ankle at the end of contact were equal between the rigid and non-rigid ankles, but, the reduction of foot velocity was smaller under the rigid setting meaning a greater amount of energy was transferred from to ball but with a smaller reduction in velocity. This indicates the effective mass was greater under the rigid setting, supporting Kellis and Katis (2007) and Lees and Nolan (1998) who state the effective mass is increased from a rigid foot and ankle. Shinkai, et al. (2013) found effective mass to also increase with the physical mass of players, and therefore, effective mass is dependent on the physical mass of the performer and the rigidity of the ankle during impact.

A less rigid ankle during kick impact results in a greater energy loss compared to a more rigid ankle. During football kicking, energy can be lost in both the striking limb and the ball. For our study ball position was held constant at impact start, and although small changes existed in the relative foot-ball position as the ankle position changed during impact, it was assumed that energy loss in the ball did not differ between the conditions. Under this assumption, the difference in coefficient of restitution was solely due to the differing rigidity of the ankle joint. This lost elastic energy was due to the ankle remaining in plantarflexion at the end of impact, 6.3 J of energy were stored in the spring mechanism. Ball velocity between the two ankle configurations would be equal if this stored energy was transferred into translational kinetic energy of the ball. The translational kinetic energy of the ball was 76.7 J for the non-rigid ankle, and an increase of 6.3 J to 83.0 J is equivalent to a ball velocity of 19.1 m/s, comparable to that measured for the rigid ankle (19.0 m/s).

When all impact conditions were controlled for, increasing rigidity was beneficial to impact efficiency, and therefore ball velocity. Previous analyses that did not identify an improved efficiency with increased rigidity may have been confounded by other parameters. For example, Ball, et al. (2010) suggested a number of impact characteristics such as ball orientation and impact location that were not measured may also influence the impact phase. This highlights the benefits of mechanical testing where all parameters could be controlled. To reduce the number of parameters that can vary when testing with human performers, an intra-individual method could be employed to reduce variation in parameters such as physical mass, strength and shoe type. Experimental limitations did exist for the present study, because the mechanical limb did not include soft tissue as present in the human body (muscle, tendon, ligament). This soft tissue may influence the contribution of shank mass toward impact. While the simplification of the ankle and foot structure within the present study has provided a strong theoretical background for the application of kicking, future research is warranted with human participants to fully solve the question about ankle rigidity and energy transfer. The practical applications of this work indicate that strategies to reduce the magnitude of ankle plantarflexion during impact might increase ball velocity. Effective strategies to reduce change in ankle plantarflexion and in-turn increase impact efficiency might include controlling the impact location on the foot, to reduce the external torque applied to the ankle, and increasing the muscle stiffness within the ankle joint, to increase the internal torque applied to the ankle. Future work, however, is required to determine the effectiveness of these strategies.

5.5. Conclusion

Two aims existed for the present study: to validate the ankle motion of a mechanical kicking machine with a non-rigid ankle and to determine if differences exist between a rigid and non-rigid ankle. The non-rigid ankle was in dorsiflexion for the first 31% of impact and moved into plantarflexion for the remainder of the phase. Plantarflexion at impact end was 8.2 ± 0.7°. This was a similar pattern and magnitude to both punt and instep kicking. Further, the contact time was also comparable to human kicking, and the ankle motion of the mechanical kicking machine was therefore valid. Differences existed between the rigid and non-rigid ankle settings for impact efficiency (foot-to-ball speed ratio). The higher impact efficiency was obtained by an increase in effective mass and a reduction in energy losses. The greater effective mass for the rigid ankle was quantified through the conservation of momentum and the energy transferred from the foot to the ball. Rigidity of the ankle joint controls the contribution of mass from the shank used in the collision. Energy losses were quantified from coefficient of restitution and the elastic energy stored in the spring mechanism preventing plantarflexion. As the foot remained in plantarflexion at the end of impact, energy stored in the joint was lost. Increasing ankle rigidity, to decrease the forced plantarflexion, is beneficial for impact efficiency and therefore ball velocity.

5.6. Contribution of individual chapter to overall thesis

The aim of Chapter 5 was to identify if ankle plantarflexion during foot-ball impact influenced impact efficiency. This research question contributed to aim 1 of the overall thesis. This research question was answered used the mechanical kicking machine. It was identified ankle plantarflexion was influential to impact efficiency. Further discussion of how to increase impact efficiency can be found in section 10.2. Chapter 6 built upon this study by identifying several strategies that players could use to reduce ankle plantarflexion, to in-turn increase impact efficiency.

Chapter 6: Study 4 - Strategies to improve impact efficiency in football kicking

This chapter has been published in the journal Sports Biomechanics and has undergone the peer-review process.

Abstract: In football, kicking with high ball velocity can increase scoring opportunities and reduce the likelihood of interception. Efficient energy transfer from foot to ball during impact is important to attain a high ball velocity. It is considered impact efficiency can be increased by reducing the change in ankle plantarflexion during foot-ball impact. However, conflicting evidence exists, questioning its effectiveness as a coaching cue. The aim of the present study was to systematically analyse joint stiffness, foot velocity and impact location with a mechanical kicking machine to determine if change in ankle plantarflexion during foot-ball impact and ball velocity are influenced. Sagittal plane data of the shank, foot and ball were measured using high-speed-video (4,000 Hz). Increasing joint stiffness reduced change in ankle plantarflexion and increased ball velocity from a greater effective mass. Increasing foot velocity increased change in ankle plantarflexion and increased ball velocity. Distal impact locations increased change in ankle plantarflexion and reduced ball velocity as coefficient of restitution decreased. These results identify that change in ankle plantarflexion is a dependent variable during foot-ball impact, and does not directly influence ball velocity. Coaches can assess ankle motion during impact to provide feedback to athletes on their impact efficiency.

6.1. Introduction

Kicking is an important skill across the football codes, used to score goals and pass the ball to fellow team members. By impacting the ball with their foot, a player imparts a combination of flight characteristics that ultimately determines the outcome of the kick. Ball flight characteristics include velocity, trajectory, and spin. While all flight characteristics must be controlled for a kick to be successful, increasing ball velocity has many benefits during gameplay. By kicking with a higher ball velocity, a player can increase the distance they can attempt to score a goal thus increasing the number of scoring opportunities, and reduce the likelihood of interception for the opposition by decreasing flight time. Therefore, technical strategies that enhance ball velocity during kicking are important for performance.

Foot velocity has been identified as the most important technical component toward final ball velocity. The relationship between foot and ball velocity has been identified through several experimental designs: correlations within groups, comparisons of different players, comparisons within players performing different tasks, and theoretical equations (Andersen, et al., 1999; Nunome, et al., 2006a; Peacock, et al., 2017a; Shinkai, et al., 2013; Smith, et al., 2009).

Due to each players limitation in producing foot velocity, it is also important that players impact the ball efficiently. Reducing the magnitude of change in foot and ankle position during impact have been considered important factors toward impact efficiency (Asami & Nolte, 1983; Ball, et al., 2010; Kellis & Katis, 2007; Lees & Nolan, 1998; Peacock, et al., 2017a; Sterzing, et al., 2009). Despite what appears to be a clear relationship between foot and ankle motion during impact with final ball velocity and a sound theory describing the mechanism, conflicting results have also been identified. Nunome, et al. (2006b) identified a player within their analysed group produced a large magnitude of change in ankle plantarflexion and a large magnitude of ball velocity, and questioned the relationship between ankle motion with ball velocity. Shinkai, et al. (2013) identified non-significant relationship between change in ankle plantarflexion and foot-ball speed ratio in their analysis of 51 players performing the soccer instep kick.

One key issue when analysing the influence of change in foot and ankle position during impact with final ball velocity is the influence of confounding impact characteristics. While most players experience forced, passive ankle plantarflexion during impact across kicking techniques (Nunome, et al., 2006b; Peacock, et al., 2017a; Shinkai, et al., 2009), factors of foot velocity, impact location and the position of the ankle at the beginning of impact have been suggested to influence this motion (Peacock, et al., 2017a; Sterzing, et al., 2009). Theory indicates the resulting ankle and foot motion during impact will be due to the sum of internal and external torques applied. An external torque greater than the internal would result in plantarflexion, and vice-versa: the external torque will be determined from the magnitude and point of application of the force applied to the foot in relation to the ankle joint, and the internal torque will be determined from the stiffness within the ankle. Further, due to the strong dependence of final ball velocity on initial foot velocity (Andersen, et al., 1999), it is possible conflicting results between several studies were caused from analysing the direct relationship between foot and ankle motion with final ball velocity: greater ball velocities may have been achieved by greater foot velocities, and ankle motion may have been influenced by foot velocity and impact location.

The aim of this study was to further explore ankle motion during foot-ball impact. Conflicting results exist as to the importance of ankle motion toward final ball velocity, likely due to confounding impact characteristics; therefore, a controlled methodology is needed to appropriately identify its influence. The aim of this study was to systematically analyse three characteristics and identify their relationship with change in ankle plantarflexion and ball velocity: foot velocity, proximal-distal impact location on the foot, and joint stiffness under a non-rigid ankle. Due to the difficulties with systematically analysing individual characteristics during foot-ball impact with players (Peacock & Ball, 2016), a mechanical kicking machine designed to replicate human ankle plantar/ dorsal flexion during impact performed kicks while each characteristic was individually changed. This will provide useful information for future studies analysing foot-ball impact and for coaches looking to improve an individual’s technique. It was hypothesised that strategies which reduced the magnitude of ankle plantarflexion would increase impact efficiency and/ or ball velocity.

6.2. Methods

6.2.1 Mechanical kicking machine

A mechanical kicking machine (Figure 6.1 (A)) performed punt kicks with an Australian Rules Football ball ('Match Ball', Sherrin, Australia). The use of this limb allowed for a systematic exploration of impact characteristics, an issue that has limited this research previously and would be extremely difficult to perform with players. The key design feature of the limb for the present study was controllable ankle stiffness; and the influence of impact location, foot velocity, and ankle stiffness were systematically assessed. Because it is established the ankle is forced into passive plantarflexion during impact (Shinkai, et al., 2009), the controllable ankle stiffness was designed to prevent ankle plantarflexion. This was achieved via a spring mechanism: synthetic rope, representing the tendon, connected to the dorsal aspect of the foot and passed across the anterior aspect of the ankle joint (with a radius of 4 cm) before connecting to the shank via a spring mechanism (Figure 6.1(B)). As the ankle underwent plantarflexion, the distance between the origin and insertion of the synthetic rope increased and compressed the spring mechanism. Ankle stiffness was controlled via two processes within the spring mechanism: firstly, the initial compression of the spring could be altered, which increased the stiffness of the ankle as indicated by Hook's law; secondly, four different springs, each with different stiffness' were used (50 N/mm, 86 N/mm, 174 N/mm, & 222 N/mm). The total length of each spring was 102 mm, and the initial compression could be set between the range of 1 to 27 mm. It was identified the ankle motion produced by this limb validly replicated the human ankle during impact, due to similarities with previous literature focusing on foot-ball impact (Peacock, et al., 2017a; Shinkai, et al., 2009). This pilot testing was completed with a foot velocity of 16.5 m/s, spring stiffness of 50 N/mm and initial spring deflection of 19 mm. Other key design features of the limb included the segment lengths, masses and shape of the impacting surface to replicate that of a typical Australian Football League player.

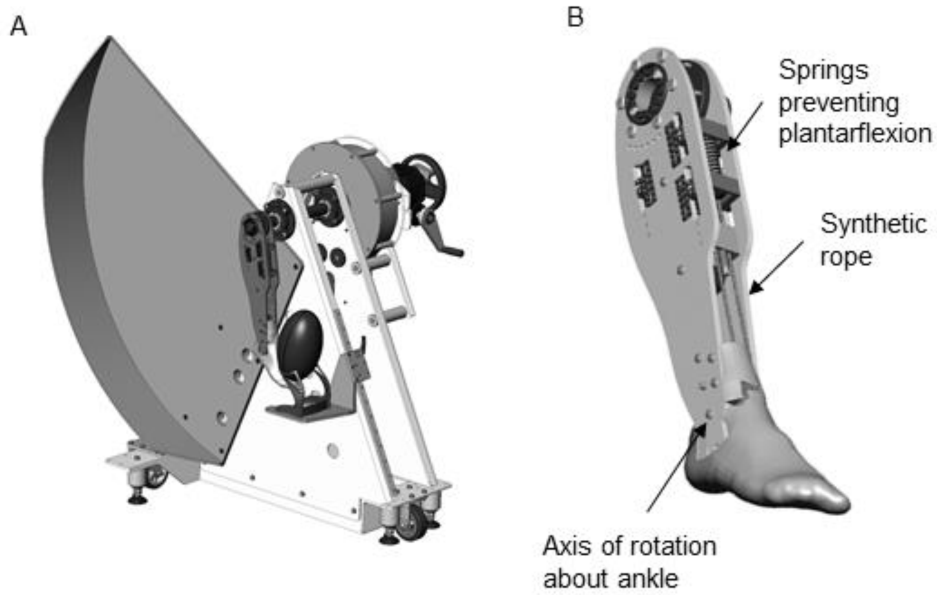

Figure 6.1: Mechanical kicking machine (A) and limb with rotation about the ankle (B).

Three impact characteristics were explored systematically for this study: foot velocity, impact location and ankle plantarflexion stiffness. Foot velocity was altered by adjusting the starting point of the limb over 11 positions as it began its forward swing while impact location and ankle stiffness were held constant at 0.39 cm and 1118 N. Impact location was adjusted through the platform supporting the ball over 11 positions; moving the height of this platform changed the position of the ball relative to the foot, thus producing different impact locations across the proximal-distal direction from the foot centre. No changes were made to the position across the medial-lateral dimension, while foot velocity and ankle stiffness were held at 16.5 m/s and 1118 N. Ankle stiffness was adjusted through the spring mechanism that prevented ankle plantarflexion; twenty-four unique stiffness' of the ankle were tested; the initial compression of each spring was set at six positions between the range of 25 to 5 mm, increasing by 4 mm increments. Impact location and foot velocity were held constant at 0.39 cm and 16.5 m/s.

6.2.2 Data collection and analysis

High-speed-video cameras recorded each trial at 4,000 Hz (Photron SA3, Photron Inc., USA). Markers were tracked in the sagittal plane to measure raw X-Y coordinates (ProAnalyst, Xcitex Inc., USA). Data were smoothed using a low-pass Butterworth filter, with a cut-off frequency of 170 Hz. The choice of cut-off frequency was based on five criteria: Fourier analysis, previous literature (Nunome, et al., 2006b; Peacock, et al., 2017a), visual inspection of data curves, and inspection of change in metric parameters.

Reflective tracking markers were attached to key landmarks of the foot and ball (Figure 6.2). Key anatomical landmarks were computed from the tracking markers using the procedure of (Peacock, et al., 2017a). The foot centre was calculated from the midpoint between the foot top and the foot bottom. The foot top was located at the approximate distal end of the tibia, and the foot bottom was located at the approximate location of the third phalange, both on the dorsal aspect of the limb. These two locations represented the most proximal and distal points on the dorsal aspect of the foot, thus the foot centre position was the centre of the impacting surface on the foot. Foot velocity was calculated from the first derivative of the foot centre over five frames prior to impact. Ankle plantarflexion was calculated from markers attached to the shank, ankle (axis of rotation), and the head of the fifth metatarsal, and the change in its position was calculated from the initial and final positions at ball contact and release. Ball centre and orientation were calculated from tracking markers attached to the ball and velocity was calculated from the first derivative of positional data.

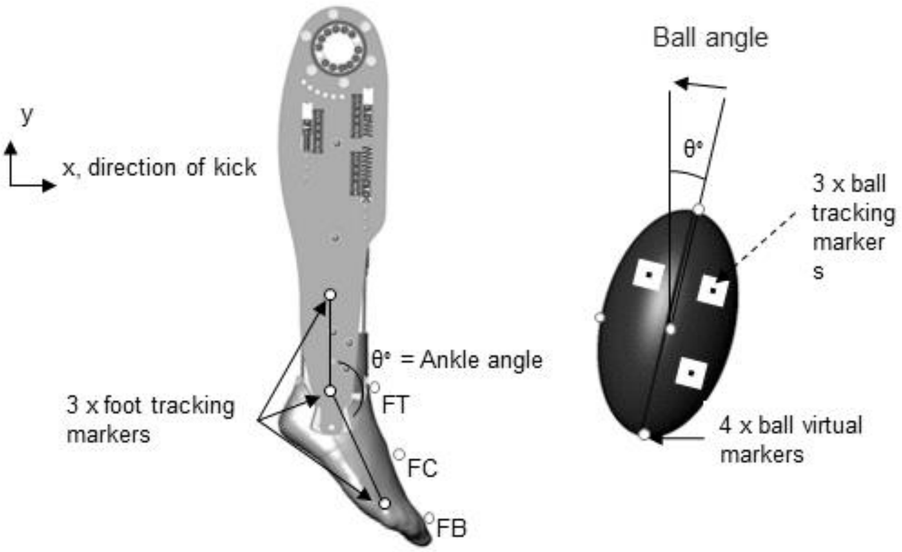

Figure 6.2: Reflective tracking markers and key anatomical landmarks.

A novel method was developed to calculate the impact location on the foot (Figure 6.3). Previous methods to calculate the impact location in soccer kicking were not suitable due to the unique ball shape (Ishii, et al., 2012). Because the radius of the Australian Football ball was not constant due to its ellipsoidal shape, the intersecting point between foot and ball was dependent on the orientation of the ball, the orientation of the foot, and the relative position of the two objects. The dorsal aspect of the foot was modelled as a linear line (Equation 6.1), and this model included information on the foot orientation and foot position in space. The ball shell was modelled as an ellipse projected from its central position (Equation 6.2). The x and y coordinates of the ball shell model were rotated to the orientation of the ball (Equation 6.3 and Equation 6.4). The impact location of the foot was defined as the intersecting point between the two models (foot and ball) at ball contact, and was represented as a vector in relation to the midpoint between the top and bottom points of the foot. Positive values indicated a distal impact location from this location.

$$F_y = \frac{(FB_y - FT_y)}{(FB_x - FT_x)} \cdot F_x + \left(\frac{(FB_y - FT_y)}{(FB_x - FT_x)}\right) \cdot -FB_x + FB_y \qquad \text{Equation 6.1}$$

Where Fy = the position of the dorsal aspect of the foot, FBy = the y-coordinate of the bottom of the dorsal aspect of foot, FTy = the y-coordinate of the top of the dorsal aspect of the foot, FBx = the x-coordinate of the bottom of the dorsal aspect of foot, FTx = the x-coordinate of the top of the dorsal aspect of foot, Fx = the x-coordinate of the dorsal aspect of the foot.

$$\left(\frac{BS_x - BC_x}{R_x}\right) + \left(\frac{BS_y - BC_y}{R_y}\right) = 1 \qquad \text{Equation 6.2}$$

Where BSx = position of the ball shell in the x-coordinate, BCx = position of the ball centre in the x-coordinate, Rx = the short radius of the ball, BSy = position of the ball shell in the y-coordinate, BCy = position of the ball centre in the y-coordinate, Ry = the long radius of the ball.

$$BS_{x,R} = BS_x \cdot cos\theta - BS_y \cdot sin\theta \qquad \text{Equation 6.3}$$

Where $BS_{x,R}$ = x-coordinate of the rotated ball shell, θ = ball orientation.

$$BS_{y,R} = BS_x \cdot sin\theta + BS_y \cdot cos\theta \qquad \text{Equation 6.4}$$

Where $BS_{y,R}$ = y-coordinate of the rotated ball shell.

This method was limited because the foot and ball were assumed to be modelled by the respective equations; the ball as an ellipse and the dorsal aspect of the foot as a linear line. Inconsistencies in the true dorsal aspect of the foot from this linear line, in addition to the finite sampling rate of the camera (4,000 Hz) meant there was not one finite impact location at visually identified ball contact. Inspection of the model at ball contact identified either the foot and ball were not in contact (Figure 6.3(A)) or the ball was partially deformed (Figure 6.3(B)). Therefore, the impact location of the foot was defined by the point on the foot that produced the greatest amount of ball deformation at visually identified ball contact. Ball contact was defined as the largest distance between the ball surface and the perpendicular direction of the foot surface in the direction of its path (the direction of ball deformation). One finite impact location on the foot could be calculated with this definition. To validate this method, a correlation was between the calculated foot impact location and the platform height. Impact location displayed a near perfect linear relationship with platform height (R2 = 0.99; $p < 0.001$), and the developed method to calculate impact location on the foot was therefore valid.

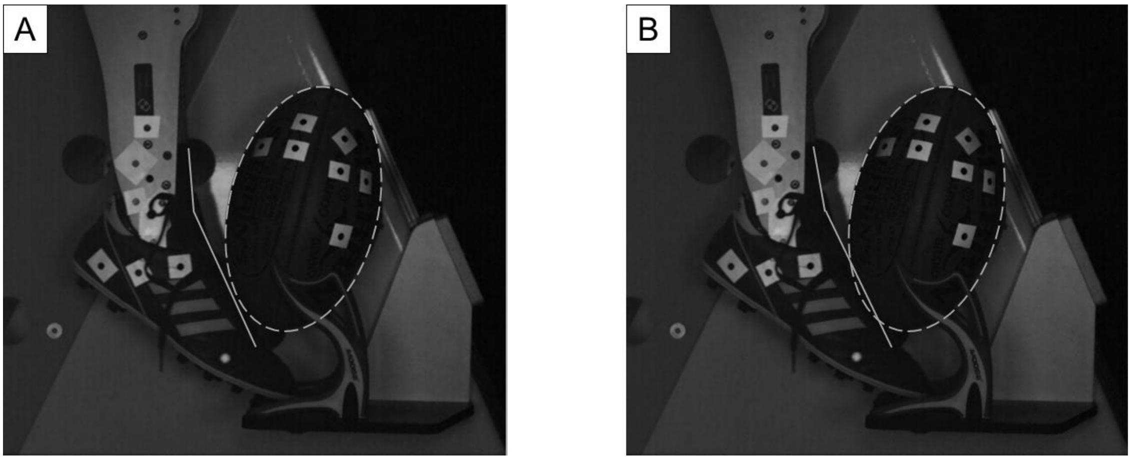

Figure 6.3: Video overlay of foot model (solid line) and ball model (dashed line) at ball contact. Figure A identifies when the foot and ball models were not in contact at visually identified ball contact, as depicted by the foot model being to the left of the ball model. Image B identifies when the ball was partially deformed at ball contact, as depicted by the foot model being to the right of the ball model.

6.2.3 Statistical analysis

To identify the relationship between each parameter pairing, linear, 2nd order, 3rd order polynomials and power curves were fitted to the data. As there was no reason to expect a linear relationship for each pairing, it was appropriate to expand the analysis to include other types of curves if they fit the data more appropriately. The choice of most appropriate relationship was based on five criteria (in no order): values of R^2, p-value, visual inspection of data plots, inspection of residual plots, and the statistical test from Hayes (1970). The statistical test from Hayes (1970) was important to provide objectivity through this process.

6.3. Results

6.3.1 The influence of foot velocity

A third order relationship was identified between foot velocity and change in ankle plantarflexion (Figure 6.4(A)). In the low range of foot velocity, change in ankle plantarflexion increased exponentially. In the high range of foot velocity, change in ankle plantarflexion decreased. Ball velocity increased linearly with foot velocity (Figure 6.4(B)).

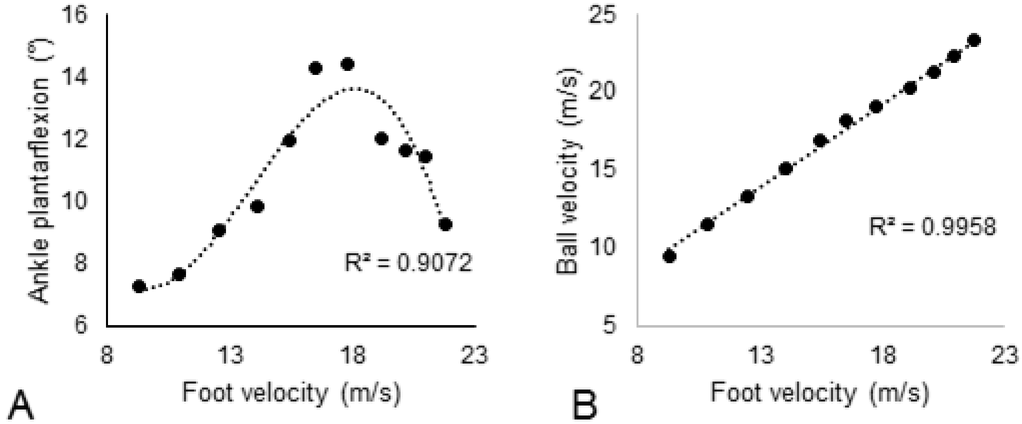

Figure 6.4: The relationship between foot velocity and ankle plantarflexion (A); the relationship between foot velocity and ball velocity (B). Impact location was held constant at 0.4 cm and joint stiffness was held constant at 1118 N.

6.3.2 The influence of impact location

A second order relationship was identified between proximal-distal impact location and change in ankle plantarflexion (Figure 6.5(A)). In the proximal impact locations, change in ankle plantarflexion decreased when the impact location was moved toward the ankle. In the distal impact locations, change in ankle plantarflexion plateaued. A negative, linear relationship was identified between impact location and ball velocity (Figure 6.5(B)).

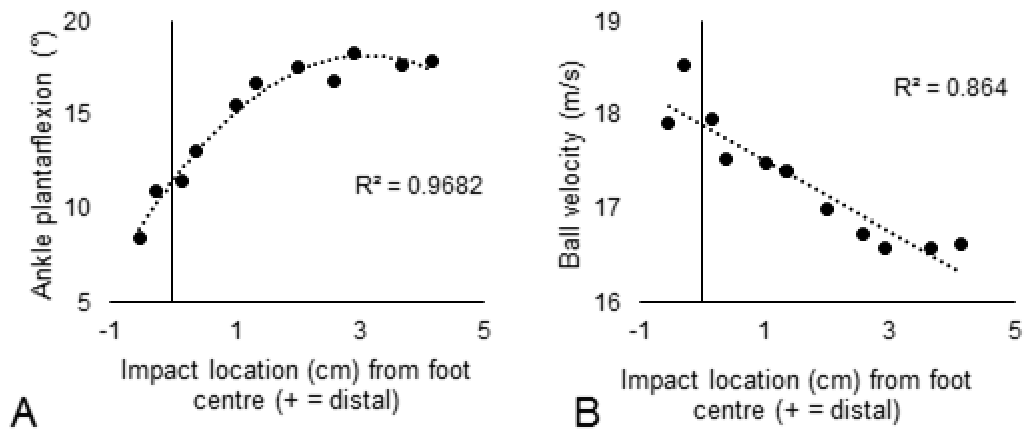

Figure 6.5: The relationship between proximal-distal impact location and ankle plantarflexion (B); the relationship between proximal-distal impact location and ball velocity (B). Foot velocity was held constant at 16.5 m/s and joint stiffness was held constant at 1118 N.

6.3.3 The influence of joint stiffness

A negative linear relationship was identified between change in ankle plantarflexion and joint stiffness (Figure 6.6(A)). A positive linear relationship existed between ball velocity and joint stiffness (Figure 6.6(B)).

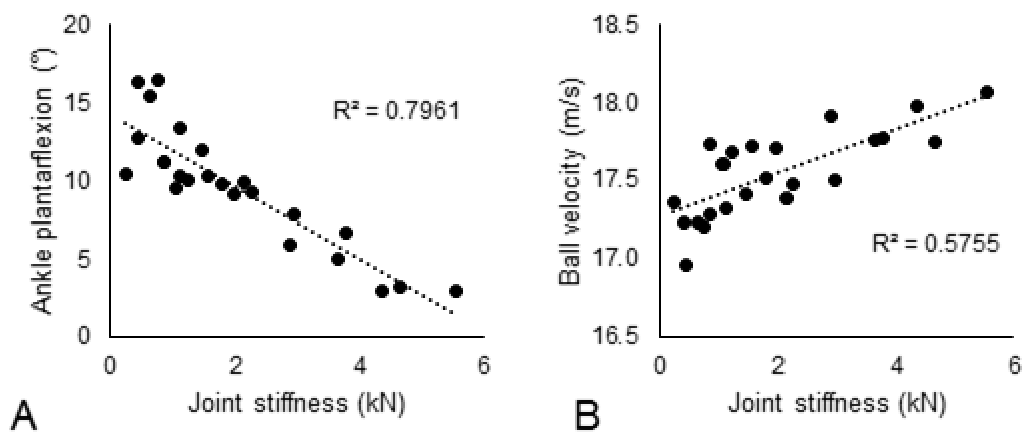

Figure 6.6: The relationship between joint stiffness and ankle plantarflexion (A); the relationship between joint stiffness and ball velocity (B). Impact location was held constant at 0.4 cm and foot velocity was held constant at 16.5 m/s.

6.4. Discussion and implications

6.4.1 The influence of foot velocity

Foot velocity influences change in ankle plantarflexion during impact. Change in ankle plantarflexion increased with foot velocity due to the greater external torque applied about the ankle. Change in ankle plantarflexion increased in the low range of foot velocity, indicating the external torque increased with foot velocity. Change in ankle plantarflexion decreased in the high range of foot velocity. This could indicate the external torque reduced, but, post-hoc analysis of the ankle motion during impact (Figure 6.7) identified the ankle was dorsiflexing at the start of impact for the higher range of foot velocity. Comparatively, the low range of foot velocities were forced into plantarflexion immediately. This dorsiflexion motion at the start of impact combatted against the forced plantarflexion, thus decreasing the overall magnitude. It was identified the majority of elite and experienced players do dorsiflex at the start of impact for both instep and drop punt kicking (Peacock, et al., 2017a; Shinkai, et al., 2009), and may have been an active strategy used by the players.

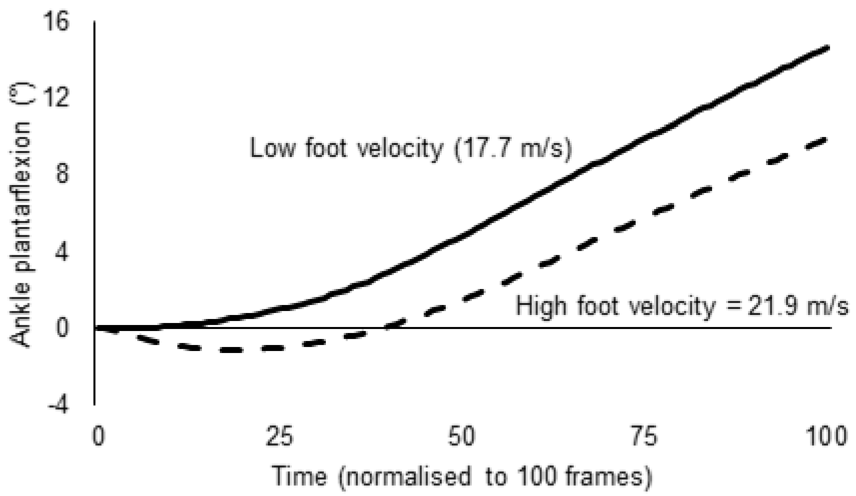

Figure 6.7: Post-hoc analysis of ankle plantarflexion for two trials from the low (solid line) and high (dashed line) foot velocities through impact. Each plotted line was comparable to other trials in their respective groups.

Dorsiflexing at the beginning of impact meant a linear relationship existed between foot and ball velocity. Peacock and Ball (2017) found impact efficiency decreased with foot velocity during their analysis with a mechanical kicking featuring a rigid ankle, a mechanical process of the ball during impact. This suggested the relationship between foot and ball velocity was not linear, but a power curve where the increase in ball velocity diminished. The authors compared the non-linear and power curves, but revealed only a minimal difference where the linear curve sufficed in explaining the relationship between foot and ball velocity. For the present study, it was expected the power and linear curves to differ more notably because the non-rigid ankle would also plantarflex with an increased foot velocity, further reducing impact efficiency. However, this study again identified the linear relationship most appropriately described the relationship between foot and ball velocity, but the dorsiflexing motion at the beginning of impact possibly negated the potential reduction in ball velocity. As the foot was dorsiflexing, energy was unable to be stored in the spring mechanism and was beneficial to ball velocity.

6.4.2 The influence of impact location

The proximal-distal impact location influences change in ankle plantarflexion during impact. The external torque applied to the ankle decreased when impacting toward the ankle. For the proximal impact locations, change in ankle plantarflexion increased as the impact location moved distally along the foot. It was expected change in ankle plantarflexion to further increase linearly throughout all impact locations due to the linear increase in torque associated with the moment arm, however, there was only a minimal increase across the distal impact locations. Post-hoc analysis of ankle motion during impact identified the distal impact location was forced into a greater magnitude of plantarflexion earlier through impact, due to the higher external torque applied to the ankle. In the final phase of impact, the ankle plantarflexion plateaued, and even dorsiflexed a small magnitude in the most distal impact location (Figure 6.8). This ankle motion at the end of impact has not previously been reported (Peacock, et al., 2017a; Shinkai, et al., 2009), which represents a difference between the mechanical and human limbs. Inspection of the video files identified in the distal impact locations the full range of motion within the ankle joint was reached, thus additional support to the spring mechanism was provided by the rigid structures of the ankle joint. Further, some elastic energy of the spring mechanism was released in the most distal impact location, evidenced by the dorsiflexion motion toward the end of impact. Regardless, this difference had no effect on final ball velocity; inspection of the ball velocity profile during impact identified ball velocity did not increase in the final phase of impact, similarly identified by Peacock, et al. (2017a).

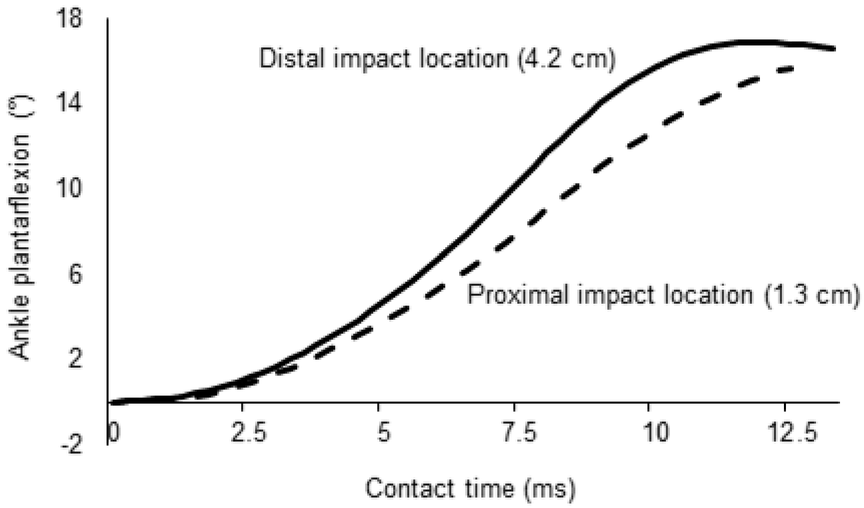

Figure 6.8: Post-hoc analysis of ankle plantarflexion for two trials from the proximal (dashed line) and distal (solid line) impact locations. Each plotted line was comparable to other trials in their respective groups.

Ball velocity was highest when impacting the ball closest to the ankle, meaning the dorsiflexion at the end of impact did not improve performance. Peacock and Ball (2017) identified ball velocity increased when the impact location on the foot was moved distally, because the velocity of the impacting point on the foot increased as it moved further from the axis of rotation (the knee). However, the ankle was rigid under their analysis, and thus a greater external torque applied to the ankle did not force the ankle into plantarflexion. Impacting distally, which forces the ankle into greater plantarflexion during impact, is detrimental to ball velocity. Post-hoc analysis between impact location and coefficient of restitution, and between impact location and effective mass identified significant linear relationships ($p < 0.05$). Coefficient of restitution decreased with distal impact locations, and effective mass increased with distal impact locations. However, because it was identified the ankle reached its maximum range of motion prior to the end of impact, foot velocity was subsequently increased in these trials and the calculations of effective mass and coefficient of restitution were overstated. Distal impact locations increased effective mass, however, this relationship was considered to be a result of reaching the full range of motion. If the full range of motion was not met, effective mass would not have changed. Coefficient of restitution decreased systematically with impact location in the distal direction, despite the distal values being overstated due to reaching the full range of motion. This indicates the negative effect of distal impact locations on coefficient of restitution should be larger in magnitude. Most importantly, this identifies distal impact locations decrease coefficient of restitution. Because the ankle is forced into greater magnitude with distal impact locations, more energy is stored as elastic energy in the spring mechanism and is thus not returned to velocity in either the foot or ball.

An optimal impact location on the foot is likely to exist. This study did not identify an optimal impact location. However, it is expected ball velocity would decrease if the impact location were continually moved proximally because the velocity of the impacting point decreases as it moves closer to the axis of rotation (the knee). A limitation of the present study was the range of impact locations analysed, it was not possible for any more impact locations in the proximal direction to be analysed because the area covered by the deformed ball exceeded that of the 3d printed shank and foot. Ishii, et al. (2012) identified an optimal impact location during their analysis of the instep kick. They reported ball velocity to be highest at an impact location approximately 1 cm distally toward the ankle from their defined foot centre of mass. Despite a greater range of impact locations analysed by Ishii, et al. (2012) compared to the present study, and a different method used to measure impact location from, a similar relationship appears to exist with ball velocity on the distal side of the foot: ball velocity reduces as the impact location moves distally from the approximate centre of mass.

6.4.3 The influence of joint stiffness

The stiffness within the ankle joint influences change in ankle plantarflexion during impact. In this analysis, increasing ankle joint stiffness via the spring mechanism increased the internal torque applied by the ankle and reduced change in ankle plantarflexion during impact. In human kicking, two strategies have been identified to increase the stiffness within the ankle joint: increasing muscular strength and adopting a more plantarflexed position at the start of impact. Ball, et al. (2010) identified junior players were forced into greater plantarflexion than seniors, despite the lower force applied to the ball. The authors cautiously suggested the lower strength of junior players may have caused the greater magnitude of plantarflexion, but, did indicate variation in other impact characteristics such as ball orientation and impact location may have also influenced the ankle motion between the groups. Adopting a more plantarflexed position at the start of impact to increase ankle stiffness by relying on anatomical structures was identified by both Sterzing, et al. (2009) and Peacock, et al. (2017a). By performing a qualitative analysis of one individual within their group during soccer instep kicking, Sterzing, et al. (2009) suggested the footwear designs such as the sole plate and heel counter may restrict a players' ability to rely on anatomical structures within the ankle and foot. Peacock, et al. (2017a) identified in Australian football that players were able to significantly reduce the magnitude of change in ankle plantarflexion during impact by adopting a more plantarflexed position at impact start, where additional stiffness was provided by the hard-tissue structures at the end of the anatomical range of motion. Coaches should employ each of these strategies to increase the stiffness within the ankle joint of their players with a holistic approach. Firstly, assessing footwear designs to determine how they limit the range of motion; secondly, testing the players' ability to rely on anatomical structures at the end of the ankle range of motion; thirdly, improving strength to facilitate the ability to adopt a more plantarflexed position at the start of impact.

Increasing ankle joint stiffness increased ball velocity. This is the first study to provide empirical evidence that increasing ankle stiffness under a non-rigid ankle was beneficial to ball velocity. Several other studies have suggested increasing stiffness will translate to increased ball velocities (Ball, et al., 2010; Peacock, et al., 2017a; Sterzing, et al., 2009). Sterzing, et al. (2009) performed an ANOVA analysis of ball velocity between five kicking conditions (3 shod, 1 barefoot, 1 sock) and identified a p-value of 0.05 at the group level. No post-hoc analyses were performed between specific conditions, but visual inspection of the data revealed a trend toward increased ball velocity in the barefoot and socked conditions over the shod conditions. Further, this analysis may have been influenced by values of foot velocity. While observing differences in change in ankle plantarflexion, suggested to be due to an increased joint stiffness, Peacock, et al. (2017a) and Ball, et al. (2010) did not find statistically significant differences in foot-ball speed ratio. The difference in foot-ball speed ratio identified by Ball, et al. (2010) between the junior and senior groups was $p = 0.02$ with a medium effect, but was classified as non-significant due to Bonferroni adjustment. However, foot-ball speed ratio may have also been influenced by different body mass of the junior and senior groups, as identified by Shinkai, et al. (2013). The result of this study identifies that increasing stiffness does increase ball velocity.

Increasing joint stiffness increased ball velocity through effective mass, as a greater contribution of shank mass was included in the collision. Post-hoc analyses identified three trials reached the full range of ankle motion (the three with the largest ankle plantarflexion), and were removed from further post-hoc analysis. A positive significant linear relationship was identified between joint stiffness and effective mass. Somewhat surprising, a negative significant linear relationship was identified between joint stiffness and coefficient of restitution. This is in contrast to Sterzing, et al. (2009), who stated increased rigidity may have increased energy dissipation (coefficient of restitution). Further, it seems paradoxical that coefficient of restitution decreased with an increased stiffness; under a constant force (due to constant foot velocity), it was expected the magnitude of elastic energy stored in the spring mechanism to remain constant but with a reduced magnitude of change in ankle plantarflexion. This relationship may have been influenced by the four springs used (24 stiffness’ achieved from 4 springs at six initial deflections). Additional analysis within each of the four springs identified a dissimilar pattern: coefficient of restitution was not influenced by the initial deflection in three of the four springs, however, effective mass was influenced in all. Group comparisons of the springs also identified the two springs with the greatest stiffness (174N/mm & 222 N/mm) produced significantly ($p < 0.05$) lower coefficient of restitutions than the two springs with lowest stiffness (50 N/mm & 86 N/mm). In the regression analysis of the entire group, this meant coefficient of restitution reduced with an increasing stiffness due to the different springs and not the different levels of stiffness applied to the ankle joint. Further work is required to explore the role of coefficient of restitution with joint rigidity, but, it is clear that joint rigidity increases effective mass whereby a greater contribution of shank mass is included in the collision.

6.4.4 Practical applications

Change in ankle plantarflexion during foot-ball impact does not directly influence impact efficiency. This study identified how ball velocity and impact efficiency were influenced by three impact characteristics: foot velocity, impact location and joint stiffness. Change in ankle plantarflexion was a dependent variable under each of the analysed conditions. That is, change in ankle plantarflexion is a consequence of other impact characteristics. This identifies that change in ankle plantarflexion itself does not influence ball velocity and impact efficiency. Rather, other characteristics, such as those systematically analysed in the present study, influence ball velocity and impact efficiency. Practically, future researchers should not look at the relationship between change in ankle plantarflexion with impact efficiency and ball velocity without taking into account factors of foot velocity, impact location and others that relate to the internal and external torque applied to the ankle joint. Future work should investigate how factors that influence the internal and external torque applied to the ankle joint influence impact efficiency, such as impact location which has received little-to-no attention with human kickers. It is also important to note that this work was performed with a mechanical kicking machine, not human players. Differences in energy transfer for human players might be expected due to the mechanical design, but, the ankle motion was shown to be a valid representation of a human. Thus, the key theory of internal vs. external torques discussed in this paper is valid.

While it was just argued that change in ankle plantarflexion is not the independent variable that influences impact efficiency, the results in this study identify that ball velocity and impact efficiency were generally largest when change in ankle plantarflexion was minimised. Practically, this means that coaches can analyse the foot and/ or ankle motion during impact to provide useful feedback to athletes. With the development of camera technology, such as mobile phone cameras capable of recording up to 960 Hz, the analysis of foot-ball impact is becoming a possibility for everyday coaches. If a player produces a large magnitude of ankle plantarflexion, the results within this study indicate impact efficiency and ball velocity can be increased by (1) increasing the stiffness within the joint, and (2) by impacting the ball proximally toward the ankle. However, it is not known what levels of change in ankle plantarflexion translate to the greatest impact efficiency in human kickers. Additionally, coaches should also consider the distance and/ or speed that players are kicking, as a high foot velocity will induce a greater external torque applied to the joint.

6.5. Conclusion

This study systematically analysed joint stiffness, foot velocity and impact location with a mechanical kicking machine to determine their influence on change in ankle plantarflexion and ball velocity. Increasing joint stiffness reduced change in ankle plantarflexion and increased ball velocity. Increasing foot velocity increased change in ankle plantarflexion and ball velocity. Impacting distally on the foot increased change in ankle plantarflexion and reduced ball velocity. These results identify change in ankle plantarflexion was a dependent variable during foot-ball impact, and did not directly influence impact efficiency. The practical outcomes of this work are two-fold: (1) researchers should not assess the direct relationship between change in ankle plantarflexion with impact efficiency or ball velocity without taking into account the impact characteristics that influence the internal and external torque applied to the ankle, as change in ankle plantarflexion, impact efficiency and ball velocity are dependent upon other impact characteristics; (2) coaches can use ankle motion as a tool to assess the quality of impact, as impact efficiency was generally largest when change in ankle plantarflexion was minimal.

6.6. Contribution of individual chapter to overall thesis

The aim of chapter 6 was to identify if several impact characteristics (foot velocity, impact location, joint stiffness) influenced impact efficiency and/ or ball velocity, which contributed to answering aim 1 of the overall thesis. This research question was answered by performing a systematic exploration of foot-ball impact characteristics with the mechanical kicking machine. Further discussion of how to increase impact efficiency can be found in section 10.2. The results from this chapter were also used to inform the task chosen to analyse in Chapters 7 and 8. Foot velocity was identified to influence ankle plantarflexion, and a constant task of a 30m kick was chosen to be examined for the intra-individual analysis.

Chapter 7: Study 5 - Is there a sweet spot on the foot in kicking?

This chapter has been published in Journal of Sports Sciences and has undergone the peer-review process.

Abstract: In the collision between a striking implement and ball, the term "sweet spot" represents the impact location producing best results. In football kicking, it is not known if a sweet spot exists on the foot because no method to measure impact location in three-dimensional space exists. Therefore, the aims were: (1) develop a method to measure impact location on the foot in three-dimensional space; (2) determine if players impacted the ball with a particular location; (3) determine the relationship between impact location with kick performance; (4) discuss if a sweet spot exists on the foot. An intra-individual analysis was performed on foot-ball impact characteristics of ten players performing 30 Australian football drop punt kicks toward a target. (1) A method to measure impact location was developed and validated. (2) The impact locations were normally distributed, evidenced by non-significant results of the Shapiro-Wilk test ($p > 0.05$) and inspection of histograms, meaning players targeted a location on their foot. (3) Impact location influenced foot-ball energy transfer, ball flight trajectory and ankle plantar/dorsal flexion. (4) These results indicate a sweet spot exists on the foot for the Australian football drop punt kick. In conclusion, the impact location is an important impact characteristic.

7.1. Introduction

A successful outcome of any football kick is achieved by imparting a combination of flight characteristics. Kicking is used by players in all football codes to score goals, gain ground and/ or pass the ball to fellow team members. In Australian football drop punt kicking, because the ball is in projectile motion after it is impacted by the foot, it will only reach a desired destination if the necessary combination of flight characteristics is imparted onto the ball during foot-ball contact. Within gameplay, it can be advantageous to impart a certain combination of flight characteristics: increasing ball velocity while maintaining a low angle of elevation will reduce the time the ball is moving between players, which, in-turn, can reduce the likelihood of interception by the opposition; increasing ball velocity with a larger elevation angle can increase the distance the ball travels before striking the ground, providing opportunities to shoot from greater distances from the goal or clear the ball further down the ground when clearing the ball from defence. Regardless of the techniques used within gameplay, all players reach their desired target by applying a combination of flight characteristics by impacting the ball with their foot.

Researchers have identified biomechanical characteristics influential to flight characteristics across kicking techniques. During the foot-ball impact phase, the key phase a performer imparts ball flight characteristics during the kick, foot velocity, effective mass, and ankle motion have been identified as important impact characteristics. Foot velocity has found to be the most important factor for ball velocity (Asami & Nolte, 1983; Ball, 2008a, 2011; Kellis & Katis, 2007; Lees, Asai, Andersen, Nunome, & Sterzing, 2010; Peacock & Ball, 2016, 2017), and is a parameter that players can use to control kick distances (Peacock, et al., 2017a). The effective mass of the striking limb, be it due to the physical mass of the performer (Shinkai, et al., 2013) or the mass of the footwear used (Amos & Morag, 2002; Moschini & Smith, 2012; Sterzing & Hennig, 2008), is also an important contributor toward ball velocity. However, the extent that players can use this factor to increase ball velocity is limited: increasing the physical mass of the shoe may translate to an increased effective mass, but, in-turn, foot velocity reduces where the overall momentum of the limb remains constant (Amos & Morag, 2002; Moschini & Smith, 2012). Recently, focus has been applied to the ankle motion and its role during impact. The ankle has been found to be forced into passive plantarflexion during impact (Peacock, et al., 2017a; Shinkai, et al., 2009), and minimising this motion has been identified beneficial to ball velocity (Peacock & Ball, 2018a).

The impact location on the foot during kicking is emerging as an influential characteristic to kick outcome, as identified by recent mechanical modelling studies. By analysing foot-ball impact with a mechanical kicking machine, impact location across medial-lateral and proximal-distal directions on the foot was shown to influence ball flight trajectory, ball velocity, ball spin and ankle plantarflexion (Peacock & Ball, 2017, 2018b). For human kickers, impact location on the foot is also emerging as influential to kick outcome. Mathematical modelling and finite element analyses revealed impact location across either the proximal-distal or medial-lateral directions of the foot was influential to ball velocity and ball spin (Asai, et al., 2002; Ishii, et al., 2009, 2012).

The relationship between impact location and kick outcome measures with human kickers has not been fully explored, and the analysis with the mechanical kicking machine indicates further research is warranted. Currently, no method has been developed to measure impact location across the medial-lateral and proximal-distal directions on the foot. A complex problem exists when measuring the point of intersection between the foot and ball, due to non-uniform changes in the foot surface relative to the segments centroid position. Furthermore, the difficulty of measuring the point of intersection is again increased in kicking codes that use a non-spherical ball, also due to the non-uniform location of the ball surface relative to the balls centroid position. Thus, a method to calculate impact location must be developed to fully understand the influence of impact location of human kickers.

Players anecdotally report there is a sweet spot on the foot, further suggesting impact location influences kick outcome. The term “sweet spot” has traditionally been used by researchers in the analysis of striking implements with a ball (rackets, bats) to represent the impact location that delivers maximum performance (Brody, 1981; Cross, 1998), and the term is also used by players when assessing how they strike the ball. Specifically, if they struck the ball with the desired location of their foot. Interestingly, the analysis of striking implements not only revealed a sweet spot does exist, but the location of the sweet spot changes depending on how performance is measured (Brody, 1981). For example, in an analysis of a cricket bat, Bower (2012) found the ball speed sweet spot was distally toward the toe of the bat by 11 cm compared to the apparent coefficient of restitution sweet spot.

The purpose of the present study was to determine the importance of impact location on the foot. To explore this issue, the Australian football drop punt kick was analysed. Four specific aims existed. Firstly, to develop a method to measure the impact location on the foot across both dimensions that would present impact location as a distance from the foot centre across the proximal-distal and medial-lateral impact locations. Secondly, to determine if players attempted to strike the ball with a particular location on the foot. Thirdly, to identify the relationship between impact location on energy transfer and ball flight trajectory, specifically foot-ball speed ratio, coefficient of restitution, ankle plantar/dorsal flexion, effective mass and azimuth ball flight angle. Fourthly, to discuss the concept of "sweet spot" in the application of football kicking using the information gathered from the present analysis and discuss if a sweet spot exists on the foot.

7.2. Methods

7.2.1 Task, data collection and analysis

After gaining informed consent approved by the university human research ethics committee, ten players between the age of 20 to 28 years old with various expertise playing Australian Football (amateur through to elite competition) were recruited for the study (Table 7.1). Each player performed 30 drop punt kicks toward a target 30 meters in distance with a standard Australian Football ball (Sherrin Match Ball; size = 5; mass = 0.455 kg; inflation = 69 kPa) in a laboratory setting that featured an athletics track surface. This kicking task simulated kicking to a fellow team member on the field. The total number of kicks analysed varied between each player due to the foot and/ or ball not remaining in the calibrated volume throughout the duration of foot-ball impact (Table 7.1). Despite this, a broad range of kick outcomes (i.e. kicks that went to the left and right of the target, and hit the target) were captured, enabling an intra-individual analysis to be performed.

Table 7.1: Characteristics of individual players.

Player	Gender	Height (m)	Mass (kg)	Shoe	Number of kicks analysed
1	Female	1.68	59	Training shoe	27
2	Male	1.78	87	Football boot	24
3	Male	1.85	87	Training shoe	25
4	Male	1.92	87	Football boot	29
5	Male	1.85	91	Football boot	22
6	Male	1.80	86	Football boot	25
7	Male	1.77	84	Football boot	25
8	Male	1.78	99	Football boot	28
9	Male	1.77	67	Indoor football boot	25
10	Female	1.57	55	Football boot	20

Three high-speed-video cameras were synchronised and positioned to record each kicking trial (Photron SA3 & MC2, Photron Inc., USA). The measurement system was set up with the Y-axis of the global coordinate system aligned from the kick location to the target, the X-axis representing the medio/lateral dimension (right direction = positive), and the Z-axis in the vertical dimension. The cameras were calibrated from a fixture consisting of 60 points (Xcitex Inc., USA), yielding a root mean square error of < 1.0 mm within the measurement system (ProAnalyst software, Xcitex Inc., USA).

A six degrees of freedom model comprising the shank, foot and ball was created for each player. During a static trial, the distal, proximal and centroid positions of the shank and foot were obtained from reflective markers attached to the lateral and medial epicondyles of the knee, the lateral and medial ankle malleolus, and the head of the fifth (lateral aspect) and first (medial aspect) metatarsals. Additional reflective markers were attached to the most dorsal aspect of the foot at the head of the metatarsals and at the malleolus to generate the surface location of the foot relative to the foot segment for calculation of impact point (discussed below). The centroid position and three radii of the ball (Figure 7.1b; r_x, r_y, r_z) were determined from markers attached at both ends of the long axis and two short axes. These key anatomical landmarks were projected from tracking markers that remained on the players during the kicking trials. The shank and foot were each represented by five spherical reflective markers 13 mm in diameter, fixed to the limb using rigid strapping tape. Tracking markers on the ball consisted of flat rectangular pieces of reflective tape (2.5 x 2.5 cm) with an 8mm black circular sticker attached to the middle. Spherical markers could not be attached to the ball during kicking trials as their presence would impede the player's ability to hold the ball as it is dropped, possibly contact the ball during impact, and influence ball flight.

Data of each kicking trial were measured at 4,000 Hz from 20 frames before to 20 frames after visually identified ball contact and release, respectively. Markers were tracked in ProAnalyst software (Xcitex Inc., USA) and three-dimensional X-Y-Z data of individual tracking markers were imported into Visual3d software (C-Motion Inc., USA) where the six degrees of freedom model was applied. Data were smoothed with a low pass Butterworth filter at a cut-off frequency of 280 Hz. The choice of smoothing procedure was based on three criteria, comprising the results from direct Fourier transform analysis (identifying the amplitude of the signal between 20 to 400 Hz), the cut-off frequencies used in previous studies examining foot-ball impact of kicking (Nunome, et al., 2006; Peacock, et al., 2017), and visual inspection of the data curves at different cut-offs.

Impact characteristics were calculated within Visual3d software. Initial and final velocities of the foot and ball (individual axes & resultant) were calculated from the average velocity of the segment centre of gravity over five frames before and after impact. Foot-ball speed ratio was calculated from initial foot resultant velocity divided by final ball resultant velocity. Effective mass was calculated from the change in ball momentum divided by the change in foot velocity. Coefficient of restitution was calculated using the initial and final resultant velocities of the foot and ball. Change in ankle plantar/dorsal flexion angle was calculated from the six degrees of freedom model (final angle subtract initial angle). Ball azimuth angle was calculated within the global coordinate system over five frames after ball release (Peacock & Ball, 2017).

7.2.2 Calculation of impact point

A novel method was developed to calculate the impact location on the foot by modelling the foot and ball as rigid bodies within Matlab software (R2016b, The Mathworks, Inc.). The anterior surface foot was modelled as a semi-elliptical cylinder (Figure 7.1a; Equation 7.1-4) and the ball an ellipsoid (Figure 7.1b; Equation 7.5). Both models were shells projected from their centroid position based on their geometric properties derived during a static capture. The anterior surface of the foot was constructed as a 200 x 200-point grid of X-Y-Z coordinates. Between each kick there were two variables that distinguished the impact location; relative foot-ball orientation and relative foot-ball displacement. Therefore, the grid was rotated and translated to the relative orientation and position of the foot and ball. To identify the intersecting point on the foot and the ball, each position of the grid was entered into the equation of the ball (Equation 7.5), which solved the depth of the point relative to its shell. Any point on the shell yielded a value of 1, a point that was in the shell yielded a value of < 1, and a point with a value > 1 was outside the shell. The impact location on the foot was assumed to yield the smallest value from the entire grid. From identifying the X-Y-Z coordinate of impact location, the impact location across the medial-lateral and proximal-distal direction was calculated as the distance from the foot centre.

$$x_l = \frac{w_l}{2} \cos \emptyset \qquad \text{Equation 7.1}$$

Where x_l = the x-coordinate of the foot grid for a given length of the foot; w_l = the width of the foot for a given length, calculated from Equation 2; θ = a vector comprising 200 linearly spaced angles between 0° to 180°.

$$w_l = \frac{(w_d - w_p)}{2 \cdot l} \cdot w_l + w_p \qquad \text{Equation 7.2}$$

Where w_d = the width of the foot at the distal end of the segment; w_p = the width of the foot at the proximal end of the segment; l = the length of the foot.

$$y_l = h_l \sin \emptyset \qquad \text{Equation 7.3}$$

Where y_l = the y-coordinate of the foot grid for a given length of the foot; h_l = the height of the foot at a given length.

$$h_l = \frac{(h_p - h_d)}{l} \cdot h_l + h_d \qquad \text{Equation 7.4}$$

Where h_p = the height of the foot at the proximal end of the segment; h_d = the height of the foot at the distal end of the segment.

$$\frac{{x_l}^2}{{r_x}^2} + \frac{{y_l}^2}{{r_y}^2} + \frac{l^2}{{r_z}^2} = d \qquad \text{Equation 7.5}$$

Where r_x = the short radius of the ball; r_y = the short radius of the ball (note: $r_x = r_y$); r_z = the long radius of the ball; d = the depth of the coordinate relative to the ball shell.

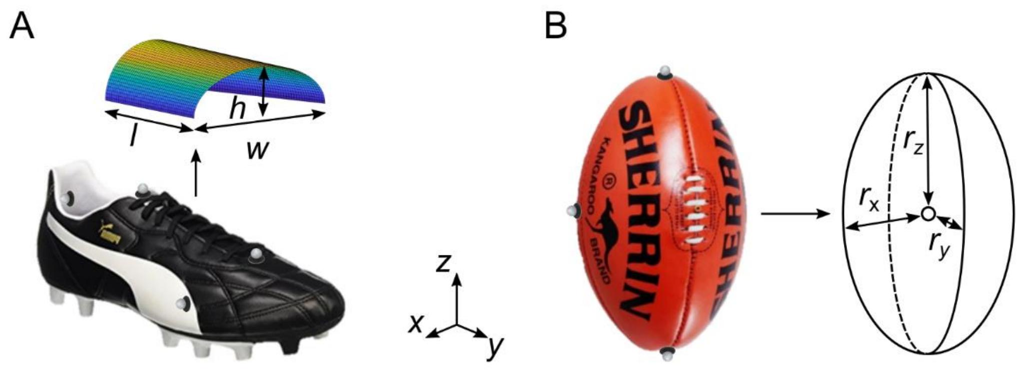

Figure 7.1: A) the grid representing the anterior aspect of the foot. B) the model of the ball shell. Approximate locations of static markers are attached to the foot.

7.2.3 Statistical analysis

To determine if the method to calculate impact location on the foot was valid (aim 1), criterion validation was performed. Criterion validation was performed across both dimensions of the foot (medial-lateral and proximal-distal) by calculating the standard error of estimate to determine the level of error within the measurement in real-world units. The error was calculated at the 95% confidence interval. Additional data were produced under a static condition using a three-dimensionally printed foot with a boot attached for the validation. Under the static condition, the position of the ball relative to the foot was moved systematically across each dimension while ball orientation was held constant. The criterion measure was the distance between the bottom edge of the ball to the centre of the foot, and the practical measure was the calculated impact location for each dimension being assessed. A modified version of linear regression was used to calculate the standard error of the estimate that included a coefficient for the intercept but no coefficient for the slope. This was considered more appropriate than the standard regression including also including a coefficient for the slope, because both measures were in the same units (meters) but were offset by a constant distance because ball orientation was held constant (the distance from the bottom point of the ball to the impact location).

To determine if players aimed to strike the ball with a particular location on their foot (aim 2), the measured impact locations were tested for normality. The distribution of impact location across for the proximal-distal and medial-lateral impact locations were tested for normality both visually from histograms and through normality tests, using the Shapiro-Wilk test ($p > 0.05$ indicating normality) within SPSS software, as recommended by Ghasemi and Zahediasl (2012).

To determine the relationship between impact location with kick outcome measures (aim 3), bivariate regressions were performed. The two fundamental ball flight characteristics are ball velocity and kick direction of travel: foot-ball speed ratio, coefficient of restitution, ankle plantar/dorsal flexion, and effective mass have all been used to describe different factors associated with energy transfer from foot to ball, and ball azimuth angle has been used to describe the ball direction of travel; we determined the influence of impact location on these measures. To achieve this, a bivariate regression analysis was performed within Matlab Software using the Curve Fitting App. Linear and quadratic curves were assessed, and the type of relationship chosen was based on: inspection of the scatterplots, inspection of residuals, a theoretical underpinning, and the significance test from Hayes (1970) to indicate if the second order regression significantly improved the fit. Previously it was identified the proximal-distal dimension was mostly influential to energy transfer, and the medial-lateral dimension was influential to ball azimuth (Peacock & Ball, 2017), therefore, to reduce the analysis, each dimension of the foot was assessed using only the respective performance measures.

The sweet spot location on the foot for each of the kicking measures were also identified by interpreting the coefficients of the regression equations. The sweet spot is the impact location that delivers maximum performance for the respective measure. Maximum performance for azimuth ball flight angle was 0°, and we identified the impact location on the foot from the regression equation that yielded a ball flight angle of 0° (Figure 7.3). For ankle plantar/dorsal flexion during impact, because it has been established reducing ankle motion is beneficial to performance, we set the sweet spot at a change in ankle angle of 0°, and identified the impact location across the proximal-distal direction of the foot that corresponded to this point, as indicated from the regression equation. Foot-ball speed ratio, coefficient of restitution and effective mass are all scalar values, and increasing them is considered beneficial to performance as they will all increase ball velocity. Therefore, the sweet spot location for these measures is found at the highest point, which, can only be identified from the turning point in the quadratic equation (see Figure 7.4 as an example). No turning point in the quadratic equations (the maximum performance for the given measure) were identified in the range of data for some individuals, therefore, no sweet spot was identified for that individual. Statistical confidence on these locations were determined from 90% confidence intervals, calculated from the standard error of the coefficients.

7.3. Results

7.3.1 Validation of impact location measurement

Criterion validation of the model identified the error to be less than the error within the measurement system, and was therefore valid for use. The standard error across both dimensions of the foot was < 1 mm, and the 95% confidence interval was also < 1 mm. Therefore, the methodology was appropriate to calculate impact location to the error within the measurement system, 1 mm.

7.3.2 The distribution of impact locations between kicks.

All players produced a normal distribution of impact locations across both the medial-lateral and proximal-distal directions of the foot, evidenced by the non-significant ($p > 0.05$) results of the Shapiro-Wilk tests and visual inspection of the histograms. The mean impact location across the medial-lateral direction was identified to be on the medial side of the foot for all players, whereas the mean impact locations across the proximal-distal direction varied to be either proximally or distally from the foot centre between players (Table 7.2; Figure 7.2 for Player 4).

Table 7.2: The mean and standard deviations of impact locations across the medial-lateral and proximal-distal directions of the foot, measured from the foot centre. Positive values represent the lateral and distal direction of the foot.

Player	Medial-lateral impact location (mm)	Proximal-distal impact location (mm)
1	-6 ± 3*	12 ± 22*
2	-8 ± 3*	-29 ± 15*
3	-4 ± 3*	4 ± 14*
4	-7 ± 2*	11 ± 13*
5	-10 ± 2*	6 ± 18*
6	-10 ± 3*	24 ± 13*
7	-8 ± 3*	5 ± 22*
8	-2 ± 2*	-1 ± 17*
9	-8 ± 3*	12 ± 16*

10	-5 ± 3*	-5 ± 24*

* indicates normally distributed, as quantified from the Shapiro-Wilk Test ($p > 0.05$).

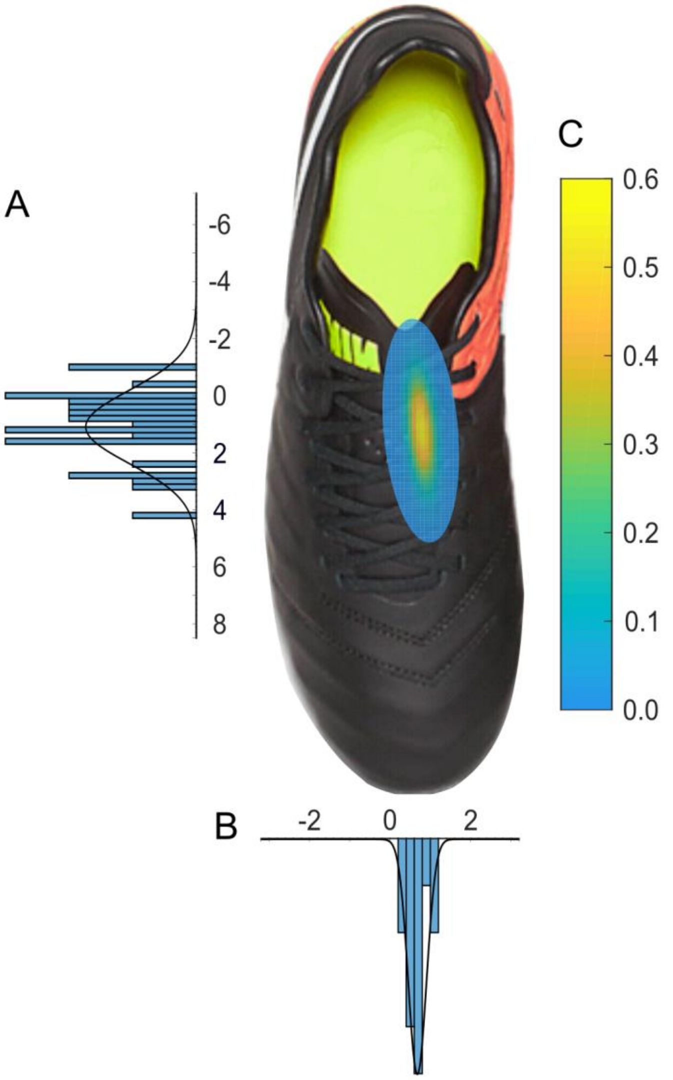

Figure 7.2: The impact location for Player 4. A) Histogram of impact location across the proximal-distal impact location (cm from foot centre of mass). B) Histogram of impact location across the medial-lateral impact location (cm from foot centre of mass). The bivariate distribution plot has been superimposed onto the foot, and the scale (C) represents the relative distribution.

7.3.3 The relationship between impact location and kick outcome.

A positive linear relationship existed for nine players between medial-lateral impact location with ball azimuth flight angle. The sweet spot, the impact location that delivered an azimuth ball flight of 0°, occurred on the medial aspect of the foot for all players (Table 7.3; Figure 7.3 for Player 8). The direction of the relationship meant that impact locations to the lateral side of this sweet spot resulted in an azimuth ball flight in the lateral direction.

Table 7.3: Relationship between medial-lateral impact location and azimuth ball flight angle.

Player	Linear		Second order		Sweet spot location
	R-squared	Classification	R-squared	Classification	
1	**0.47^**	**Large**	0.59^*	Nearly Perfect	-6 ± 1
2	**0.58^**	**Nearly Perfect**	0.58^	Nearly Perfect	-7 ± < 0.1
3	**0.34^**	**Large**	0.35^	Large	-4 ± 1
4	**0.52^**	**Nearly Perfect**	0.53^	Nearly Perfect	-7 ± 1
5	**0.40^**	**Large**	0.40^	Large	-12 ± 1
6	**0.39^**	**Large**	0.39^	Large	-12 ± 1
7	0.08	Small	0.10	Medium	-8 ± 2
8	**0.45^**	**Large**	0.45^	Large	-2 ± < 0.1
9	**0.27^**	**Large**	0.27^	Large	-10 ± 2
10	**0.20^**	**Medium**	0.30^	Large	-3 ± 1

^ indicates $p < 0.05$; * indicates significance from Hayes (1970); bolded relationship represents chosen relationship.

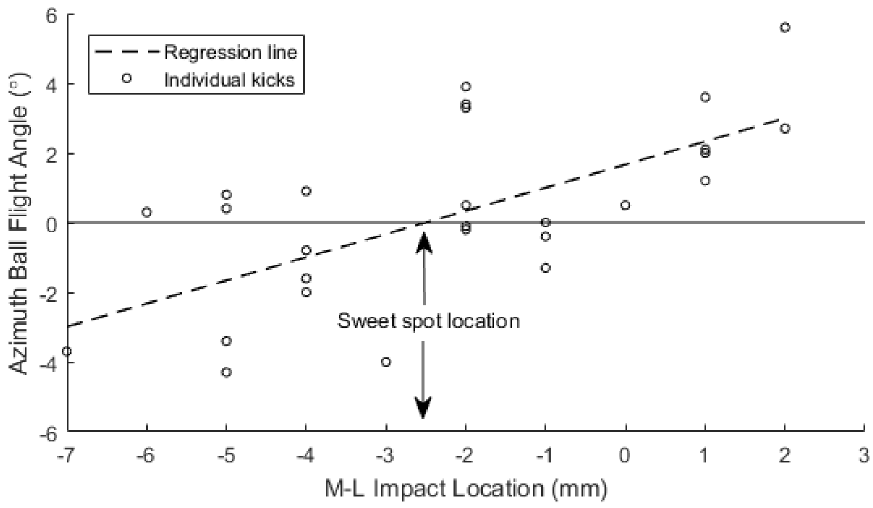

Figure 7.3: The relationship between medial-lateral impact location and azimuth ball flight angle for Player 8. The sweet spot location (the point on the horizontal axis) can be identified by identifying the azimuth ball flight angle (vertical axis at 0°) from the regression line. Positive values represent the lateral direction from foot centre (impact location) and ball flight trajectory (azimuth ball flight angle).

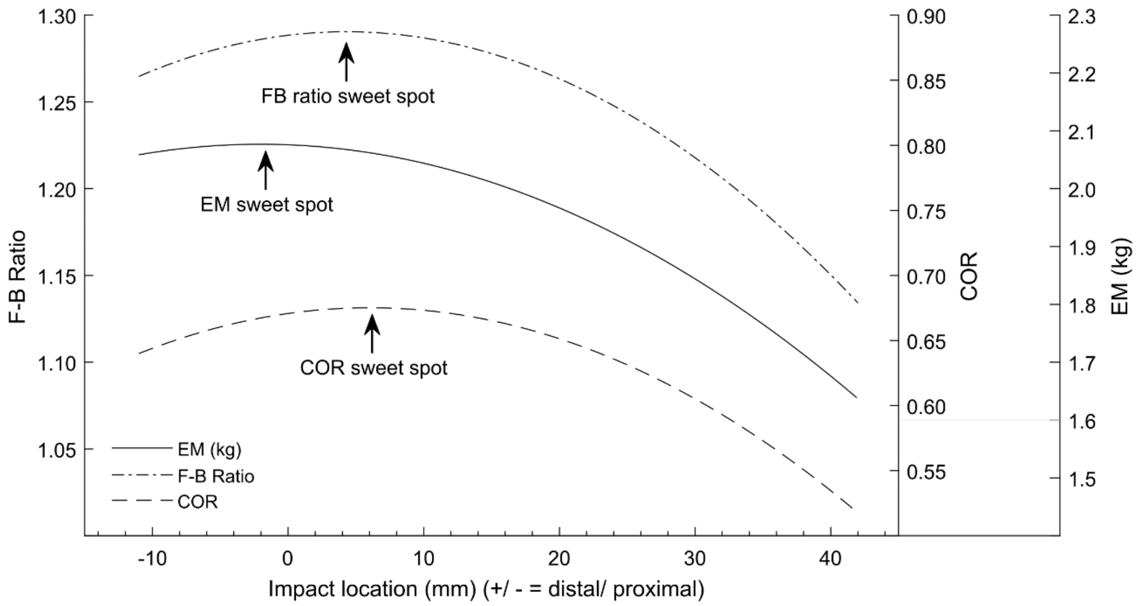

Figure 7.4: The proximal-distal (P-D) sweet spot locations for Player 4, as identified by the quadratic regressions between impact location with foot-ball speed ratio (FB Ratio),

coefficient of restitution (COR), and effective mass (EM). Positive values of impact location represent the distal location from the foot centre.

A positive linear relationship was identified in all players between proximal-distal impact location with ankle plantar/dorsal flexion (Table 7.4). The sweet spot, the location that produced a change in ankle angle of 0°, varied between players to occur on either proximally or distally from the foot centre. As players impacted the ball at a location distally from the sweet spot, the magnitude of plantarflexion increased.

Table 7.4: Relationship between proximal-distal impact location and change in ankle plantar/dorsal flexion.

Player	Linear R-squared	Linear Classification	Second order R-squared	Second order Classification	Sweet spot location
1	**0.94^**	**Perfect**	0.94^	Perfect	-12 ± 3
2	**0.89^**	**Perfect**	0.89^	Perfect	-18 ± 2
3	**0.81^**	**Perfect**	0.82^	Perfect	-4 ± 3
4	**0.73^**	**Nearly Perfect**	0.78^*	Nearly Perfect	9 ± 2
5	**0.84^**	**Perfect**	0.84^	Perfect	-11 ± 4
6	**0.64^**	**Nearly Perfect**	0.71^*	Nearly Perfect	8 ± 5
7	**0.93^**	**Perfect**	0.93^	Perfect	1 ± 2
8	**0.93^**	**Perfect**	0.94^*	Perfect	9 ± 1
9	**0.88^**	**Perfect**	0.89^	Perfect	5 ± 2
10	**0.87^**	**Perfect**	0.87^	Perfect	-27 ± 5

^ indicates $p < 0.05$; * indicates significance from Hayes (1970); bolded relationship represents chosen relationship.

Quadratic relationships between proximal-distal impact location and foot-ball speed ratio and a sweet spot location were identified in four players (Table 7.5; Figure 7.4 for Player 4). When players impacted the ball either side from the sweet spot location, foot-ball speed ratio decreased. Negative linear relationships were identified between proximal-distal impact location and foot-ball speed ratio in Player 2 and Player 7. A positive linear relationship existed between proximal-distal impact location and foot-ball speed ratio for Player 3.

Table 7.5: Relationship between proximal-distal impact location and foot-ball speed ratio.

Player	Linear		Second order		Sweet spot location
	R-squared	Classification	R-squared	Classification	
1	<0.01	Trivial	<0.01	Trivial	-
2	**0.11**	**Medium**	0.11	Medium	-
3	**0.10**	**Medium**	0.10	Medium	-
4	0.33^	Large	**0.53^***	**Nearly Perfect**	4 ± 7
5	0.01	Trivial	0.08	Small	-
6	<0.01	Trivial	0.04	Small	-
7	**0.23^**	**Medium**	0.26^	Large	-
8	0.01	Small	**0.31^***	**Large**	-2 ± 6
9	<0.01	Trivial	**0.34^***	**Large**	7 ± 6
10	0.44^	Large	**0.77^***	**Nearly Perfect**	-25 ± 9

^ indicates $p < 0.05$; * indicates significance from Hayes (1970); bolded relationship represents chosen relationship.

Five players displayed a linear relationship between proximal-distal impact location and effective mass that was negative in direction for all (Table 7.6). Three players displayed a quadratic relationship, and a sweet spot could be identified in each (Figure 7.4 for Player 4).

Table 7.6: Relationship between proximal-distal impact location and effective mass.

Player	Linear R-squared	Linear Classification	Second order R-squared	Second order Classification	Sweet spot location
1	0.11	Small	**0.28^***	**Small**	3 ± 6
2	**0.20^**	**Medium**	0.20	Medium	-
3	< 0.01	Trivial	< 0.01	Trivial	-
4	0.42^	Large	**0.52^***	**Nearly Perfect**	-2 ± 6
5	**0.61^**	**Nearly Perfect**	0.63^	Nearly Perfect	-
6	0.09	Small	0.12	Medium	-
7	**0.75^**	**Nearly Perfect**	0.76^	Nearly Perfect	-
8	**0.59^**	**Nearly Perfect**	0.60^	Nearly Perfect	-
9	0.17	Medium	**0.23^***	**Medium**	3 ± 12
10	**0.54**	**Nearly Perfect^**	0.60^	Nearly Perfect	-

^ indicates $p < 0.05$; * indicates significance from Hayes (1970); bolded relationship represents chosen relationship.

Quadratic relationships and a sweet spot location were identified between proximal-distal impact location with coefficient of restitution for five players (Table 7.7; Figure 7.4 for Player 4). A positive linear relationship was in one player, Player 5.

Table 7.7: The relationship between proximal-distal impact location and coefficient of restitution.

Player	Linear		Second order		Sweet spot location
	R-squared	Classification	R-squared	Classification	
1	0.02	Small	0.02	Small	-
2	0.01	Trivial	0.02	Small	-
3	0.03	Small	**0.15***	**Medium**	-4 ± 3
4	0.20^	Medium	**0.37^***	**Large**	9 ± 2
5	**0.15^**	**Medium**	0.17	Medium	-
6	0.00	Trivial	0.03	Small	-
7	0.05	Small	0.08	Small	-
8	0.08	Small	**0.41^***	**Large**	9 ± 1
9	0.11	Medium	**0.35^***	**Large**	5 ± 2
10	<0.01	Trivial	**0.30^***	**Large**	-27 ± 5

^ indicates $p < 0.05$; * indicates significance from Hayes (1970); bolded relationship represents chosen relationship.

7.4. Discussion

The aim of the present study was to determine the influence of impact location on kick outcome by quantitatively answering three aims: (1) by developing and validating a method to calculate impact location across both the medial-lateral and proximal-distal dimensions of the foot; (2) by determining if players aimed to strike the ball with a particular location on their foot; and (3), by identifying the relationship between impact location with kick outcome measures, and interpreting the regression equations to identify if there was an impact location that delivered the greatest performance. From an analysis of the Australian football drop punt kick, the key results of this study were: (1) the developed method to calculate impact location was valid; (2) the measured impact locations were normally distributed; and (3) the impact location across the medial-lateral and proximal-distal directions of the foot influenced kick outcome, and, an impact location that produced the highest performance was identified for some individuals.

7.4.1 Did players target a specific location on their foot?

In the present analysis of the Australian football drop punt kick, all players produced a normal distribution of impact locations across both dimensions of the foot, indicating they targeted a specific location. Because none of the players were novices, but had kicking experience, the targeted impact location was best for the task. End-point variability did exist within this distribution, but its influence was random, where the mean impact location was located at, or close to, the true sweet spot. Players impacted the ball with a precise location on their foot.

7.4.2 Medial-lateral impact location

The medial-lateral impact location influenced azimuth ball flight angle. Nine of ten players produced a linear relationship between medial-lateral impact location with azimuth ball flight angle (Table 7.3), supporting the findings of Peacock and Ball (2017) who also identified this pattern in their analysis with a mechanical kicking machine analysing the drop punt kick. As discussed by Peacock and Ball (2017), the oblique impact theory indicates the angle of the intersecting surfaces influences the angle of trajectory. Across the medial-lateral dimension of the foot, the surface angle of the foot changes substantially, where azimuth ball flight trajectory will be 0° at the impact location where the medial-lateral surface angle is perpendicular to the direction of the target. For all players, this location was on the medial aspect of the foot due to its asymmetrical shape, as found by Peacock and Ball (2017) on their mechanical kicking machine. Because the surface angle of the foot changes substantially across the medial-lateral dimension, the impact location across the medial-lateral direction on the foot is a key variable toward azimuth ball flight angle.

7.4.3 Proximal-distal impact location

The proximal-distal impact location influenced ankle plantar/dorsal flexion during foot-ball impact (Table 7.4). A linear relationship was identified for all players between impact location with ankle plantar/dorsal flexion, where impacting the ball distally from this location corresponded to an increased ankle plantarflexion. Because ankle motion during foot-ball impact is passive (Nunome, et al., 2006b; Peacock & Ball, 2018a, 2018b; Shinkai, et al., 2009), the resulting ankle motion is largely dependent upon the torque applied to the ankle joint. Between kicks in the present study, the average force applied to the foot changed minimally because the kick distance was constant (impact force associated with kick distance; (Peacock, et al., 2017a)). Therefore, the resulting torque applied about the ankle was mostly dependent upon the moment arm, which is the distance between the proximal-distal impact location and the ankle joint. Thus, the proximal-distal impact location is an influential characteristic to ankle plantar/dorsal flexion during impact, in addition to the starting angle of the ankle (Peacock, et al., 2017a) and the stiffness of the ankle joint (Ball, et al., 2010; Peacock & Ball, 2018b).

Impact location influenced foot-ball speed ratio in most players and a location that produced the greatest impact efficiency was identified in four players (Table 7.5). Foot-ball speed ratio has been used previously to describe the efficiency of energy transferred from foot to ball (Ball, et al., 2010; Peacock, et al., 2017a; Shinkai, et al., 2013; Smith, et al., 2009), and we identified in players an impact location that produced the highest impact efficiency, as quantified by foot-ball speed ratio. Further, we identified three players produced linear relationship with foot-ball speed ratio, meaning impact efficiency was influenced by the impact location in these players as well. These results suggest the impact location across the proximal-distal direction was influential to energy transfer.

While an impact location yielding the highest efficiency was not identified across all players, it is hypothesised an optimal relationship does exist but the range of impact locations measured was not large enough. Because we analysed drop punt kicking, where the ball is dropped prior to being impacted by the ball, it was not possible to systematically control impact location. The range of impact location in the present study ~70 mm, far less than the overall length of the foot. Furthermore, foot-ball angle is another variable that could not be controlled due to the ball drop. For a given impact location, the resulting area covering the foot due to deformation is also dependent upon the relative foot-ball orientation. Foot-ball angle has also been identified to influence ball velocity (Peacock & Ball, 2017). The variation in foot-ball angle will add noise to the relationship between impact location with kick outcome measures (not just impact efficiency). It is hypothesised a quadratic relationship will exist in all players between impact location with impact efficiency. As players impact distally on the foot, the ankle and foot are forced into plantarflexion which reduces impact efficiency. Impacting proximally produces a lower velocity of the impacting point compared to a more distal location, which Peacock and Ball (2017) identified was detrimental to ball velocity. Supporting this hypothesis, Ishii, et al. (2012) identified a quadratic equation to impact location and standardised ball speeds in all five of their tested players performing the soccer instep kick. Because the authors were analysing the soccer instep kick where the ball is stationary prior to being impact, the impact location could be and was controlled by altering the height of the ball above the ground with a tee; the total range of tested impact locations was 140 mm across the proximal-distal direction.

It could not be clearly identified how impact location influenced impact efficiency in human kickers. In the present analysis, coefficient of restitution and effective mass were both associated with proximal-distal impact location between players (Table 7.6 and 7.7). In their analysis with a mechanical kicking machine, Peacock and Ball (2018b) found distal impact locations decreased ball velocity. This decrease in ball velocity was due to decreases in coefficient of restitution as the greater magnitude of ankle plantarflexion at the end of impact with distal impact locations meant more elastic energy was stored in the spring mechanism (that represented the muscle tendon unit) and was not transferred to ball velocity. Conversely, increases to joint stiffness, which also decreased ankle plantarflexion and increased ball velocity, increased effective mass and had no effect on coefficient of restitution as less of the kinetic energy from the shank could be transferred to the ball via the ankle joint. This mechanical modelling suggested different strategies to reduce ankle plantarflexion influenced impact efficiency through different mechanisms. Specifically, proximal impact locations influence impact efficiency through coefficient of restitution and not effective mass. In this analysis with human kickers, however, it could not be clearly seen that impact location influenced coefficient of restitution and not effective mass, as identified in the mechanical kicking machine.

The difference between impact location influencing energy transfer mechanisms for the human kicking and the mechanical kicking machine might be explained by two reasons. Firstly, variance in other impact characteristics, such as foot-ball angle, might influence individual energy transfer mechanisms and confound each individual relationship by adding random noise (as discussed previously with foot-ball speed ratio). Secondly, the observed difference might be due to differences in design between the mechanical kicking machine and the human ankle. During ankle plantarflexion of the kicking machine, all energy had to be stored in the spring mechanism. This storage of elastic energy during ankle plantarflexion can occur with stretching of the muscle tendon unit for the human ankle. But, plantarflexion of the human ankle can also occur from an increase in length of the muscle component within the muscle tendon unit. Furthermore, the lengthening of the muscle component is more likely to occur as impact location moves distally. This is due to the increased moment arm with distal impact locations that requires an increased internal muscle force to maintain an isometric contraction – which is possibly exceeded at distal impact locations. As the muscle tendon unit increases length – not from stretching where the elastic energy would be stored but during an eccentric muscle contraction – the shank's ability to contribute kinetic energy to the collision is impaired because of the diminished force cannot be transferred through the muscle tendon unit to maintain rigidity. Thus, the decreased effective mass is due to less of the shank mass (or, the kinetic energy) included in the collision.

Important to note, muscle activation of the ankle dorsal flexors still appears to be important toward producing high impact efficiency and ball velocity. Because the muscles can act as a brake during muscle lengthening (Dickinson, et al., 2000; Williams, Regnier, & Daniel, 2012), the foot does not rotate freely around the bottom of the shank. This introduces some component of the shank toward the collision. Therefore, while no studied has determined the efficaciousness, these results support previous suggestions that players could perform strength training of the ankle musculature to improve impact efficiency (Ball, et al., 2010; Peacock & Ball, 2018a, 2018b).

7.4.4 Is there a sweet spot on the foot?

The sweet spot is a term classically used in the analysis of striking implements for the impact location that produces the best results for the outcome of the task. We argue two key points that support a sweet spot exists on the foot during Australian football drop punt kicking. Firstly, all players produced a normal distribution of impact locations, meaning, they specifically targeted a location on their foot. There was a distribution of impact locations, but this distribution was random due to end-point variability. Secondly; the impact location influences the outcome of the task. The medial-lateral direction influences azimuth ball flight trajectory, and the proximal-distal direction influences ankle motion and energy transfer. Depending on the desired flight characteristics imparted onto the ball, players should look to impact the ball with the corresponding impact location on the foot that would yield those flight characteristics. Across the medial-lateral dimension for the present study, as an example, the sweet spot location was identified to be on the medial aspect of the foot as it the task required players to kick straight toward the target. While not directly associated with ball flight, but an important characteristic nonetheless, is the influence of impact location on ankle plantar/dorsal flexion. Impacting the ball on the foot with a distal impact location will force the ankle into a large magnitude of ankle plantarflexion, which will put the player at a greater risk of injury (Tol, et al., 2002) and produce pain within the ankle and metatarsophalangeal joint. From these two points, we conclude that a sweet spot does exist on the foot. But, it is important to mention, the location of the sweet spot is likely to change depending on the task and how performance is measured. Future research could explore how players functionally adapt their impact characteristics to satisfy different task constraints.

7.5. Conclusion

The present study identified the importance of impact location on the foot to the outcome of the Australian football drop punt kick by quantitatively answering the following three aims: (1) a method to calculate the impact location across the medial-lateral and proximal-distal dimensions of the foot was developed and validated to the accuracy of the measurement system (< 1.0 mm); (2) it was identified that players impacted the ball with a specific location on their foot, evidenced by normal distributions of the impact location across both dimensions of the foot; and (3) impact location influenced kick outcome measures (energy transfer, ball flight trajectory, ankle motion), and the location producing the best results (sweet spot) for several measures was identified. From these results, we conclude there is a sweet spot on the foot during the Australian football drop punt kick.

7.6. Contribution of individual chapter to overall thesis

Impact location on the foot was identified in previous chapters (Chapter 4 and 6) to influence impact efficiency, ankle plantarflexion and ball flight characteristics (aims 1 and 2 of the present thesis). The aim of the present Chapter was to again determine the effect of impact location on impact efficiency, ankle plantarflexion and ball flight characteristics, but analysing human kickers instead of using the mechanical kicking machine. The results from the present chapter support the findings from previous work and contribute to answering aims 1 and 2 of the overall thesis. A further discussion of how proximal-distal impact location influences impact efficiency and ankle plantarflexion is found in section 10.1.3. A discussion of how medial-lateral impact location influenced ball flight characteristics is found in section 10.2.1.

Chapter 8: Study 6 - Kick impact characteristics of accurate football kicking

This chapter has been published in the journal Human Movement Science and has undergone the peer-review process.

Abstract: Accurate kicking is essential to team success in Australian football. It is not known how foot-ball impact characteristics influence kicking accuracy, nor is it known if variability in foot-ball impact characteristics is functional or dysfunctional to performance. The aim of this study was to identify the relationship between foot-ball impact characteristics and kicking accuracy and determine if variability in foot-ball impact characteristics influenced performance variability. Ten players performed 30 drop punt kicks toward a target with an Australian football ball. Kicking accuracy (measured as the horizontal distance from the target in the perpendicular direction of the kick), initial ball flight characteristics, and foot-ball impact characteristics, including a novel method to calculate impact location on the ball, were measured. Variability was indicated using standard deviation of foot-ball impact and ball flight characteristics. Multiple linear regression analysis identified azimuth ball flight trajectory as the most important ball flight characteristic influencing kicking accuracy, not ball flight characteristics associated with ball curve. Intra-individual multiple linear regressions identified azimuth ball impact location and foot-ball angle were the two most important factors explaining variance in azimuth ball flight trajectory, the chosen performance measure. Variability existed between and within players. Reduced variability in azimuth ball flight trajectory, the chosen performance measure, was associated with reduced variability in foot-ball impact characteristics. This result indicated variability in foot-ball impact characteristics was dysfunctional for performance in the analysed task. Foot-ball

impact characteristics and variability in foot-ball impact characteristics influences accuracy of Australian football drop punt kicking.

8.1. Introduction

Kicking is an important skill across the football codes. Under certain gameplay situations, the demand of accuracy for kicking is high. In Australian football, kicking with high accuracy is required to successfully score goals, to pass to team members, and to clear the ball when relieving defensive pressure. The drop punt kick is the most common kicking style in Australian football. The drop punt kick is characterised by the player releasing the ball from his/ her hands, forcefully impacting the ellipsoidal ball with the long axes of the foot and ball aligned, and imparting a distinct back-spin for ball flight. Because the ball is in projectile motion after it leaves the foot, accurate kicking is achieved by imparting an appropriate combination of flight characteristics required to reach the target.

Research exploring the foot-to-ball impact phase (hereafter referred to foot-ball impact) of Australian football drop punt kicking has focused almost entirely upon the production of ball speed. It is clear that foot speed immediately prior to impact is the most important contributor toward ball speed (Ball, 2008a, 2011; Ball, et al., 2010; Peacock & Ball, 2017) and is a strategy used by players to alter kick distances (Peacock, et al., 2017a). Despite the large contribution of foot speed to ball speed, players must still control other ball flight characteristics to ensure adequate energy transfer from foot to ball. Recent analyses with a mechanical kicking machine have identified ball orientation and impact location at the beginning of impact and ankle stiffness throughout impact influence ball speed (Peacock & Ball, 2017, 2018a, 2018b).

How players configure their foot-ball impact characteristics to attain accurate kicking is almost entirely unexplored. Research has identified how individual impact characteristics influence individual ball flight characteristics across different football kicking codes. However, given the importance of kicking accuracy required for goal scoring, passing and overall team success, further work is required to provide the link between these impact characteristics with a measurement of kicking accuracy. In the Australian football drop punt kick, impact location, ball orientation and foot speed were influential to ball flight characteristics of back-spin rate and azimuth ball flight trajectory in an analysis with a mechanical kicking machine (Peacock & Ball, 2017). In the soccer instep kick, a trade-off between impact location and ball speed and ball spin has been identified (Asai, et al., 2002; Ishii, et al., 2009). These studies indicate the importance of foot-ball impact characteristics toward individual ball flight characteristics, and work is required to provide the link between impact and kicking accuracy.

While identification of the direct mechanisms associated with accurate football kicking is important, understanding how a player varies their technique over several repetitions can also help explain kicking accuracy. The ultimate measure of performance for accurate kicking is the final position of the ball relative to the desired target. In gameplay of Australian football, an attempt at goal is only successful when the final position of the ball travels within the goal posts. Performance variability is the distribution of the final position over several repetitions, and can be easily identified in gameplay by attempts at goal that were either successful or unsuccessful. Arguably of more importance to human movement scientists is the variability in the movement pattern that produces the outcome of the task (Bartlett, Wheat, & Robins, 2007). Somewhat surprisingly, it has been identified that better skilled players, those that produce less performance variability (i.e. more consistent, successful accurate outcomes), produce more movement variability in the proximal segments than the less skilled counterparts (Arutyunyan, Gurfinkel, & Mirskii, 1968; Robins, Davids, Bartlett, & Wheat, 2008). Thus, to achieve accurate end-point positions, skilled players do not consistently produce an ‘ideal’ or ‘optimal’ technique (Glazier, Reid, & Ball, 2015). In the context of football kicking, some researchers have sought to identify if better skilled football players utilise increased or decreased variability in the approach and swing phases of various football kicking techniques (Ford & Sayers, 2015; Morris, Sayers, & Stuelcken, 2016; Sayers & Morris, 2012). It has been argued that increased variability can be functionally used by players to adapt to different gameplay conditions incurred from fatigue, surface conditions and playing environment (Ford & Sayers, 2015). Thus, increased variability can be either functional or dysfunctional, depending on the event or phase of analysis throughout the kicking execution (i.e. proximal segments, end-point position or performance outcome).

It is not known if accurate drop punt kicking is achieved through increased or decreased variability at foot-ball impact, nor has this been assessed in any football kicking technique. The analysis of impact characteristics during the golf drive identified better skilled players reduced variability in impact characteristics (Betzler, Monk, Wallace, & Otto, 2012, 2014). This finding is relevant for football kicking, as golf and football kicking both accelerate the ball via a collision. However, the ball shape distinctly differs between the tasks, with an ellipsoidal shape used in Australian football and spherical ball in golf. This unique ball shape of Australian football may lead to degeneracy at foot-ball impact of the drop punt kick. Peacock and Ball (2017) identified individual impact characteristics (impact location, ball orientation, etc.) influenced several ball flight characteristics. Players could therefore use multiple combinations of impact characteristics to achieve similar ball flight characteristics and accurate kick outcomes. Skilled players might utilise this redundancy to remove any errors in technique introduced during the leg swing of the kicking skill by functionally varying foot-ball impact characteristics. Thus, when performing the Australian football drop punt kick, there are two distinctly different strategies that a player might be able to use to produce accurate football kicking, (1) reducing the magnitude of variability in foot-ball impact characteristics or (2) functionally increasing variability in foot-ball impact to mitigate errors incurred during the forward swing and ball drop.

The aim of the present study was to identify how foot-ball impact characteristics influence kicking accuracy in the Australian football drop punt kick. Accurate drop punt kicking in Australian football is important to overall team success, as it is the main technical skill used for scoring and passing moderate and long distances. The link between foot-ball impact characteristics with kicking accuracy has not been established, nor is it understood how accuracy is influenced by movement variability at foot-ball impact. Thus, to further understand how accurate kicking is obtained, the first aim of the study was to identify the relationship between foot-ball impact and kicking accuracy by (1A) identifying the relationship between ball flight characteristics and kick accuracy and (1B) identifying the relationship between foot-ball impact and ball flight characteristics. This process of working backwards from the outcome systematically allowed the direct mechanisms to be identified. The second aim of the study was to identify if performance variability was associated with increased or decreased levels of variability in foot-ball impact characteristics.

8.2. Methods

8.2.1 Task, data collection and analysis

After signing informed consent forms approved by the university's human research ethics committee, ten players of various experience (2 – 15 years playing competitively) kicked a standard Australian football (Sherrin Match Ball; inflation = 69 kPa) from a defined kicking area toward a player 30 meters in distance. Each player performed this kick 30 times. The player catching the ball was instructed to move across the 30-meter line perpendicular to the kick direction and catch the ball. This task simulated a common pass performed in gameplay of Australian football. Accuracy was defined as the horizontal displacement between the constant central position and the catch position in the perpendicular direction of the kick. Kicking accuracy was measured by a two-dimensional video camera (50 Hz) and digitised using ProAnalyst software (Xcitex Inc., USA). Values were calculated as a directional vector (positive values represented kicks that were caught on the lateral side of the kicking limb).

Three-dimensional foot-ball impact and initial ball flight characteristics were measured at 4,000 Hz for each kick. Three high-speed video cameras (Photron SA3 & MC2, Photron Inc., USA) were synchronised and positioned to record reflective markers attached to the lateral aspect of the shank, foot and ball from 20 frames before to 20 frames after foot-ball contact. The Photron SA3 camera was positioned perpendicular to the direction of the kick, and two Photron MC2 cameras were positioned at an offset angle of approximately 40°. The shank and foot were each represented by five spherical reflective markers 13 mm in diameter, fixed to the limb using rigid strapping tape. Five tracking markers on the ball consisted of flat rectangular pieces of reflective tape (2.5 x 2.5 cm) with an 8mm black circular sticker attached to the middle. Markers were tracked in ProAnalyst software to produce three-dimensional X-Y-Z data. The system was calibrated using the right-hand rule, with the Y-axis pointing toward the target, Z-axis vertically and X-axis perpendicular to both axes. The calibrated space was approximately x = 1.0 m, y = 1.5 m and z = 0.5 m, and the root mean square error within the calibrated area of the measurement system was < 1.0 mm.

Three-dimensional segmental data of the shank, foot and ball for each kicking trial were computed from the raw coordinate data using a six degrees of freedom rigid body model (Visual3d software, C-Motion Inc., USA). The six degrees of freedom rigid body model was determined from static captures of the distal and proximal segment positions and tracking markers. The location of the knee, ankle and metatarsophalangeal joints (1st and 5th) were determined from markers attached to the medial and lateral aspect of each joint. Data were smoothed with a low pass Butterworth filter with a cut-off frequency of 280 Hz. The choice of smoothing procedure was based on previous literature that explored various cut-off frequencies within foot-ball impact using residual analysis and visual inspection (Nunome, et al., 2006b; Peacock, et al., 2017a). To accommodate for convention differences between left and right footed kickers, the direction was reversed for all vector measures (kicking accuracy, azimuth ball flight trajectory, etc.) calculated in the x-dimension of the global coordinate system for the left footed kickers. This ensured positive values in the x-dimension of the global coordinate system corresponded to the lateral aspect of the foot.

Initial ball flight characteristics were calculated within Visual3d and Microsoft Excel from data calculated over five frames after ball release from the foot (Figure 8.1 and 8.2). Azimuth ball flight trajectory and elevation ball flight trajectory were calculated from the X and Y, and Y and Z velocity components of the ball geometric centre in the global coordinate system, respectively (Figure 8.1A). Ball angle and angular velocity were calculated within Visual3d using the rigid body model within the global coordinate system (Figure 8.1B). The kick position, defined as the position of the ball at the first frame of ball release within the X-axis of the global coordinate system, was also calculated to ensure any changes in this position were included in the regression equation. This accounted for the scenario where a kick that was completed 1 meter to the lateral aspect of the target with an azimuth flight of 0° would correspond to a measured kick accuracy of 1 meter.

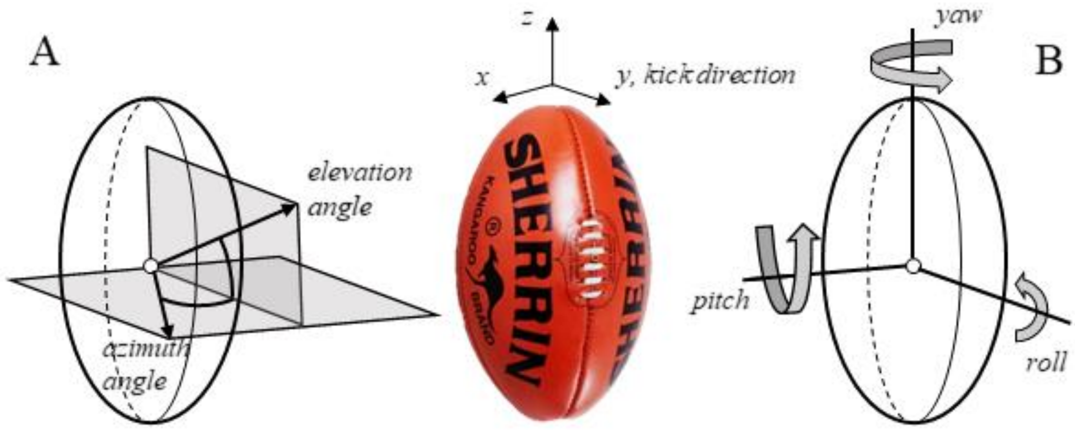

Figure 8.1: Visual representation of ball flight characteristics. A) Ball flight trajectory. B) Ball angular dimensions.

Foot-ball impact characteristics were calculated within Visual3d, Microsoft Excel and Matlab software. The oblique impact theory indicates the trajectory and spin of an object after impact is influenced by the surface angle of the two objects in the collision. In the context of football kicking, the oblique impact theory indicates foot trajectory, foot velocity, ball impact location, foot angle and ball angle will determine the ball flight characteristics. Therefore, we measured these parameters. Foot trajectory was calculated from the centre of mass of the foot over five frames prior to impact in the azimuth and elevation dimensions. Ball impact location was calculated in three-dimensional space using a novel method (described below) that presented the impact location as two coordinates, azimuth ball impact location and elevation ball impact location. Foot angle, ball angle and foot-ball angle were calculated from the defined coordinate system of each segment (Figure 8.2). Foot and ball angles were calculated in reference to the global coordinate system, and foot-ball angle was calculated by the ball angle in reference to the foot angle. Initial foot and ball velocity magnitudes were also calculated, however, given the task was submaximal, there was little change in both foot and ball velocity for all players and these parameters were removed from further analysis.

A novel method was developed to calculate the impact location on the ball within three-dimensional space using Matlab software and Microsoft Excel. Previous methods developed to calculate impact location were not suitable for the present study, as a given impact location was dependent upon the relative foot-ball displacement, the relative foot-ball angle, ball shape and foot shape. The method reported by Ishii, et al. (2012) was developed for a spherical ball in two-dimensional space, and the method by Peacock and Ball (2017) did not accommodate changes to relative foot-ball orientation, foot-ball displacement, nor foot shape. Hence, a method to calculate impact location, where each of these variables were included, needed to be developed. This was achieved by modelling the foot and ball as rigid bodies and calculating the intersecting point at ball contact. Because the foot and ball are not rigid bodies during impact, the developed method to calculate impact location was not assessed during impact, but all impact characteristics were measured at the instant of ball contact. Modelling of the foot and ball was achieved by geometric equations of shapes that replicated the foot and ball. The foot was modelled as a semi-elliptical cylinder that incorporated dimensions of the individual's foot shape (Equation 8.1-4; Figure 8.2A). The ball was modelled as an ellipsoid using dimensions of the ball taken under a static capture (Equation 8.5; Figure 8.2B). To calculate impact point on the ball, a 200 x 200 X-Y-Z coordinate mesh was developed for the foot surface. This matrix of coordinates was then rotated and translated in respect to the position of the ball, using the foot-ball angle and displacement. Then, each coordinate of the foot surface was entered into the equation of the ball surface (Equation 8.5) which solved the position of each coordinate relative to the surface of the ball. A coordinate outside the shell of the ball solved a value > 1, a coordinate on the shell of the ball solved a value $= 1$, and a coordinate within the shell of the ball solved a value < 1. The impact point on the ball was calculated from the distance between the ball centre and the X-Y-Z foot coordinate that yielded the smallest value when entered into Equation 8.5. Due to the ellipsoidal shape of the ball, the distance between the ball centre and the impact point changes depending on the impact location, unlike a soccer ball that has a constant radius. Therefore, the impact location was presented as two angles from the centre of the rear point of the ball (Equation 8.6-7; Figure 8.3).

$$x_l = \frac{w_l}{2}\cos\emptyset \qquad \text{Equation 8.1}$$

Where x_l = the x-coordinate of the foot grid for a given length of the foot; w_l = the width of the foot for a given length, calculated from Equation 2; θ = a vector comprising 200 linearly spaced angles between 0° to 180°.

$$w_l = \frac{(w_d - w_p)}{2 \cdot l} \cdot w_l + w_p \qquad \text{Equation 8.2}$$

Where w_d = the width of the foot at the distal end of the segment; w_p = the width of the foot at the proximal end of the segment; l = the length of the foot.

$$y_l = h_l \sin\emptyset \qquad \text{Equation 8.3}$$

Where y_l = the y-coordinate of the foot grid for a given length of the foot; h_l = the height of the foot at a given length.

$$h_l = \frac{(h_p - h_d)}{l} \cdot h_l + h_d \qquad \text{Equation 8.4}$$

Where h_p = the height of the foot at the proximal end of the segment; h_d = the height of the foot at the distal end of the segment.

$$\frac{{x_l}^2}{{r_x}^2} + \frac{{y_l}^2}{{r_y}^2} + \frac{l^2}{{r_z}^2} = d \qquad \text{Equation 8.5}$$

Where r_x = the short radius of the ball; r_y = the short radius of the ball (note: $r_x = r_y$); r_z = the long radius of the ball; d = the depth of the coordinate relative to the ball shell.

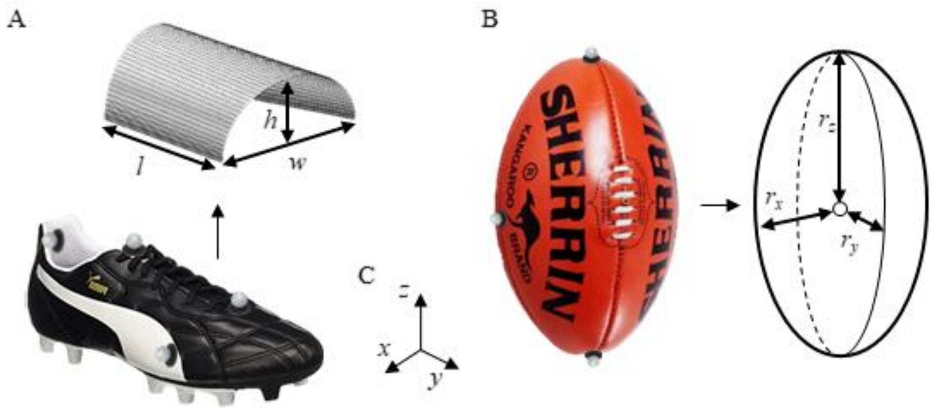

Figure 8.2: Surface models of the foot (A) and ball (B).

$$BIL_{el} = \tan^{-1}\left(\frac{-y}{-z}\right) \qquad \text{Equation 8.6}$$

Where BIL_{el} = ball impact location across the elevation plane; y = the distance between impact location and the ball centre in the y dimension; z = distance between impact location and ball centre in the z dimension.

$$BIL_{az} = \tan^{-1}\left(\frac{x}{y}\right) \qquad \text{Equation 8.7}$$

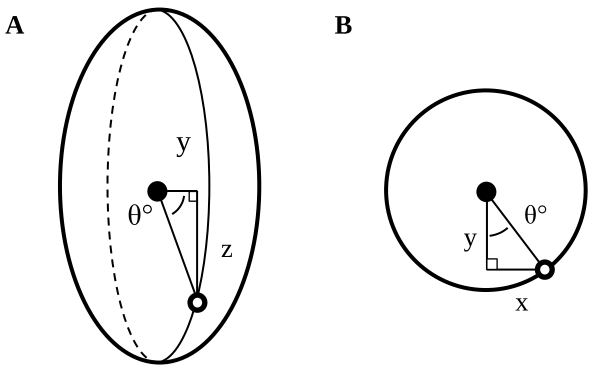

Figure 8.3: Measurement of ball impact location across the elevation plane (A) and the azimuth plane (B).

8.2.2 Statistical analysis

To identify the relationship between ball flight characteristics and kicking accuracy (aim 1A), multiple linear regression analysis was performed. Because this analysis was based on the ball during its flight, it was performed on all trials across all players. Only kicks successfully caught by the receiving player were analysed as these were the only trials that kicking accuracy could be reliably measured. Kicks that landed prior to reaching the target or kicks that travelled overhead of the target were removed for this component of analysis. In total, 115 kicks were included in the regression. The mean and standard deviations of these kicking trials were reported to provide a summary of the ball flight characteristics and kicking accuracy. The multiple linear regression was performed using the stepwise method. The dependent variable was kicking accuracy, and the independent variables were azimuth ball flight trajectory, ball angular velocity, ball angle, and kick position. One outlier was identified by calculating Mahalanobis distance using a cut-off of $p < 0.001$ (Tabachnick & Fidell, 2001), leaving a total N of 114.

To identify the relationship between foot-ball impact characteristics and ball flight characteristics (aim 1B), multiple linear regression analysis was performed within SPSS software on an intra-individual level. To follow a systematic approach, and because ball azimuth flight angle was the most important flight characteristic influencing kicking accuracy, we performed the regression using only azimuth ball flight trajectory as the dependent variable. This was performed on an intra-individual level to identify if the variance changed between players, possibly due to individual techniques adopted during foot-ball impact. Ball impact location across the azimuth and elevation dimensions, foot-ball angle (three dimensions) and foot trajectory across the azimuth dimension were entered as the independent variables. Because Tabachnick and Fidell (2001) recommend a 5:1 case: parameter ratio, and not all of the 30 kicks per player could be analysed due to markers obstructed or moving out of the capture area, foot-ball angle was calculated to replace foot angle and ball angle. The same regression analysis procedure was performed as previously stated for the relationship between ball flight characteristics and kick accuracy. The mean and standard deviation of each individual for these impact characteristics and for azimuth ball flight trajectory were additionally presented.

To determine if performance variability was associated with an increased or decreased variability in foot-ball impact (aim 2), variability (standard deviations) of ball flight and foot-ball impact characteristics were calculated of each player. Correlations were performed between variability in standard deviation of azimuth ball flight trajectory and standard deviation of azimuth ball impact location, and between standard deviation of azimuth ball flight trajectory and standard deviation of foot-ball angle Y. The statistics of r, effect size (Cohen, 1988) and p-value were calculated to describe the correlations.

8.3. Results

The relationship between ball flight characteristics and kicking accuracy was identified. The mean and standard deviation of kicking accuracy and ball flight characteristics were quantified (Table 8.1). The model identified from the stepwise regression identified 69.9% of variance in kicking accuracy was explained by six ball flight characteristics (Table 8.2). The standardised coefficients from the regression model identified azimuth ball flight trajectory was most influential to the measurement of kicking accuracy; the standardised coefficient had a three-fold greater effect on kicking accuracy than all other ball flight characteristics.

Table 8.1: The descriptive statistics of kicking accuracy and ball flight characteristics (N = 114).

	Mean (std)
Kicking accuracy (m)	0.2 (1.5)
Azimuth ball flight angle (°)	1.6 (3.6)
Elevation ball flight angle (°)	22.3 (5.7)
Kick position (m)	0.2 (0.2)
Ball angle X (°)	0.6 (11.7)
Ball angle Y (°)	-0.7 (8.5)
Ball angle Z (°)	-4.1 (13.6)
Angular velocity X (rad/s)	26.0 (6.7)
Angular velocity Y (rad/s)	0.4 (5.0)

Angular velocity Z (rad/s)	0.5 (8.5)

Table 8.2: Regression results of ball flight characteristics predicting kicking accuracy (N = 114).

	Azimuth ball flight trajectory	Kick position	Ball yaw angle	Ball pitch angular velocity	Ball yaw velocity	Elevation ball angle	Intercept
Coefficient	0.34	-1.95	0.03	-0.05	-0.03	-0.04	2.55
Standard error (m)	0.03	0.50	0.01	0.02	0.01	0.02	0.66
Standardised coefficient	0.84	-0.28	0.24	-0.24	-0.15	-0.17	-

The foot-ball impact characteristics and azimuth ball flight trajectory were quantified for each player (Table 8.3). Foot-ball impact characteristics explained over 74% of variance in azimuth ball flight trajectory for all players except one (Table 8.4). Azimuth ball impact location was the only impact characteristics influential to all players, and produced the largest standardised coefficients for all players. Further, azimuth ball impact location had greater than a two-fold effect over the remaining impact characteristics in all players except one. Foot-ball angle Y was influential in eight of the ten players, and the standardised coefficients were in the range of 0.16 – 0.48 in magnitude. Elevation ball impact location and foot-ball angle X were influential in two players, and azimuth foot trajectory was influential in one player.

Table 8.3: The mean and standard deviation of azimuth ball flight angle and kicking characteristics for all individuals.

	Azimuth ball flight angle (°)	Azimuth foot trajectory (°)	Azimuth ball impact location (°)	Elevation ball impact location (°)	Foot-ball angle X (°)	Foot-ball angle Y (°)	Foot-ball angle Z (°)
P01 (N = 27)	0.2 (5.0)	3.8 (1.3)	8.1 (7.3)	45.4 (4.4)	60.8 (8.1)	-0.2 (10.6)	45.2 (12.3)
P02 (N = 24)	-2.2 (4.4)	4.1 (2.0)	2.7 (5.4)	47.3 (2.5)	64.7 (3.2)	-12.3 (6.8)	22.4 (8.8)
P03 (N = 25)	-0.8 (3.6)	1.3 (2.2)	1.5 (2.9)	52.1 (3.3)	52.4 (6.5)	-13.9 (4.1)	-11.8 (8.0)
P04 (N = 29)	0.2 (3.2)	2.3 (2.0)	0.8 (3.6)	45.5 (2.6)	57.2 (3.9)	-10.8 (4.4)	15.8 (7.5)
P05 (N = 22)	3.0 (3.6)	5.0 (1.8)	-6.0 (4.1)	49.1 (2.0)	55.5 (4.5)	-1.0 (4.1)	35.0 (9.1)
P06 (N = 25)	3.4 (3.0)	7.1 (1.1)	-3.0 (3.7)	45.4 (3.6)	52.1 (4.0)	-9.3 (4.4)	26.8 (9.0)
P07 (N = 25)	-0.2 (6.3)	5.6 (1.8)	-1.1 (5.6)	41.1 (5.1)	60.4 (8.5)	-5.0 (7.7)	-7.1 (12.3)
P08 (N = 28)	0.2 (2.6)	2.7 (1.6)	1.2 (2.3)	48.3 (4.5)	54.3 (3.6)	-10.1 (5.0)	5.7 (8.0)
P09 (N = 25)	4.0 (4.0)	4.8 (1.1)	-2.7 (4.6)	45.7 (4.6)	56.1 (6.0)	-9.2 (6.1)	14.5 (10.4)
P10 (N = 20)	-3.0 (3.2)	2.2 (1.4)	2.8 (3.4)	51.7 (4.2)	59.4 (7.0)	-3.6 (6.2)	7.3 (11.0)

Table 8.4: Regression results of foot-ball impact characteristics predicting azimuth ball flight trajectory. The coefficient (*B*), standard error (*σe*) and standardised coefficients (*β*) of statistically significant (p < 0.05) foot-ball impact characteristics predicting azimuth ball flight trajectory. Foot-ball angle Z was entered into the regression; however, this parameter was statistically non-significant and omitted from the table.

		Constant	Azimuth ball impact location (°)	Elevation ball impact location (°)	Foot-ball angle X (°)	Foot-ball angle Y (°)	Azimuth foot trajectory (°)	R-squared
	B	10.86	-0.54	-0.20		-0.07	0.75	
P01	*σe*	3.68	0.05	0.08		0.04	0.30	90.2%
	β		-0.79	-0.18		-0.16	0.19	
	B	-2.53	-0.79			-0.20		
P02	*σe*	0.64	0.06			0.05		89.6%
	β		-0.96			-0.31		
	B	-8.00	-1.08		0.11	-0.23		
P03	*σe*	2.17	0.10		0.04	0.07		89.1%
	β		-0.86		0.19	-0.26		
	B	-1.89	-0.70			-0.25		
P04	*σe*	1.14	0.12			0.10		56.1%
	β		-0.79			-0.34		
	B	-1.57	-0.76					
P05	*σe*	0.71	0.10					74.9%
	β		-0.87					
	B	-10.98	-0.71		0.18	-0.28		
P06	*σe*	4.27	0.09		0.08	0.08		77.2%
	β		-0.86		0.24	-0.41		

	B	13.70	-1.13	-0.37		
P07	*σe*	3.59	0.08	0.09		89.9%
	β		-0.99	-0.30		
	B	-1.28	-0.84		-0.25	
P08	*σe*	0.60	0.11		0.05	74.7%
	β		-0.74		-0.48	
	B	0.09	-0.76		-0.20	
P09	*σe*	0.74	0.08		0.06	80.3%
	β		-0.87		-0.31	
	B	-1.13	-0.90		-0.17	
P10	*σe*	0.36	0.08		0.04	87.8%
	β		-0.96		-0.33	

A relationship was identified between variability in impact characteristics with variability in kick outcome. The variability (standard deviation) of azimuth ball flight trajectory, the chosen performance measure, differed between individuals (Table 8.5). The variability (standard deviation) of azimuth ball impact location and foot-ball angle Y, the two most important foot-ball impact characteristics explaining azimuth ball flight angle, also differed between players. There was a relationship between the variability in foot-ball impact characteristics with the variability in azimuth ball flight trajectory: significant positive correlations with very large effect sizes were present between standard deviation in azimuth ball flight trajectory with azimuth ball impact location ($r = 0.80$, $p = 0.001$) and with foot-ball angle Y ($r = 0.71$, $p = 0.006$).

Table 8.5: The standard deviations of azimuth ball flight trajectory, azimuth ball impact location, and foot-ball angle Y for each player, ranked from lowest to highest using azimuth ball flight trajectory as the performance indicator.

Ranking	Player	Azimuth ball flight angle	Azimuth ball impact location	Foot-ball angle Y
1	P08	2.6	2.3	5.0
2	P06	3.0	3.7	4.4
3	P04	3.2	3.6	4.4
4	P10	3.2	3.4	6.2
5	P03	3.6	2.9	4.1
6	P05	3.6	4.1	4.1
7	P09	4.0	4.6	6.1
8	P02	4.4	5.4	6.8
9	P01	5.0	7.3	10.6
10	P07	6.3	5.6	7.7

8.4. Discussion

How players attain accurate kicking in the Australian football drop punt kick is not fully understood. Therefore, we determined how foot-ball impact influences kicking accuracy by analysing 30m drop punt kicks at an intra- and inter-individual level. Firstly, we identified the relationship between foot-ball impact characteristics, measured at the instant of ball contact, and a measurement of kicking accuracy. The key result of this analysis was that azimuth ball flight trajectory was the most important ball flight characteristic, and azimuth ball impact location and foot-ball angle Y were the two most important impact characteristics. Secondly, we also explored variability in foot-ball impact characteristics to determine if kicking accuracy was obtained from an increased or decreased variability. The key result of this analysis was the positive relationship between absolute variability in impact characteristics (azimuth ball impact location and foot-ball angle Y) and absolute variability in azimuth ball flight trajectory. These relationships indicate that less performance variability was obtained by reducing variability in foot-ball impact characteristics.

8.4.1 Biomechanical factors explaining kicking accuracy

Inaccurate kicking was mostly due to imparting the incorrect azimuth ball flight trajectory. The standardised coefficient from the regression model for azimuth ball flight trajectory had greater than a three-fold effect than the remaining ball flight characteristics on horizontal kicking accuracy. Further, the sum of the standardised coefficients of the individual ball flight characteristics that contribute the ball curve (ball orientation and ball spin) was 0.81, still less than the standardised coefficient (0.84) for azimuth ball flight trajectory. Azimuth ball flight trajectory and ball curve are two independent factors that will determine horizontal kicking accuracy. Ball curve represents the deviation of the ball from its initial plane of projectile motion, and is influenced by not only environmental conditions of wind, but also the aerodynamic forces due to ball spin and in the case of the ellipsoidal ball sports, ball orientation. In particular, any off-centred back-spin, such as a tilt about the yaw and roll ball angles, and angular velocity about the yaw and roll ball angles, will produce an aerodynamic force pushing the ball off plane (Alam, et al., 2009; Goff, 2013). In our analysis of the drop punt kick, the most important ball flight characteristic for kicking accuracy were not those influential to ball curve, but azimuth ball flight trajectory. This difference of influence was due to the magnitude of variability between the flight characteristics that players produce in the drop punt kick, and how this magnitude of variability influenced ball flight characteristics. Simply put, players can control ball curve more so than they can control azimuth ball flight trajectory. This may be due to the shape of the foot and ball, where players 'roll' the ball up the foot during impact to apply the distinct back-spin. Therefore, while it is still important for players to control factors influencing ball curve, these results indicate inaccurate kicking was mostly due to imparting the incorrect azimuth ball flight trajectory.

The oblique impact theory applied through the duration of impact can be used to explain the relationship between foot-ball impact characteristics and azimuth ball flight trajectory. The oblique impact theory indicates the direction of travel of the ball after impact will be influenced by the surface angle between the foot and ball during impact. When the surface angle between the foot and ball and the trajectories of the foot and ball are perpendicular, the ball will be propelled in the direction of the foot trajectory. The results from this study support the application of the oblique impact theory. Azimuth ball impact location, measured at the instant of ball contact, was the most influential impact characteristic to azimuth ball flight trajectory (Table 8.4). The direction of the coefficient from the regression indicated medial impact locations on the ball produced a lateral ball flight trajectory. As indicated by the oblique impact theory, an impact location on the medial aspect of the ball is characterised by the perpendicular direction of the surface angle pointing laterally from the foot direction of travel. Similarly, Peacock and Ball (2017) found lateral foot impact locations translated to a lateral azimuth flight trajectory. Both the present and previous studies recorded impact location at the instant of ball contact, not through the duration of foot-ball impact. However, due to the mostly planar motion of the foot and ball during impact (in the sagittal plane) and the alignment of the long axes of the ball and foot aligned in the drop punt kick, the impact location across the medial-lateral aspect of the foot at the beginning of impact mostly corresponds to the impact location during impact. Changes to foot-ball angle Y can influence this relationship though. When the long axis of the ball is not aligned with the long axis of the foot, the contact area between the foot and ball will spread across the medial-lateral direction of the foot during impact. This is again supported by the direction of the coefficient of foot-ball angle Y in the regression, that was negative in direction for all eight players (Table 8.4). With a negative foot-ball angle Y, the top side of the ball is tilted laterally whereby the impact location will spread onto the lateral aspect of the foot and/ or the medial aspect of the ball. These results support the validity of the oblique impact theory applied through the duration of impact to explain the relationship between foot-ball impact characteristics and azimuth ball flight trajectory. Further examination of the dynamic contact area between the foot and ball is made in Chapter 9.

8.4.2 The influence of variability on kicking accuracy

Decreased performance variability was associated with reduced variability in foot-ball impact characteristics (Table 8.5), indicating players who produced less variability in foot-ball impact characteristics produced less variability in azimuth ball flight trajectory. It is important to note; the task goal was not to impart the lowest standard deviation in azimuth ball flight trajectory but to kick to the target as accurately as possible. Players could have imparted an off-centred azimuth ball flight trajectory that was offset by ball curve for some trials, whereby the standard deviation for azimuth ball flight trajectory would be increased but with no change to the outcome (kicking accuracy). Despite this, azimuth ball flight trajectory was chosen as the performance measure because kicking accuracy could not reliably be measured for every kick (as a large number of kicks for most performers fell short of or travelled over the target due to errors in the vertical component) and only a small sample of kicks would have been available to determine the relationship between variability in impact and performance variability (the measurement of kick accuracy). Given the nature of the task analysed in the present study that required players to kick straight from a confined kicking area, there was no benefit to use a ball curve, nor was it observed that players did purposely use a ball curve. Furthermore, azimuth ball flight trajectory was the most important ball flight characteristic to kicking accuracy. Therefore, to provide a strong sample size for this analysis it was appropriate to use azimuth ball flight trajectory as the performance measure. The positive relationship between standard deviation in impact characteristics and standard deviation in azimuth ball flight trajectory indicates performance variability was reduced by reducing variability in foot-ball impact characteristics.

It was expected that a functional use of variability in foot-ball impact characteristics would have produced a high standard deviation in foot-ball impact characteristics with low a standard deviation in azimuth ball flight trajectory. The results of this study indicated that performance variability was decreased with reduced variability in foot-ball impact characteristics. This indicates variability in foot-ball impact characteristics was dysfunctional, similar to the findings in golf by Betzler, et al. (2012, 2014). This is likely due to the extremely short duration of impact and the timing of the reflexes in the human body. The monosynaptic reflex, the quickest reflex in the body, is in the range of 20-40 ms between individuals (Latash, 2012). Given the duration of impact in football kicking is approximately 10-12 ms (Peacock, et al., 2017a), far less than the timing of the monosynaptic reflex, it is not possible for players to receive feedback just prior to and during impact to make the necessary corrective changes. This might also explain why better skilled golf players also reduce variability, as the contact time between golf head and ball is less than 1 ms (Roberts, Jones, & Rothberg, 2001). Therefore, players can only impart the desirable flight characteristics by impacting the ball with the exact necessary impact characteristics.

8.4.3 General discussion

The results in this study and in previous work (Peacock & Ball, 2017) indicate there is not one sole foot-ball impact characteristic that is a primary factor influential to kicking accuracy, rather, kicking accuracy is influenced by the combination of impact characteristics. Dissimilarly, Hennig (2011) stated there was one primary factor influential to kicking accuracy in the soccer instep kick; the homogeneity of pressure between the shoe and ball. The homogeneity of the pressure between the shoe and ball is influenced by bony prominences on the foot, and is expressed by the difference in pressure between adjacent positions on the dorsal aspect of the foot surface. Footwear designs that have thinner padding produce a non-homogenous pressure, as pressure peaks are produced on the anterior surface of the foot due to bony prominences (Hennig & Sterzing, 2010). The homogeneity of pressure between foot and ball, caused by bony prominences and footwear designs, however, does not explain all aspects of football kicking accuracy. In particular; why do players produce a breakdown of accurate and inaccurate kicks while wearing the same shoe and kicking with the same foot, when the homogeneity of the pressure distribution between foot and ball (caused by bony prominences) will be constant? Furthermore, adding padding on the surface of the foot to specifically produce a more homogenous pressure was found to have a non-significant effect on kicking accuracy (Hennig & Althoff, 2018). The results in this study indicate it is the combination of foot-ball impact characteristics that is influential to kicking accuracy. As players produce variability in the combination of impact characteristics, either functional or dysfunctional, the ball flight characteristics change. Players must control all foot-ball impact characteristics to attain kicking accuracy, such as impact location and foot-ball angle (where applicable depending on ball shape).

The results of this study identify the importance of precision when completing repetitions of a kick with set task constraints. To improve performance in a consistent task, coaches should provide specific feedback that assists players to reduce variability in impact location and foot-ball angle (the two most important foot-ball impact characteristics). These results might indicate the importance of training players to impact the ball with a consistent technique for all kicking tasks. But, it has been argued that players should have the ability to functionally vary technique to allow for perturbations in the environment, gameplay and task (Bartlett, et al., 2007; Ford & Sayers, 2015). It could not be determined how players adapt foot-ball impact to satisfy different task constraints because only one set of task constraints was analysed in this study.

The results in this study identify better performance was achieved by reducing variability in impact characteristics, which asks the question of where does variability exist throughout the kicking skill to functionally assist in delivering the kicking foot to the appropriate position on the ball. Future work is required on the coordination between the body and ball in the lead up until impact, such as coordination between the foot and ball during the forward swing. Functional variability might exist in foot-ball impact characteristics, but, it is clear players cannot adapt their impact characteristics during the extremely short impact phase of the kick. However, it is likely players functionally vary impact characteristics between kicking tasks, such as different approach angles. Future work is required to understand variability in foot-ball impact characteristics between different kicking tasks.

The limitations of this work were the assessment of kicking accuracy (measured only in the horizontal plane) and the methods used in the regression statistics. In gameplay of Australian football and other football codes, accurate kick outcomes are often also constrained in the vertical dimension. This is exemplified in Australian football by a successful pass requiring the ball does not travel over or fall short of the desired team member. In other football codes, such as soccer and rugby, the ball must also travel underneath or over the horizontal crossbar, respectively. Future work should investigate the causes of errors in the vertical dimension of kicking accuracy. Another limitation of the present study was the multiple regression statistics. While the multiple regression statistics did identify the influence of each individual impact characteristic, it was also necessary to reduce the number of analysed parameters due to the limited sample sizes (small number of performed and subsequently analysed kicks). An example of this is combining individual foot and ball angles into foot-ball angle. Important information regarding foot and ball angles might have been lost due to this process. Having a larger number of kicks to be analysed would have permitted the inclusion of more variables in the statistical models and could have been achieved by pooling all kicks into one large data set. But, given differences in each players foot shape existed and individual techniques may have been employed, it was not appropriate to pool all trials together as the data would no longer have been independent. Furthermore, the use of linear statistics may have concealed the measured influence of some parameters toward the dependent variables that are non-linear.

8.5. Conclusion

The aim of the present study was to identify the characteristics that influence accurate kicking. Kicking accuracy within the drop punt kick, measured as the horizontal distance between the target and the outcome, was mostly explained by azimuth ball flight trajectory and not factors associated with ball curve. From this, azimuth ball impact location and foot-ball angle Y were identified as the most important impact characteristics influencing azimuth ball flight trajectory. Variability existed within and between players during kicks as they completed the accuracy based task. It was identified less variability in the performance measure was attained by producing less variability in impact characteristics.

8.6. Contribution of individual chapter to overall thesis

The aim of the present study was to identify how foot-ball impact characteristics influence kicking accuracy. These results contribute to answering aim 2 of the overall thesis. Previous chapters with the mechanical kicking machine identified ball angle, impact location and foot trajectory each influenced ball flight characteristics. The present study, identified using human kickers, support these previous findings. The full discussion of impact influencing kicking accuracy is found in section 10.2.2. An important finding of the present thesis is the dynamic nature of the contact area between the foot and ball during impact. The present chapter identified this dynamic nature explained some key results, such as the influence of foot-ball angle Y on azimuth ball flight angle. Building on from this finding, Chapter 9 aimed to quantify this dynamic motion of the contact area between the foot and ball.

Chapter 9: Study 7 - The contact area between foot and ball during impact

Abstract: During foot-ball impact, it has been qualitatively observed that the ball 'rolls' up the foot. This 'rolling' motion visually appears to contain a change in ball angle and the impact location on the foot moving proximally. An important step in this thesis is to quantitively measure this occurrence, due to its importance in explaining some of the key results. Therefore, the aim of this chapter was to quantify the contact area between foot and ball during impact: measure the magnitude of ball deformation of an ellipsoidal ball and the impact location on the foot. This was achieved by re-analysing data from Chapter 6 and expanding the pre-developed two-dimensional model to calculate impact location throughout the duration of impact and calculate the magnitude of ball deformation. The results from this analysis confirmed the qualitative observation of the ball rolling up the foot: during impact, ball angle increased and the impact location on the foot moved proximally. This result can explain several findings within the present thesis on kicking accuracy and further expand our knowledge on ankle motion during impact.

9.1. Introduction

Analysis of the foot-ball impact phase in kicking has been performed by using initial, final, and average discrete parameters of impact, by measuring time-series data during impact by recording data at high sampling frequencies (> 2,500 Hz), or, by using a combination of both discrete and time-series parameters. Calculating parameters during impact can be difficult due to the deformation of the foot and ball. Several authors have developed methods that can measure deformation of the foot and ball, whereby identifying the unique motion of the foot and ball during impact has been identified. Some notable findings from this analysis of the impact phase include: the transfer of energy from foot to ball occurs over the first three-fourths of impact duration, not the entire duration of the phase (Peacock, et al., 2017a; Shinkai, et al., 2009); while most players are forced into distinct plantarflexion by the end of impact, the ankle motion during impact of most individuals features an initial movement of dorsiflexion prior to plantarflexion (Peacock, et al., 2017a; Shinkai, et al., 2009); and, several authors have developed methods that can calculate instantaneous force during impact in order to understand the risk of injury (footballer's ankle) (Iga, Nunome, Inoue, & Ikegami, 2013; Iga, et al., 2017; Shinkai, et al., 2009; Tol, et al., 2002). Within this thesis, foot-ball impact has primarily been analysed by using the pre- and post-conditions of impact, whereby the relationship between initial impact conditions and ball flight characteristics has been identified. Additional analysis of the what occurs during impact has been performed for unexpected results; for example, ankle plantarflexion was identified to decrease at higher foot velocities despite a greater external torque applied to the joint ankle, where it was identified the initial dorsiflexion motion had increased (Chapter 6.4.1).

Anecdotal observations of the video files from impact foot-ball impact have identified the ball 'rolls' up the foot during impact. Given the transfer of velocity from foot to ball has previously been identified to occur not instantaneously, but over three-fourths of impact, understanding how the ball moves on the foot during impact can help further understand the interaction. Anecdotal observations of video files from foot-ball impact over the past five years by the author of this thesis has identified the contact area during impact is dynamic: it increases in size with deformation and translates as the ball changes angle. These anecdotal observations can explain the results from this thesis that could not be explained solely by changes to the characteristics at the start of impact. In Chapter 8, the multiple linear regressions indicated a systematic shift in foot-ball angle Y will alter azimuth ball flight trajectory, despite the surface angle at the beginning of impact being consistent due to not change in the impact location. The observation of the ball rolling up the foot, however, can explain this result. With a shift in the foot-ball angle Y, the direction of the ball 'rolling' up the foot along the longitudinal axis of the ball will be at an angle to either the medial or lateral sides of the foot. This result indicates that what occurs during impact, not solely at ball contact, is influential to kick outcome.

An important step within this thesis is to quantify the anecdotal observations of the ball 'rolling' up the foot during impact. The key theory identified within this thesis on kicking accuracy, whereby the surface angle between foot and ball throughout the duration of impact influences the direction of the force vector applied to the ball, currently does not have quantitative evidence supporting all results. By quantifying the anecdotal observation of the ball 'rolling' up the foot, evidence will be provided to support the notion of the surface angle during foot-ball impact and not just at the beginning of impact influences the outcome of the kick. Therefore, the aim of this chapter was to quantify the contact area on the foot during impact of an ellipsoidal ball: develop and validate a method to calculate the magnitude of ball deformation and the change in impact location on the foot.

9.2. Methods

The previously established method within this thesis to calculate impact location two-dimensionally was expanded throughout the duration of impact. Given the method was based on the static non-deformed size of the foot and ball, it was not appropriate to use this on the human kickers due to the deformation of the foot, or, more appropriately, change in shape of the impacting surface of the foot (Asami & Nolte, 1983; Nunome, et al., 2014). This method could, however, be used on the mechanical kicking machine because deformation of the foot did not occur. The data from Chapter 5 (comparison of rigid to non-rigid ankles) were reanalysed and impact location was calculated throughout the entire duration of impact.

9.2.1 Data collection

Two-dimensional sagittal plane data were collected from high-speed video (Photron SA3, Photron Inc., USA, 4,000 Hz, resolution 768 x 512 pixels) zoomed to include just the kicking area. Tracking markers (12.9 mm spherical and 8 mm flat) on the limb and ball were tracked from 20 frames before ball contact to 20 frames after the ball had left the boot (identified visually from the video) using ProAnalyst software (Xcitex Inc., USA). To eliminate movement of the boot influencing foot and ankle data, the foot tracking marker was attached directly to the fifth metatarsal by cutting a hole in the boot and tapping a thread into the foot. This marker was also occluded for approximately 10 frames through the middle of the tracking stage as it passed through the tee supporting the ball, and these points were interpolated within the tracking software. Raw X and Y coordinates were exported to Visual3d software (C-Motion Inc., USA) to be analysed with a custom-made pipeline. Firstly, virtual markers were computed using the method from Peacock, et al. (2017a) (Figure 9.1). All raw X-Y coordinates were then exported to Matlab software (R2016b, The Mathworks Inc., USA) to calculate ball deformation by modelling the foot and ball.

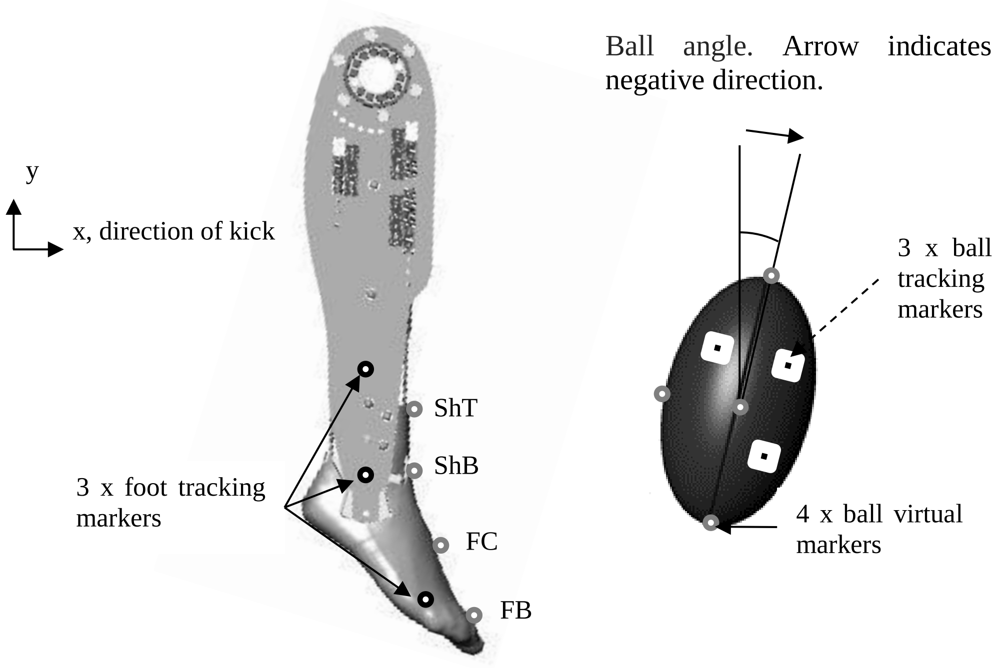

Figure 9.1: Orthogonal reference and tracking and virtual markers of the limb and ball. Virtual markers are represented by the grey outline of the circular markers.

9.2.2 Deformation of an ellipsoidal ball and calculation of impact location

The dorsal aspect of the foot/ boot was modelled as a linear line (LL), between the points ShBx,y and FBx,y (Figure 9.2). Only the foot/ boot segment was included within the model as the point of maximal deformation was identified, both initially qualitatively and subsequently quantitatively, to not occur on the shank for the present study. The coordinates of any point along the most antero-dorsal aspect of the foot could be computed by entering in either the x or y value into Equation 9.1, to yield the residual coordinate.

$$LL_y = m \cdot LL_x + b1 \qquad \text{Equation 9.1}$$

Where; LLy = the y-coordinate along the dorsal aspect of the foot, LLx = the x-coordinate along the dorsal aspect of the foot, and;

$$m = \frac{(FB_y - ShB_y)}{(FB_x - ShB_x)}$$ Equation 9.2

$$b1 = m \cdot -FB_x + FB_y$$ Equation 9.3

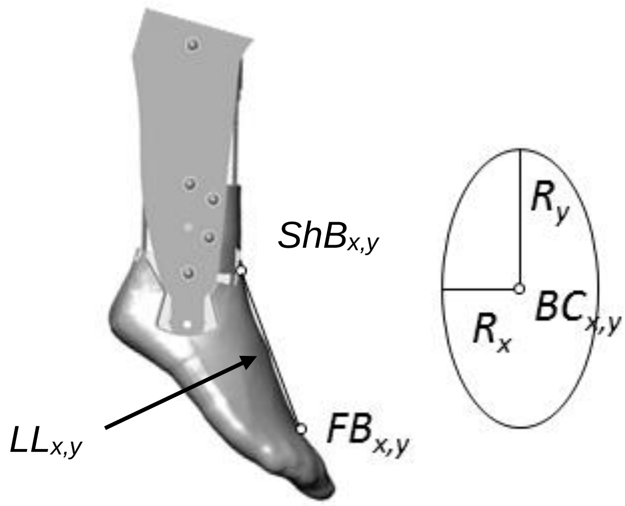

Figure 9.2: Location of landmarks

For the remainder of the foot and ball model, the x-coordinates (LLx) were treated as an independent variable, with an infinite number of points between the positions of ShBx and FBx. Secondly, as identified by Ishii, et al. (2009), deformation is best represented as displacement between the foot and ball running as a vector in the perpendicular direction to the linear line representing the foot (Figure 9.3). This vector can be computed using Equation 9.4, and also requires the x-coordinate on the dorsal aspect of the foot.

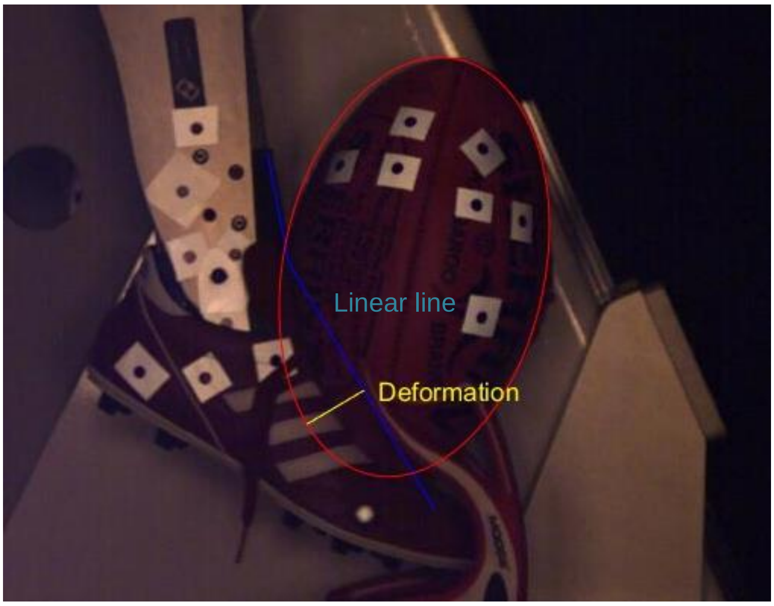

Figure 9.3: Representation of foot and ball model

$$PL_y = n \cdot PL_x + b2 \qquad \text{Equation 9.4}$$

Where; PLy = the y-coordinate of the perpendicular line, PLx = the x-coordinate of the perpendicular line, and;

$$n = -m^{-1} \qquad \text{Equation 9.5}$$

$$b2 = -n \cdot LL_x + LL_y \qquad \text{Equation 9.6}$$

To calculate the displacement between the foot and the ball, the intersecting point between the perpendicular line and the shell of the ball needed to be calculated. This was achieved by modelling the ball as an ellipse (Equation 9.7), adjusting for rotation of the ball (Equation 9.8) and translation of the foot and ball in space (Equation 9.9), solving Equation 9.4 (with updated field of Equation 9.9) into Equation 9.7, and then finally using the quadratic equation (Equation 9.10) to find the intercepting point. The quadratic equation yields two points, because a linear line passes through an ellipse at two points. But, because the foot always impacted the ball in the bottom left quadrant, due to the direction of the kick and the placement of the camera (right hand-side sagittal plane), only the '-' sign was needed. Equation 9.11 will yield the x-coordinate of the intersecting point, and solving this into Equation 9.4 will yield the y coordinate. Lastly, to calculate the resultant displacement between the foot and ball, Equation 9.11 will find the displacement.

$$\frac{(x)^2}{{R_x}^2} + \frac{(y)^2}{{R_y}^2} = 1 \qquad \text{Equation 9.7}$$

Where; x = the x-coordinate of the ball shell, y = the y-coordinate of the ball shell, Rx = short radius of the ball and Ry = long radius of the ball.

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \qquad \text{Equation 9.8}$$

Where; *x'*, *y'* = the new ball shell position and replace *x, y* in equation 9, and θ is the ball orientation.

$$b3 = b2 + (n \cdot BC_x - BC_y) \qquad \text{Equation 9.9}$$

Where; BC*x*,*y* = ball centre x-coordinate, y-coordinate.

$$PS_x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} + BC_x \qquad \text{Equation 9.10}$$

Where a = x^2 constants, b = x constants and c = constant. Note BCx has been added as part of the translation process.

$$Deformation = \sqrt{(LL_x - PS_x)^2 + (LL_y - PS_y)^2} \qquad \text{Equation 9.11}$$

Where LLx,y = the x,y-coordinates along the dorsal aspect of the foot; PSx,y are the x,y-coordinates of the perpendicular line (equation 6) intercepting the shell of the ball (equation 9), with updated terms of equation 10 and 11 to account for ball rotation and translation, to be finally solved using the quadratic formula (equation 12).

These steps will yield the deformation of any point along the dorsal aspect of the foot. Plotting Equation 9.11 as a function for LLx between the points of ShBx and FBx will yield a parabola, and its' maximum will yield the point of maximum deformation across the dorsal aspect of the foot, and was chosen as the impact point on the foot. Impact location was calculated using Equation 9.12 (Figure 9.4).

$$Impact\ location = \sqrt{(LL_x - FC_x)^2 + (LL_y - FC_y)^2} \qquad \text{Equation 9.12}$$

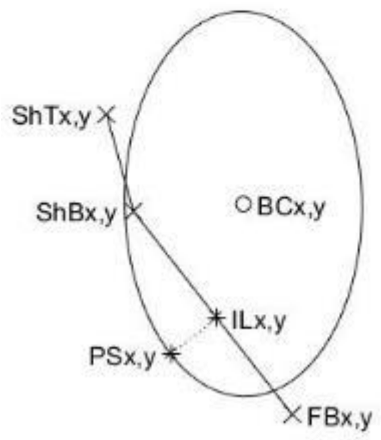

Figure 9.4: Foot and ball model, 25 frames into contact (near the point of maximal deformation). The points ILx,y and PSx,y represent the x-y coordinates of the impact location on the foot and the maximum displacement between the foot and ball shell in the perpendicular direction, respectively. The solid linear line between the points ShBx,y and FBx,y represent the dorsal aspect of the foot and the dotted linear line between the points ILx,y and PSx,y is the deformation distance. All other points have been previously defined.

9.2.3 Parameter calculation

The profile of impact, comprising foot velocity, ball velocity and the magnitude of ball deformation, were calculated for each ankle configuration. The mean and standard deviation of the 10 trials for each condition were calculated. Foot velocity was calculated as the first derivative of the virtual marker FC. Ball velocity was calculated from the first derivative of the virtual marker BC, representing the geometric, undeformed centre of the ball. The magnitude of ball deformation was calculated from Equation 9.11.

Ball angle and impact location were calculated throughout the duration of impact. The mean and standard deviation of the 10 trials for each condition were calculated. Ball angle was calculated from the BC and BT markers and calculated in the global coordinate system with the counter-clockwise direction representing the positive direction (Figure 9.2). Impact location was calculated along the most antero-dorsal aspect of the foot in relation to the FC along the proximal-distal direction. A distal impact location was represented as a positive value.

A video overlay of the foot and ball model was created to provide a visual analysis of the foot and ball model. This analysis provided a visual representation of how the models performed during impact in relation to the anecdotal observation of the ball rolling up the foot during impact. The models representing the foot and ball and the location and magnitude of ball deformation were plotted as overlays on top of the original video file of one kicking trial. Due to the print nature of this Chapter within this thesis, a video could not be presented. However, to still include this analysis, five screenshots were taken at key events: 1 frame prior to ball contact, at ball contact, at the point of maximal deformation, 1 frame prior to ball release, at the point of ball release. The results of this analysis were presented for one kick.

9.3. Results

Similar impact profiles were identified for the non-rigid and rigid ankle settings, and only the non-rigid ankle was presented to reduce repetition. Maximal deformation occurred prior to the crossover of foot and ball velocity (Figure 9.5). Impact location on the foot moved proximally and ball orientation increased during impact (Figure 9.6). The magnitude of ball deformation, calculated frame by frame for one video file, with images from the respective video file at five points in time are presented in Figure 9.7.

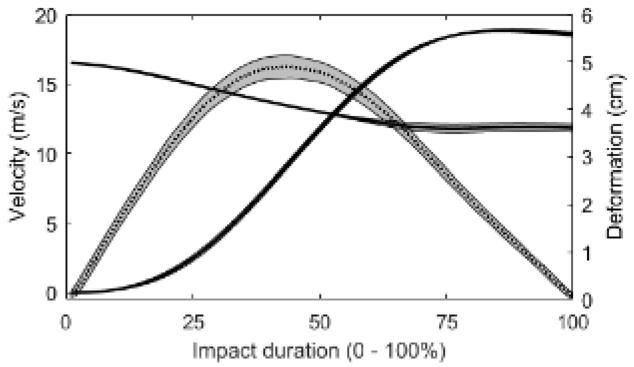

Figure 9.5: The profile of impact. Foot velocity (solid black line; primary axis), ball velocity (grey line; primary axis) and ball deformation (dashed black line; secondary axis) through the duration of impact.

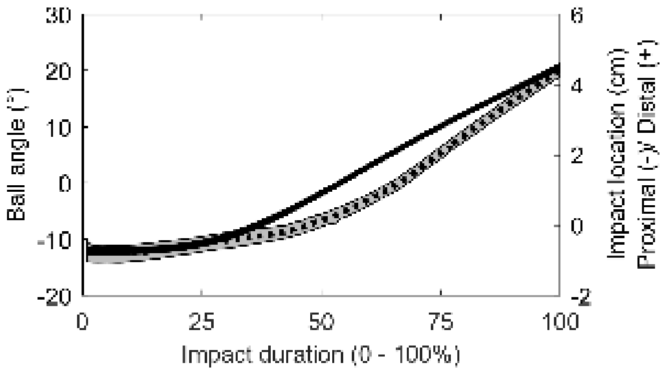

Figure 9.6: Ball orientation (solid black line; primary axis) and impact location (dashed black line; secondary axis).

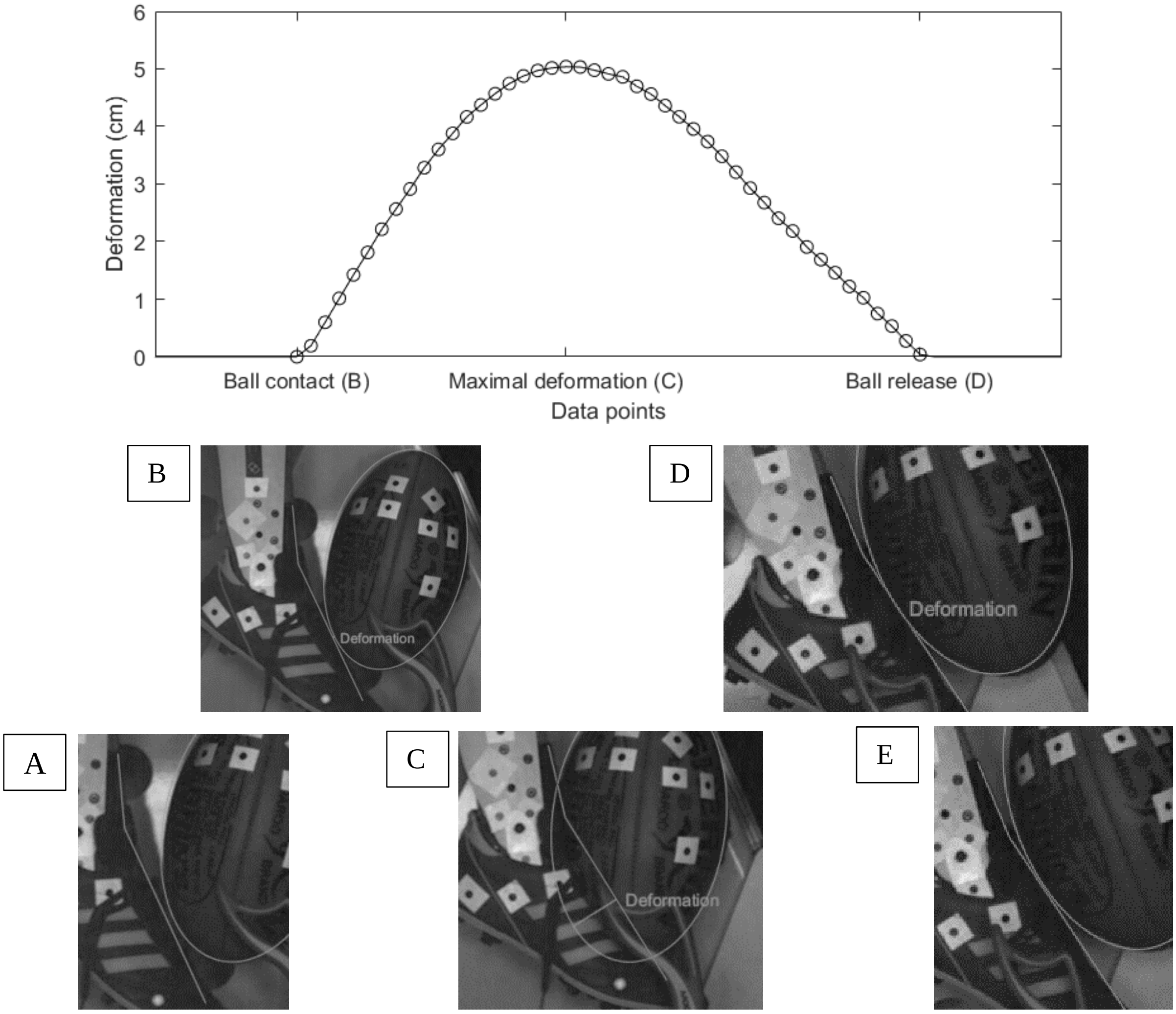

Figure 9.7: Ball deformation and corresponding video images at five points in time for one particular trial. Images A and E are the immediate frame prior to ball contact (B) and after ball release (E).

9.4. Discussion

The impact location on the most antero-dorsal aspect of the foot moved proximally during impact, quantifying the anecdotal observations of the ball 'rolling' up the foot. The calculation of ball deformation and impact location was made on the most antero-dorsal aspect on the foot, where the anecdotal observations of the ball 'rolling' up the foot is quantified by the change in impact location to the proximal direction and the increase in ball angle (Figure 9.6). At the most antero-dorsal aspect of the foot, where the linear line was projected from, the ball would have been mostly flatly deformed across the length of the foot due to the mostly linear surface and rigid properties of the foot. It can be qualitatively visually analysed in Figure 9.7C the edge of the ball extends beyond the linear line representing the most antero-dorsal aspect of the foot toward the original, undeformed shell of the ball. This might indicate the linear line did not represent the deformation, whereby the magnitude of ball deformation is overstated. However, due to viewing ball deformation from the sagittal view, the non-flat deformation of the ball across the medial-lateral direction occludes the true position of the antero-dorsal aspect of the foot. The ball is not flatly deformed during impact across the medial-lateral direction due to the three-dimensional geometric properties of the foot, corresponding to the depth within the cameras field of view. The foot surface across the medial-lateral direction can loosely be described as a semi-spherical/ semi-ellipsoidal shape (discussed more in the methods of Chapter 8 and 9), and the qualitative visual analysis of the video file (Figure 9.7C) indicates the ball 'wraps' around this surface. This occludes the view of the most antero-dorsal aspect of the foot, explaining why it visually appears the measurement of ball deformation is overstated. However, given the rigid properties of the foot, it can be assumed the most antero-dorsal aspect of the foot is non-deformed, where the measurement of ball deformation along this plane of the foot is not overstated. Therefore, the anecdotal observation of the ball 'rolling' up the foot is quantified by the impact location on the foot moving proximally during impact as the ball changes its angle.

The profile of impact indicated that the point of maximal ball deformation occurred prior to the crossover of foot and ball velocity (Figure 9.5), which represents a point of difference to impact of a soccer ball. Shinkai et al (2009) and Tsaousidis & Zatsiorsky (1996) identified the point of maximal deformation occurred when foot and ball velocity were equal. It is logical to expect maximum deformation to occur when foot and ball velocity are equal because prior to this point the foot is travelling faster than the ball, thus deforming it, and after this point the ball is travelling faster than the foot, thus it is reforming. The different profile found for the AF ball used in present study is likely due to its shape and motion during impact where it 'rolls up' the foot. Based on the change in ball orientation and impact location on the foot evident during impact

(Figure 9.6), the area of intersection between the foot and ball is changing. The stiffness of non-round and ellipsoidal shaped balls change depending on where it is deformed due to their non-constant radius. Under a quasi-static measurement of ball stiffness, Holmes (2008) identified the stiffness of a rugby league ball was greater when compressed on the belly compared to the point, due to the ‘shape factor’ of the deforming ball changing. When comparing the belly to the point of the ball, stiffness would be reduced at the point because a smaller area of the ball is being deformed. For example, a 3 cm deformation on the point of the ball is equal to an area of approximately 5.7% in the sagittal plane, compared to 11.5% when the belly of the ball is also deformed 3 cm. When the ball rolls up the foot and the belly is impacted, a different part of the ball is being impacted and the ‘shape factor’ is changing, increasing the stiffness of the ball. During impact of a soccer ball there would be no change in ball stiffness if it were to roll up the foot, as there is no change in ‘shape factor’ due to the spherical shape. The point of maximal linear ball deformation in the sagittal plane can logically be considered to occur at the crossover of foot and ball velocity for a spherical ball. The point of maximal linear ball deformation in the sagittal plane for a non-round ball will be dependent upon the change in ball orientation during impact: if there was no change in ball orientation maximum linear ball deformation will occur at the crossover of foot and ball velocity, as indicated by the results of a soccer ball where the ball radius is constant (Shinkai, et al., 2009); if the ball orientation is changing toward the belly, the maximum linear ball deformation will occur prior to the crossover of foot and ball velocity as seen in Figure 9.5. Future work should explore the timing of maximum linear ball deformation for an ellipsoidal ball if the orientation was changing toward the point: these results indicate the maximum linear deformation will occur after the crossover of foot and ball velocity. This also indicates future work modelling an ellipsoidal ball to calculate deformation should calculate the area in the sagittal plane. Or, even more appropriately, the volume of deformation in three-dimensional space to measure the ball centre of gravity during impact rather than the linear displacement. The difference between the relative timing of maximal deformation between impact of an ellipsoidal ball and a spherical ball is due to differences in the shape of the balls.

The formation of ball flight characteristics occurs through the duration of impact. Given the increase in ball speed occurs over three-fourths of impact duration (Peacock, et al., 2017a; Shinkai, et al., 2009), it can be logically expected the formation of other ball flight characteristics to also occur over a duration of ball contact. The results of the ball angle during impact also indicates the formation of ball flight characteristics occurs over the duration of impact and not instantly. Interestingly, the change in ball angle ceased prior to three-fourths of impact duration as previously identified for ball velocity: post-hoc analysis of ball angular velocity identifies the increase in velocity reduced substantially at approximately 40% of impact duration, and actually decreased in magnitude at approximately 70% of impact duration (Figure 9.8). This pattern of ball angular velocity differs to the relatively uniform increase and plateau in ball translation velocity observed in both this Chapter (Figure 9.5) and previous analyses (Peacock, et al., 2017a; Shinkai, et al., 2009). This could be explained by several factors: the change in ball orientation on the foot during impact and the pressure applied from ball to foot due to ball deformation. The orientation of the ellipsoidal ball influences the torque applied to the ball, as identified previously in Chapter 4.4.3 . As the ball orientation changes during impact, the torque applied from foot to ball will also change. During impact the change in ball orientation corresponded to the long axis of the ball is becoming more parallel to the surface angle along the length of the foot (Figure 9.9). It was previously identified under both parallel and perpendicular foot surface – ball long axis orientations that ball angular velocity was 0°/s (Chapter 4.4.3 Ball orientation about the x-axis; Figure 9.10). A second explanation of the reduction in ball angular velocity during impact is that as the ball is deformed onto the foot surface, a pressure is applied from the ball onto the foot. Analysis of the deformation area can indicate the pressure distribution, whereby the pressure along the foot surface during the deformed area will produce a torque both positive and negative in the global coordinate system. Assuming the ball deformation applies a force in the perpendicular direction to the surface of the foot along its length, the direction and location of the force vector can be qualitatively analysed and is applied to both aspects about the ball centre (Figure 9.11). The angular velocity of the ball will decrease if the net torque applied to the ball is in the negative direction, whereby the force vector (the net pressure applied between foot and ball) is applied superior to the ball centre of mass. Future work is required to quantify this pressure analysis, whereby the use of a force plate foot segment on the mechanical kicking machine can provide true force measurements that will be invaluable for the analysis of energy transfer from foot to ball. It can be seen; however, the formation of ball flight characteristics occurs through the duration of impact whereby the change in impact location and ball orientation influences the interaction.

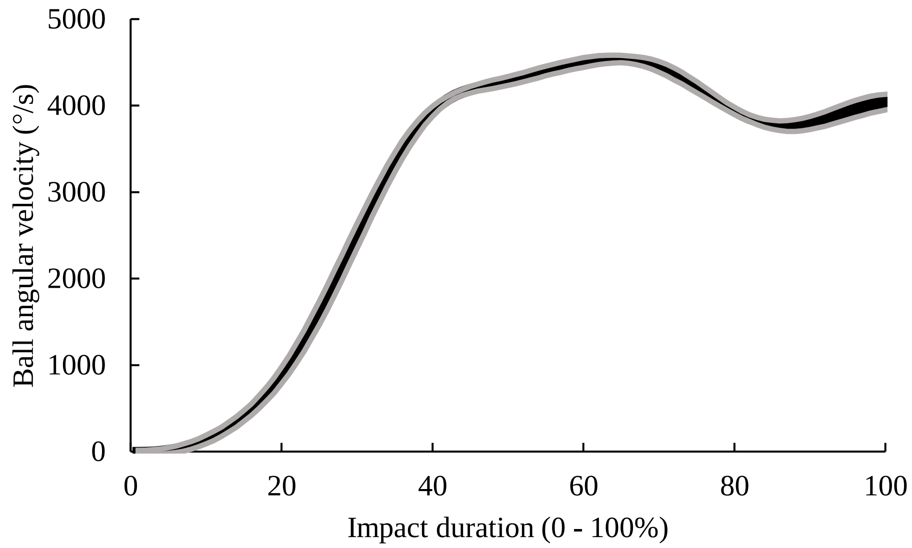

Figure 9.8: Ball angular velocity during impact (mean = black line; standard deviation = grey lines).

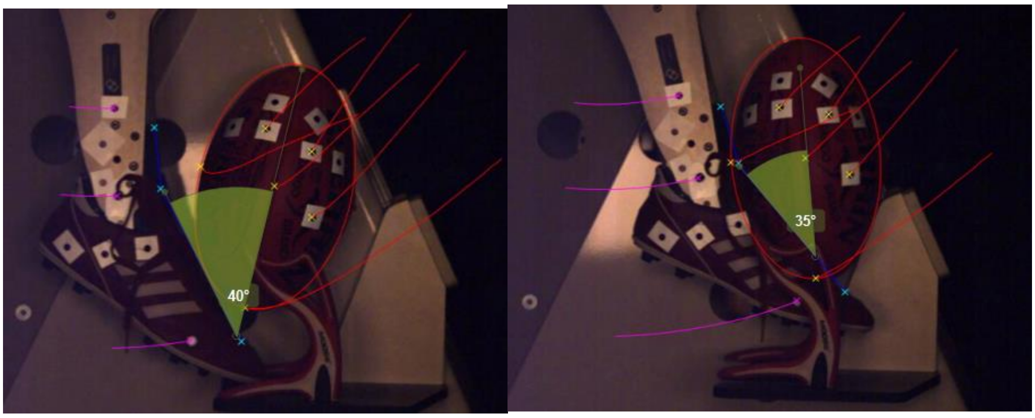

Figure 9.9: Change in foot surface – ball long axis orientation during impact. Comparisons are provided at the instance of ball contact (A) and approximately three-fourths of impact duration (frame 30 of 44) (B).

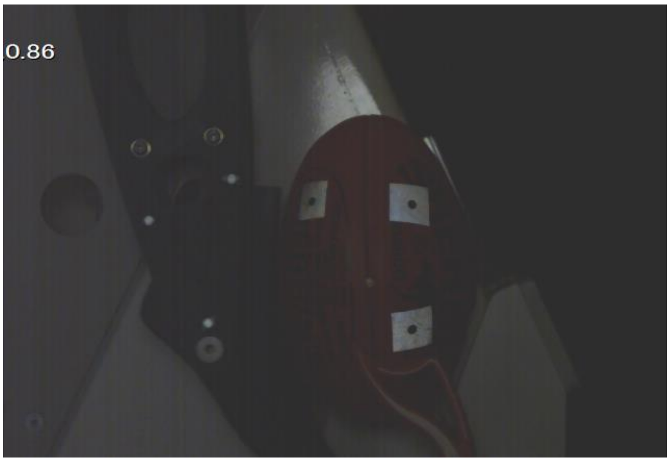

Figure 9.10: A snapshot at foot-ball contact when ball angular velocity was 0°/s because the foot surface and ball long axis were parallel (Chapter 4.4.3 Ball orientation about the x-axis).

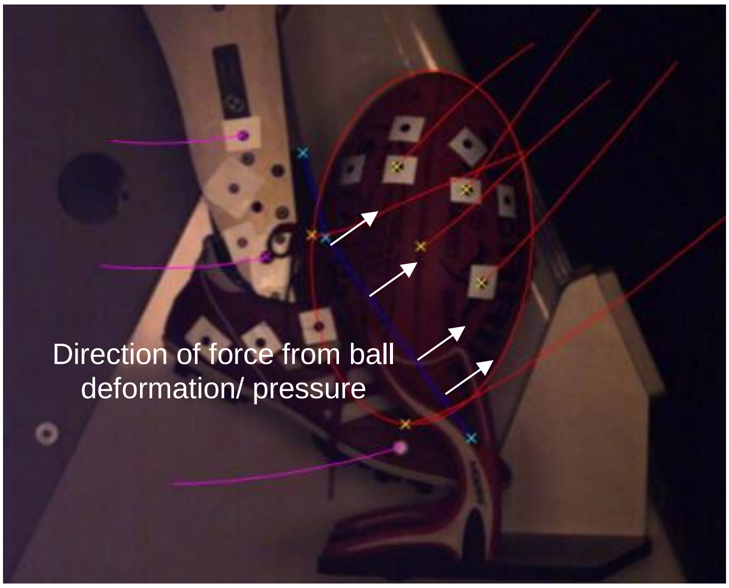

Figure 9.11: Estimation of force direction from ball deformation acting perpendicular to the foot surface.

The results in this chapter support the explanations for the results within this thesis that have relied on a qualitative analysis. It was identified in this chapter that the impact location moves dynamically during impact. The multiple linear regression in Chapter 8 identified increases to foot-ball angle Y translated to lateral azimuth ball flight trajectories. If all conditions of impact were held constant but with a systematic increase in foot-ball angle Y, there would be no change to the surface angle at the beginning of impact. This provides evidence against the surface angle at the beginning of impact influencing the outcome, the key theory identified within this thesis to explain differences in kicking accuracy. The result within this Chapter, whereby the impact location moves dynamically during impact, supports the expansion of the impact location throughout the duration of impact. It can be speculated that increases to foot-ball angle Y (where the top of the ball is tilted laterally) will change the direction of the impact location to move laterally on the foot during impact. As the impact location moves laterally, the surface angle of the foot points laterally from the direction on the kick, explaining why azimuth ball flight trajectory changes with foot-ball angle Y. This result provides evidence for the theory identified within this thesis that the surface angle during impact influences the azimuth ball flight trajectory.

Future analysis should be performed in three-dimensional space to directly confirm the dynamic nature of impact location moving medial-laterally.

Shinkai, et al. (2009) hypothesised the impact location on the foot moved distally in the soccer instep kick. After first recording the impact phase at a sample rate (5,000 Hz) capable of identifying the interaction during impact, they observed the ankle moved into initial dorsiflexion prior to distinct plantarflexion. They hypothesised the impact location was proximal from the foot centre of mass at the initial period of impact to produce the initial dorsiflexion, followed by the impact location then moving distally onto the distal side of the foot centre of mass to produce plantarflexion. In Chapter 6 (where the present data set came from), it was similarly identified the ankle was produced initial dorsiflexion before the distinct plantarflexion. The result within this chapter identifies the impact location moved proximally throughout the duration of impact, indicating the ankle motion pattern of initial dorsiflexion followed by plantarflexion observed within Chapter 6 was not due to the impact location on the foot during impact transitioning from the proximal to distal side of the foot. Rather, the initial dorsiflexion motion was due to the ankle containing an initial dorsiflexion angular velocity at the beginning of impact. The impact location in the sagittal plane was measured to occur distally from the ankle joint onto the foot segment, as measured by the point of maximal deformation on the most antero-dorsal aspect of the foot. This impact location produces an external plantarflexion ankle torque, which first reduces the dorsiflexion ankle angular velocity before increasing the plantarflexion angular velocity. It could be speculated a similar mechanism may have occurred in the study of Shinkai, et al. (2009), whereby the ball reaction force was applying a plantarflexion ankle torque. However, to further understand the factors that influence ankle motion during impact of soccer kicking, future work with the mechanical kicking machine that quantifies the direction of impact location and change in ball angle during impact with a soccer ball should be performed to provide direct evidence.

The results within the present chapter have practical implications. As the contact area is dynamic, i.e. it is constantly changing throughout foot-ball impact, players must control this dynamic nature to ensure they impart the desirable ball flight characteristics. As identified within the present thesis and this chapter, key parameters such as foot-ball angle influence this dynamic behaviour of foot-ball impact. Players and coaches must be aware of the importance of foot-ball angle on the dynamic nature of kick to ensure they kick successfully.

9.5. Conclusion

The aim of this chapter was to quantify the anecdotal observation of the ball ‘rolling’ up the foot during impact. By extending the developed method within this thesis to calculate impact location throughout the duration of impact, the motion of an ellipsoidal ball ‘rolling’ up the foot was quantified. This observation was quantified by the impact location moving proximally along the foot and the ball increasing its angle (as calculated in the global coordinate system) during impact.

9.6. Contribution of individual chapter to overall thesis

The present chapter contributed to the overall thesis by quantifying the dynamic motion between the foot and ball during impact. This dynamic motion has implications for how individual foot-ball impact characteristics influence impact efficiency, ankle motion during impact, and ball flight characteristics (aims 1 and 2 of the overall thesis).

Chapter 10: General discussion

Successful football kicking is achieved by players imparting an appropriate combination of flight characteristics onto the ball by impacting the ball with their foot. This thesis explored the relationship between foot-ball impact phase and kick outcome. Critical review of the literature identified two key areas of the relationship between foot-ball impact characteristics and kick outcome that required further exploration: the influence of impact characteristics on ankle plantarflexion, impact efficiency and ball velocity; and the influence of foot-ball impact characteristics on ball flight characteristics and kicking accuracy. These two issues were explored via two key experimental designs: systematic analysis with a mechanical kicking machine and intra-individual analysis with human players.

10.1. How do foot-ball impact characteristics influence impact efficiency and ankle plantarflexion

Foot-ball impact characteristics influenced ankle plantarflexion, impact efficiency, and ball velocity, as identified from both the mechanical kicking machine and the human kickers. For the mechanical kicking machine, systematic changes to individual impact characteristics translated to changes in ankle motion, impact efficiency, and/ or ball velocity. For the human kickers, impact efficiency and ankle plantarflexion was identified to differ between kicks due to variation in foot-ball impact characteristics. Further comparisons between players also identified how physical characteristics influenced ball velocity. From these analyses, the effectiveness of reduced ankle plantarflexion as a coaching cue was determined, and impact efficiency was influenced by the physical mass of the performer, impact location between foot and ball, ball orientation, and ankle stiffness.

10.1.1 The influence of foot-ball impact characteristics on impact efficiency

10.1.1.1 Physical mass of the performer

The physical mass of the performer influences impact efficiency. Post-hoc analysis between the physical mass of the individual players and the mean foot-ball speed ratio for all kicks identified increasing physical mass increased impact efficiency (r = 0.72; $p < 0.01$). This has been previously identified by Andersen and colleagues and by Shinkai and colleagues (Andersen, et al., 1999; Shinkai, et al., 2013). Increasing the physical mass of the striking limb via weights, however, has been identified to have no effect on ball velocity because foot velocity reduces (Amos & Morag, 2002; Moschini & Smith, 2012). However, no work has determined the longer-term effect of increased shoe mass on foot velocity and ball velocity, whereby a longer exposure to increased foot mass may assist in an increased strength and/ or coordination pattern that increases the final foot velocity. Future work should explore this area to determine if it is an effective strategy of improving kicking performance.

10.1.1.2 Proximal-distal impact location

Impact efficiency was influenced by proximal-distal impact location in the mechanical kicking machine and in seven of ten human kickers. For the rigid ankle of the mechanical kicking machine, distal impact locations increased impact efficiency because the linear velocity at the impacting point increased with no increase to ankle plantarflexion. For the non-rigid ankle, however, distal impact locations reduced impact efficiency because the ankle was forced into a greater magnitude of ball velocity. In the human kickers, an optimal relationship was identified in four players, a positive relationship was identified in two players and a negative relationship was identified in one player. These results identify that proximal-distal impact location for both the mechanical kicking machine and the human kickers was influential to impact efficiency.

Differences did exist between the mechanical kicking machine analyses and within the human players as to what impact location produced the highest impact efficiency. Ishii and colleagues (Ishii, et al., 2009, 2012) identified an optimal impact location on the foot in their analyses of the soccer instep and soccer sidestep kicks. The results in this thesis, while an optimal relationship was only identified in four of the human kickers, do not oppose an optimal relationship between proximal-distal impact location with impact efficiency. For the mechanical leg, not all impact locations were analysed. For the rigid ankle, the optimal is likely to exist along the distal direction at a location where the contact area between foot and ball is compromised by not covering the foot. But, because players do not impact the ball beyond the phalanges, it was not representative of human kickers to test the most distal locations across the phalanges. For the non-rigid ankle, the most proximal impact location that the contact area during impact did not exceed the three-dimensionally printed foot segment was analysed. Beyond this point, the contact area between foot and ball exceeded three-dimensionally printed foot segment. Assuming the three-dimensionally printed material did extend up to the knee-cap to represent the surface of the entire shank segment, impacting proximally beyond this point may continue to increase ball velocity for a limited distance, but, ball velocity will reduce at a location because the linear velocity of the impacting point is reducing due to moving closer to the axis of rotation (knee). For the human kickers, players likely restricted the impact locations to a limited range on their foot. Given the players were experienced kickers, they would have purposely reduced the impact locations to an area that did not produce substantial pain due to hyper-plantarflexion, supported by the relationship between proximal-distal impact location with ankle plantarflexion. Further, it is possible they also restricted the impact locations to an area that produced an ample impact efficiency for the task. Statistical variance in the impact locations was achieved from the variability players produced, which is different to that by Ishii and colleagues, who used a tee with different heights to facilitate a greater range of impact locations (Ishii, et al., 2012). Thus, because not all impact locations were analysed with the mechanical limb and because players restricted their impact locations to within a desired range, the full extent of proximal-distal impact location was not analysed and thus these results do not oppose the optimal relationship between proximal-distal impact location with impact efficiency and ball velocity. Therefore, it is suggested that coaches should assist players in exploring the proximal-distal impact location on their foot to determine the location that is best for the task.

10.1.1.3 Medial-lateral impact location

Ball velocity and impact efficiency were influenced minimally by medial-lateral impact location over the range of impact locations tested. The relationship between medial-lateral impact location with ball velocity was analysed with the mechanical kicking machine, and ball velocity showed little dependence on impact locations tested. Ball velocity reduced from a maximum of 25.0 m/s to a minimum of 24.5 m/s, from a location just medial from the foot centre to the most medial impact location tested. The entire width of the foot was not analysed; however, it was considered ball velocity would continue to reduce as impact location was moved away from the foot centre as identified by Asai, et al. (2002). This suggests medial-lateral impact location is an important characteristic for impact efficiency and ball velocity.

The influence of medial-lateral impact location on other impact characteristics, such as azimuth ball flight trajectory, is likely to be far more detrimental to performance in gameplay. For the most medial impact location tested with the mechanical kicking machine, when ball velocity reduced from 25.0 m/s to 24.5 m/s, azimuth ball flight trajectory was -8°. For a 35 m kick toward goal, which is a conservative distance that players will find difficult to reach whereby any reduction in ball velocity should be avoided, the ball will land 4.9 m to the side of the goal (assuming ball curve is not influenced). Conversely, by neglecting air resistance and using a constant elevation angle of 35°, the reduction in ball velocity from 25.0 to 24.5 m/s will translate to a 2.4 m reduction in kick distance. It can also be considered that if air resistance was not neglected the ball would still reach the target, as the kick distances were 59.9 and 57.4 m, respectively. The change to azimuth angle within the tested range is far more detrimental in absolute distances compared to the reduction in kick distance due to velocity. In a game situation, this would miss the goals for all football codes: the goals in Australian football are 6.4 m wide; the goals in rugby league and union are 5.5 m and 5.6 m wide; the goals in soccer are 7.3 m wide. Each attempt at goal under this scenario, when the player aimed for the centre of the goals, would be unsuccessful, whereas the kick distance would still surpass 35 m. Thus, while medial-lateral impact location likely does influence ball velocity and impact efficiency, the influence of medial-lateral impact location has the greatest effect on kick outcome by influencing azimuth ball flight trajectory.

10.1.1.4 Ball orientation

Ball orientation is influential to the magnitude of energy transferred to the ball. The mechanical kicking machine identified ball velocity and ball spin were highest at a given ball orientation. Post-hoc analysis of these results combining both translation and rotational kinetic energy identifies the highest kinetic energy transferred to the ball occurred at an orientation of 45° degrees in the global axis (Figure 10.1). Further post-hoc analysis of the data identifies the foot-ball angle (calculated from the surface angle of the foot surface) was 59° (Figure 10.2A). Interestingly, this angle is greater than that usually used by drop punt kicking but consistent with rugby place kicking (see Figure 10.2B and Figure 5 in Nunome, et al. (2014)). Using a reduced foot-ball angle will decrease the distance between the ball centre of mass and the impact location on the foot, whereby any off-angled foot-ball angle Y will have less of an influence on the resulting ball flight path. This, however, is speculation, and future research is required to determine the how foot-ball angle influences kick outcome, not just impact efficiency, on kicking with human players.

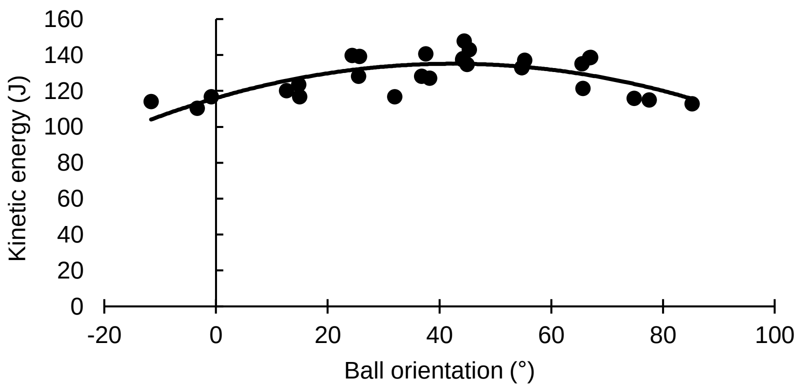

Figure 10.1: The relationship between ball orientation and kinetic energy (both translational and rotational) for the mechanical kicking machine.

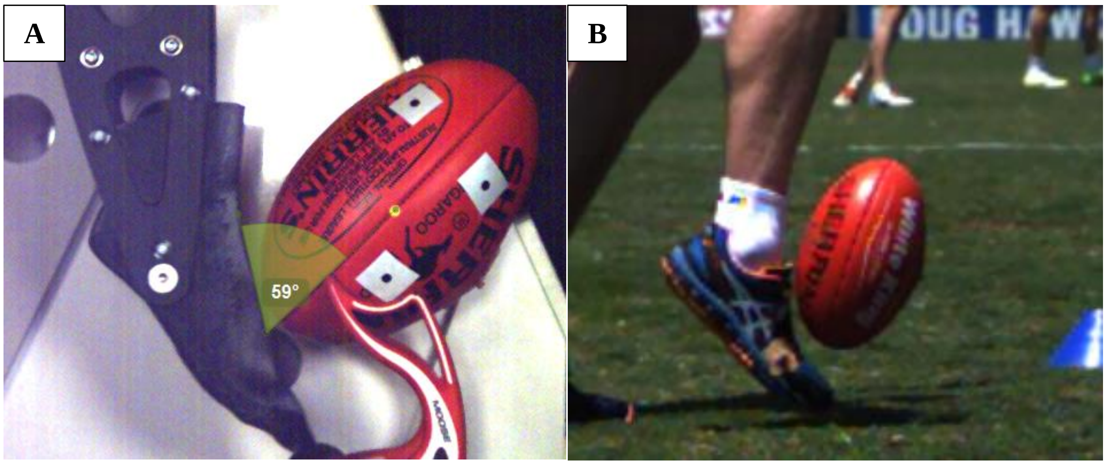

Figure 10.2: foot-ball angle that produced highest kinetic energy for the mechanical kicking machine (A) and the foot-ball angle commonly used in drop punt kicking (B).

10.1.1.5 Ankle stiffness

Increasing ankle stiffness increases impact efficiency. Increasing ankle stiffness was identified to increase impact in both studies with the mechanical kicking machine, in the comparison of non-rigid to rigid ankle and in the analysis of a non-rigid ankle. Several strategies have been discussed within the literature to increase ankle stiffness within human kickers: adopting a position of greater ankle plantarflexion at the beginning of foot-ball impact, increasing the stiffness of the muscle tendon units surrounding the ankle joint, and by actively dorsiflexing at the beginning of impact.

Adopting a position of greater ankle plantarflexion at the start of impact increases the stiffness of the ankle as the muscle tendon unit stiffness is increased. Increasing the stiffness of the spring in the mechanical kicking machine (replicating dorsiflexion muscle tendon unit) was identified to reduce ankle plantarflexion and increase the effective mass of the striking limb. It is well documented the stiffness of the human muscle tendon unit also increases when stretched (Morse, Degens, Seynnes, Maganaris, & Jones, 2008), thus adopting a more plantarflexed position will theoretically increase the stiffness of the ankle joint during foot-ball impact. This strategy has previously been suggested in football kicking (Peacock, et al., 2017a; Sterzing, et al., 2009). Post-hoc analysis of the human kickers in this study weakly supports the effectiveness of this strategy Table 10.1; significant ($p < 0.05$) negative linear relationships between change in ankle plantarflexion with plantarflexion at the beginning of impact were identified in four of the 10 players, indicating adopting a more plantarflexed position reduced change in plantarflexion during foot-ball impact for some players. It is important to note that proximal-distal impact location was identified as an important factor influencing change in ankle plantarflexion. To accommodate this factor, further correlations between ankle angle at impact start and change in ankle angle but partial to proximal-distal impact location identified a significant relationship in two players, not four. This result suggests this strategy might not be effective. This may be explained by players not purposely using a range of different ankle positions at impact start, whereby the statistical power would be low for the regression. Alternatively, the previous results (Peacock, et al., 2017a; Sterzing, et al., 2009) did not account for differences in impact location in their statistical analysis, as performed here, and may have influenced the results, whereby this strategy might not actually be effective. However, given the strong theoretical support of this strategy from both the mechanical kicking machine and increasing stiffness of a stretched muscle tendon unit (Morse, et al., 2008), future work should be performed to determine the full effectiveness of this strategy in human kickers. This could be achieved by either generating a range of different ankle positions at the start of impact for a given kick distance where a correlation could be performed partial impact location, as performed here. Or, a group comparison such as a pre- and post- intervention would also be feasible, where players are trained to increase ankle plantarflexion at the beginning of impact.

Table 10.1: Correlation (r) between ankle dorsiflexion angle at impact start and change in ankle plantarflexion; correlation (r) between ankle dorsiflexion angle at impact start and change in ankle plantarflexion partial to impact location across the proximal-distal direction on the foot.

	Correlation (r)	Partial correlation (r)
P01	0.745*	0.644*
P02	-0.182	0.030
P03	-0.279	-0.093
P04	0.344*	0.486*
P05	0.139	0.109
P06	-0.276	-0.028
P07	0.414*	-0.116
P08	0.241	0.054
P09	0.393*	0.147
P10	0.325	0.210

* indicates significance

The strength of an athlete is a mechanism that has been suggested to influence change in ankle plantarflexion during foot-ball impact (Ball, et al., 2010). Resistance training has been identified to increase both the stiffness of the tendon structure and muscle strength and size (Kubo, Kanehisa, & Fukunaga, 2002), and thus is another possible mechanism to reduce ankle plantarflexion during impact and increase foot-ball speed ratio. The effects of resistance training could be two-fold. Firstly, performing resistance training on the dorsiflexion muscle tendon unit of the ankle joint will increase their stiffness, reducing the magnitude of plantarflexion as it is stretched during foot-ball impact. Secondly, performing resistance training on the plantarflexion muscles of the ankle joint as well, to co-activate the plantarflexion and dorsiflexion muscle groups to pre-stretch the muscle tendon unit of the key dorsiflexion muscle group will again increase stiffness. Future work should investigate the efficacy of resistance training to improve stiffness of the ankle joint and how this influences performance in football kicking.

While the stretch reflex within the dorsiflexion muscle group won’t respond to the initial conditions at impact, it might increase the stiffness of the ankle joint as it is forced into plantarflexion during the forward leg swing. The reflex of the ankle dorsiflexion muscle group was discussed previously to not be influential during foot-ball impact because the response time was far greater than the impact duration. But, the stretch reflex mechanism might still be active during foot-ball impact, due to the motion dependent forces applied to the foot/ ankle during the forward leg swing. Koike and Bezodis (2017) identified two of three players produced a dorsiflexion torque just prior to impact in the rugby place kick. Their model to calculate torque included the motion dependent terms (centrifugal/ Coriolis forces), whereby the dorsiflexion torque could have been provided from passive structures at the end of the plantarflexion range of motion, the stretch reflex process, the muscular torque (which they stated), or a combination of all factors. It was also identified in the mechanical limb during the analysis with the non-rigid ankle that when foot velocity was increased with a constant ankle stiffness, the motion dependent forces increased the magnitude of energy stored in the spring mechanism and released into dorsiflexion motion just prior to impact. Thus, because an external plantarflexion torque is applied to the ankle prior to the beginning of foot-ball impact, the stretch reflex might contribute to ankle stiffness during foot-ball impact.

Another technique to restrict the passive response of the ankle during impact is by actively dorsiflexing at the beginning of impact. Chapter 5 identified in the analysis of foot velocity that dorsiflexion motion at the beginning of impact increased, restricting the change in ankle plantarflexion in the higher foot velocities despite the greater external forces applied. Dorsiflexing at the beginning of impact, was considered to increase impact efficiency because the storage of energy in the spring mechanism, occurring under a plantarflexion motion, was delayed. It was also identified by Peacock, et al. (2017a) and Shinkai, et al. (2009) that players dorsiflex at the beginning of impact in drop punt and instep kicking. The analysis by Koike and Bezodis (2017) does also suggest muscular force may have been applied immediately prior to impact, possibly to actively dorsiflex leading into impact. Dorsiflexing at the beginning of impact will compromise the ability to adopt the most plantarflexed position at the beginning of impact, because with any dorsiflexing motion the ankle is moving away from a position of plantarflexion. It was beyond this thesis to identify which strategy might be most effective, or if a combination of both strategies is best. Future work should explore the effectiveness of actively dorsiflexing at the beginning of impact to increase impact efficiency.

The analysis of impact location for the human players identified that players targeted a location on their foot that corresponded to a change ankle plantarflexion of less than 3°, a location near the highest impact efficiency. The mean proximal-distal impact location for each player yielded a change in ankle plantar/ dorsal flexion of < 3° during impact. It could not be identified why players targeted this specific location, but it does identify that players targeted a location on their foot that produced little-to-no change in ankle plantarflexion during foot-ball impact. This might suggest that strategies to reduce the magnitude of ankle plantarflexion will not be effective because there is already little-to-no change in ankle position. However, while a player might exhibit a change in ankle plantarflexion of 0° from start to finish of foot-ball impact, this does not indicate the ankle was completely rigid during impact as a change in ankle angle of 0° can also be achieved by undergoing an equal magnitude of ankle plantarflexion and dorsiflexion during impact. For example, further analysis of the ankle motion for Player 4 identified during trials that experienced a small change in ankle plantarflexion during impact (< ± 1°), there was no linear ankle motion from beginning to end of impact, but a combination of both plantarflexion and dorsal flexion during impact (Figure 10.3). Under these kicks, using the total change in ankle plantarflexion might indicate the foot was acting as a rigid body, or close to a rigid body, because if the magnitude of dorsiflexion is equal to plantarflexion the elastic energy stored is released. However, due to the hysteresis of the muscle tendon unit (Taylor, Dalton JR, Seaber, & Garrett JR, 1990), the magnitude of released elastic energy would be less than the stored energy. Thus, not all cases where the ankle undergoes a change in ankle angle of 0° is it acting like a rigid body.

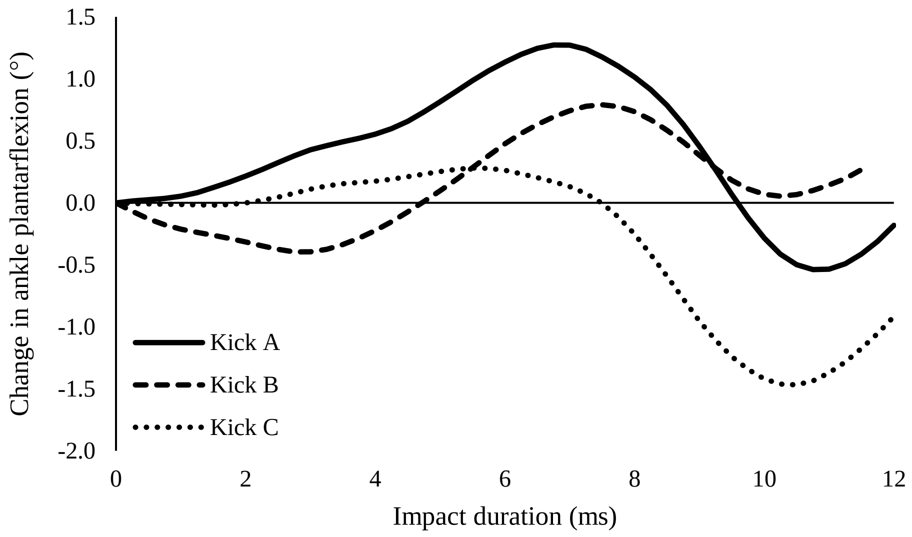

Figure 10.3: Ankle plantar/dorsal flexion of three kicks that underwent a total change in ankle angle of less than 1°.

It is recommended players should employ strategies to reduce ankle plantarflexion for two reasons. Firstly, when impacting at the 'sweet spot' for change in ankle plantarflexion along the foot, where the change in ankle angle is 0°, it was just identified the ankle still goes through a change in position during impact and is not completely rigid. Theoretically, increasing stiffness of the ankle at this change in ankle plantarflexion 'sweet spot' may reduce the peaks and troughs of the ankle motion during impact and increase impact efficiency (Figure 10.4, comparison between line A and line B). Secondly, employing strategies to reduce ankle motion might increase the 'power zone' on the foot, an area on the foot that produces a foot-ball speed ratio above a certain threshold. While players targeted the location on their foot that produced minimal ankle plantarflexion during impact, they also yielded end-point variability and impacted at a distance from this location in some trials. Employing strategies to increase the stiffness of the ankle for these impact locations away from the change in ankle plantarflexion 'sweet spot' might increase the 'power zone' (Brody, 1981). Mathematically, this will decrease the quadratic coefficient of the second order relationship between proximal-distal impact location with foot-ball speed ratio. For example, a player might produce an area of 3 cm where foot-ball speed ratio is above 1.30, but the area might increase to 5 cm by employing strategies to increase ankle stiffness (Figure

10.4, line A compared to line C). This suggestion was also made by Ishii, et al. (2012), whereby they suggested increasing the ankle joint torque assisted in increasing ball velocity at distal impact locations. Furthermore, their model also suggested the 'sweet spot' was shifted distally. As a player may be able to hold the ankle joint fixed when impacting distally which will be travelling at a higher linear velocity, thus is beneficial to ball velocity.

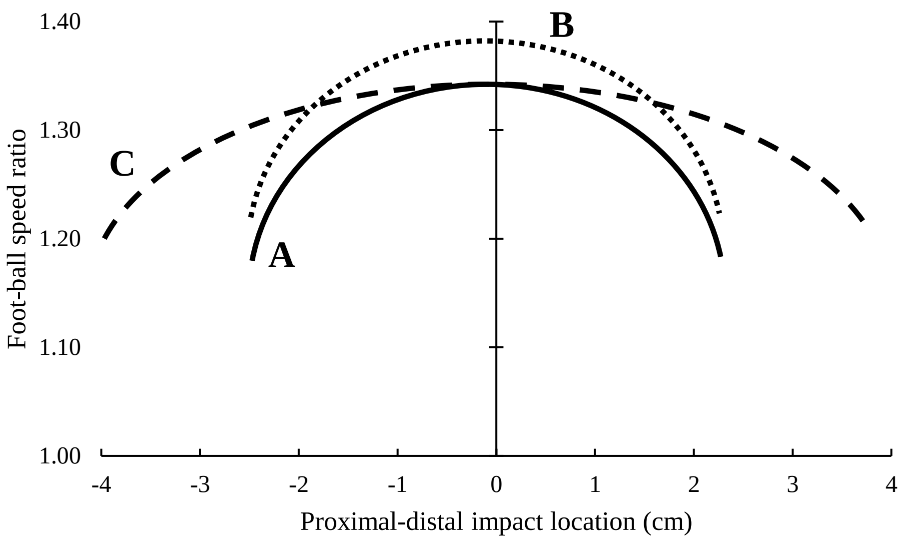

Figure 10.4: Theoretical analysis of the relationship between proximal-distal impact location and foot-ball speed ratio in response to increasing the stiffness of the muscle tendon unit. Line A represents the untrained ankle. Line B represents an increase foot-ball speed ratio due to reduced ankle motion during foot-ball impact. Line C represents an increase in the 'power zone', whereby a stronger muscle tendon unit may allow for greater end-point variability in impact location.

10.1.1.6 Foot velocity can increase ball velocity but decreases impact efficiency

Foot velocity can be used to increase ball velocity despite a reduction in impact efficiency. Impact efficiency will decrease due to both a reduction in coefficient of restitution of the ball and due to an increased external torque applied to the ankle joint. It is currently not known if there are any strategies a player can use to negate the negative effect of increasing foot velocity on impact efficiency, and could be a direction of future work. The influence of foot velocity on the impact phase is still important for coaches, as they should be aware of the influence of foot velocity on ankle motion and that impact efficiency will decrease as they kick further distances.

10.1.2 Does reducing change in ankle plantarflexion during foot-ball impact influence impact efficiency?

Reducing the magnitude of ankle plantarflexion was suggested as an effective strategy to increase impact efficiency. However, critical review of the literature identified no empirical evidence supporting the strategy. Thus, the effectiveness of the coaching cue ‘maintaining a foot firm and reducing the magnitude of ankle plantarflexion during impact’ was not known. The following section will determine the effectiveness of reducing ankle plantarflexion to increase ankle plantarflexion.

Ankle motion during impact is a passive response to the initial conditions at ball contact. Nunome and colleagues (Nunome, et al., 2006b) first suggested ankle motion during impact was passive, and the results within this thesis of both the mechanical kicking machine and the human performers support this suggestion. The response of an ankle that is passive in nature was identified from the mechanical kicking machine, whereby the resulting change in ankle position during impact is influenced by the internal and external torque applied to the ankle during impact and the pre-existing motion of the ankle. The response of the ankle for human kickers was identified to be passive due to the similarities with the relationship between the proximal-distal impact location and change in ankle plantar/dorsiflexion in human kickers. For both human players and the mechanical kicking machine, a distal impact location increased the magnitude of ankle plantarflexion because the external torque increased. Each of the human kickers produced either perfect or near perfect relationships between proximal-distal impact location with change in ankle plantarflexion. Thus, the ankle motion for human kickers is passive during impact and is determined by the internal and external torque applied to the joint and the pre-existing motion of the ankle joint.

Ankle motion is passive due to the extremely short duration of the impact phase. The impact phase lasts approximately 7 – 16 ms (Peacock, et al., 2017a; Shinkai, et al., 2009). The transfer of energy from foot to ball occurs over about three fourths of the phase (Peacock, et al., 2017a; Shinkai, et al., 2009), where any active contribution by the ankle must therefore occur within three-fourths of impact, or 5 – 12 ms from ball contact depending on the overall contact time. However, any active response from the ankle occurs after this time. The monosynaptic reflex, the quickest reflex in the body, is in the range of 20 – 40 ms between individuals (Latash, 2012). But, specific research on the dorsiflexion muscle group, the muscle group that is stretched during plantarflexion, has identified the muscle fires at 50 ms post muscle-twitch and peaks at 150 – 300 ms (Sinkjaer, Toft, Andreassen, & Hornemann, 1988). Given the force applied from foot to ball increases over the initial period of impact (Iga, et al., 2017; Shinkai, et al., 2009) and ankle plantarflexion typically begins at 2-3 ms post contact (Peacock, et al., 2017a; Shinkai, et al., 2009), the muscle twitch of the dorsiflexion muscle group can be expected to occur at 2 – 3 ms post ball contact. This means the muscle will fire at 52-53 ms post ball contact, and then increase its contribution until 153 ms post ball contact. However, the impact phase has ceased when the contribution of ankle dorsiflexion muscle work occurs, where the ankle is passively responding to the initial conditions at ball contact during the entire foot-ball impact phase.

It has been suggested that players might use several strategies to actively control the resulting change in ankle position, which might suggest the ankle motion is active and not passive. Several strategies have been identified to reduce the magnitude of ankle plantarflexion: dorsiflexion just prior to impact (Chapter 5), increasing the magnitude of plantarflexion at the beginning of impact (Peacock, et al., 2017a; Sterzing, et al., 2009), and increasing the muscle stiffness (Ball, et al., 2010). It is important to differentiate between these active strategies and passive response of the ankle. The passive response of the ankle refers to the motion of the ankle during impact in response the initial conditions at ball contact. Active strategies are either pre-programmed task specific strategies or are a result of feedback gained during the leg forward swing when there is ample time to functionally adapt the execution. The initial conditions of impact, which the ankle passively responds to, comprises these active strategies. While players might actively alter the conditions of the ankle at the start of impact, the ankle responds passively during impact to these strategies and the external torque applied to the joint.

All results within this study did identify impact efficiency was largest when change in ankle plantarflexion was minimised, supporting the coaching cue of maintaining a firm ankle during impact. Each of the strategies that reduced ankle plantarflexion translated to increased impact efficiency in the mechanical kicking machine: comparison of rigid to non-rigid ankle; proximal-distal impact location; increasing ankle stiffness; and actively dorsiflexing at the beginning of impact. These results support the strategy of reducing ankle plantarflexion to improve impact efficiency. The results of human kicking identified that impact efficiency was highest within a change in ankle plantar/dorsiflexion of less than 3°. The limitation of the analysis with the mechanical kicking machine was that no change in ankle position of dorsiflexion was created by the interventions applied, where it could not be identified if ankle plantarflexion should continually be reduced (to produce dorsiflexion) or if there is an optimal magnitude of ankle plantarflexion. The analysis of human kickers identified ankle dorsiflexion did occur regularly, providing the opportunity to explore if continual reduction in plantarflexion (to produce dorsiflexion) or if an optimal level of ankle plantarflexion is best for impact efficiency. Of the four players that a sweet spot location could be identified on the proximal-distal direction of the foot by foot-ball speed ratio, this impact location translated to a change in ankle plantarflexion of < 3°. This suggested an optimal level of ankle plantarflexion was best for impact efficiency. Further, post-hoc bivariate analysis of the human kickers identified six of ten players produced a significant relationship directly between change in ankle plantarflexion with impact efficiency, with all players again producing the highest impact efficiency at a change in ankle angle of < 3° plantar/dorsiflexion. The results within this thesis identify that reducing the magnitude of ankle plantarflexion to within a small magnitude (< ±3°) produced the highest impact efficiency.

Reducing the magnitude of ankle plantarflexion did not always increase ball velocity. While the results in this thesis identified that reducing the magnitude of ankle plantarflexion to a small magnitude produced the highest impact efficiency, specifically reducing the magnitude of ankle plantarflexion did not always increase ball velocity. Reducing the external torque applied to the ball was identified to reduce the magnitude of ankle plantarflexion during impact. Reducing the magnitude of foot velocity at ball contact can reduce the external torque, however, the linear relationship between foot velocity and ball velocity indicates that any reduction to foot velocity, while it might reduce the magnitude of ankle plantarflexion, will reduce ball velocity. Thus, reducing ankle plantarflexion does not increase ball velocity, rather, it increases impact efficiency.

Reducing change in ankle plantarflexion did not directly influence impact efficiency because ankle motion was passive during impact. While it was identified that restricting the magnitude of ankle plantarflexion to within a small magnitude ($< \pm 3°$) produced the highest impact efficiency, reducing change in ankle plantarflexion, as a theoretical construct, did not influence impact efficiency because ankle motion was passive during impact. Players could not solely actively reduce change in ankle plantarflexion to improve impact efficiency. Rather, they controlled the internal/ external torque applied to the ankle or the pre-existing ankle motion at the beginning of impact. It is the strategies that players used to alter the internal/external torque applied to the ankle joint and/ or the pre-existing ankle motion at the beginning of impact that influenced impact efficiency. The results within this thesis identify that increasing rigidity, impacting closer to the 'sweet spot' on the foot, increasing the dorsiflexion angular velocity immediately prior to impact, and reducing foot velocity each increased impact efficiency.

Assessing ankle motion can be used by coaches as a valid tool to provide feedback on the quality of impact. The previous discussion on ankle motion influencing impact efficiency was philosophical, but the practical outcomes from this work identified that assessing ankle motion can be used as a valid tool to assess the quality of impact because impact efficiency was generally largest when ankle plantarflexion was minimised. The highest identified impact efficiency was greatest for the individuals with a change in ankle plantarflexion of $< \pm 3°$, whereby coaches can assess the ankle motion during impact to provide feedback on how they can reduce this motion to a small magnitude. If players do display a large magnitude of ankle plantarflexion, they can reduce this magnitude through several strategies such as altering the impact location and increasing the rigidity of the ankle joint. Individual strategies to increase impact efficiency are discussed in Chapter 10.1.1 .

The mixed results on the effectiveness of reducing ankle plantarflexion in previous literature were likely due to confounding impact characteristics. Critical review of the literature identified mixed results on the effectiveness of reduced ankle plantarflexion to increase impact efficiency and/ or final ball velocity. Studies discussing the issue identified reduced ankle plantarflexion had a positive influence on impact efficiency or ball velocity (Asami & Nolte, 1983), had statistically no influence on impact efficiency or ball velocity (Ball, et al., 2010; Nunome, et al., 2006b; Peacock, et al., 2017a; Shinkai, et al., 2013; Sterzing, et al., 2009), or they were not original papers exploring the issue (Kellis & Katis, 2007; Lees & Nolan, 1998). However, these analyses (excluding the literature reviews) were performed at a group level. Individual differences in physical mass, impact location, and foot velocity each would have influenced ankle plantarflexion, impact efficiency and ball velocity. The results from this thesis, performed on an individual level, identified that strategies to reduce ankle plantarflexion were beneficial to impact efficiency.

10.1.3 Limitations and future directions to increase impact efficiency

The work within this thesis identified several strategies that a player can employ to increase impact efficiency, but future work should be performed to determine the effectiveness of these strategies. Increasing joint stiffness, increasing the pre-existing ankle dorsiflexion motion, or impacting the ball at the optimal impact location on the foot were each identified to increase impact efficiency. Future work should explore how players can implement these strategies over long term to determine their effectiveness against a control group. For example, it was identified that increasing the stiffness of the ankle joint improved impact efficiency in the mechanical kicking machine, and it was discussed that resistance training on the musculature around the ankle joint might be an effective method to implement this strategy as previous work has identified resistance training increases the muscle tendon unit stiffness. However, it was not identified if performing resistance training, in comparison to a control group, increases impact efficiency. This highlights the limitation of the work within this thesis, where the theoretical aspects on impact efficiency were identified, and future research is required to determine the effectiveness of these strategies in comparison to a control group.

10.2. How do foot-ball impact characteristics influence ball flight characteristics and kicking accuracy

10.2.1 The influence of foot-ball impact characteristics on ball flight characteristics and kicking accuracy

Ball flight trajectory and velocity, not factors associated with ball spin, were more important ball flight components for kicking accuracy. Azimuth ball flight trajectory was identified as the most important factor toward the horizontal component of kicking accuracy in Chapter 8, and further analysis of this dataset identifies ball elevation angle and ball velocity were most influential to the vertical component of the vertical plane. Theoretically, vertical component of kicking accuracy will be influenced by ball velocity, elevation angle and spin rate. Further multiple linear regression analysis of these three variables from the dataset analysed in Chapter 8 explained 35.4% of variance within the vertical component of kicking accuracy, whereby elevation angle and ball velocity were most important/ influential as indicated by the standardised coefficients (Table 10.2). The influence of ball aerodynamics, as represented by back-spin rate, had less of an influence on the vertical component of the vertical plane, as similarly identified in the horizontal component where azimuth ball flight trajectory was the most important variable. These results indicate errors in kicking accuracy were more influenced by the trajectory and velocity of the ball, and less explained by the factors associated with ball spin. This might be due to the dynamics of the drop punt kick, where the ball ‘rolls’ up the foot. The ability to apply the distinct back-spin might be easily to achieved as the ball rolls up the foot and rotates about its longitudinal axis. Important to note, wind will also influence ball curve in the outside environment but was not included in this analysis.

Table 10.2: Multiple linear regression results predicting the vertical component of kicking accuracy. This regression was performed using the same methods and dataset from Chapter 8.

	B	*σe*	*β*
Constant	-5.961	1.94	
Ball back-spin	-0.034	0.011	-0.276
Elevation angle	0.114	0.024	0.815
Ball velocity	0.243	0.066	0.578

B = coefficient; *σe* = standard error of coefficient; *β* = standardised coefficient.

A lower magnitude of variance in the vertical component of kicking accuracy was explained by the ball flight characteristics (35.4%) in comparison to the percentage of variance explained by ball flight characteristics influential to the horizontal component (69.9%). Two factors might explain why a lower variance was explained by the ball flight characteristics. Firstly, a multiple linear regression was used to identify the influence of individual ball flight characteristics. As the name suggests, a linear regression assumes the influence of each independent variable in explaining the variance in the dependent variable is linear. Not all ball flight characteristics, however, are expected to have a linear influence on the ball flight path. Back-spin rate, for example, will influence the lift force applied to the ball during its flight and therefore the measurement of vertical kicking accuracy. The influence of back-spin rate on the lift force not linear, but exponential (Equation 10.1). Thus, the influence of some ball flight characteristics on the vertical measurement of kicking accuracy might not be represented fully by the linear regression.

$$F_L = \frac{1}{2} C_L \rho A v^2$$ Equation 10.1

Where F_L = lift force; C_L = dimensionless lift coefficient; ρ = air density; A = cross-sectional frontal area; v = velocity.

Secondly, the unexplained variance might be due to the measurement of the vertical component of kicking accuracy, which was susceptible to a larger magnitude of error compared to the horizontal component. If the receiving player moved off the 30m line when catching the ball, an error in the measurement occurred because the catch position and the true position of the ball passing through the 30m plane are not equal due to the downward trajectory of the ball toward the ground. While the videos were screened to eliminate kicks where the ball fell short of or travelled overhead of the receiving player, it is possible the ball was caught where the receiving player moved a small distance (< 0.5 m) off the 30 m plane. Due to the downward trajectory of the ball just prior to being caught, the measurement of kicking accuracy will be understated as the receiving player moves toward the kicker, and the measurement of kicking accuracy will be overstated as the receiving player moves away from the kicker. A quantitative error analysis could not have been performed because the three-dimensional vector of the ball was not recorded at and immediately prior to being caught, however a two-dimensional analysis of one kick identified the horizontal ball speed was 0.8 m/s and the vertical speed was 13.0 m/s over the final two frames prior to being caught for a kick that was off-target. If, hypothetically, the ball was travelling at an angle of 50° from the horizontal, the ball would be travelling at 10.9 m/s toward the target. As can be seen in the Figure 2 of Goff (2013), the ball arrives to the ground with a greater elevation angle than the take-off angle due to the lift and drag forces applied to the ball during flight, thus this 50° approximation is ample for this analysis given the take-off elevation angle of the kick was measured 19.0°. If the player catching the ball moved 0.5 m off the 30 m plane of the kick distance toward the kicker, the ball would be caught 0.05 seconds earlier, producing an error of 0.004 m in the horizontal component and 0.65 m in the vertical component. This larger magnitude of error in the vertical component might explain why a larger percentage of variance was unexplained by ball flight characteristics. While multiple linear regression can identify the influence of several independent variables on one dependent variable, future research exploring the ball flight characteristics influencing the vertical component of kicking accuracy should develop employ a method capable of detecting non-linear influence of parameters and use a measurement that is less susceptible to error.

Foot elevation angle was an important factor influencing ball elevation angle in human kickers. To get an indication of the impact characteristics that influence the vertical component of kicking accuracy, an additional multiple linear regression was performed to identify the variability in foot-ball impact characteristics that influenced ball elevation angle. Ball velocity was identified as the second most important factor, and an analysis of factors that influence ball velocity have been discussed heavily in this thesis and will not be discussed again in this section. Understanding what factors influence ball elevation angle is a new analysis to progress the understanding of kicking accuracy in human kickers. Foot velocity, foot-ball angle about the X axis, and proximal-distal impact location were identified to have substantial influences on elevation angle in the mechanical kicking machine (Chapter 4). Therefore, to get an indication of the variability that players produce in their impact characteristics and how it relates to vertical kicking accuracy, a multiple linear regression analysis was performed to identify the dependence of ball flight elevation angle on foot velocity, foot-ball angle X and foot elevation angle for two players. Because the ankle was rigid in this analysis with the mechanical kicking machine, the influence of proximal-distal impact location was not representative of human kickers and was not included in this analysis. Foot elevation trajectory was included in the regression analysis because it was discussed as being influential in the analysis within the mechanical kicking machine despite not systematically analysed, and because players are able to vary foot elevation angle between kicks. The regression results indicated that foot elevation trajectory was the only predictor for both players, and explained 79.1% and 84.2% of the variance (Player 4; Player 6). Given the clear results for both players, whereby foot elevation trajectory explained such a large portion of variance, it was warranted to perform a bivariate analysis for all players between these two variables. This analysis identified a similar result: foot elevation trajectory was a significant predictor for all individuals, with 9 of 10 players displaying either a perfect or near perfect linear relationships and the remaining player producing a second order relationship (Table 10.3). This result identifies the foot trajectory was an important factor for ball elevation angle, and therefore an important factor influential to the vertical component of kicking accuracy.

Table 10.3: Bivariate regressions of the relationship between foot elevation trajectory and ball elevation angle.

Player	Relationship	R-value	p-value	Effect classification
1	Linear	0.76	<0.01	Nearly Perfect
2	Linear	0.74	<0.01	Nearly Perfect
3	Linear	0.85	<0.01	Perfect
4	Linear	0.89	<0.01	Perfect
5	Linear	0.66	<0.01	Nearly Perfect
6	Linear	0.92	<0.01	Perfect
7	Second order	0.54	0.01	Nearly Perfect
8	Linear	0.95	<0.01	Perfect
9	Linear	0.82	<0.01	Perfect
10	Linear	0.56	<0.01	Nearly Perfect

Expanding the oblique impact theory to the entire duration of impact provided a theoretical basis to describe the interaction between foot-ball impact with ball flight characteristics. The oblique impact theory was used to describe the relationship between foot-ball impact characteristics with ball flight characteristics in the mechanical kicking machine and human kickers. The limitation of this theory is that it assumes the collision between two objects occurs instantly, whereas the collision between foot and ball during impact occurs over a time of approximately 10-12 ms as the ball deforms over the foot. Given it was previously identified the transfer of energy from foot and ball occurs over three fourths of impact duration (Peacock, et al., 2017a; Shinkai, et al., 2009), the formation of ball flight characteristics was logically expected to also occur over this time period and not instantaneously at the beginning of impact. Supporting this was the analysis within Chapter 9 of a non-uniform increase in ball angular velocity through impact, similar to that found by Shinkai, et al. (2009) with sagittal plane ball velocity. Thus, the oblique impact theory applied to the duration of impact describes how the combination of flight characteristics are determined.

The oblique impact theory indicates ball flight characteristics are influenced by the surface angle of the contact area between foot and ball and the foot-ball angle. The results within this thesis identified the application of the oblique impact theory to the duration of impact provided a theoretical framework to explain why individual impact characteristics influence ball flight characteristics. There are three components to the oblique impact theory that explain how ball flight characteristics are influenced. Firstly, the surface angle between the foot and ball will influence the direction of the force vector applied to the ball. Impact locations that are off-centre across the medial-lateral direction, where the perpendicular direction of the surface angle does not point toward the target, will alter the direction of the force vector to the perpendicular direction of the surface angle. For example, the surface angle of the impact location on the lateral aspect of the foot points laterally to the target, where the force vector is applied in the lateral direction. Secondly, the force vector applied to the ball may produce a torque, where a component of that force vector is producing rotational energy at the expense of translational energy. For an ellipsoidal or any non-spherical ball, the foot-ball angle is an important component to the torque. Thirdly, energy is continually transferred from foot to ball as the ball deforms over the foot during impact, whereby the dynamic nature of impact influences the outcome. As the ball deforms over the foot and the contact area moves, the direction of the force vector applied from foot to ball and the torque applied to the ball will change.

Foot-ball impact characteristics influenced kicking accuracy. This thesis explored how foot-ball impact characteristics influenced kicking accuracy through two steps. Firstly, the relationship between impact characteristics with ball flight characteristics was identified with the mechanical kicking machine and human kickers. The key result of this analysis was that changes to each impact characteristic influenced ball flight characteristics, as explained by the oblique impact theory applied to the duration of impact. Secondly, the relationship between ball flight characteristics and a measurement of kicking accuracy was identified, where it was found ball flight characteristics influenced kicking accuracy. The culmination of this work identified that foot-ball impact characteristics influenced kicking accuracy. Important to note, however, foot-ball impact characteristics will not always influence kicking accuracy due to the adaptive variability that exists within both foot-ball impact and ball flight characteristics. Because the ball must first travel on its flight path before reaching the target, a player can kick to a constant target by (1) impacting the ball with a different combination of impact characteristics to produce constant ball flight characteristics, or (2) impacting the ball with a different combination of ball flight characteristics to produce a different combination of ball flight characteristics that will reach a constant target. Thus, it is possible that future work may identify an instance where a constant measurement of kicking accuracy is attained by different combinations of impact characteristics. In plainer terms, two different measurements of kicking accuracy must be attained by two different combinations of impact characteristics (neglecting external environment such as wind), but two different combinations of impact characteristics will not always produce two different measurements of kicking accuracy due to adaptive variability.

The work in this thesis has covered all aspects of kicking accuracy in gameplay, either directly or indirectly. In gameplay, a kick is deemed successful if it reaches its desired target. In Australian football, a successful shot at goal occurs when the ball travels within the horizontal distance separated by the goal posts. In soccer, a successful shot at goal occurs when the ball travels both within the horizontal distance separated by the upright posts, but also underneath the crossbar. In the rugby codes (league, union and American football), the ball must travel over the cross bar and within the horizontal posts. Thus, to score goals across each football code, a player must ensure the ball passes through a vertical plane at a set distance that has horizontal constraints and in some codes specific vertical constraints (under/ over the crossbar). A successful attempt at passing can be considered far more advanced because the constraints in both the horizontal and vertical planes are often large: the team member receiving the ball can only move a set distance during the ball flight to receive any off-target ball; the kicker must ensure the ball is not intercepted from opposition; and, the ball must not cross the boundary of the field. The direct measurement of kicking accuracy within this thesis was made solely in the vertical plane for a submaximal distance, where it was identified variability in the ball velocity vector (comprising the velocity, elevation angle and azimuth angle) explained most of the variance in the measurement of accuracy. However, the factors influential to the measurement of accuracy in the horizontal plane were covered indirectly. In the horizontal plane, the perpendicular distance to the kick direction is synonymously governed by the same factors that influence the horizontal component of the vertical plane. While the magnitudes of each variable will differ, the effective kick distance, will also be governed by the factors influential to the vertical component of the vertical plane as indicated by Goff (2013). Thus, all aspects of kicking accuracy have been addressed within this thesis.

10.2.2 Why players produce inaccurate kicks: a new theory defining human kicking accuracy

The oblique impact theory identifies the combination of impact characteristics will influence kicking accuracy. Theoretically, all players should be able to successfully kick toward a submaximal target. But, players do not always kick directly toward their target. Rather, they produce inaccurate kicks, as identified within this thesis and by Dichiera, et al. (2006). This following section will discuss why players produce inaccurate kicks.

Players cannot respond and functionally vary foot-ball impact characteristics to mitigate errors introduced at ball contact. The results of this thesis identified that players who produced less variability in the performance measure (azimuth ball flight trajectory) produced less variability in their impact characteristics (ball impact location and foot-ball angle). This indicated that players produced more consistent outcomes by varying their impact characteristics less. This is due to the extremely short duration of the impact phase where the foot moves passively: a player is unable to receive feedback during impact and make corrective changes to their technique to ensure the task constraints are satisfied. Because a player is unable to make corrective changes during foot-ball impact, they must impact the ball with a correct combination of impact characteristics to satisfy the task constraints. Further, this indicates the ability to detect errors and functionally vary the movement pattern does not occur during impact. Future work is required to understand how and where players detect and functionally vary their movement pattern during the kick to mitigate errors within the kick.

Players can express adaptive variability in foot-ball impact characteristics to satisfy different task constraints. The inter-individual variability indicated that each player used a unique combination of impact characteristics to satisfy the task constraints imposed in the analysed study. The variability in these impact characteristics between players was not random, but could be explained by the oblique impact theory. It was identified players used a trade-off between the impact location on the ball with a different foot-ball angle. This indicates that players can use variability to adapt to different task constraints, but does not identify that players do. However, theoretically, players must use a different combination of impact characteristics to generate a different flight path required to complete a different task with changing constraints. This thesis did not explore how players functionally vary impact characteristics to suffice differing task constraints. However, one player did alter their approach for an additional kick (after they completed their 30 required kicks), providing an insight into how players might functionally vary impact characteristics. A comparison of this one kick with an angled approach, whereby the player approached the kicking area with a lateral trajectory, to their straight approach kicks indicates players do functionally alter their impact characteristics. Specifically, to combat the angled approach, evidenced by a lateral ball velocity and lateral azimuth foot trajectory prior to impact, the player used a lateral azimuth ball impact location to still maintain a consistent azimuth ball flight trajectory (Table 10.4). This functional change in foot-ball impact characteristics by the player is supported by the theory identified within the present thesis, whereby the lateral ball impact location will counteract the lateral foot trajectory. Thus, players must express functional variability in impact characteristics to satisfy different task constraints, but future work should explore the strategies used by the players.

Table 10.4: Comparisons of foot-ball impact characteristics from kicks with different task constraints; indicating how players might functionally vary to satisfy different task constraints.

	M-L ball velocity (m/s)	Azimuth foot trajectory (°)	Azimuth ball impact location (°)	Azimuth ball flight trajectory (°)
Straight approach (N = 30)	0.3	2.1	0.6	0.2
Angled approach (N = 1)	1.1	9.2	8.4	-0.8

The work within this thesis provides a new theory of how kicking accuracy is attained: variability in the combination of foot-ball impact characteristics. Kicking accuracy is attained by impacting the ball with an appropriate combination of impact characteristics that will satisfy the task constraints. The oblique impact theory applied through the duration of impact provides a theoretical basis of how impact characteristics determine the ball flight characteristics. A player can functionally vary the combination of impact characteristics to produce stable ball flight characteristics, but, a player cannot detect errors within impact and functionally vary their impact characteristics to mitigate these errors due to the short phase. To kick accurately, a player must impart an appropriate combination of flight characteristics. As errors are introduced into these impact characteristics, the outcome of the task is affected. The effect of these errors may or may not produce an unsuccessful outcome: if the margin of error in the outcome of the task (i.e. error in the execution) is within the boundaries of the target area (i.e. goal post width), then the task will still be successful despite these errors.

This theory builds upon what Hennig and colleagues (Hennig, 2011, 2014; Hennig & Althoff, 2018; Hennig & Sterzing, 2010) stated as the primary mechanism of kicking accuracy. Hennig and colleagues stated the primary factor influencing kicking accuracy is the homogeneity of the pressure across the dorsal aspect of the foot during impact (Hennig, 2011, 2014; Hennig & Althoff, 2018; Hennig & Sterzing, 2010). Hennig, et al. (2009) explored the pressure distribution on the foot over kicks for two footwear designs, and stated that the pressure distribution, individualised to each footwear design, was the primary factor influencing kicking accuracy. However, between kicks within each footwear design, the outcome differs. This was identified in the analysis within the present thesis. It can be considered that the pressure distribution across the anterior aspect of the foot will be consistent when a player consecutively performs a kick, because the same foot and footwear are used. But, between these executions of the kick, when the pressure distribution on the foot will be consistent, the outcome of the task differed. This theory of the pressure distribution for a given footwear and foot cannot explain all aspects of kicking accuracy, and thus cannot be a primary factor of kicking accuracy. The theory in this thesis builds upon the work of Hennig and colleagues. Accurate kicking is attained by players using an appropriate combination of impact characteristics that will enable the ball to travel on a necessary flight path to reach the target. Players produce variability between kicks creating a different combination of ball flight characteristics, which may or may not produce variability in the outcome of the task. Hennig and colleagues identified the pressure distribution was an important factor toward kicking accuracy (Hennig, 2011). The results from this work do not oppose this finding: having a more consistent pressure distribution across the foot surface will ensure that despite the variability a player produces, there will be less effect on the ball flight characteristics. The pressure distribution by itself, however, cannot explain all aspects of kicking accuracy, but is one component. The overall components of kicking accuracy comprise the combination of ball flight characteristics to suit the task constraints (comprising functional variability and the pressure distribution), and the errors that players produce in the combination of ball flight characteristics relative the outcome of the task within game (i.e. ensuring the ball travels within the goal posts, not exactly in the middle of the goal posts).

10.2.3 Strategies to improve kicking accuracy

Reducing the magnitude of variability at foot-ball impact characteristics was identified to reduce performance variability. The players that produced less variability in their ball flight characteristics produced less variability in their impact characteristics. Therefore, to reduce performance variability, players should produce less error in their impact characteristics. The ability to detect and mitigate errors throughout the execution of the kick prior to impact should be learned. Future work identifying how players detect and mitigate errors should be performed.

Functionally varying impact characteristics is required to satisfy different task constraints. To successfully perform a range of different kicks, players must impact the ball with a different combination of impact characteristics. Thus, learning how to functionally vary impact characteristics is important for players to kick under different conditions. The results from testing the human kickers identified that for a constant task, players used a singular mode of execution whereby more consistent performance was achieved through refinement of the singular execution to reduce errors. This suggests that to learn how to functionally vary the combination of impact characteristics, players should not repeat a task of consistent constraints because they will not explore alternate combinations of impact characteristics. There is a large body of literature and knowledge that has explored motor skill learning, and will not be addressed here.

Players should use a combination of impact characteristics that produce a stable outcome of the task within the range of variability produced. The results within this thesis indicate that all players produced variability, and the more consistent performing players produced less variability. In gameplay, while it might appear a player produces stable outcomes (i.e. all shots at goal being successful), these results indicate they will still produce a small magnitude of variability, but this variability is within the range of successful completion of the task (i.e. the range of outcomes might be within 1 m, but the width of the goals are 1.2 m). Thus, non-functional variability will likely never be removed from a player's movement pattern. Because players produce variability in their impact characteristics, they should employ a combination of impact characteristics that produces stable outcomes despite this variability. These regions of stability can be identified from the relationships of each individual impact characteristic and ball flight characteristics, whereby future analysis should create explicit mathematical models to further explore this method. Two examples will be provided below: the foot-ball angle and the footwear design.

Players might not use the foot-ball angle of maximum impact efficiency to provide stability in elevation angle. Given the strong dependence of ball elevation angle on foot-ball angle X as identified with the mechanical limb (Chapter 4.3.), it was expected foot-ball angle X to be more influential to ball elevation angle than identified by the multiple linear regression in the human kickers due to the variability they would produce. The results from the mechanical kicking machine identified that ball elevation angle and back-spin rate were quite stable between the absolute ball orientation range of 15 - 40° as this is the peak of the sine-wave that was fitted to the relationship. This absolute ball orientation corresponds to a foot surface-ball angle between the range of 30-65°. Previously (Chapter 10.1.1.4 Ball orientation), it was discussed that players performing the drop punt kick did not use a foot-ball angle that transferred the highest magnitude of kinetic energy from foot to ball. Rather, an anecdotal observation suggested players use a smaller angle. The stability of elevation angle on foot surface-ball angle in the range of 30-65° might explain why players don't use the foot-ball angle that produces a higher transfer of kinetic energy. It is possible that player use a foot-ball angle within the range of stability over the foot-ball angle producing highest ball velocity to accommodate for the variability they produce between their executions. Further post-hoc analysis identifies the mean foot-ball angle used by players was 21 - 33° between players, which is not far from the range of 30 - 65° that provided stability in the mechanical kicking machine. Differences did exist in the method of calculating these parameters: the foot surface-ball angle and foot-ball angle are different. Differences will also exist between players in the foot surface angle and the measurement of foot angle. Further, the influence of foot trajectory will also influence the effective surface angle of the foot applied to the ball. Regardless, the analysis of foot-ball angle X with the mechanical kicking machine identifies that regions of stable outcomes exist within a range of impact characteristics. Future work to create mathematical models that predict the outcome in three-dimensional space is required to fully explore and identify these regions of stability.

Footwear designs that contain a constant surface angle across the range of impact locations on the foot will theoretically produce stable ball flight characteristics. Changes to impact location across the medial-lateral direction directly influenced azimuth ball flight trajectory due to the change in the surface angle across this dimension. The players that produced the least variability in the ball flight characteristics produced the least variability in the impact location, indicating reductions to variability will reduce performance variability for the task. However, in addition to reducing this variability, reducing the change in the surface angle of the foot surface will mechanically reduce the influence of this variability on the outcome of the task. Altering the footwear designs so the surface angle is constant within the range of impact locations used due to variability will theoretically be beneficial to producing stable ball flight characteristics. This mechanism has been suggested before (Nunome, et al., 2014). A similar mechanism was tested by Hennig and colleagues (Hennig, et al., 2009) where they added padding to the foot, however, they identified no statistically significant differences in performance. Further exploration is warranted due to the limited approach taken. This footwear design might come at the expense of the ability to functionally vary the impact location on the foot, which was identified as a mechanism to satisfy different task constraints. Thus, future work is required to understand how players functionally vary to different task constraints and design footwear to supplement the strategies used by players. Alternatively, given the execution of a skill is influenced by the task constraints (Davids, 2010), a player might use a different strategy to satisfy different task constraints if there is no change to the surface angle on the foot. Future work should explore the area of footwear designs to improve all-round kicking performance.

10.2.4 Limitations and future directions to improve kicking accuracy

Exploring the relationship between ball flight characteristics and kicking accuracy using models should be performed. A linear regression was performed to identify the ball flight characteristics that influenced kicking accuracy. However, as previously discussed, several flight characteristics are known to have a non-linear influence on the flight path. Thus, more work is required to explore the ball flight path of the ellipsoidal ball and kicking accuracy are related.

Further exploration of the stable regions of impact characteristics is required to determine the effectiveness of this strategy. Identifying regions of stability in impact characteristics where the range of variability produced by the player has a little influence on the outcome of the task is theoretically hypothesised to benefit performance. The limitation of the examples explored thus far for this method, foot-ball angle and footwear design, was that they were based on either a bivariate analysis or a theoretical idea. The creation of mathematical models representing the interaction in three-dimensional space comprising several key variables – foot trajectory, foot surface properties, ball shape – will identify these regions of stability when a larger number of variables are included. Further, combining models of both ball flight and impact can enable a holistic approach to identify the stable regions. Stable regions were discussed within foot-ball impact characteristics, and it is possible they might also exist within the ball flight characteristics and the flight path. Increasing the likelihood of kicking success could be achieved by aligning the stable regions for impact and ball flight characteristics. Using a similar approach to that of the present thesis, combining a theoretical and applied experimental design, will provide a strong foundation for this analysis. For example, developing a model for one individual player based off experimental data, identifying the stable regions, and applying corrective changes to the individual and re-testing to determine the effectiveness of this strategy. Similarly, exploring the foot-ball interaction can be manipulated to produce or increase these stable regions is an exciting future direction. Producing footwear designs that have little change in the surface angle are theoretically hypothesised to improve performance.

Identifying how players functionally vary their technique to satisfy different task constraints and mitigate errors introduced in the execution is important for understanding kicking performance under different contexts. Understanding how and where players functionally vary their technique execution is an important future direction, whereby this knowledge could be used to develop coaching cues. Further, this knowledge could also be used to understand how footwear designs can be optimised for an individual. Creating footwear designs that increase stable regions was discussed as a method to improve performance. However, understanding how players functionally vary their impact characteristics when wearing both traditional footwear designs and the footwear designs with flat surfaces is important in exploring the effectiveness of this strategy.

10.3. Differences between mechanical kicking machine and the human kicking limb

10.3.1 Impact characteristics of the mechanical kicking machine and the human kicking limb

The relationship between foot-ball impact characteristics with ball flight characteristics was explored through both the mechanical kicking machine and human kickers, setting this thesis up to identify components of the relationship free from confounding impact characteristics. To explore the relationship with the mechanical kicking machine, a systematic exploration of individual impact characteristics was performed and bivariate regressions identified the type of relationship. To explore the relationship in human kickers, ten players performed 30 kicks providing between 20 – 30 kicks within each player for both bivariate and multiple linear regression analyses. The combination of both experimental and statistical designs set this thesis up to identify robust relationships between foot-ball impact characteristics with ball flight characteristics. The influence of confounding impact characteristics was highlighted within the literature review in this thesis, in the discussion on ankle motion most notably. While confounding impact characteristics have not previously been identified as a key issue influencing the relationship between foot-ball impact characteristics with kicking accuracy, this experimental design, of both systematic exploration and intra-individual analysis, immediately eliminated, controlled for, and reduced the number of confounding impact characteristics. Thus, the work within this thesis has likely reduced the number of studies that produce incorrect conclusions due to this issue of confounding impact characteristics, as identified with ankle motion, and can be used as a foundation for future research.

Consistency in some aspects of the relationship between foot-ball impact with ball flight characteristics was identified between the mechanical kicking machine and human kickers. Most representative to highlight the consistency of the relationships is the direction of the coefficients for the relationship between both medial-lateral impact location on the foot and azimuth ball impact location with azimuth ball flight trajectory (Table 10.5). From the bivariate regression analysis, positive slopes were identified between all players and the mechanical kicking for the relationship between medial-lateral impact location with azimuth ball flight trajectory, indicating lateral impact locations translated to lateral azimuth ball flight trajectories. From the multiple linear regression, consistent results were also identified between players with each player displaying a negative slope. While negative slopes for the multiple linear regression might represent the opposite pattern to the bivariate regression, this was due to a different parameter used – azimuth ball impact location rather than medial-lateral impact location on the foot – whereby a medial azimuth ball impact location translates to a lateral impact location on the foot. Thus, the negative slopes of the multiple linear regressions indicate consistent direction of slopes for both human kickers and the mechanical kicking limb.

Table 10.5: Numerical representation of relationship between medial-lateral impact location with azimuth ball flight trajectory and the relationship between azimuth ball impact location with azimuth ball flight trajectory.

	M-L impact location with azimuth ball flight angle	Azimuth ball impact location with azimuth ball flight trajectory
Mechanical kicking machine	y = 27x + 7	N/A
P01	y = 13x + 8	y = -0.54x + …
P02	y = 13x + 8	y = -0.79x + ...
P03	y = 8x + 3	y = -1.08x + …
P04	y = 10x + 7	y = -0.70x + …
P05	y = 10x + 13	y = -0.76x + …
P06	y = 6x + 10	y = -0.71x + …
P07	y = 6x + 4	y = -1.13x + …
P08	y = 7x + 2	y = -0.84x + …
P09	y = 7x + 10	y = -0.76x + …
P10	y = 5x - 1	y = -0.90x + ...

Where y = azimuth ball flight trajectory; x = medial-lateral impact location/ azimuth ball impact location, respectively.

Differences existed in the magnitudes of the slopes and in both the direction and magnitudes of the intercepts. As identified in Table 10.5, differences existed between each player and between the human kickers and the mechanical kicking machine in the magnitude of the slope and the intercepts. These differences might suggest inconsistent relationships were identified across these comparisons, questioning the validity of the conclusions drawn. However, these inconsistencies can be explained by two factors: individual differences in technique and foot shape, and random statistical variance from variability in other impact characteristics. This thesis identified the surface angle of the contact area between foot and ball influences ball flight characteristics. Differences in the combination of impact characteristics used and the foot shape of each player will influence the surface angle of the contact area between foot and ball across between each trial, and will be expressed as different coefficients in the bivariate regressions due to a different variance in the independent and dependent variables. For example, a player with a narrow foot, where the total change in the normal direction of the foot surface angle occurs over a smaller linear distance (Figure 10.5), is expected to produce a higher coefficient for slope because a greater change in azimuth ball flight trajectory occurs over a shorter distance. A different combination of impact characteristics, such as a systematic negative tilt in foot-ball angle Y, where the contact area spreads medially from the impact location at the beginning of impact, will require a more lateral impact location at the beginning of impact to ensure the overall contact area is maintained, again influencing the relationship between impact location with ball flight trajectory. Because variability in other impact characteristics – such as foot-ball angle Y – can also influence azimuth ball flight trajectory, the coefficients in the regression can again be influenced by this variability. Thus, differences in the magnitude of the coefficient for the slope and the intercept can be explained by factors associated with an individual (foot shape) and the variability they produce in foot-ball impact characteristics.

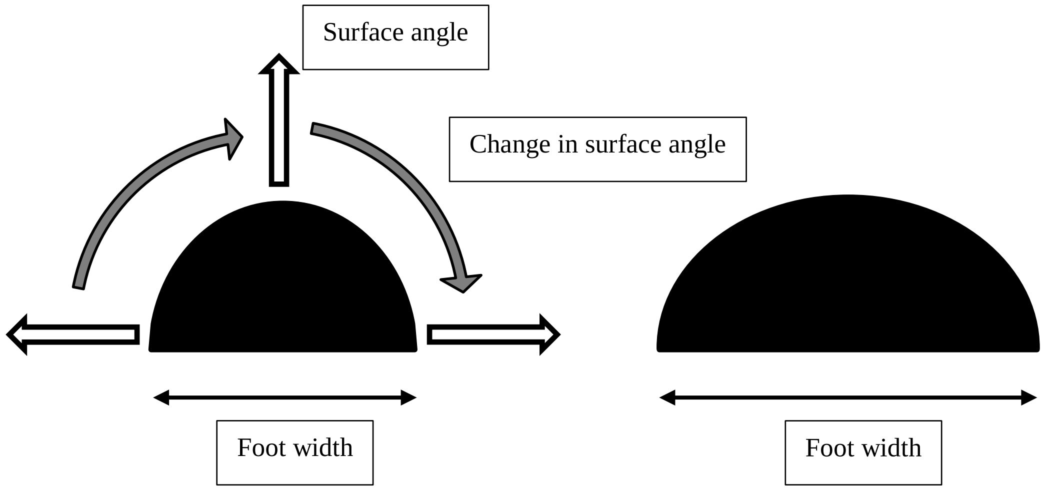

Figure 10.5: A greater slope is anticipated for a narrower foot, because the change in surface angle occurs over a shorter linear distance.

Another notable difference between the mechanical kicking machine and the human limb is the design of the ankle joint. The ankle plantar/dorsal flexion motion was identified to validly replicate that of human kickers, whereby the consistencies between the mechanical kicking machine and the human kickers in the relationship between proximal-distal impact location and ankle plantarflexion further cements the validity of this motion. The human ankle joint, however, also contains ankle abduction/ adduction and inversion/ eversion. The role of three-dimensional ankle motion was not included within this thesis, but was explored by the author. It was identified that ankle inversion/ eversion correlated highly with azimuth ball flight trajectory (Peacock, Ball, & Taylor, 2017b). This indicates that kicks off-centre were characterised by a large magnitude of ankle displacement. But, as discussed previously, ankle motion is not an independent variable during foot-ball impact, and that is why this additional analysis was not included in the experimental chapters. Rather, the correlation between ankle inversion/ eversion with azimuth ball flight trajectory was due to off-centre impact location on the foot. As identified with the changes in proximal-distal impact location with ankle plantarflexion, an impact location away from the ankle joint produces a torque forcing the ankle to change its angle. This also occurs across the medial-lateral direction, with off-centred impact locations producing a change to ankle inversion/ eversion. This is also evident in soccer kicking: Shinkai, et al. (2009) identified distinct ankle abduction and eversion due to the impact location occurring slightly medially of the foot in the instep kick. While ankle motion itself is not the independent variable influencing azimuth ball flight trajectory, increasing the strength to prevent the change in ankle angle with off-centre impact locations theoretically will help reduce the change in azimuth ball flight trajectory. As identified with the mechanical kicking machine, increasing the stiffness of the dorsiflexion spring reduced the magnitude of ankle plantarflexion. A similar mechanism is expected to occur across the medial-lateral direction, whereby strengthening the ankle might help reduce the change in ankle angle during impact of off-centred impacts. As the ankle is forced into inversion/ eversion, the surface angle on the foot points further away from the target. This change in surface angle compounds the influence of the poor impact location on azimuth ball flight trajectory. Reducing this magnitude of ankle inversion/ eversion is expected to reduce the effect of a poor impact location, by reducing the change in surface angle of the ankle as it changes its orientation during impact. Future work should perform a prospective intervention study to identify the effectiveness of strengthening the ankle joint to improve accuracy and ball velocity in human kickers.

Energy transfer mechanisms also differed between the kicking machine and human players. In the mechanical kicking machine, it was observed that coefficient of restitution decreased with distal impact locations and effective mass remained constant. For the human limb, distal impact locations were observed to influence both effective mass and coefficient of restitution. This difference was likely due to the design of the mechanical kicking machine: the rigid foot segment and simple ankle configuration. The influence of the non-rigid properties of the human foot with different impact locations was not assessed in the mechanical kicking machine, and may have influenced these results. As the foot undergoes deformation the effective mass of the striking limb may also be influenced. The ankle joint of the mechanical kicking machine, characterised by energy stored in the spring mechanism with any magnitude of ankle plantarflexion, is not entirely representative of the human ankle. While energy can be stored in the human muscle tendon unit when it is stretched (Morse, et al., 2008), as similarly observed in the mechanical spring, the human muscle tendon unit can also increase its length without elastic energy being stored. As the human ankle underwent plantarflexion with distal impact locations, it is possible the muscle component of the muscle tendon unit increased its length without elastic energy being stored. This mechanism might influence the effective mass of the limb and not the coefficient of restitution, because elastic energy is not being stored. These different designs of the ankle joint and foot segment between the mechanical and human limbs might explain the observed differences in energy transfer mechanisms. Despite these differences, consistent findings from both experimental designs were observed for foot-ball speed ratio, a more holistic measurement of impact efficiency comprising both effective mass and coefficient of restitution. The consistent finding was that proximal-distal impact location influenced impact efficiency.

10.3.2 Smoothing procedures for the mechanical kicking machine and the human kickers

Different smoothing procedures were used throughout the experimental chapters despite a constant frame rate (4,000 Hz). A low-pass Butterworth filter was applied for all chapters, but the cut-off frequency differed. The cut-off frequency for Chapters 3, 4 and 9 was 280 Hz (kicking machine). The cut-off frequency for Chapters 5 and 6 was 170 Hz (kicking machine). The cut-off frequency for Chapters 7 and 8 (human kickers) was 280 Hz. Previous work exploring foot-ball impact of Australian football kicking used a cut-off frequency of 280 Hz for sagittal plane data captured at 4,000 Hz (Peacock, et al., 2017a). The majority of chapters used the cut-off frequency similar to that of previous work (Peacock, et al., 2017a), at 280 Hz. The smoothing used for Chapters 5 and 6 were a point of difference. The different cut-off frequency was due to the results of the discrete Fourier Transform analysis looking at different cut-offs between 10 to 400 Hz and visual inspection of the signals at different cut-offs. Less magnitude of signal was evident above 170 Hz, and this difference might be due to the design of the kicking limb. Possible design features responsible for this difference might include the spring-controlled ankle motion. Despite this difference, other studies exploring foot-ball impact but in soccer kicking have used cut-offs of

200 Hz (Nunome, et al., 2006b; Tsaousidis & Zatsiorsky, 1996), so the chosen cut-off of 170 Hz is not an anomaly compared to other studies investigating foot-ball impact and the data were not oversmoothed.

10.4. Transfer of knowledge between kicking styles

Although the work in this thesis was performed solely with an Australian football ball, there are no results within this thesis that indicate the theory identified about energy transfer and kicking accuracy cannot be transferred to other kicking codes. While the dynamics differ between drop punt, place kicking and soccer kicking due to different ball shapes, and approaches, these dynamics are not anticipated to influence the transfer of this theory to other kicking types. Some key results identified, such as variability in foot-ball angle, cannot influence kicking with a spherical ball, but foot angle is still expected to be important. The key findings of this thesis are (1) ankle plantarflexion does not directly influence impact efficiency; (2) the oblique impact theory applied through the duration of impact validly explained the relationship between impact and ball flight characteristics; and (3) players produce variability in their impact characteristics. There are no results in this thesis that suggest these findings cannot be transferred to other kicking codes.

Chapter 11: Conclusion

This thesis explored the relationship between foot-ball impact characteristics with ball flight characteristics and kick outcome. The aims of this thesis were to (1) determine how foot-ball impact characteristics influence impact efficiency measures (foot-ball speed ratio, coefficient of restitution, and effective mass) and ankle plantarflexion, and (2) determine how foot-ball impact characteristics influence ball flight characteristics and kicking accuracy. Two methodologies were specifically chosen to answer these aims: using a mechanical kicking machine to perform a systematic exploration of impact characteristics and an intra-individual analysis of human kickers. These methodologies reduced the influence of confounding impact characteristics, a key issue that has influenced the analysis of foot-ball impact in the past. The general finding of this thesis is that foot-ball impact characteristics influenced impact efficiency and kicking accuracy.

Impact characteristics influenced impact efficiency and ankle plantarflexion. Players can increase impact efficiency and reduce the magnitude of ankle plantarflexion during foot-ball impact by altering their impact characteristics. Specifically, increasing the ankle joint stiffness, impacting closer toward the ankle joint, reducing foot velocity and altering foot-ball angle were each identified to increase impact efficiency or energy transfer from foot to ball. The results in this thesis generally supported the strategy of reducing the magnitude of ankle plantarflexion to increase impact efficiency as an effective coaching cue. All results from the mechanical kicking machine identified that reducing ankle plantarflexion through the various strategies increased impact efficiency. The results from the human kickers were also favourable to the strategy, as evidenced by the highest level of impact efficiency being associated with a change in ankle plantarflexion of $< \pm 3°$. These results support the coaching cue ‘maintaining a firm ankle’ during impact as being effective. But, philosophically, it was argued that because ankle motion was passive during impact, due to the extremely short duration of the phase, players did not actively control the magnitude of ankle plantarflexion. This meant ankle plantarflexion did not directly influence impact efficiency, rather, ankle motion was a passive response to the initial conditions of impact.

Foot-ball impact characteristics influenced kicking accuracy. Prior to this thesis, little was known about how foot-ball impact influenced ball flight characteristics and kicking accuracy. The second aim of this thesis was to identify how foot-ball impact characteristics influenced ball flight characteristics and kicking accuracy. The relationship between foot-ball impact and ball flight characteristics was explored with both a mechanical kicking machine (via systematic exploration) and by performing an intra-individual analysis of human kickers. The oblique impact theory applied to the duration of impact provided a theoretical explanation linking foot-ball impact and ball flight characteristics. Subsequent analysis of ball flight characteristics and a measurement of kicking accuracy identified that ball flight characteristics influenced kicking accuracy. From these results, it was concluded foot-ball impact characteristics influence kicking accuracy. Between the execution of kicks, players varied their impact characteristics. This variability can be functional, as players must vary their impact characteristics to satisfy different task constraints. This variability can also be non-functional. More consistent performance of the singular task, where the task constraints were held constant, was obtained by players reducing the magnitude of variability in their impact characteristics. Because the impact phase was extremely short (~10-12 ms), players were unable to receive feedback from the initial conditions of impact and make corrective changes. Inaccurate kicks were due to players using an incorrect combination of impact characteristics, such as impacting the far lateral or medial sides of the ball when kicking toward a target that was positioned straight ahead.

In conclusion, this thesis identified foot-ball impact characteristics influenced impact efficiency, ankle motion, ball flight characteristics, and kicking accuracy. These results have practical implications for the improve of kicking performance. Maintaining a firm ankle, a commonly used coaching cue, and other coaching cues, were discussed throughout the thesis. The methods used within this study, of a mechanical kicking machine and subsequent human testing, were successful in avoiding the issue of confounding impact characteristics. Several areas of future research were identified. Most notable, several strategies involving interventions were identified as potentially effective at improving kicking performance. However, future work is required to determine the effectiveness of these interventions. Future work exploring foot-ball impact should also employ methods that remove the likelihood of confounding impact characteristics, such as an intra-individual analysis where individual differences in the physical size, shape and technique of the performers will be eliminated.

Chapter 12: References

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Appendix A: Published manuscript of Study 1

THE IMPACT PHASE OF DROP PUNT KICKING: VALIDATION AND EXPERIMENTAL DATA OF A MECHANICAL KICKING LIMB

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The purpose of this study was to validate a mechanical kicking limb and analyse changes in foot speed on impact characteristics of drop punt kicking. Foot speed was recorded as 9.1 – 21.2 m/s, and covered a range of kick distances. Ball speed (13.0 – 29.7 m/s), contact distance (10.7 – 20.2 cm) and contact time (14.75 – 11.75 ms) were comparable to drop punt kicking. Impact efficiency (F:B ratio = 1.37 – 1.48, coefficient of restitution = 0.66 – 0.79) were high, caused by near perfect rigidity in the design of the limb. Overall, the limb was found to be a valid representation of a human performer. Foot speed displayed significant relationships with ball speed (r = 0.998), contact time (r = -0.89), contact distance (r = 0.99) and F:B ratio (r = -0.694). The relationship between foot speed and COR (-0.347) was not significant.

KEY WORDS: Australian football, high speed video, collisions, energy transfer.

INTRODUCTION: The human limbs (hands, feet) are frequently used among ball sports to strike the ball at a specific location directing it onto a desired flight path (i.e. volleyball 'spike', football 'kick'). Across the football codes, the execution of the entire kicking skill differs due to the shape of the ball used and the constraints of performing each kick. For example, a spherical ball is kicked off the ground in soccer and an ellipsoidal ball is dropped from the hand prior to impact in drop punt kicking.

Impact phase research has, for the most part, yielded similar results but with some notable exceptions. Despite the different executions of the skills, four phases through the impact phase have been identified with similar patterns reported in soccer and drop punt kicking (Peacock, 2013; Shinkai, 2009). On the other hand, relationships between some impact characteristics have not been consistent across the codes. An increase in foot speed has been linked to decreased contact time in soccer kicking (Nunome, Ball & Shinkai, 2014). For drop punt kicking, this relationship has been similarly found in one comparison of kicking tasks (Peacock, 2013), but has not been found in other comparisons (Ball, 2008b; Ball, Smith & MacMahon, 2010; Smith, Ball & MacMahon, 2009). Further, foot to ball speed ratio (F:B ratio) is considered a good measure of impact efficiency and a medium, positive relationship has been identified with ankle rigidity (Shinkai, Nunome, Suito, Inoue & Ikegami, 2013). It is somewhat expected F:B ratio and ankle rigidity are linked due to relationships between increased rigidity and ball speed in another soccer kicking study (Asami & Nolte, 1983). For drop punt kicking however, comparisons of kicking groups found the measure to not differ significantly when rigidity was increased (Ball, et al., 2010; Peacock, 2013).

Mechanical testing is an important addition to analyse the impact phase. An increased variability is expected between kicking trials of performer-based studies, particularly in drop punt kicking due to the execution in the skill where the ellipsoidal ball is dropped from the hand prior to impacting the foot. Mechanical testing will allow for the isolation of specific variables so a methodical exploration is made available if found to be valid, and thus should be used in conjunction with performer-based studies. The aim of the present study was to validate a mechanical kicking limb by using previous literature and analyse changes in foot speed on impact characteristics during punt kicking.

METHODS: A mechanical kicking limb performed punt kicks using a standard AF ball (Sherrin 'Match Ball', inflation: 69 kPa). Limb construction was based off information found in the literature, including just the shank and foot segments rotating about a fixed point representing the knee. These lower limb segments were found to be most influential during the impact phase, and so the thigh was not included (Andersen, Dörge & Thomsen, 1999; Ball, 2008a). The shank was constructed from a metal frame, with length (0.455 m) and mass (5.8 kg) similar to a typical AF player (height = 1.85m, mass = 85kg) (Winter, 1990). The shape of the impacting object has been identified to influence impact characteristics (Bull Andersen, Kristensen & Sorensen, 2008), so to obtain the correct foot impacting area, impact location on the ball and relative foot-to-ball angle, a human foot was scanned and printed as a rigid body whilst in a plantar-flexed position (Peacock, 2013) and attached to the shank.

The limb was validated by using the results found in the literature of AF and soccer kicking and a range of foot speeds were generated while keeping all other impact characteristics constant across the kicking trials. Three reflective markers were attached to both foot and ball. Data points were tracked at 4,000 Hz from three high speed video cameras (Photron SA3 and MC2, Photron Inc., USA) and reproduced in 3d using ProAnalyst (Xcitex Inc., USA) and Visual3d software (C-Motion Inc., USA). A low pass Butterworth filter of 280Hz smoothed all data (Peacock, 2013). Impact characteristics were calculated using Matlab software (The Mathworks Inc., USA). Pearson's correlation calculated the relationship between foot speed with impact characteristics.

The centre of the foot and ball were treated as a virtual landmark based off their tracking markers. Using these virtual landmarks, foot and ball speed were averaged over five frames before and after impact. F:B ratio and coefficient of restitution (COR) were computed using these measures. Contact time was visually identified using from one of the high speed video cameras located perpendicular to impact. Contact distance was measured by the distance the centre of the ball travelled from contact to release. Effective mass was calculated using conservation of momentum equations (Shinkai, et al., 2013).

RESULTS: The mechanical limb generated a range of foot speeds between 9.1 to 21.2 m/s. Ball speed was 13.0 – 29.7 m/s, and correlated significantly with foot speed (r = 0.998, Figure 1A). Contact distance was 10.7 – 20.2 cm and correlated significantly with foot speed (r = 0.990). Contact time was 14.75 – 11.75 ms, and correlated significantly with foot speed (r = -0.890). Foot to ball speed ratio (Figure 1B) was 1.48 – 1.39 and correlated significantly with foot speed (r = -0.694). Though not significant, COR (0.75 – 0.67) displayed a moderate relationship with foot speed (Figure 1B, r = -0.347). Effective mass was calculated to be 2.29 ± 0.19 kg across the kicking trials.

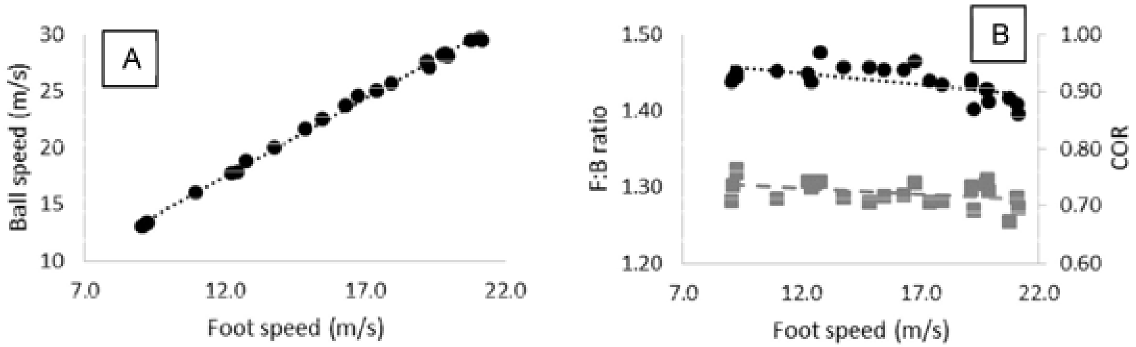

Figure 1: Correlations between foot speed with ball speed (A), F:B ratio (B, black round ticks, primary axis) and COR (B, grey square ticks, secondary axis).

DISCUSSION: The foot speeds recorded are similar to performers' kicks of varying distance. The foot speed of drop punt kicking has ranged from 17.7 m/s for 20m kicks and 22.1 m/s for maximal distance (Peacock, 2013). The 17.7 m/s recorded for 20m kicks in Peacock (2013) were also considered high for the kick distance, due to a task specific strategy by the elite performers to maximise accuracy. The foot speeds of the present study (9.1 to 21.2 m/s) are

therefore considered representative of kicks ranging in distance from 10 to 60 m (maximal distance), and the limb was successfully designed to cover a range of kick distances.
The impact characteristics indicate the mechanical limb was a very close representation of a human performer during the impact phase. Ball speed, contact time, contact distance and effective mass were similar to those recorded in AF (Table 1), however, F:B ratio was slightly higher. In soccer kicking where performers had a calculated effective mass comparable to that of the present study, F:B ratio was found to be in the range of 1.37 – 1.53 (Shinkai, 2013). These values are very similar to that of the present study, and indicate the mechanical limb was almost a perfect representation of the impact phase with only F:B ratio being slightly higher.

Table 1: Summary of impact characteristics across the literature of AF kicking.

Study	Ball speed (m/s)	Contact distance (cm)	Contact time (ms)	Effective mass (kg)	F:B ratio
Present study	13.0–29.7	10.7–20.2	14.75–11.75	2.29 ± 0.19	1.48–1.39
Peacock (2013)	17.7 ± 1.1	20.3 ± 2.4	13.2 ± 1.4	2.39 ± N/A	1.25 ± 0.04
Peacock (2013)	22.1 ± 2.5	22.8 ± 2.9	12.1 ± 1.3	2.04 ± N/A	1.28 ± 0.06
Smith et al. (2009)	32.6 ± 4.4	22 ± 2	11.53 ± 1.25	N/A	1.23 ± 0.11

The slightly higher value of F:B ratio is considered to be due to two factors of the limb's design. Firstly, there was no rotational displacement about the ankle and; secondly, there was no shoe attached to the foot. This indicates the limb represented near perfect rigidity throughout the impact phase. Future designs should consider implementing reduced rigidity about the ankle and foot, to analyse ankle motion strategies (Peacock, 2013).
Foot speed correlated almost perfectly with ball speed and contact distance. Previous comparisons of kick distances have displayed ball speed and contact distance to increase with foot speed (Ball, 2008b; Peacock, 2013). As expected, this shows increases in foot speed should be made by players to increase ball speed if they are able to keep all other impact characteristics constant. The increased contact distance was possibly caused by greater deformation of the ball, but, this was not measured. As noted by Nunome, et al., (2014), a method to calculate the deformation of an ellipsoidal shaped ball should be developed to substantiate this claim.
Impact efficiency, as indicated by F:B ratio, decreased as foot speed increased. Contrasts exist in the literature of F:B ratio in comparisons of drop punt kicking. Though ankle rigidity was not analysed in this study, the studies by Ball et al., (2010) and Peacock (2013) reported a significantly larger foot speed in the conditions of increased ankle rigidity, and thus a two-fold effect may have taken place: increased foot speed would have decreased F:B ratio, but an increased ankle rigidity may have increased F:B ratio. To confirm this hypothesis, future studies should analyse the link between ankle rigidity and impact efficiency while variability in foot speed is minimised.
Although not significant, the relationship between foot speed and COR was negative with a medium effect. A previous analysis using a pendulum to analyse the impact of soccer kicking reported COR decreased with increases in pendulum speed (Andersen, Kristensen & Sorensen, 2008). Further, this negative relationship between foot speeds and COR is found in other impacts of sporting codes (Cross, 2013). This literature suggests a negative relationship between foot speed and COR should exist, however the cause behind the non-significance of this relationship could not be explained by the results calculated. Possibilities may include the aging effect of the ball or variances in manually placing the ball on the kicking tee between trials, however further work is required.
Contact time decreased as foot speed increased, a similar mechanism to soccer kicking (Nunome et al., 2014). This has been previously identified in a comparison of accuracy and

maximal distance drop punt kicks (Peacock, 2013), however, dissimilar results have been reported in other comparisons (Ball, 2008b; Ball, Smith & MacMahon, 2010; Smith, Ball & MacMahon, 2009). The exact reasoning behind the mixed results of drop punt kicking is beyond the scope of this study, but a high variability can exist between trials and possibly influenced these previous studies. The results of the present study and Peacock (2013) indicate the relationship between foot speed and contact time is not specific to just soccer kicking, but also punt kicking. This also highlights the need to conduct more mechanical testing due to the ability to investigate individual parameters.

CONCLUSION: This study successfully validated a mechanical kicking limb and analysed the change in foot speed on impact characteristics. The design of the limb was found to be a very close representation of a human performer during drop punt kicks of various distances, and future designs should consider implementing reduced rigidity about the ankle and foot to decrease impact efficiency. Foot speed was found to produce relationships with the measured impact characteristics, excluding COR.

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Appendix B: Published manuscript of Study 2

Sports Eng
DOI 10.1007/s12283-017-0237-y

ORIGINAL ARTICLE

The relationship between foot-ball impact and flight characteristics in punt kicking

James C. A. Peacock[1,2] · Kevin Ball[1,2]

Abstract In football kicking, a player imparts the initial flight characteristics by impacting the ball with his foot. Imparting the correct combination of flight characteristics is the basis of a successful kick. However, examination of the relationship between foot-ball impact and flight characteristics for a non-spherical ball, the ball shape in Australian football and rugby, has been limited to ball velocity. Consequently, little is known of the relationship with other flight characteristics of ball trajectory and spin. The aim of this study was to determine the relationship between impact and initial ball flight characteristics. A mechanical limb, designed to replicate the impact phase of Australian football, performed punt kicks. Four impact characteristics were systematically examined to determine their influence on flight characteristics: foot velocity, medial–lateral impact location, proximal–distal impact location and ball orientation. This study identified each flight characteristic (ball velocity, elevation angle, azimuth angle and spin rate) were influenced by multiple impact characteristics (foot velocity, ball orientation and/or impact location). For example, elevation angle was increased by foot velocity, relative foot-ball orientation and proximal–distal impact location on the foot. Foot velocity had the largest influence on ball velocity (linear slope = 1.43). Medial–lateral impact location had the largest influence on azimuth angle (linear slope = 2.73). Ball orientation had the largest influence on elevation angle and back-spin rate, both measures were sine dependent (elevation angle curve amplitude = 19.4°; back-spin rate curve amplitude = 2754°/s). Players must control all impact characteristics to successfully kick to their desired destination.

Keywords Football kicking · Punt · High-speed video · Impact efficiency · Trajectory · Collision

1 Introduction

Impact forms one of many fundamental skills for ball sports. Across the football codes, kicking is considered one of the most important skills of the game [1]. Players impart ball flight characteristics by impacting the ball with their foot to achieve a desirable outcome, such as scoring goals and passing the ball to fellow team members. There are multiple combinations of flight characteristics that can achieve the same outcome for a kick. For example, a consistent flight distance can be achieved by increasing the velocity and decreasing the trajectory (assuming the trajectory is below the optimum angle based off the projection height).

Within gameplay, however, there are specific flight characteristics that can increase the chance of success for a kick. Impacting the ball at a higher velocity can enable shots at goal to be taken from further distances and reduce the likelihood of interception from opposition by decreasing flight time. Players can actively alter ball velocity and kick distance by changing impact characteristics. The most notable mechanism for players to change ball velocity is to control foot velocity before contact. The relationship between foot velocity and ball velocity has been identified in several experiment designs [1–4]. Players can also

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increase ball velocity by increasing rigidity within the ankle joint and foot segment [2, 4, 5], and altering footwear characteristics such as mass and stiffness [5–7].

While ball velocity is an important characteristic in gameplay situations, a player must control all flight characteristics to reach a desired destination. The flight path, and therefore the destination, is influenced by the initial trajectory, spin direction and spin rate due to their influence on aerodynamic properties of air resistance and lift force [8–10]. Furthermore, players can purposely impart a spin as the curve of a ball in flight can open the angle of goal and avoid interception from the opposition. When impacting a spherical ball (such as soccer), spin qualities are influenced by impact characteristics of foot velocity, the distance between the ball centre and the line of force applied to the ball, attack angle of the foot and the coefficient of friction between the foot and the ball [11, 12].

For football codes that use a non-spherical ball, such as Australian Football (AF) and Rugby league (RL) that feature an ellipsoidal shape ball, little experimental data exist for impact characteristics influential to flight characteristics other than the relationship between foot and ball velocity [4, 13]. Studies have analysed impact characteristics [2–4], initial flight characteristics [14, 15], and aerodynamics [8]. For example, Holmes [14, 15] identified the initial flight characteristics of rugby kicking such as ball velocity and spin rate. But, these studies analysing kicking with the ellipsoidal ball did not determine the relationship between foot-ball impact characteristics and kick outcome or the initial flight characteristics. Thus, it is not known how players control the flight path, and therefore the destination it reaches.

Oblique impact theory suggests spin qualities and flight trajectories are influenced by the line of force application in respect to the ball centre of mass [15]. The findings of spherical balls likely exist in kicking of an ellipsoidal ball. But, some of the most common types of kicks used in AF and RL, drop punt and place kicking, are distinctly characterised by back-spin about the short axis. The application of force (magnitude, direction, and point of application) with respect to ball orientation, to obtain the back-spin, has different dynamics to that of kicking a spherical ball. Therefore, the relationship between impact and flight of kicking an ellipsoidal ball compared to a spherical ball will be different.

The aim of this study was to determine the relationship between impact and initial flight characteristics featuring an AF ball (ellipsoidal shape). The impact characteristics of foot velocity, medial–lateral impact location, proximal–distal impact location, and ball orientation were systematically explored. Their relationship with initial flight characteristics of ball velocity, trajectory (azimuth angle and elevation), and spin rate was determined.

2 Methods

A mechanical kicking limb performed drop punt kicks with a standard Australian Football (AF) ball ('Match Ball', Sherrin, Australia) inflated to the Australian Football League recommended pressure (69 kPa). The mechanical limb was developed to provide the ability to systematically explore the effect of one impact characteristic on the outcome of the foot–ball interaction without the influence of other characteristics. The striking limb comprised the shank and foot (Fig. 1) because previous studies had identified these to be influential during the collision [1, 16, 17]. Designed to replicate a typical AF player, the shank was of metal construction comprising two outer plates with a length of 0.455 m between the proximal and distal joints [based on an AF player's average height = 1.85 m, and using anthropometric data from Winter (1990) [18]]. At the proximal end of the shank, the 'knee joint' was modelled as a freely rotating axis to mimic flexion and extension. For the foot segment, the foot and bottom part of the shank on the right side of a human that was 1.78 m tall were scanned whilst in a plantar-flexed position (the position adopted during the kick) and printed as a three-dimensional object made of ABS plastic. To achieve the appropriate length of the foot, the size of the scanned image was scaled up by the ratio of 1.85:1.78 based on the height of the person (1.78 m) and a typical AF player (1.85 m). The use of a human foot was important as the shape of the contacting surface with the ball will influence impact [19, 20] and subsequent ball flight (Fig. 2). For the purposes of this study, the 'ankle joint' was locked so no movement occurred between the foot and shank. These two segments were joined at the distal end of

Fig. 1 The mechanical limb

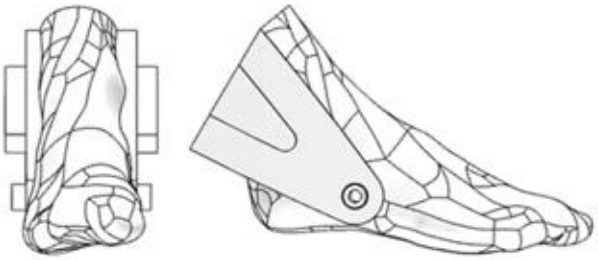


Fig. 2 Foot segment attached at the distal point of shank

the shank with two plates fixed to the medial and lateral sides of the foot, and designed so that no contact between these plates and the ball occurred.

The rotating limb segment was powered by a counterweight via a pulley system that was connected by the frame supporting the limb. Different foot velocities at ball contact were produced by manipulating the starting point of the limb. The pulley system was designed for the counterweights to cease applying torque to the rotating limb immediately before contact. For each kicking trial, the ball was positioned on a kicking tee (Moose Kicking Tee Pty Ltd, Australia) that was placed on a platform built into the frame. The tee allowed for a straight swing through of the leg, typical of AF kicks [21], without any contact being made between the foot and the tee. Adjustments could be made to the impact location moving the tee on the platform (for medial–lateral), or adjusting the height of the platform in relation to the foot (proximal–distal). Because the foot was rigid in construction, the orientation of the foot was unable to change and therefore only ball orientation about the *x-axis* (see Fig. 3 for ball orientation calculation) was required to calculate relative foot-to-ball angle in the sagittal plane. Ball orientation about the *x-axis* was adjusted by altering the position of the ball on the tee.

To analyse the impact phase, three high-speed video cameras (Photron SA3 and MC2, Photron Inc., CA, USA)

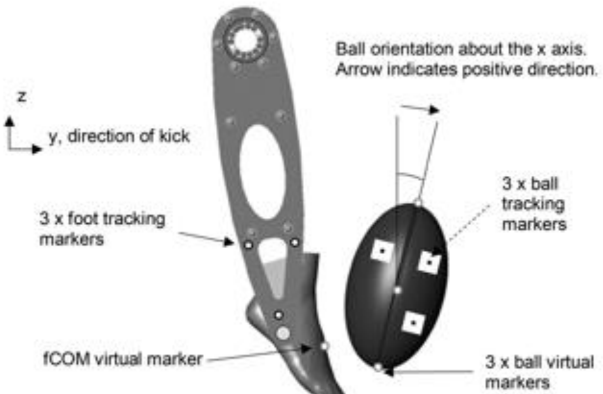


Fig. 3 Reflective and virtual markers attached to the limb and ball

were synchronised, and recorded each trial at 4000 Hz. Ball contact and ball release were visually identified from the camera placed directly perpendicular to the direction of the kick, and each video trial was cut down to 20 frames before and after impact. Three tracking points were attached to the limb using 12.7 mm retro-reflective spherical markers (B&L Engineering, CA, USA). Three tracking points were attached to the ball using a square piece of reflective tape (25×25 mm) with a black circular sticker (radius = 8 mm) fixed to the middle (3M Scotchlite 7610 reflective tape, 3M©, MN USA). These points were tracked in ProAnalyst software (Xcitex Inc., MA USA) to generate three-dimensional coordinates with a root mean square error of 0.9 mm. Calibration involved digitising 32 known points within a space of $0.12 \times 0.45 \times 0.3$ m, which covered the entire capture field.

Visual3d software (C-Motion Inc., MD USA) reproduced virtual landmarks from a pre-recorded static capture of the foot centre of mass (fCOM) based off three tracking markers attached to the limb, and the ball geometric centre (bGC), top point of the ball and bottom point of the ball from three tracking markers attached to the ball (Fig. 3). All data were smoothed with a low-pass, second order Butterworth filter with a cut-off frequency of 280 Hz [4, 22]. The fCOM was found at the midpoint between the lateral malleolus and the head of the first metatarsal [18]; however, because the lateral malleolus was not visible due to the construction of the limb, this point was approximated on the dorsal surface of the foot (see Fig. 3 for approximate location), and remained consistent throughout the analysis. The bGC was calculated from the average position between two markers attached to the top and bottom points of the ball captured during under static setting.

Impact and ball flight characteristics were calculated in Matlab software (The Mathworks Inc., USA) (Fig. 4). Foot and ball velocity were calculated from the first derivative of the fCOM and bGC positional data averaged over five frames before and after contact. Impact location in the medial–lateral direction was defined as the distance between the fCOM and bGC, with positive values indicating a lateral displacement from the fCOM. Impact location in the proximal–distal direction was defined as the distance between the bottom point of the ball and the fCOM along the anterior surface of the foot, with positive values indicating a distal displacement from the fCOM. Relative foot-to-ball angle was not calculated because the shape of the foot varied pending on the area of impact on the foot. Rather, ball orientation about the *x-axis* was calculated and used as an indication of the relative foot-to-ball angle in the sagittal plane. Ball orientation was calculated in the sagittal plane (Fig. 3). Azimuth and angle of elevation were calculated as the average of five frames after release from the foot (Fig. 4). Back-spin rate was

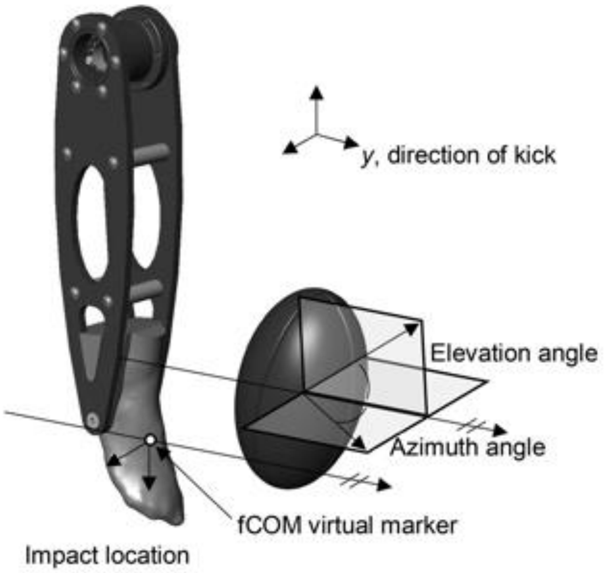


Fig. 4 Orthogonal reference system, approximate location of fCOM virtual marker and parameter calculation of impact location on the foot, elevation angle and azimuth angle. *Arrows* and *angles* represent positive directions

calculated about the global *x-axis*. Foot-to-ball speed ratio, $F{:}B_{\text{ratio}}$, was calculated from

$$F : B_{\text{ratio}} = \frac{v_{\text{bGC}}}{u_{\text{fCOM}}}, \tag{1}$$

where v was the final velocity u was the initial velocity. The coefficient of restitution, CoR, was calculated from

$$\text{CoR} = \frac{v_{\text{bGC}} - v_{\text{fCOM}}}{u_{\text{fCOM}}}. \tag{2}$$

Both foot-to-ball speed ratio and coefficient of restitution were used as measures of impact efficiency, because foot-to-ball speed ratio has been used as a measure of impact efficiency for the impact of AF kicking [2–4], and the coefficient of restitution quantifies the amount of energy lost during a collision and can therefore also be considered a measure of efficiency.

The study examined foot velocity, medial–lateral impact location, proximal–distal impact location, and relative foot-ball orientation in the sagittal plane. Each input measure was analysed independently, where all remaining inputs were held constant. The baseline setting comprised a foot velocity of 16.7 m/s, impact location in the medial–lateral direction of −1.15 cm from the foot centre of mass, impact location in the proximal–distal direction of 2.61 cm from the foot centre of mass and ball orientation in the *x-axis* of 47.4°. Five trials were captured at this baseline setting and used across all datasets. Kicks were performed in four datasets with all parameters held constant within each dataset with the exception of the parameter of interest. For dataset 1 (21 trials), foot velocity was varied from 9.1 to 21.2 m/s. For dataset 2 (17 trials), impact location in the medial–lateral direction was analysed using a range of positions between −3.55 and 0.84 cm across the foot centre of mass. For dataset 3 (17 trials), impact location in the proximal–distal direction was analysed over a range of positions between −5.70 and 7.30 cm across the foot centre of mass. For dataset 4 (28 trials), ball orientation about the *x-axis* was analysed using a range of positions between −11.6° and 85.3°.

A curve-fitting procedure was used to identify the relationship between each impact characteristic and each flight characteristic. The choice of curve fitted to the data was based on two criteria: literature indicating previously identified relationships and theoretical models. Visual inspection of plotted data and residual plots were screened to confirm if the plotted relationship suited the data, and outliers were screened during this process.

3 Results

Five outliers were removed from the foot velocity dataset, thought to be due to a break-in process of the ball and were removed from the remainder of the analysis. Foot velocity was influential to all initial flight characteristics (Fig. 5). Ball velocity (Fig. 5a), elevation angle (Fig. 5c) and back-spin rate (Fig. 5d) increased linearly with foot velocity. Azimuth angle decreased linearly with foot velocity (Fig. 5b). Impact efficiency measures of foot-to-ball speed ratio and coefficient of restitution both decreased linearly with foot velocity (Fig. 5e, f).

Medial–lateral impact location was influential to ball velocity, azimuth angle and back-spin rate (Fig. 6). Optimal relationships were identified between medial–lateral impact location and ball velocity (Fig. 6a) and back-spin rate (Fig. 6c). Maximums were identified at a medial–lateral impact location approximately −0.5 cm from the foot centre; however, the dependence of ball velocity on impact location was low. Azimuth angle increased linearly with impact location across the medial–lateral direction (Fig. 6b). Elevation angle increased linearly with impact location across the medial–lateral direction (Fig. 6d), but the magnitude of the slope was small suggesting low dependence.

Proximal–distal impact location was influential to ball velocity (Fig. 7a), elevation angle (Fig. 7c) and spin rate (Fig. 7d), and all increased linearly with impact location across the distal direction. A linear curve was fitted to proximal–distal impact location with azimuth angle (Fig. 7b), and the magnitude of slope was small suggesting low dependence.

Ball orientation about the *x-axis* was influential to ball velocity, elevation angle and spin rate (Fig. 8). An optimal relationship was identified between ball orientation and

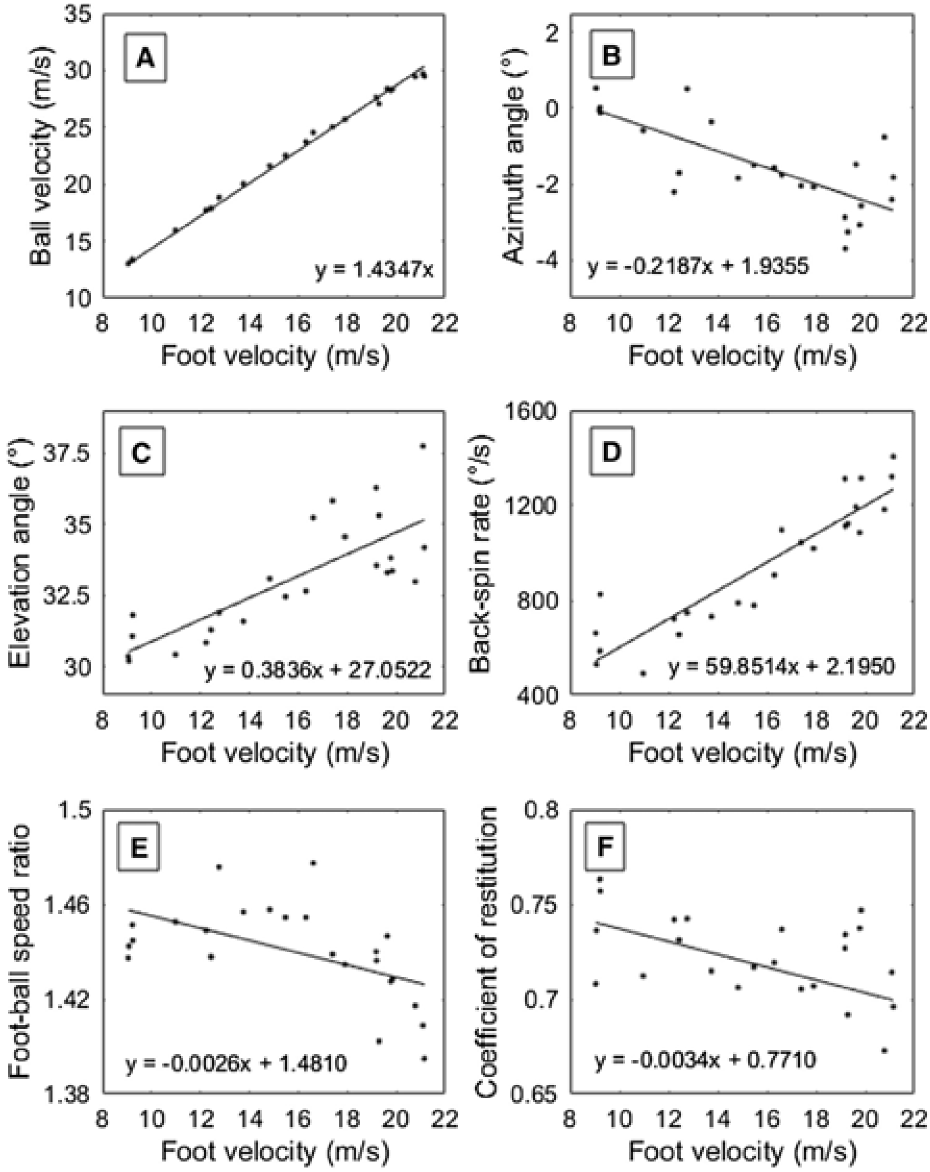


Fig. 5 The relationships between foot velocity and ball velocity (**a**), azimuth angle (**b**), elevation angle (**c**), back-spin rate (**d**), foot–ball speed ratio (**e**), and the coefficient of restitution (**f**)

ball velocity (Fig. 8a), with a maximum identified at an orientation of approximately 43°. Sine curves were fitted to the relationships between ball orientation and elevation angle (Fig. 8c) and back-spin rate (Fig. 8d). A linear curve was fitted to the relationship between ball orientation and azimuth angle (Fig. 8b), but the magnitude of slope was small suggesting low dependence.

4 Discussion

A player must control flight characteristics for a kick to be successful. To date, little is known of the relationship between foot-ball impact and all flight characteristics, the phase of kicking when a player imparts the flight characteristics. Therefore, the aim of this study was to determine the relationship between impact and ball flight characteristics through systematic exploration.

4.1 Foot velocity

Ball velocity increased linearly with foot velocity (Fig. 5a). This linear relationship was comparable to previous results [16, 23, 24]. Andersen et al. [16] developed a model to predict ball velocity from the angular momentum of the leg and coefficient of restitution, which indicated ball velocity increased linearly with foot velocity. They found the results of soccer instep kicking fitted the model appropriately. Similarly, group comparisons have identified increases in foot velocity translated to increases in ball velocity [4].

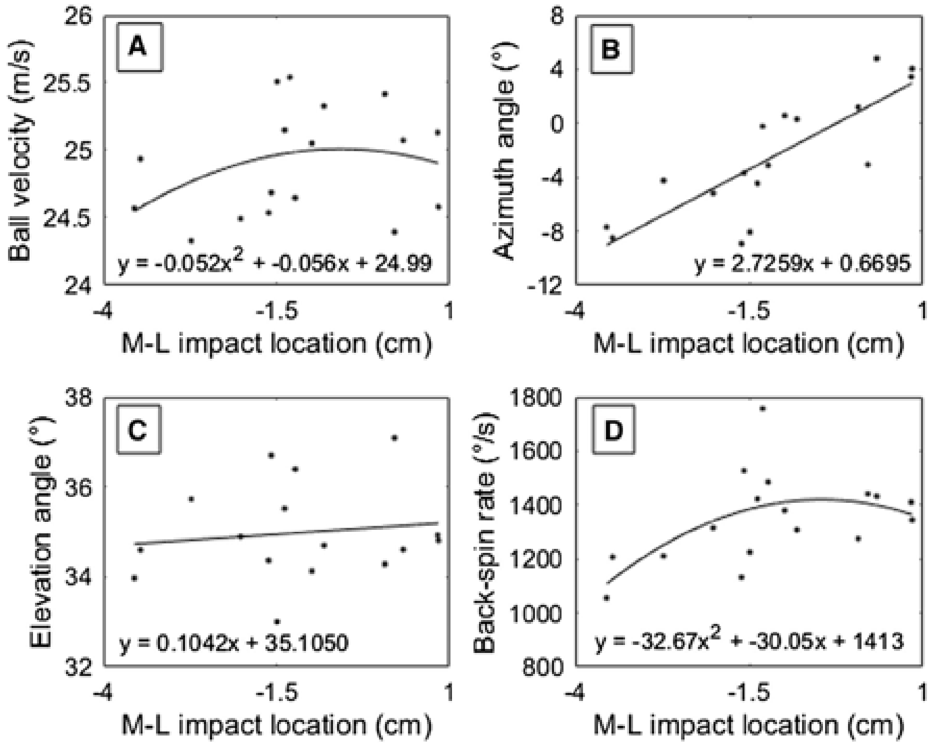


Fig. 6 The relationships between impact location across the medial–lateral direction and ball velocity (**a**), azimuth angle (**b**), elevation angle (**c**), and back-spin rate (**d**)

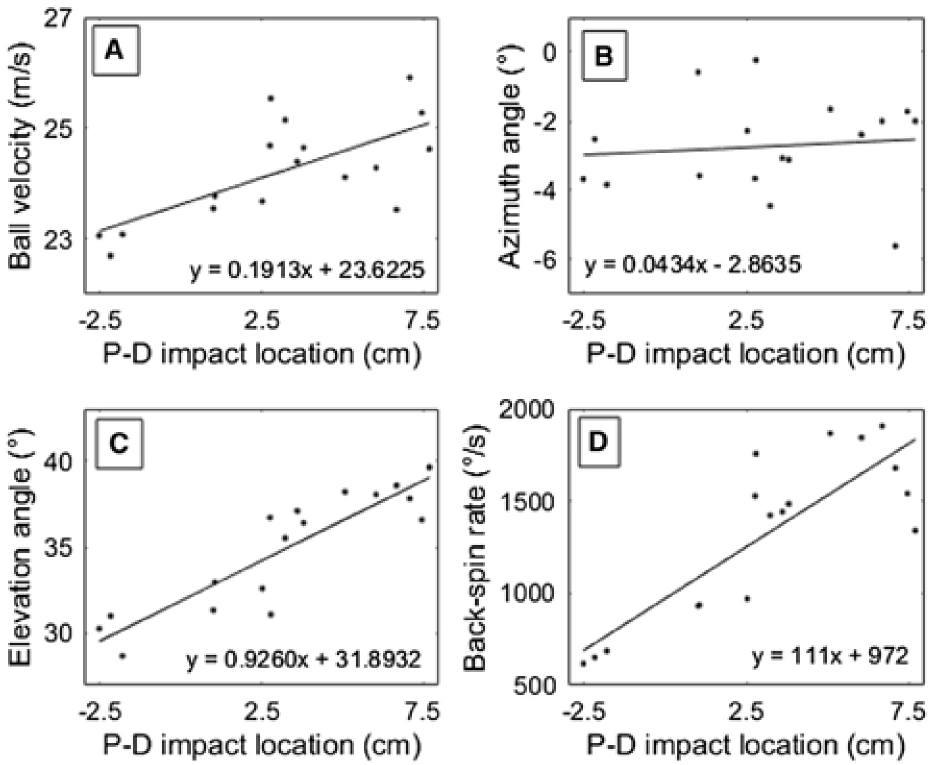
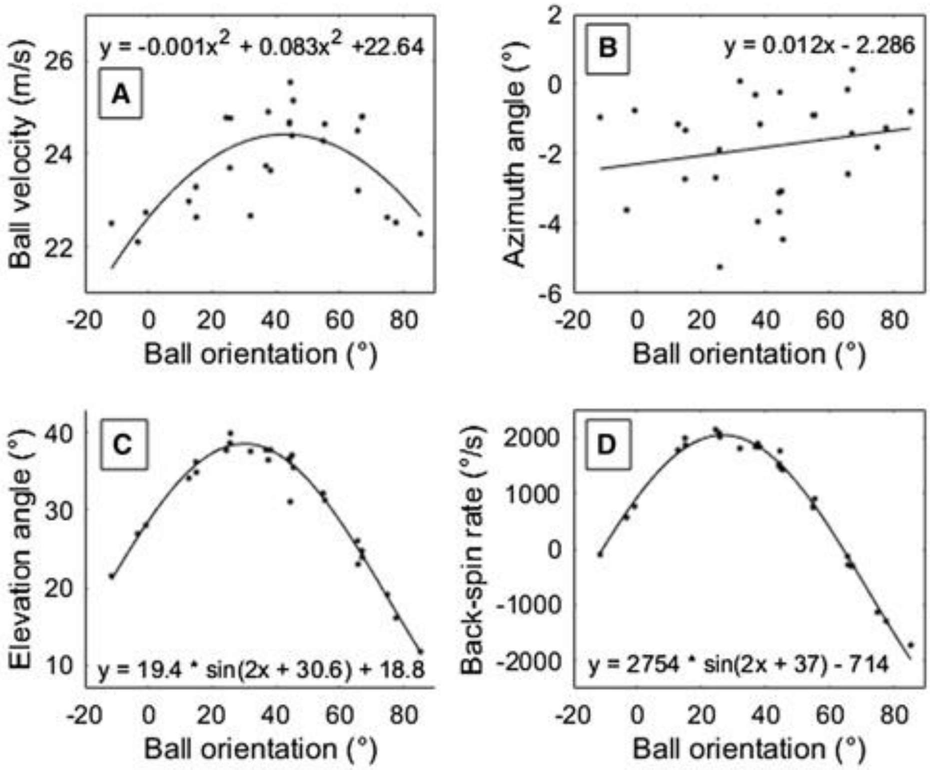


Fig. 7 The relationships between impact location across the proximal–distal direction and ball velocity (**a**), azimuth angle (**b**), elevation angle (**c**), and back-spin rate (**d**)

Fig. 8 The relationships between ball orientation about the *x-axis* and ball velocity (**a**), azimuth angle (**b**), elevation angle (**c**), and back-spin rate (**d**)



Foot velocity negatively influenced impact efficiency (Fig. 5e, f), but the magnitude of reduction had little overall effect on the relationship between foot velocity and ball velocity. Negative linear relationships were identified between foot velocity and foot–ball speed ratio and coefficient of restitution, a similar finding to previous analyses of inelastic objects in collisions [25]. Foot–ball speed ratio represents the slope of the linear relationship between foot and ball velocity. Because foot–ball speed ratio was not constant, the relationship between foot and ball velocity was not linear. Post hoc curve fitting between foot velocity and ball velocity with a power curve to represent the negative slope of foot–ball speed ratio also fits the data well (equation: $y = 1.599x^{0.962}$). But, a comparison of the power and linear curves over the range of foot velocity that a player can produce (up to 26.5 m/s [21]) revealed a minimal difference between the two curves (Fig. 9). The linear curve adequately described the dependence of ball velocity on foot velocity for the range of values a player can produce.

Back-spin rate increased linearly with foot velocity (Fig. 5d). The increase in back-spin rate was caused from a combination of the magnitude of force applied to the ball and the ellipsoidal shape of the ball with its orientation on the foot. The oblique impact theory indicates spin generated during impact is created from a result of the moment that is applied to the ball when the force vector does not pass through the centre of mass of the ball, and is proportionate to the product of the magnitude of the force and the moment arm [15]. Across the foot velocity dataset, the magnitude of force increased with foot velocity, increasing the moment applied to the ball.

Fig. 9 Post hoc analysis of the relationship between foot velocity and ball velocity. The *solid line* represents the linear curve, and the *dashed line* represents the power curve

Foot velocity influenced the trajectory of ball flight (Fig. 5b, c), but each flight component was influenced by different factors associated with an increased foot velocity. Elevation angle increased linearly with foot velocity, due to a greater elevation trajectory of the foot during foot–ball contact. The contact distance between foot and ball increased linearly with foot velocity (post hoc analysis; linear relationship; $r^2 = 0.989$). As the foot was at the beginning of the upward arc as it rotated about the knee, the elevation angle of the foot increased with the increased contact distance. Azimuth angle decreased linearly with foot velocity, due to the nonhomogeneous geometric properties of the foot. The trajectory of the ball in the azimuth direction was determined solely by the geometric surface of the foot across the medial–lateral direction. Oblique impact theory indicates the trajectory of the foot and the angle of foot surface impacting the ball changes the angle of the force vector applied to the ball. The trajectory of the foot was held constant for the present study and therefore was not influential. When foot velocity increased, the surface impacting the ball changed. This was due to a two-step process. Firstly, an increased foot velocity meant a greater area of the ball covered the foot. Secondly, because the surface of the foot was asymmetrical about the proximal–distal axis, the force direction applied to the ball across the azimuth dimension was speed dependent. This supports previous work that has suggested designing footwear with a more symmetrical surface will be beneficial to a more consistent ball flight, also associated with kicking accuracy [26].

4.2 Impact location

Ball velocity and back-spin rate increased linearly as impact location moved distally (Fig. 7a, d). The linear velocity of the impacting point increased as the impact location was moved distally, increasing the force applied to the ball. However, continuing to move the impact location distally has limitations. Firstly, there is an endpoint where if the impact location was moved beyond the length of the foot, the ball would be partially or not impacted at all. Secondly, a limitation of the analysis was that the ankle joint was fixed. Plantar flexion during impact of AF kicking has been reported to range from 2.2° to 7.2° depending on the task [2, 4], and an increased ankle plantarflexion during impact has been associated with decreased impact efficiency [27]. Furthermore, these studies analysed kicks that were struck 'well'. An impact towards the toe, while contacting the foot on an aspect that is moving faster, will result in a greater moment arm tending to force the foot into plantar flexion, reducing the performance advantage may be lost. Future work should implement reduced rigidity about the ankle when analysing impact location to determine the influence of changes in rigidity on kick outcome.

Ball velocity and back-spin rate were maximum with a medial–lateral impact location of 0.5 cm from the foot centre (Fig. 6a, d). The results of Asai et al. [11] indicated an optimal relationship existed between impact location across the medial–lateral direction and ball velocity in instep soccer kicking, and a similar mechanism was expected to occur with back-spin rate. The results of the present study, however, identified little reduction in ball velocity and a moderate reduction in back-spin rate when impact location was moved either medially or laterally from −0.5 cm from the foot centre. Asai et al. [11] observed a much greater reduction in ball velocity, reducing from 26.0 to 0 m/s when impact location was moved medially 16 cm, and to 6.2 m/s when moved laterally 16 cm. This reduction occurred because of the distance the impact location was moved. The change in impact location from foot centre for the present study was only −3.6 to 0.8 cm from the foot centre of mass in the medial–lateral direction. Further changes of impact location from foot centre were limited by the ball supporting the tee, because moving the impact location further would have resulted in the foot impacting the tee and not impacting the ball cleanly, thus altering the impact conditions.

Moving impact location laterally increased azimuth angle linearly and had no influence on elevation angle (Fig. 6b, c). These relationships can be explained by the shape of the foot; as the impact location was moved laterally, the surface angle of the foot changed pointing from the medial to lateral direction, which in-turn altered the ball flight trajectory to move from the medial to lateral direction. Moving the impact location laterally had no effect on elevation angle, because there was no change in the shape of the foot surface across this direction. Post hoc analysis revealed that angular velocity about the *y-axis* of the ball was linearly dependent upon impact location across the medial–lateral direction, considered also to be due to change in angle of the foot surface. This supports accuracy may be enhanced through footwear designs that promote a more symmetrical surface.

Moving impact location distally increased elevation angle linearly and had no influence on azimuth angle (Fig. 7b, c). The relationship between elevation angle and change in the impact location in the proximal–distal direction was not due to the shape of the foot, but due to the higher linear velocity at the impacting point. As the impact location was moved distally, a higher linear velocity of the impacting point was applied to the ball, influencing the force vector applied to the ball. Moving the impact location distally had no effect on azimuth angle, because there was no change in the surface angle of the foot.

4.3 Ball orientation about the x-axis

Ball orientation about the *x-axis* influenced back-spin rate and elevation angle (Fig. 8c, d). The sine curve fits the data well, outlining the dependence of these flight characteristics on ball orientation about the *x-axis*. Holmes [15] performed a ball drop test to determine the influence of ball orientation on flight parameters, tested between the range of 0° and 90°. Their results identified a sine dependence likely to be present over a change in ball orientation about the *x-axis* of 0°–180°. We hypothesise the amplitude of both sine waves, and the vertical midpoint of the elevation angle sine wave were dependent on the velocity and elevation trajectory of the foot prior to impact. This is supported by the previous analysis of foot velocity, where it was identified under a constant ball orientation; increasing foot velocity resulted in an increase to ball velocity and elevation angle.

Ball velocity was maximum at a ball orientation about the *x-axis* of approximately 43° (Fig. 8a). Holmes [15] performed a bounce test and identified the coefficient of restitution for an Australian Football ball was greater at the point compared to the centre. The results of the present study support this finding, where ball velocity was greater when impacted at the point (ball orientation of 65° = ball velocity of 24 m/s) compared to the centre (ball orientation of −25° = ball velocity of 20 m/s). However, ball velocity was even higher when impacted at 43°, the maximum ball velocity of 24.4 m/s.

5 Conclusion

This study systematically explored four impact characteristics of kicking an ellipsoidal shaped ball to determine the relationship with initial flight characteristics. Each flight characteristic was influenced by multiple impact characteristics. Ball velocity increased linearly with foot velocity and proximal–distal impact location. Impacting the ball 0.5 cm medially from the foot centre, or with a ball orientation about the *x-axis* of 43° produced the highest ball velocity. Azimuth angle increased linearly with foot speed and with medial–lateral impact location. Elevation angle increased linearly with foot velocity and proximal–distal impact location. The relationship between elevation angle and ball orientation about the *x-axis* followed a sine curve, over the period of 180°. Back-spin rate increased linearly with foot velocity and proximal–distal impact location. The relationship between back-spin rate and ball orientation about the *x-axis* also followed a sine curve over the period of 180°.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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Appendix C: Published manuscript of Study 3

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The influence of joint rigidity on impact efficiency and ball velocity in football kicking

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ABSTRACT

Executing any skill with efficiency is important for performance. In football kicking, conflicting and non-significant results have existed between reducing ankle plantarflexion during foot-ball contact with impact efficiency, making it unclear as to its importance as a coaching instruction. The aims of this study were to first validate a mechanical kicking machine with a non-rigid ankle, and secondly compare a rigid to a non-rigid ankle during the impact phase of football kicking. Measures of foot-ball contact for ten trials per ankle configuration were calculated from data recorded at 4000 Hz and compared. The non-rigid ankle was characterised by initial dorsiflexion followed by plantarflexion for the remainder of impact, and based on similarities to punt and instep kicking, was considered valid. Impact efficiency (foot-to-ball speed ratio) was greater for the rigid ankle (rigid = 1.16 ± 0.02; non-rigid = 1.10 ± 0.01; $p < 0.001$). The rigid ankle was characterised by significantly greater effective mass and significantly less energy losses. Increasing rigidity allowed a greater portion of mass from the shank to be used during the collision. As the ankle remained in plantarflexion at impact end, stored elastic energy was not converted to ball velocity and was considered lost. Increasing rigidity is beneficial for increasing impact efficiency, and therefore ball velocity.

1. Introduction

Many ball sports involve a performer accelerating the ball by impacting it with a distal body segment or piece of equipment. The outcome of this collision can be quantified by its initial flight characteristics, such as velocity, spin and trajectory, because they all influence the flight path of a projectile (Goff, 2013). Attaining a high ball velocity is a desirable characteristic for performance, enabling the ball to travel further or to reach a target in a shorter time. In game situations, this can reduce the possibility of interception from the opposition and provide more opportunities for scoring from further distances. The velocity of the distal body segment (Kellis and Katis, 2007; Lees and Nolan, 1998) or piece of equipment (Cross, 2011) immediately prior to the collision is an important component for final ball velocity. However, the ability to produce a high velocity can be limited by a players' physical capacity, so impacting the ball with a higher efficiency will generate a higher ball velocity for a given striking velocity.

In football kicking, where the foot impacts the ball, the ankle is passively plantarflexed during the collision due to the high forces and short impact duration of approximately 10 ms (Shinkai et al., 2009). A reduction in the forced plantarflexion has been associated with an increase in ball velocity (Asami and Nolte, 1983; Peacock et al., 2017), by improving impact efficiency from an increase in the effective mass (Kellis and Katis, 2007; Lees and Nolan, 1998). Furthermore, it can also be considered that when the ankle remains in plantarflexion at the end of impact, elastic energy stored within the joint is not converted to ball velocity and can therefore be considered lost, and might cause a further reduction in impact efficiency. The relationship between impact efficiency with effective mass and energy losses also has theoretical support; the conservation of momentum combined with the coefficient of restitution (Eq. (1)) indicates impact efficiency (foot-to-ball speed ratio) and ball velocity would be improved from an increase in either the effective mass or coefficient of restitution.

$$v_b = \left(\frac{1+e}{1+m_b/m_f}\right) \cdot u_f + \left(\frac{e-m_b/m_f}{1+m_b/m_f}\right) \cdot u_b \quad (1)$$

where v_b = ball velocity after it leaves the foot, e = coefficient of restitution, m_b = ball mass, m_f = foot mass, u_f = initial foot velocity, u_b = initial ball velocity.

While some studies have identified a reduction in the forced plantarflexion to be beneficial to kick performance, there are some

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that have observed non-signif cant f ndings with small effect sizes or individual players questioning the association. Peacock et al. (2017) identif ed a signif cantly different magnitude of plantarf exion between distance and accuracy kicks but impact eff ciency was non-signif cant with a small effect, indicating a reduction in forced plantarf exion may not be associated with impact eff ciency. Furthermore, Nunome et al. (2006) identif ed a player that produced a relatively high ball velocity also displayed a relatively high plantarf exion, again questioning the association of reduced plantarf exion with impact eff ciency. Further to support no association between reduced plantarf exion with impact eff ciency, Shinkai et al. (2013) stated that when the ball mostly impacted the foot on the centre of mass, ball impact was most likely assumed to be a collision between the foot and ball, and therefore motion of the ankle does not inf uence the outcome. This questions the coaching instruction of attaining a f rm ankle for kicking performance, and more generally the inf uence of joint rigidity in sporting skills when attaining high ball velocity. Therefore, the aim of this study was to determine the inf uence of plantarf exion during foot-ball impact on impact eff ciency and ball velocity.

To determine the inf uence of plantarf exion during foot-ball impact on impact eff ciency, a mechanical kicking machine with a rigid and a non-rigid ankle conf guration was used. Kicking is a dynamic skill where many characteristics can inf uence the outcome of a kick, therefore, a methodology to control other impact characteristics, such as a mechanical kicking machine, was warranted. The rigid setting of the mechanical kicking machine has already been validated (Peacock and Ball, 2016), but not the non-rigid conf guration. The f rst aim of the study was to validate the ankle motion of the non-rigid ankle conf guration. The second aim was to compare the rigid and non-rigid ankle conf gurations.

2. Methods

2.1. Mechanical kicking machine with adjustable ankle rigidity

A mechanical kicking machine performed trials with an Australian football (AF) ball ('Sherrin Match Ball', Russell Corporation, Scoresby, Australia; mass = 0.456 kg, inf ation = manufacturers recommendation and league requirement of 69 kPa) (Fig. 1A). To replicate drop punt kicking of elite AF players, the kick leg was constructed to match the length and mass of the shank and foot, and foot shape of an AF player (height: 1.85 m; mass = 85 kg). This mechanical kicking machine was used previously with a rigid foot segment and was found to be a valid representation of drop punt kicking (Peacock and Ball, 2016).

To analyse the inf uence of ankle rigidity on impact eff ciency, a spring mechanism preventing plantarf exion was added to the previously validated mechanical kicking machine (Fig. 1A). The spring mechanism was considered appropriate to represent the ankle motion during impact, as both the spring and human ankle during impact are passive (Shinkai et al., 2009), where it is considered the initial conditions at the start of impact determine the phase (Nunome et al., 2006). The leg conf guration (Fig. 1B) comprised two segments: a shank and a foot segment. The shank segment was constructed of two metal plates (length = 0.455 m; mass = 4.2 kg) that attached to the trigger mechanism of the kicking machine (leg and trigger mass = 21.15 kg). While the mass of the trigger was high, it contributed little to the moment of inertia because it was close to the axis of rotation. The foot segment was attached to the distal end of the shank segment and plantar/-dorsal ankle rotation occurred via two bearings. Because the shape of the impacting surface inf uences the interaction (Andersen et al., 2005, 2008), and because the impacting area during drop punt kicking covers the bottom part of the shank (Nunome et al., 2014), the bottom part of the shank and entire foot of a human was 3d scanned and integrated into the limb design. The foot segment was constructed by a 3d printer, made of ABS plastic with a weight of 1.09 kg. It was assumed the foot acted as a rigid body during impact. A football boot (Adidas Kaiser 5; mass = 0.364 kg) was placed on the foot segment. Overall, the moment of inertia of the entire kick leg was estimated to be 0.71 kg m^2. It was assumed each body were rigid during impact, the only motion was rotation about the knee and ankle joints.

By setting the ankle to be either rigid or non-rigid at the start of impact, this enabled a direct comparison to determine the inf uence of ankle rigidity while all other impact characteristics were held constant (foot speed, impact location, ball orientation, moment of inertia, etc.). The rigid ankle was obtained by locking out rotation of the foot segment by inserting a bolt between shank and foot segments (see insert of Fig. 1B). The non-rigid ankle was obtained by synthetic rope representing connective tissue and two springs representing elastic tissue within the joint. The synthetic rope

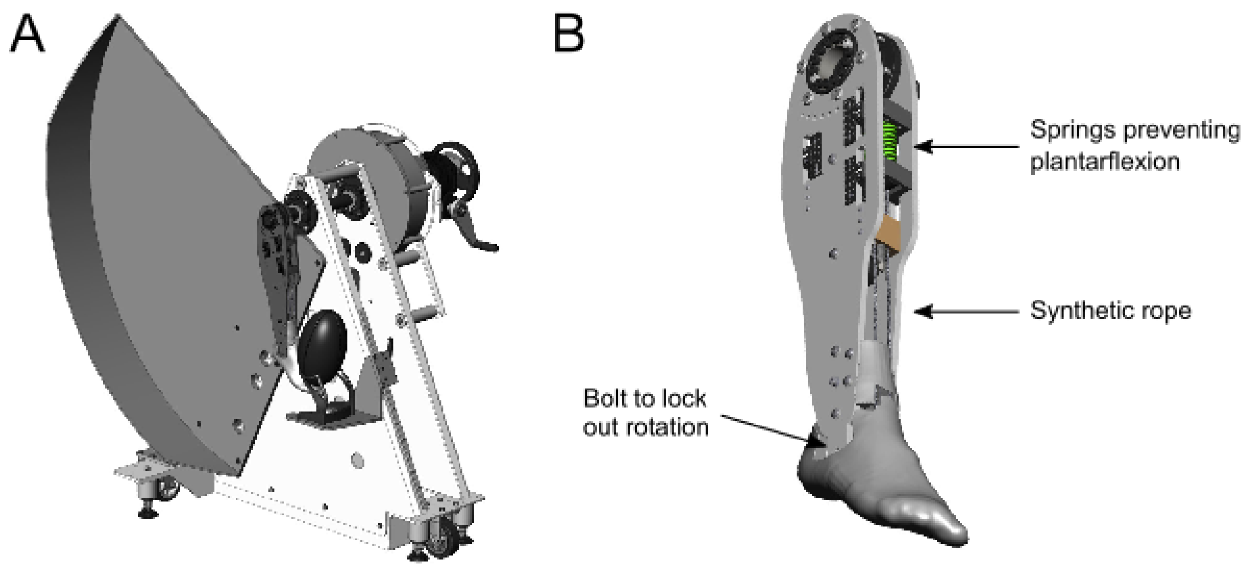

Fig. 1. (A) The mechanical kicking limb. (B) Ankle rotation design with controlled rigidity via spring mechanism.

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stemmed from the foot segment and passed across the anterior side of the ankle joint, before connecting to two springs just below the knee joint (Fig. 1B). The torque preventing plantarflexion could be calculated by multiplying spring stiffness by the radius of 40 mm (the displacement between the ankle axis of rotation and the contact point of the tendon across the anterior aspect of the joint). It was assumed the synthetic rope did not stretch while the ankle was forced into plantarflexion, enabling the linear deformation of the spring to be calculated from the ankle plantar/dorsal flexion motion. To determine if the non-rigid ankle validly represented ankle motion of human performers, the ankle motion of the mechanical limb was compared to previous literature.

2.2. The initial conditions of impact for the comparison of ankle rigidity

The imposed initial conditions of impact were a foot velocity prior of 16.4 ± 0.2 m/s across all trials, and spring stiffness at the ankle joint of 950 N for the non-rigid setting (yielding a torque preventing plantarflexion of 38 N m). The angle of the rigid ankle was set at 155.6°, and the angle of the non-rigid ankle was set at 156.8°. Impact location was set to impact the foot approximately at its centre of mass. Pilot testing identified this setting to obtain a change in ankle angle of approximately 8° plantarflexion, a similar value obtained in both AF (7.2 ± 2.2°) and soccer (7.1 ± 5.8°) performer studies where the ankle was passively plantarflexed during impact (Peacock et al., 2017; Shinkai et al., 2009). Ten trials were recorded for each setting on the same testing session using the same ball, and to minimise the possibility of order effects (given the ball can 'soften') five trials were completed under the rigid setting, followed by 10 trials under the non-rigid setting, and five final trials under the rigid setting.

2.3. Data collection

Two-dimensional sagittal plane data were measured through high-speed video camera (Photron SA3, Photron Inc., USA, 4000 Hz, resolution 768 × 512 pixels) zoomed into include just the kicking area. Tracking markers (12.9 mm spherical and 8 mm flat circular) on the limb and ball were tracked from 20 frames before ball contact to 20 frames after the ball had left the boot (identified visually from the video) using ProAnalyst software (Xcitex Inc., Woburn MA, USA). To eliminate movement of the boot influencing foot and ankle data, the foot tracking marker was attached directly to the fifth metatarsal by cutting a hole in the boot and tapping a thread into the foot. This marker was also occluded for approximately 10 frames through the middle of the tracking stage as it passed through the tee supporting the ball, and these points were interpolated within the tracking software. The interpolation feature was considered suitable because there was no change in direction of the marker during this period.

2.4. Data analysis and parameter calculation

Raw X and Y coordinates were exported to Visual3d software (C-Motion Inc., Germantown MD, USA) to be analysed with a custom-made pipeline. Firstly, four virtual markers were derived from the three tracking markers of the foot using the method from (Peacock et al., 2017). These virtual markers were on the anterior aspect of the foot, and were found at the top of the shank segment (ShT), bottom of the shank segment (ShB), centre of the foot (FC) and bottom of the foot (FB) (Fig. 2). All parameters were calculated within Visual3d and Microsoft Excel (Microsoft Corporation, Redmond WA, USA) software from the measured X-Y coordinate data. Foot and ball velocity were calculated from the first derivative of X-Y coordinate data, and were smoothed with a low-pass Butterworth filter at a cut-off frequency of 170 Hz. The choice of cut-off filter was based upon three criteria: discrete Fourier Transform analysis looking at different cut-offs between 10 and 400 Hz, visual inspection of the signals at different cut-offs and previous literature (Nunome et al., 2006; Peacock et al., 2017; Shinkai et al., 2009). Initial and final velocity of foot and ball were averaged over five frames.

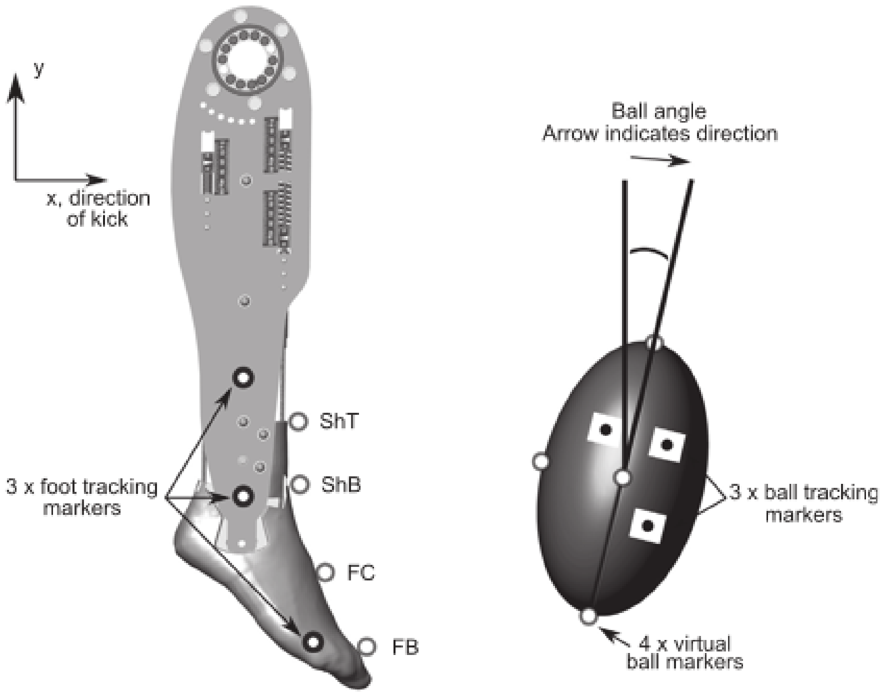

Fig. 2. Orthogonal reference and tracking and virtual markers of the limb and ball. Virtual markers are represented by the grey outline of the circular markers.

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The energy sources of interest were the kinetic energy of the ball and the elastic energy stored in the springs preventing plantarflexion of the ankle. Linear kinetic energy of the ball was quantified from its mass and linear velocity (Eq. (2)). Rotational energy was quantified from the angular velocity and moment of inertia (Eqs. (3) and (4)). Energy stored in the spring mechanism preventing plantarflexion was quantified from its deformation (Eqs. (5) and (6)). The sum of ball and ankle energy included translational and rotational kinetic energy and the energy stored within the spring mechanism (although not applicable to the rigid ankle).

$$Ball_{KE,Translational}\ (\mathrm{J}) = 1/2 \cdot m_b \cdot v_b^2 \tag{2}$$

$$Ball_{KE,Rotational}\ (\mathrm{J}) = 1/2 \cdot I_b \cdot \omega_b^2 \tag{3}$$

where I_b = inertia of the ball, calculated from Eq. (4); ω = angular velocity.

$$I_b = \frac{m\left(R_a^2 + R_b^2\right)}{5} \tag{4}$$

where R_a = the short radius of the ball; R_b = the long radius of the ball

$$d = \left(D_i + \frac{\Delta AA}{180} \cdot \pi \cdot R_t\right) \tag{5}$$

where d = spring deformation; D_i = initial spring deformation (m), ΔAA = change in ankle angle (degrees), R_t = radius of tendon across ankle joint (m).

$$Ankle_{EE}\ (\mathrm{J}) = 1/2 \cdot k \cdot d^2 \tag{6}$$

where k = spring stiffness; d = spring deformation, as calculated from the limb settings and change in ankle angle.

Impact efficiency measures of foot-to-ball speed ratio, coefficient of restitution and effective mass are presented in Eqs. (7)–(9).

$$F : B\ Ratio = \frac{v_b}{u_f} \tag{7}$$

$$COR = \frac{v_f - v_b}{u_f} \tag{8}$$

$$EM\ (\mathrm{kg}) = \frac{m_b \cdot (v_b - u_b)}{v_f - u_f} \tag{9}$$

2.5. Statistical analysis

A two-tailed, two-sampled equal variance T-test was performed and effect sizes were calculated. The P-value was set at 0.05 to indicate significance and effect sizes were defined as: $d < 0.2$ = none, $d < 0.5$ = small, $d < 0.8$ = medium and $d > 0.8$ = large (Cohen, 1988). A Holm's correction was applied to reduce the likelihood of type 1 statistical errors (Holm, 1979).

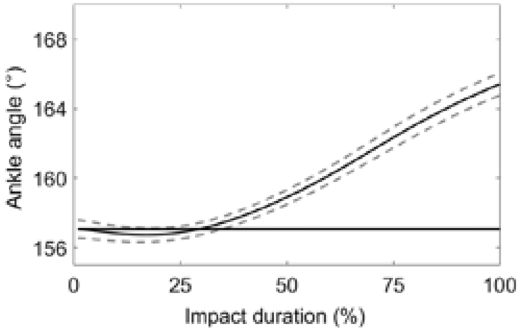

Fig. 3. Non-rigid ankle motion through impact (±standard deviation). The flat black line represents ankle angle at impact start, plotted throughout the duration of impact as a reference to the change in angle during impact.

3. Results

3.1. Validation of mechanical limb segment

The non-rigid ankle was in dorsi-flexion for the first 31% of impact duration, followed by distinct plantarflexion for the remainder of impact (Fig. 3). The total change in ankle angle between ball contact and ball release was 8.2 ± 0.7° and the total impact duration was 10.7 ± 0.3 ms.

3.2. Comparison of ankle rigidity settings

Foot-to-ball speed ratio, ball velocity and translational kinetic energy of the ball were significantly greater under the rigid ankle (Table 1). The effective mass of the striking limb was greater under the rigid ankle: effective mass as calculated through the conservation of momentum was greater for the rigid ankle, and although the elastic energy in the ankle for the rigid setting was naught, the sum of ball kinetic energy and ankle elastic energy were equal under the rigid and non-rigid ankle settings despite a smaller reduction in foot velocity under the rigid ankle. Energy losses during the collision were significantly greater under the non-rigid ankle: coefficient of restitution was greater under the rigid ankle and 6.3 ± 0.6 J of elastic energy was stored in the spring mechanism at the end of impact as the ankle remained in plantarflexion.

4. Discussion

4.1. Validation of non-rigid ankle limb configuration

Kicking is a dynamic skill where many impact characteristics, if not accounted for, can influence the outcome of a kick. Therefore, to determine the influence of one characteristic on kick outcome, specifically ankle plantarflexion for the present study, a mechanical kicking machine with the ability to control ankle motion was developed. The first aim of the present study was to validate the non-rigid ankle motion by comparing to previous research.

The passive motion of the non-rigid ankle was representative of human ankle motion during drop punt and instep soccer kicking based on similar motion of the ankle during impact, overall change in ankle plantarflexion, and contact time. The ankle was in dorsi-flexion for the first 31% of impact duration, followed by distinct plantarflexion for the remainder. This ankle movement pattern was similar to both drop punt and instep kicking, where both Peacock et al. (2017) and Shinkai et al. (2009) identified the majority of analysed players within the tested groups produced a similar pattern. The overall change in ankle plantarflexion was 8.2 ± 0.7°, a comparable value to both drop punt kicking (7.2 ± 2.2°) and soccer instep kicking (7.1 ± 5.8°) (Peacock et al., 2017; Shinkai et al., 2009). Further, the overall contact time (10.7 ± 0.3 ms) was consistent with human kicking values of both the drop punt (13.2 ± 2.2 ms) and soccer instep (9.0 ± 0.4 ms) kicks (Peacock et al., 2017; Shinkai et al., 2009). Based on these similarities, it can be concluded the ankle motion of the mechanical kicking machine validly represented human football kicking. This result supports ankle motion during impact as being passive, as the ankle motion was validly replicated by a spring mechanism that was passive in motion.

4.2. Comparison of rigid to non-rigid ankle

During impact the ankle is forced into passive plantarflexion due to the high forces and short time of the interaction (Shinkai et al.,

Table 1
Kick impact characteristics.

	Rigid	Non-rigid	T-test	Holm's Corrected P-value threshold	Effect size	
					Value (Cohen's d)	Classification
Foot-to-ball speed ratio	1.16 ± 0.01	1.11 ± 0.01	*p* < 0.001*	0.007	1.79	Large
Ball velocity (m/s)	19.0 ± 0.3	18.3 ± 0.2	*p* < 0.001*	0.013	1.61	Large
Translational kinetic energy of ball (J)	82.3 ± 2.5	76.7 ± 1.5	*p* < 0.001*	0.017	1.60	Large
Effective mass (kg)	2.1 ± 0.1	1.7 ± 0.1	*p* < 0.001*	0.008	1.72	Large
Σ ball kinetic and ankle elastic energy (J)	88.6 ± 2.5	89.1 ± 1.3	*p* = 0.32	0.050	0.22	Small
Reduction in foot velocity (m/s)	4.1 ± 0.2	4.8 ± 0.3	*p* < 0.001*	0.010	1.63	Large
Coefficient of restitution	0.42 ± 0.01	0.40 ± 0.02	*p* = 0.01*	0.025	0.96	Large
Change in ankle angle (°)	–	8.3 ± 0.7	–	–	–	N/A
Energy stored in ankle (J)	–	6.3 ± 0.6	–	–	–	N/A

* Denotes significance.

2009). Contrasting results exist as to whether impact efficiency is improved when reducing this plantarflexion. Therefore, the aim of this study was to compare a rigid and a non-rigid ankle while all other impact characteristics were held constant. The key results were that impact efficiency was greater under the rigid ankle, due to an increase in effective mass and decrease in energy losses.

A more rigid ankle increases the effective mass of the striking limb compared to a less rigid ankle, where a greater portion of mass from the shank is included in the collision. The higher effective mass for the rigid ankle was evidenced by two mechanisms: firstly, effective mass as calculated through the conservation of momentum was greater for the rigid ankle; secondly, the sum of ball kinetic energy and elastic energy stored in the ankle at the end of contact were equal between the rigid and non-rigid ankles, but, the reduction of foot velocity was smaller under the rigid setting meaning a greater amount of energy was transferred from to ball but with a smaller reduction in velocity. This indicates the effective mass was greater under the rigid setting, supporting Kellis and Katis (2007) and Lees and Nolan (1998) who state the effective mass is increased from a rigid foot and ankle. Shinkai et al. (2013) found effective mass to also increase with the physical mass of players, and therefore, effective mass is dependent on the physical mass of the performer and the rigidity of the ankle during impact.

A less rigid ankle during kick impact results in a greater energy loss compared to a more rigid ankle. During football kicking, energy can be lost in both the striking limb and the ball. For our study ball position was held constant at impact start, and although small changes existed in the relative foot-ball position as the ankle position changed during impact, it was assumed that energy loss in the ball did not differ between the conditions. Under this assumption, the difference in coefficient of restitution was solely due to the differing rigidity of the ankle joint. This lost elastic energy was due to the ankle remaining in plantarflexion at the end of impact, 6.3 J of energy were stored in the spring mechanism. Ball velocity between the two ankle configurations would be equal if this stored energy was transferred into translational kinetic energy of the ball. The translational kinetic energy of the ball was 76.7 J for the non-rigid ankle, and an increase of 6.3 J to a total of 83.0 J is equivalent to a ball velocity of 19.1 m/s, comparable to that measured for the rigid ankle (19.0 m/s).

When all impact conditions were controlled for, increasing rigidity was beneficial to impact efficiency, and therefore ball velocity. Previous analyses that did not identify an improved efficiency with increased rigidity may have been confounded by other parameters. For example, Ball et al., (2010) suggested a number of impact characteristics such as ball orientation and impact location that were not measured may also influence the impact phase. This highlights the benefits of mechanical testing where all parameters could be controlled. To reduce the number of parameters that can vary when testing with human performers, an intra-individual method could be employed to reduce variation in parameters such as physical mass, strength and shoe type. Experimental limitations did exist for the present study, because the mechanical limb did not include soft tissue as present in the human body (muscle, tendon, ligament). This soft tissue may influence the contribution of shank mass toward impact. While the simplification of the ankle and foot structure within the present study has provided a strong theoretical background for the application of kicking, future research is warranted with human participants to fully solve the question about ankle rigidity and energy transfer. The practical applications of this work indicate that strategies to reduce the magnitude of ankle plantarflexion during impact might increase ball velocity. Effective strategies to reduce change in ankle plantarflexion and in-turn increase impact efficiency might include controlling the impact location on the foot, to reduce the external torque applied to the ankle, and increasing the muscle stiffness within the ankle joint, to increase the internal torque applied to the ankle. Future work, however, is required to determine the effectiveness of these strategies.

5. Conclusion

Two aims existed for the present study: to validate the ankle motion of a mechanical kicking machine with a non-rigid ankle and to determine if differences exist between a rigid and non-rigid ankle. The non-rigid ankle was in dorsiflexion for the first 31% of impact and moved into plantarflexion for the remainder of the phase. Ankle plantarflexion at impact end was 8.2 ± 0.7°. This was a similar pattern and magnitude of ankle motion to both drop punt and instep kicking. Further, the contact time was also comparable to human kicking, and the ankle motion of the mechanical kicking machine was therefore valid. Differences existed between the rigid and non-rigid ankle settings for impact efficiency (foot-to-ball speed ratio). The higher impact efficiency was obtained by an increase in effective mass and a reduction in energy losses. The greater effective mass for the rigid ankle was quantified through the conservation of momentum and the energy transferred from the foot to the ball. Rigidity of the ankle joint controls the contribution of mass from the shank used in the collision. Energy losses were quantified from coefficient of restitution and the elastic energy stored in the spring mechanism preventing plantarflexion. As the foot remained in plantarflexion at the end of impact, energy stored in the joint was lost. Increasing ankle rigidity, to decrease the forced plantarflexion, is beneficial for impact efficiency and therefore ball velocity.

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Conflict of interest

The authors declare that no conflict of interest exists between the authors and the outcome of this study.

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