# Biomechanical Considerations of the Effect of Fatigue on Kicking in Australian Rules Football

**Doctor of Philosophy**

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# Abstract

The punt kick is a fundamental skill used in team sports, including Australian Football. Australian football is a physically demanding sport played for long durations on large grounds with regular bursts of high intensity running. While these game conditions might be expected to elicit large amounts of fatigue, there has been little work examining how kick technique might change under the effects of fatigue. Importantly, changes in fatigued kicking technique have been found in soccer so it might be expected that changes will exist in the punt kick as well. The purpose of this thesis was to evaluate the effects of short and long-term fatigue on punt kicking kinematics and kinetics using elite and junior Australian Football players. Three-dimensional motion capture systems tracked maximal distance kicks from toe-off to ball contact before and during match-specific fatigue protocols. In the short-term fatigue study (Study 1), elite Australian Football players were able to maintain foot speed (performance) during fatigued kicks by increasing segmental ranges of motion and velocities, particularly at the thigh. Participants were able to make changes to their punt kicking technique in order to maintain performance after short high-intensity bursts of activity. In the longer-term fatigue studies (Study 2 and Study 3), junior Australian Football players initially displayed a decrease in foot speed, due to a decrease in knee extension moment. However, this decrease in performance appeared to be minimised through increasing velocity and angles higher up the chain at the thigh and hip. During initial stages of long-term lower intensity activity, performance decreased and participants made technique changes in an attempt to limit this decrease. Performance then improved later in the long-term protocol due to the kicking thigh widening its frontal plane angle and flexing more at the hip. Overall, fatigue caused changes to punt kicking technique.

# Doctor of Philosophy Student Declaration

Doctor of Philosophy Declaration

"I, Evan Coventry, declare that the PhD thesis entitled *Biomechanical Considerations of the Effect of Fatigue on Kicking in Australian Rules Football* 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:** **Date:**

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# Chapter 1

## 1. Introduction

Curving a penalty into the back of the net from long range in soccer, a punt clearance in American Football, launching a drop punt from a kick-out after a point has been scored in Australian Football – all of these activities require kicking a ball for maximal distance. The ability of the performer to perform these kicks successfully is vital to their team's success. Any factors that increase the kicker's ability to launch the ball longer must be enhanced, whilst any factors that are detrimental to the kicker's performance must be minimised.

Kicking in Australian Football is the main means of passing the ball and effective kicking has been associated with success (Forbes, 2003). It involves releasing the ball from the hand such that it drops towards the ground in front of the kick leg which is swung through to make contact with the ball near the ground. Of the few studies that have examined kinematics of maximal Australian Football punt kicking, technical elements such as foot speed, shank angular velocity (Ball, 2008) and angular velocity of the thigh and knee (Macmillan, 1975) have been found to be important in increasing kick distance. Surprisingly, no kinetic data has been published for Australian Football kicking, as this would give an insight into what drives these important technical elements.

Soccer kicking kinematics and kinetics have been more widely researched. Players have been reported to kick about 300 times per game (Yamanaka, Liang & Hughes, 1997) with the ball generally being kicked from the ground, as opposed to being dropped on to the foot as in Australian football. Some technical elements that have been highlighted as being essential for good performance to maximal soccer kicking are foot speed, shank angular velocity (Nunome, Lake, Georgakis & Stergioulas, 2006) and generation of hip flexion torque (Kawamoto, Miyagi, Ohashi & Fukashiro, 2007).

Fatigue is a factor that has been shown to be detrimental to the performance of sports skills such as landing (Coventry, O'Connor, Hart, Earl & Ebersole, 2006; Madigan & Pidcoe, 2003), running (Derrick, Dereu & Mclean, 2002) and lifting (Sparto, Parnianpour, Reinsel & Simon, 1997), and in some studies has been proposed to cause a redistribution of work to larger more fatigue resistant muscle groups (Coventry et al., 2006). Australian Football players have been found to cover 12.5km of distance during a game and to surge above 18 km·h$^{-1}$ on average 90.09 times for an average of 4s per sprint over 18 km·h$^{-1}$ (Wisbey & Montgomery, 2007). Soccer players can cover eight to 12km per game (Greig, 2006), and travel in speed zones above 16km·h$^{-1}$ for averages of only 2.5s (Bangsbo, Norregaard & Thorso, 1994). Even though Australian Football is played at a high intensity, for a longer duration and on a bigger ground than a soccer match (Ball, 2006), there has been no published research on fatigue and its influence on Australian Football kicking technique.

There has been some research done on the influence of fatigue on soccer kicking technique. However, it is difficult to compare data between studies due to the variety of fatigue protocols used. Some studies have used a range of non-match-specific means to induce fatigue varying from the use of isokinetic dynamometers (Apriantono, Nunome, Ikegami & Sano, 2006), step tests (Lees & Davies, 1988) or alternate split squats (Lyons, Al-Nakeer & Nevill, 2006). Subsequently results have also varied with some studies showing a detriment in performance whilst some reported an improvement. Chavez, Knudson, Harter & McCurdy (2013) identified that different protocols can change fatigue patterns and result in a different lower extremity technique in landing, therefore highlighting the importance of having a valid, and in the case of kicking a game-specific, fatigue protocol. In contrast to these short-term non-match-specific fatigue protocols, some other studies have attempted to replicate match-induced fatigue by either using an intermittent treadmill protocol (Rahnama, Reilly, Lees & Graham-Smith, 2003; Rahnama, Lees & Reilly, 2005) or a ground based running protocol (Kellis, Katis & Vrabas, 2006). The nature of these protocols will likely make the fatigued kicking performance more valid as the fatigue experienced is based on what physical workload players would be exposed to during a match. Kellis et al. (2006) found a significant decline in ball speed, angular velocity of the shank, angular position of the ankle and net and muscle moments on the shank.

While important technical information has been found for Australian Football kicking in previous research, nine of these have looked at kicking under fatigue. Given the high-intensity efforts and overall physical demands required of Australian Footballers, fatigue might be expected to influence kicking technique. Identifying if differences do exist under fatigue, and defining what these differences are, is vital in understanding the kicking motion. It is also important to identify if key technical factors differ in the fatigued kick, as findings from un-fatigued kicking might not be relevant. The following studies aimed to determine what the effect of fatigue is on Australian Football drop punt kicking technique before, during and after both short and long-term match-specific fatigue protocols. Study 1 looked at how short term fatigue, simulating a burst of activity in a match, affected kicking mechanics. Study 2 focussed on how longer term fatigue, accumulated throughout a simulated quarter of a match, affected kicking kinematics, while Study 3 concentrated on the kinetic kicking changes throughout a long-term protocol. Elite, sub-elite and junior Australian Football players were analysed and compared. It was expected that participants would display changes in their kicking technique post-fatigue.  These differences were thought to show up in changes in foot speed and shank angular velocity just before ball contact, and a possible redistribution of work to utilize the larger hip flexors in a fatigued state.

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# Chapter 2

# 2. Review of Literature

### 2. Kinematics of Kicking

Kicking is a fundamental skill in Australian Football. It is the most prevalent method of passing between players and the only method of scoring a goal. Effective long kicking is also significantly related to success (Forbes, 2003), and greater kicking distances allow for more passing options and shots at goal being able to be taken from further out (Ball, 2008).

The drop punt is the primary kicking technique used due to its accuracy and the ease of marking for the receiver (Ball, 2008; Orchard, Walt, McIntosh & Garlick, 1999). Basic skill development literature has qualitatively described the drop punt kicking technique in Australian Football in five phases (Parkin & Smith, 1984):

1) Grip and stance

    Firm grip with relaxed arms

    Elbows bent and close to body

    Laces of ball facing up

2) Approach

    Run in straight line towards target (when a very long kick is required it has been proposed that a slightly curved approach may be beneficial to allow for greater hip rotation and range of motion, but may hinder accuracy) (Baker & Ball, 1996)

    Ball held stationary over kicking leg

Eyes look ahead at target

3) Ball release

    Eyes look down and watch ball

    Ball guided down close to boot by one hand

    Opposite hand moves up, back and to the side to finish in a position level with the shoulders (Baker & Ball, 1996)

    Ball released when kicking foot is back and bent at the knee

4) Contact

    Knee of kicking leg moves through first, followed by the shank

    Knee is straight at impact

    Ball is kicked with top of foot

    Distance and elevation is determined by the height of ball contact with the foot

5) Follow-through

    Direction of kicking leg often indicates the accuracy of the kick

    Player lifts forward from the ground in the direction of the kick

Figure 1 shows the drop punt sequence. The general kicking technique consists of the coordination of multiple segments in a proximal to distal sequence in a kinematic chain (Dörge, et al., 1999). During the early phases of a drop punt most of the work is performed eccentrically by the proximal muscle groups which transfer momentum to the distal segments just prior to ball contact (Orchard et al., 1999). This allows the kicker to obtain high foot speeds through impact thus allowing greater momentum to be imparted on the ball resulting in the ball flying a greater distance through the air (Ball, 2008).

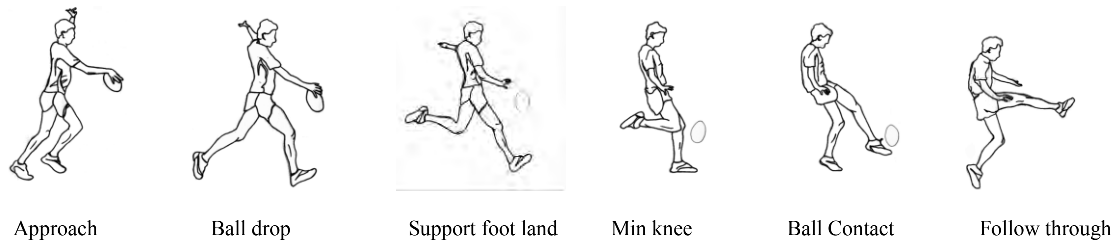


Figure 1: The Drop Punt Sequence (from Ball, 2008)

The basic kicking technique in soccer differs to the drop punt kicking technique in Australian Football. It is important to also review soccer kicking mechanics, as being a world game, there has been more research done on it than on Australian Football which is primarily played in Australia. Drop punt kicking in Australian Football requires kickers to drop the ball from their hands to their foot, while soccer kicking generally requires participants to kick the ball from the ground. The most representative of the kicking techniques used in soccer are the instep and side-foot kicks (Kawamoto, Miyagi, Ohashi & Fukashiro, 2007). The instep kick is usually used for long-distance shooting or passing as its main objective is to impart speed on the ball. The side-foot kick, where the medial side of the foot makes contact with the ball, is used for shorter shots and passes with its main objective being accuracy (Kawamoto et al., 2007). There have been many biomechanical studies undertaken on soccer kicking (Nunome, Lake, Georgakis & Stergioulas, 2006b; Davids, Lees & Burwitz, 2000; Egan, Verheul & Savelsbergh, 2007). Kicking is very important in soccer as it is used as a means of passing the ball about 300 times per match (Yamanaka, Liang & Hughes, 1997).

### 2.1.1 Foot and Ball Speed

#### 2.1.1.1 Foot and Ball Speed in Australian Football

Foot speed is an important performance measure of maximal kicking as a greater foot speed has been shown to correlate with a longer kicking distance. In an early study on elite Australian Footballer's, Macmillan (1975) reported foot speeds (23.3 to 23.7$m \cdot s^{-1}$), when subjects kicked for distance (average distance 47.4m). The corresponding ball velocity after contact ranged between 25$m \cdot s^{-1}$ and 27.2$m \cdot s^{-1}$, ($r = 0.63$ to $r = 0.91$). This worked out to be a ball:foot speed ratio of between 1.07 to 1.15. A similar ball:foot speed ratio of 1.16 ± 0.08 was found for junior Australian Footballer's kicking for maximal distance. Their foot (21.3 ± 1.3$m \cdot s^{-1}$) and ball speed (24.7 ± 2.1$m \cdot s^{-1}$) values (Ball, Smith & MacMahon, 2010) were lower than those reported by Macmillan (1975), however they were as could be expected with a younger participant group. In a study on elite Australian Football players Smith, Ball & MacMahon (2009) reported higher foot (26.5 ± 2.5$m \cdot s^{-1}$) and ball (32.6 ± 4.4$m \cdot s^{-1}$) speeds and a higher ball:foot speed ratio (1.23 ± 0.11). However, these values were higher than those reported by Macmillan (1975) and may be due to the author only studying three subjects and comparing three types of kicks, with one (stab kick) not used to attain maximal distance, therefore reducing the mean values reported. In each study, the higher the foot speeds reported, the higher the ball speeds reported.

As high foot speeds are associated with greater ball speeds, and the laws of physics dictate that release speed (ball speed) is one of the important factors in maximising the distance of a projectile (as demonstrated by Ball, 2008, who found a strong correlation between ball speed and kick distance, $r = 0.73$, $P = 0.001$), then high foot speed is also associated with longer kicking distance. When reporting on technical elements of distance kicking among elite Australian Football players, Ball (2008) found that when kicking for distance, foot speed ($26.4 \pm 1.2 m \cdot s^{-1}$) was the major contributor to kicking the ball further, with larger foot speeds being associated with longer distances (r = 0.68 with a likely range of r = 0.51 to 0.81, $P = 0.00$). These foot speed values were similar to those reported in the previous paragraph by Smith, Ball and MacMahon (2009) for a similar elite participant group. In another two-dimensional study that looked at distance drop punt kicking, this time using junior elite Australian Football players, differences in kinematics were determined between a longer kicking group (mean distance = 48.15m) and a shorter kicking group (mean distance = 43.2m). The longer kicking group displayed larger foot speeds at ball contact ($16.9 m \cdot s^{-1}$ vs $15.5 m \cdot s^{-1}$), however this was only significant at $P = 0.07$ (Baker & Ball, 1996). Ball (2008) found foot speed at ball contact to be almost 10m/s larger than the highest mean value reported by Baker and Ball (1996). The use of elite adult subjects by Ball (2008) may account for why the foot speed values were the greatest and the average distance kicked (61 ± 4m) was almost 13 metres longer than Baker and Ball's (1996) longer kicking group.

Several factors have been found to contribute to increasing foot speed. Ball (2008) found that shank angular velocity at ball contact ($1676 \pm 132° \cdot s^{-1}$) accounted for 13% of the variance in foot speed, and maximum hip linear velocity in the last stride before ball contact ($7.1 \pm 1.2 m \cdot s^{-1}$) accounted for 40% of the variance in foot speed. These were the major contributors to foot speed with larger values being associated with greater foot speeds. Macmillan (1975), in a less detailed article, described the velocity of the foot as a function of three variables: angular velocity of the knee, angular velocity of the thigh, and linear velocity of the body.

While not a study on maximal punt kicking, Ball (2011) found foot speed ($19.0 \pm 1.3 m \cdot s^{-1}$), knee ($1355 \pm 155° \cdot s^{-1}$) and shank ($1548 \pm 156° \cdot s^{-1}$) angular velocity at ball contact and sagittal pelvis range of motion ($47 \pm 7^{\circ}$) to be significantly larger for the preferred leg than the non-preferred leg when being instructed to kick 45m. Contrastingly, for the non-preferred leg, hip (138 ± 81°$\cdot s^{-1}$) and thigh (236 ± 91°$\cdot s^{-1}$) angular velocity at ball contact, and hip flexion/extension range of motion (40 ± 5°) were significantly larger, which demonstrated lower foot speeds (17.0 ± 1.4$m\cdot s^{-1}$). The decrease in foot speed for the non-preferred leg is as expected and as the authors reported could be due to the possibility of locking degrees of freedom or sub-optimal sequencing in the non-preferred leg, as indicated by the differences in movement patterns. The overall lower foot speeds reported in this study can be put down to the nature of the task, with participants being instructed to perform sub-maximal kicks. Although not a maximal kicking task and no correlations between foot speed and other kicking variables were reported, the increased reliance on the pelvis, knee and shank for the preferred foot, may be an indication that these segments and joint are important in maximising foot speed.

#### 2.1.1.2 Foot and Ball Speed in Soccer and Kicking Sports

Foot speeds have also been reported in soccer research. In a review on the published literature of the biomechanics of soccer, Lees and Nolan (1998) found mean values of maximal speed of the foot segment at impact to range from 18 to 28$m\cdot s^{-1}$. Later research found preferred foot speed values to also fall within this range (18.6$m\cdot s^{-1}$, Dörge, H., Bull-Andersen, Sorensen & Simonsen, 2002; 23.8$m\cdot s^{-1}$, Nunome, Ikegami, Kozakai, Apriantono & Sano, 2006a). However, Egan et al. (2007) reported maximum average foot velocities for experienced soccer players to be lower (14.5 ± 2.7$m\cdot s^{-1}$), likely due to participants being instructed to use a two-step approach and to kick at a target. Overall these values (14.5 to 28$m\cdot s^{-1}$) are similar to those reported for Australian Football kicking (15.5 to 26.5$m\cdot s^{-1}$).

Ball speed has also been used as an indicator of kicking success in soccer research. Lees and Nolan (1998) found that studies reported mean maximal ball speeds for adult male players to range between 20 to 30 m·s$^{-1}$. Nunome et al. (2006b) also found values for maximal instep kicking fell between this range (26.6 ± 3.4m·s$^{-1}$), as did Dörge et al. (2002) (24.7 ± 2.5m·s$^{-1}$), Lees, Kershaw & Moura (2004) (24.5 ± 1.39m·s$^{-1}$), and Luhtanen (1988) (22.2 ± 2.3m·s$^{-1}$). Nunome et al. (2006a) reported slightly higher preferred-foot ball velocities (32.1m·s$^{-1}$) for highly skilled club players when they were performing maximal instep kicks at a goal positioned 10m away. Opavsky (1988) found that running kicks (30.78m·s$^{-1}$) produced higher ball speeds than standing kicks (23.48m·s$^{-1}$). These values (20 to 32.1m·s$^{-1}$) are again very comparable to Australian Football maximal kicking ball speed data (24.7 to 32.6m·s$^{-1}$).

Quantitative research on kicking and punting in NFL football has been very limited, but some ball speed data has been reported. In a study on kicking, where the kicker attempts to kick a stationary ball through goals, Zebas & Nelson (1990), reported ball speeds of 33.9, 36.8 and 35.6m·s$^{-1}$ for kicking a ball at a goal positioned 18.8, 27.27 and 45.45m away. The reason for the consistency in the ball speeds across the different trials was concluded to be due to the same ball trajectory being sufficient to meet the task constraints in each condition. Therefore, there was no need to reduce the speed for shorter distances, or at least the kicker chose not to reduce speed when they could have. This showed that the performer, a single subject, relied highly on a stable kicking coordination pattern. The single participant also produced higher foot speeds than Australian Football kickers and soccer players.

For the instep kick in soccer, Lees and Nolan (1998) reported ball:foot ratios ranging between 1.06 (Asami & Nolte, 1983) and 1.35 (Nunome et al, 2006a), but can increase up to 1.5 for kicks that use different parts of the foot, such as the side-foot kick

(Aitcheson & Lees, 1983). However, these results can also vary due to which part of the foot the researcher uses to calculate the values. As it is often unclear whether the researcher has used the toe, the centre of mass of the foot or the ankle, these results should be interpreted with caution (Lees & Nolan, 1998). Using a modified version of a time-frequency filtering algorithm (WGN), Nunome et al. (2006b) found a ball:foot ratio of 1.35 ± 0.09. The same data set produced different values, ranging between 1.34 ± 0.09 and 1.66 ± 0.13, when different data-processing techniques were used. The Australian Football kicking ball:foot speed ratios (1.07 to 1.23) fall between those reported for soccer kicking (1.06 to 1.5).

### 2.1.2 Kick Leg Mechanics

#### 2.1.2.1 Angular Kinematics

Research into leg joint and segment movements during kicking is crucial in order to identify what mechanics are associated with creating high foot speeds near impact. Leg mechanics have been examined by comparing groups and, as previously reported, through correlation/regression analysis to identify important technical components associated with longer distance kicking.

##### 2.1.2.1.1 Angular Displacement in Australian Football Kicking

Some Australian Football kicking studies have reported segmental position values. At the top of the backswing, longer kickers have been shown to display shank positions 18° above the horizontal, with a knee angle of 102°, compared to 7° for shorter kickers, with a knee angle of 112° (Baker & Ball, 1996). At impact the thigh has been reported as being 60° behind the vertical and the shank 30° from the vertical (Baker & Ball, 1996). Thigh

(137° ± 7°) and shank (97° ± 5°) angles at ball contact relative to the horizontal were also reported by Ball (2008). More inaccurate kickers had greater posterior pelvic tilt at ball contact (accurate -12.8 ± 4.2°, inaccurate 16.1 ± 2.3°) than more accurate kickers in a 15m kicking test study, however the differences at ball contact were not significant (Dichiera, Webster, Kuilboer, Morris, Bach & Feller, 2006). It is difficult to read a lot into these differences as the more accurate group demonstrated 5° greater anterior pelvic tilt whilst standing. Range of motion values were 33.6° for the accurate group and 28.8° for the inaccurate group from the instant the support heel hit the ground, until ball contact (Dichiera et al., 2006). Ball (2011) reported sagittal pelvic angles of 31 ± 10° (posterior pelvic tilt) and transverse pelvic angles of 4 ± 3° (kick side of pelvis more anterior) at ball contact, and sagittal pelvic range of motion of 47 ± 9° for the preferred leg during from kicking leg toe-off until ball contact for participants instructed 45m kicking into a net. These greater range of motion values are expected as the nature of the task (45m vs 15m) requires a longer kick, and greater pelvic range of motion has been reported to lead to greater foot speed in soccer kicking (Lees & Nolan, 2002).

Most Australian Football displacement data has been reported as joint angles, in particular focussing on the knee. At impact ankle angles have been reported at 140°, and knee angles of 150° for longer and shorter kickers. Although the knee was 30° from being straight, it was extending through impact. If the knee were fully extended at impact it would have meant the speed of the lower limbs would have been significantly decreased and that there would also have been an increased chance of injury through possible hyper-extension of the joint (Baker & Ball, 1996). Ball (2008) reported smaller knee (139° ± 7°) and similar hip angles (154° ± 10°) at impact. Although not significant, Dichiera et al. (2006) reported a trend towards greater kicking leg knee flexion (accurate 62 ± 6.2°, inaccurate 55.8 ± 7.3°) in a more accurate group when participants were instructed to hit a target 15m away. Participants appeared to adopt a more flexed knee in order to clear the toe for kicking as there was also more flexion reported in the support limb (Dichiera et al., 2006). During the forward swing phase, Baker and Ball (1996) found the longer kicking group displayed smaller minimum knee angles (64° vs 69°) than the shorter kicking group (Baker & Ball, 1996). The knee flexion (69.1° ± 17.6°) values found at maximum hip extension (Young, Clothier, Otago, Bruce & Liddell, 2003), and the minimum knee angle (65° ± 7°) found by Ball (2008) fall between the range of the short and long kickers. The biomechanical advantage of the smaller minimum knee angle being a reduced moment of inertia about the hip, leading to enhanced rotation (Baker & Ball, 1996).

Hip angles have also been reported in some Australian Football kicking research. For the 15m passing task, Dichiera et al. (2006), found that more accurate kickers displayed greater hip flexion at ball contact ($P < 0.05$, accurate 36.3 ± 4.7°, less accurate 29.5 ± 2.1°), where hip flexion was also at its maximum. Ball (2008) reported maximal hip angles of 216 ± 16°, but these were higher than those reported at ball contact, 154 ± 10°, for the same study. The overall differences in hip flexion values between the two studies can be attributed to the differences in the requirements of the task. It appears as though kicking for distance requires the hip to flex much more and remain more flexed at ball contact than when kicking over a short distance. There may also be a difference in the definition of the angles as Ball (2008) reported the hip angle to be the angle between the thigh and trunk on the anterior aspect of the player, whilst Dichiera et al. (2006) reported 'rotations around the flexion-extension axes'.

#### 2.1.2.1.2 Angular Displacement in Soccer Kicking

Some angular displacement data has also been reported in the soccer research. Impact values were reported by Kellis, Katis & Vrabas (2006) for the hip (190.5 ± 16.7°) and knee (130.3 ± 13.7°). These angles are higher at the hip and lower at the knee than those previously reported for Australian Football kicking at ball contact. Kicking a ball from the ground appears to require a more vertical hip angle, and subsequently a greater knee bend at impact than when dropping a ball onto the foot in punt kicking. Soccer research has also reported some range of motion data. Shan & Westerhoff (2005) found both hip and knee flexion-extension (hip 130 ± 10°, knee 108 ± 8°), abduction-adduction (hip 23 ± 4°, knee 12 ± 3°) and rotation (hip 17 ± 3°, knee 17 ± 7°) range of motion values for experienced male participants during the kick step. Using a two-step approach and kicking at a target, Egan et al. (2007) reported an average hip range of motion of 53.3 ± 14.4° and knee range of motion of 74.2 ± 12.6° for experienced soccer players. Peak positional values have also been reported. Kawamoto et al. (2007), found peak values for experienced soccer players whilst doing a side-foot kick (hip extension 15.6 ± 8.7°, hip abduction 35.5 ± 6.0°, hip external rotation 17.8 ± 13.6°, knee flexion 99.2 ± 9.6° and ankle dorsiflexion 17.5 ± 8.6°).

#### 2.1.2.1.3 Angular Velocity in Australian Football Kicking

Angular velocities of joints and segments have also been reported in the Australian Football kicking literature. The product of the angular velocity and radius of rotation of the consecutive body segments, and linear velocity of the hip joint, is directly proportional to the centre of mass of the rotating foot (Dörge, et al., 2002). A large angular velocity of the shank generates a high foot speed which is important for the impact and ball release during a kick.

Knee angular velocity values have been reported in Australian Football kicking literature as the extension velocity of the knee has great influence on the shank and foot. Macmillan (1975) reported knee angular velocity (1532°·s$^{-1}$ to 2009°·s$^{-1}$) to be the major determinant of linear foot velocity (r = 0.82 to r = 0.94). Maximal knee angular velocity (1485 ± 258°·s$^{-1}$) and time to maximal knee angular velocity (0.008s ± 0.005s) were reported by Ball (2008), along with knee angular velocity at impact of 1364 ± 253°·s$^{-1}$. Ball (2011) also reported preferred foot (1355 ± 155°·s$^{-1}$) and non-preferred foot (1126 ± 201°·s$^{-1}$) knee angular velocity at impact. These values were slightly lower than Ball (2008) as they were for a 45m kick as opposed to a maximal kick.

Some hip angular velocity values have also been reported, and have been found to be far smaller than the values at the knee. Ball (2011) reported hip angular velocities to be 56 ± 65°·s$^{-1}$ at impact and 522 ± 243°·s$^{-1}$ maximally for the preferred leg and 138 ± 81°·s$^{-1}$ at impact and 442 ± 75°·s$^{-1}$ maximally for the non-preferred during a 45m kick. Whilst the hip values are much smaller than those at the knee, it is interesting to note that the knee values were smaller for the non-preferred foot at the knee and larger at the hip for the same foot at impact. This gives rise to the possibility of an altered kicking pattern through a greater hip reliance for the non-preferred foot. Ball (2008) did not report hip angular velocity, but did report hip linear velocity (5 ± 1.5m·s$^{-1}$) at impact, along with maximal hip linear velocity (7.1 ± 1.2m·s$^{-1}$). Maximum hip linear velocity accounted for 40% of the variance of foot speed (Ball, 2008).

Segmental velocities, namely the thigh and shank, have also been reported. During the forward swing phase longer kicking groups have displayed greater maximum thigh angular velocity than shorter kicking groups (973°·s$^{-1}$ vs 907°·s$^{-1}$) (Baker & Ball, 1996). Ball (2008) reported thigh angular velocities at impact of 313 ± 185°·s$^{-1}$, whilst Ball (2011) found them to be 158 ± 91°·s$^{-1}$ for the preferred leg and 236 ± 111°·s$^{-1}$ for the non-preferred leg at impact, again the values being lower than those from a maximal kick. This decrease from maximal thigh angular velocity, to the values reported at impact, coincides with an increase in the angular velocity of the shank in the latter parts of the kicking motion, and is consistent with the transference of energy principle, allowing for high end point speed at impact (Putnam, 1991).

Similar to the knee and hip, the lower segment, the shank, has been reported to have higher angular velocities than those found at the higher segment, thigh. Ball (2008) reported shank angular velocity at impact (1676 ± 132°·s$^{-1}$) and found it to be the second most strongly correlated parameter with distance (medium effect size with likely range of r = 0.31 to r = 0.75), behind foot speed. At ball contact longer kicking groups have been found to display larger shank angular velocities (1554°·s$^{-1}$ vs 1405°·s$^{-1}$) and knee angular velocities (1540°·s$^{-1}$ vs 1390°·s$^{-1}$) than shorter kicking groups. The greater shank angular velocities in the longer kicking group were thought to be in part due to the smaller moment of inertia of the thigh/leg structure at the hip due to a smaller minimum knee angle during the forward swing (Baker & Ball, 1996).

Whilst the kicking motion is initiated higher up the chain where the hip and thigh move slower, transfers momentum down the chain to the faster moving knee and shank, and ends with high foot speed at impact, interestingly the magnitude of this transfer of momentum down the chain varies. Ball (2008) reported that larger shank angular velocities and foot speeds were sometimes accompanied by smaller knee velocities. A large negative effect between knee angular velocity and thigh angular velocity at ball contact was found (r = -0.90, $P < 0.001$), suggesting some players used a thigh strategy (higher thigh angular velocity and relatively lower knee angular velocity) and others a knee strategy (higher knee angular velocity and lower thigh angular velocity) to gain greatest ball distance.

#### 2.1.2.1.4 Angular Velocity in Soccer Kicking

Studies on soccer kicking have widely recorded angular velocities of segments and to a lesser extent joints. In a review of soccer kicking literature, Kellis & Katis (2007) reported maximum knee extension velocities to range between 1014°·s$^{-1}$ (for participants 4.4 years of age; Elliott, 1980) to 1874 ± 155°·s$^{-1}$ (Manolpoulos, Papadopoulos & Kellis, 2006). All reported knee extension velocities for Australian Football fell within these ranges. Kawamoto et al. (2007), reported maximal joint angular velocity values for experienced soccer players whilst doing a side-foot kick (hip flexion 13.8 ± 1.8rad·s$^{-1}$ (790 ± 103°·s$^{-1}$), hip adduction 5.5 ± 1.8rad·s$^{-1}$ (315 ± 103°·s$^{-1}$), hip external rotation 1.5 ± 0.4rad·s$^{-1}$ (86 ± 23°·s$^{-1}$) and knee extension 16.6 ± 2.0rad·s$^{-1}$ (951 ± 115°·s$^{-1}$)). Hip angular velocity at impact was reported to be 126 ± 52°·s$^{-1}$ by Kellis et al. (2006). As was found in Australian Football kicking, knee values were higher than those at the hip, however the hip appears to flex with much greater velocity in soccer kicking than Australian Football drop punt kicking.

Linear segmental velocities for soccer research have also been reported. Nunome et al. (2006b) reported toe (22.2 ± 2.2m·s$^{-1}$), ankle (16.9 ± 1.8m·s$^{-1}$) and knee (4.8 ± 0.9m·s$^{-1}$) velocities at ball impact, using the WGN processing method. Lees et al. (2004) reported toe (16.1±1.2m.s$^{-1}$), ankle (13.8±8.9m.s$^{-1}$), and knee (8.9±0.4m.s$^{-1}$) linear velocities, but did not state if these were maximal or impact values, therefore possibly accounting for the difference in values found by Nunome (2006b). The sequence of linear velocity values found in both studies is the same however, with the highest values found lower down the chain, at the toe, corresponding with high endpoint speed.

Similar to Australian Football kicking, the thigh has been reported to display higher angular velocities than the shank. Nunome et al. (2006a) found forward angular velocity of the thigh continuously increased and reached its peak (18.3 ± 15rad·$s^{-1}$ (1049 ± 859°·$s^{-1}$)) during the later part of the kick (73.6 ± 2.9%), after which it rapidly decreased during the final phases of kicking, and even displays backward angular velocity.

The lower leg motion was started by its backward rotation and reached its peak backward angular velocity during the early part of the kick (21.5 ± 4.7%). Then forward rotation was initiated around the midpoint (55.0 ± 2.1%) of the kick, and increased continuously until ball impact or immediately before ball impact where it was at its maximum (39.4 ± 4.3 rad·$s^{-1}$ (2257 ± 246°·$s^{-1}$)) (Nunome et al., 2006a). Nunome et al. (2006b) reported slightly lower maximal shank angular velocities of 36.0 ± 4.6 rad·$s^{-1}$ (2063 ± 264°·$s^{-1}$) while Dörge et al. (1999) reported even lower maximal shank angular velocity values of 31.7rad·$s^{-1}$ (1816°·$s^{-1}$). The thigh, and particularly shank, appear to move faster in a soccer kick than an Australian Football kick.

### 2.1.3 Support Leg Mechanics

#### 2.1.3.1 Support Leg Mechanics in Australian Football Kicking

Although not as prevalent, there has been some support leg data reported in Australian Football kicking research. In a study focussing on load leg mechanics during the stance phase of a maximal punt kick, Ball (2013) found a more extended support leg (support leg knee angle at support leg foot strike, 24° flexion, r = -0.73, *P* = 0.004, maximal support leg knee flexion, 50° flexion, r = -0.71, *P* = 0.006). The author also found larger peak vertical (Fz max (3.0 ± 0.3BW for preferred and 3.1 ± 0.4BW for non-preferred foot kicks) r = 0.69, *P* = 0.019) and braking force (Fy max braking (1.0 ± 0.1BW for preferred and 1.0 ± 0.1BW for non-preferred foot kicks) r = 0.68, *P* = 0.044) during the stance phase and shorter stance contact time (0.27 ± 0.06s for preferred and 0.28 ± 0.07s for non-preferred foot kicks, r = -0.71, *P* = 0.006) to be associated with kick leg foot speed at ball contact. It was concluded that a straighter support leg, with less ground contact time and strong braking forces should be encouraged to maximise foot speed and kicking distance. Further to this, Dichiera et al. (2006) found that a more flexed support leg knee at ball contact (*P* < .05, accuracy group 31.9 ± 5.9°, less accurate group 21.1 ± 5°) and a more flexed hip at ball contact (*P* < .05, accuracy group 7.7 ± 3.3°, less accurate group 2.7 ± 2.3°) was associated with greater kicking accuracy over 15m. The support leg therefore appears to influence both distance and accuracy, with a straighter leg being more beneficial for maximal kicking distances.

#### 2.1.3.2 Support Leg Mechanics in Soccer Kicking

Similar support leg data has been reported in soccer kicking research. Kellis, Katis & Gissis (2004) reported shorter ground contact times (between 170 ± 36ms and 195 ± 40ms), smaller vertical ground reaction forces (between 2.23 ± 0.25BW and 2.07 ± 0.18BW), and smaller braking forces (anterior ground reaction forces between 0.73 ± 0.17BW and 0.55 ± 0.06BW, posterior ground reaction forces between 0.39 ± 0.03BW and 0.59 ± 0.12BW) for soccer kicks with different approach angles between 0 and 90° as compared to Australian Football kicking. Although contact time on the ground is longer, peak forces also appears to be higher for the support leg in Australian Football kicking than in soccer kicking.

### 2.2 Kinetics of Kicking

Kinetics play an important role in kicking as they determine what causes the kinematics observed in the skill's technique. The sum of the forces (moment) acting on the joint determines the change of movement (angular velocity) of the joint. These forces can be divided into the net moment produced by muscles acting on the joint (muscle moment) and the net moment produced by external forces (external moment), such as gravity and ground reaction forces (Orchard, McIntosh, Landeo, Savage & Beatty, 2003).

#### 2.2.1 Kinetics of Kicking in Australian Football

There has not been any published kinetic data on kicking in Australian Football, although some research has been undertaken. Orchard et al. (2003) discussed kinetic data when reporting the implications for quadricep strain injuries when kicking in Australian Football, but failed in include quantitative values. In an unpublished honours thesis, Ilich (2004) looked at kinematic and kinetic variables and how they compared between a distance and an accuracy drop punt kick. During the approach phase (from heel strike of kicking leg in the stride before impact to heel strike of support leg) of a distance kick, Ilich (2004) reported kinetic values listed in Table 2:

Table 2

| Variable | Min | Max | Range | SD |
|---|---|---|---|---|
| Right Hip Flex/Ext Moment (N·m) | -222.2 | 146.4 | 368.6 | 54.5 |
| Right Knee Flex/Ext Moment (N·m) | -42.6 | 54.0 | 96.6 | 5.0 |
| Right Ankle Plant/Dorsi Flexion Moment (N·m) | -9.1 | 5.2 | 14.3 | 1.7 |
| Right Hip Power (W) | -5.0 | 8.0 | 13.1 | 2.8 |
| Right Knee Power (W) | -6.7 | 1.5 | 8.2 | 1.6 |
| Right Ankle Power (W) | -0.3 | 0.7 | 1.0 | 0.2 |

These results show that greatest peak joint moment and power values were achieved at the hip, followed by the knee, then ankle. The positive values represent power generation (concentric muscle activity) and negative values represent energy absorption (eccentric contractions). In the swing phase of the distance kick (Table 3), Ilich (2004) found a similar sequence, with the ankle being the main energy absorber, followed by the knee, then hip. During the swing phase (from heel strike of the support leg to ball contact) of a distance kick, Ilich (2004) reported kinetic values listed in Table 3:

Table 3

| Variable | Min | Max | Range | SD Range |
|---|---|---|---|---|
| Right Hip Flex/Ext Moment (N·m) | -182.5 | 173 | 355.5 | 246.5 |
| Right Knee Flex/Ext Moment (N·m) | -87.6 | 83.5 | 171 | 108.8 |
| Right Ankle Plant/Dorsi Flexion Moment (N·m) | -73.6 | 14.7 | 88.3 | 189.5 |
| Right Hip Power (W) | -2.7 | 16.7 | 19.4 | 22.7 |
| Right Knee Power (W) | -8.7 | 1.9 | 10.6 | 4 |
| Right Ankle Power (W) | -9.9 | 0.9 | 10.8 | 24 |

The hip was the dominant source of energy in both the approach (Table 2) and swing (Table 3) phases of the distance kick, followed by knee, then ankle. Illich (2004) also found that at the time when the hip was generating this mechanical energy, the knee was acting as an energy absorber, acting eccentrically to control leg extension (during the forward swing). Once the hip power had peaked, knee power then became positive, indicating the proximal to distal flow of mechanical energy towards impact.

### 2.2.2 Kinetics of Kicking in Soccer

#### 2.2.2.1 Net Muscle Moments

Several soccer studies have reported kinetics of an instep kick or of similar maximal soccer kicks (Kawamoto et al., 2007; Lees & Nolan, 1998; Dörge et al., 1999; Dörge et al., 2002; Nunome et al., 2006a; Luthanen, 1988). As a means of indicating the net muscular effort generated during the kick some studies used kinematic data to estimate the net muscle moments around the joints (Lees & Nolan, 1998). Dörge et al., 2002 used Winter's (1990) inverse dynamics method starting at the ankle (the open end), to calculate the muscle moment about the hip and knee joints and the motion-dependent joint reaction forces acting as moments on the shank. The general trend in the research shows highest net muscle moments around the hip, followed by the knee, and finishing lowest at the ankle. Net muscle moments have been reported by Lees & Nolan (1998) as high as 300N·m at the hip, 160N·m about the knee (Putnam, 1983), and 30N·m about the ankle (Zernicke & Roberts, 1978). In a study on national level players, Robertson & Mosher (1985) reported hip moments of 220N·m and knee moments of 90N·m (Lees & Nolan, 1998). Luhtanen (1988) reported maximal moments of the forces at the hip (61 ± 15N·m), knee (25 ± 11N·m), and ankle (7 ± 2N·m), that were much lower than those reported in the same study for 9-11 year olds (hip 194 ± 33N·m, knee 83 ± 21N·m, ankle 20 ± 4N·m).

#### 2.2.2.2 Peak Joint Torques

The trend of largest values at the hip was also seen with peak joint torque values. For experienced soccer players performing a side-foot kick, Kawamoto et al. (2007) reported hip flexion (168 ± 20N·m), hip adduction (100 ± 39N·m), hip external rotation (41 ± 9N·m), knee extension (32 ± 7N·m) and ankle dorsiflexion (10 ± 1N·m). Dörge, et al., (1999) reported higher values for skilled soccer players performing a maximal place kick and found average peak hip muscle torques of 271.3N·m and average peak knee muscle torques of 161N·m. Nunome, Asai, Ikegami & Sakurai (2002) reported peak joint torque values for high school soccer players performing an instep kick (hip flexion 249 ± 31N·m, hip adduction 115 ± 17N·m, hip external rotation 33 ± 8N·m, knee extension 98 ± 27N·m) and a side foot kick (hip flexion 231 ± 38N·m, hip adduction 129 ± 23N·m, hip external rotation 56 ± 12N·m, knee extension 80 ± 7N·m). The previously reported Australian Football drop punt peak hip flexion moment values (173N·m) and peak knee extension values (83.5N·m) (Ilich, 2004), are within the ranges of those reported in the soccer kicking research.

### 2.2.2.3 Timing of Net and Peak Joint Torques

The timing of net and peak moments have also been reported in some soccer kicking literature. Net muscle torques have been found to be positive during almost the entire period of a soccer place kick, indicating hip flexor and knee extensor dominance. Peak torque has been used in research as a measure of strength (Rahnama, Reilly, Lees & Graham-Smith, 2003). The average hip peak muscle torque has been observed in the period of knee extension, whilst the average knee peak muscle torque was observed just before the beginning of knee extension (Dörge, et al., 1999). Based on muscle force and moment data, Dörge et al. (2002) concluded that the net positive muscle moments about the hip and knee joints throughout most of the kicking motion were a product of the muscle forces. These positive muscle moments of force were trying to flex the hip joint and extend the knee joint. Other research has shown that just before impact, negative muscle moments have been observed (Lees & Nolan, 1998). Just before impact the negative muscle moment about the knee joint was thought to be caused by the gastrocnemius muscle when the ankle was extended. At the same time there was also negative rotational acceleration about the hip joint. It was concluded that these negative muscle moments did not help increase the angular velocity of the shank, but acted as a safety mechanism to protect the joints from injury (Dörge et al., 2002).

The timing of the peak joint and net muscle moments has also yielded some mixed results with Luhtanen (1988) finding the peak hip moment to occur before the peak knee moment, whereas Putnam (1983) found the peak knee moment to occur before the peak hip moment. As reported earlier, in a study comparing the side-foot soccer kicking technique, Kawamoto et al. (2007) found that the mean foot and ball speed of the experienced group was significantly faster as compared to the inexperienced group. This was concluded to be most noticeably due to their ability to generate greater hip flexion torque throughout the backswing phase. Kawamoto et al. (2007) concluded that to increase ball velocity it is crucial to maximise the generation of hip flexion torque during the early stage of kicking. As a mature kicking action requires the thigh is brought forward while the knee is still flexing, this action stretches the extensor muscles of the thigh before they are required to shorten and aid in the generation of large end-point speed (Bober, Putnam & Woodworth, 1987; Manolopoulos et al., 2006). This phenomenon is known as the stretch-shorten cycle. Nunome et al. (2006a), also found that the forward hip muscle moment (309 ± 29N·m) was the largest for the moments related to thigh motion and reached its peak before maximal thigh angular velocity (the net moment of the thigh reached its peak almost simultaneously). The forward hip muscle moment then rapidly decreased towards ball impact. In nine reported cases the hip muscle moment had a small forward or backward value at impact, in three cases there was a noticeable backward moment before impact. The negative (backward) angular acceleration of the proximal segment (thigh) has been proposed to increase the positive (forward) angular acceleration of the adjoining distal segment (shank) (Nunome at al., 2006a). Some research points to this deceleration of the thigh being due to the actions of a hip extensor moment (Luhtanen, 1988), whilst others found no hip extension moment and have suggested the thigh deceleration is due to the knee extension moment acting reversely on the thigh (Nunome et al., 2006a). Nunome et al. (2006a) also reported that for the shank the forward knee muscle moment (130 ± 26N·m) was the largest moment, and reached its maximum value before maximal thigh angular velocity was reached. This occurred at almost the same time as that of the net moment of the shank. The forward knee muscle moment then rapidly decreased and began to display a small backward moment immediately before ball impact, speculated to be due to the resistance of the muscular system when it is forced to be stretched. Data in relation to the timing of some of the peak moments in soccer kicking is variable, however most research points to the peak hip moment to occur before the peak knee moment.

For Australian Football kicking, Ilich (2004) found similar timing of peak joint torques to most of the soccer research. The hip was shown to exhibit the dominant power, the knee absorbing mechanical energy, then becoming positive once hip power had peaked, indicating the proximal to distal flow of mechanical energy towards impact. It should be kept in mind that these results were never published. However, they do indicate a similar pattern to most of the soccer research.

#### 2.2.2.4 Rate of Force Development

Isokinetic dynamometers have also been used in research to attempt to determine how the rate of force development is related to the kicking action. Dörge et al. (2002) used a Kin-Com dynamometer to measure the rate of force development after 10, 20 and 30ms for the knee extension (2470 ± 823N·$s^{-1}$, 3280 ± 1020N·$s^{-1}$, 3890 ± 1100N·$s^{-1}$) and hip flexion (1950 ± 623N·$s^{-1}$, 2850 ± 1050N·$s^{-1}$, 4440 ± 1170N·$s^{-1}$) of skilled soccer players. The authors chose these intervals as the rise in muscular moments was seen within the first 30ms of the concentric contraction during the kick. However, the angular velocity of the knee is up to 35 rad·$s^{-1}$, which is much higher than any isokinetic device is able to achieve (Dörge et al., 2002).

#### 2.2.2.5 Timing of Muscle Activation

While estimating which muscle groups play a role in kicking has been reported through calculating net muscle torques about the joints, the specific temporal activity of muscle groups has been researched through studying electromyography (EMG) recording (Dörge et al., 1999).

##### 2.2.2.5.1 Timing of Muscle Activation in Australian Football

There has not been an abundance of studies that have focussed on the kinetics or EMG of the Australian Football kicking technique. In the only published study that recorded EMG during an Australian Football kick, Orchard et al. (1999) looked at the bilateral quadriceps, hamstrings and gluteals of both legs, along with the rectus abdominus of four professional Australian Football players, and qualitatively compared the muscle activation to lower body kinematics. Players were instructed to run in (six to eight steps) and kick the ball at an imaginary target 40m in front of them. The authors expressed muscle activity as a percentage of the maximum value recorded (not reported) at any of the six stages of the kick. The quadriceps of the kicking leg acted eccentrically in the wind-up phase ($\approx 52 \pm 9\%$), then concentrically in the forward swing ($\approx 31 \pm 9\%$), and were the most active group studied. The hamstrings of the kicking leg acted concentrically to initiate the backswing ($\approx 40 \pm 8\%$) and showed variable eccentric activity during the follow through ($\approx 20 \pm 18\%$), where two subjects showed minimal activity and the other two showed significant eccentric activity. This eccentric activity may also be a safety mechanism to protect the joints from injury, as was proposed by Dörge et al. (2002) when analysing negative muscle moments towards the end of the kick. It was concluded that the high activity in quadriceps of the kicking leg, gluteals of the stance leg, both hamstrings and rectus abdominus assist in explaining the high rates of muscular injury in Australian Football (Orchard et al., 1999).

#### 2.2.2.5.1.1 Link of Timing of Muscle Activation to Injury

Muscle activation has been speculated to be linked to injury during kicking. Hamstring strains, knee injuries and groin injuries are the most common injuries in Australian Football, with hamstring, quadriceps and groin injuries occurring more commonly than in Australia's other football codes (Orchard, Wood, Seward & Broad, 1998; Orchard et al., 1999). Repetitive loads in kicking and relatively long game durations have been proposed as two of the possible factors that may explain the comparatively higher incidences of hamstring and groin injuries. Kicking has been proposed to almost certainly increase the rate of quadriceps strain. Any study that looks at the major lower limb muscles during kicking should be able to give an insight into the injury patterns in Australian Football and could lead to injury prevention (Orchard et al., 1999).

#### 2.2.2.5.2 Timing of Muscle Activation in Soccer

There has also been a limited amount of EMG research done on soccer kicking. Dörge et al. (1999) studied EMG activity of five kicking leg muscles (m. gluteus maximus, m. vastus lateralis, m. rectus femoris, m. biceps femoris and iliopsoas) and how it compared to the kinetics of the kicking leg during a soccer place kick. The results showed there to be a clear proximal to distal segmental motion, a sequence also followed with the EMG patterns, expressed as % of maximal EMG amplitude from maximal voluntary contractions, recorded from the muscles (normalising EMG values a percentage of maximum isometric activity (MVC) has been used in non-kicking soccer research)

(Gissis, Nikolaidis, Sotiropoulos & Papadopoulos, 2004). This sequence started with activation of the m. iliopsoas (which was active during the entire motion), followed by the rectus femoris, then the vastus lateralis. The activity of these muscles was often close to 100%. Leading up to impact, in the period when the angular velocity of the thigh was positive, the activity of the m. Iliopsoas averaged 79.4% (peak 98.3% (80.0-121.1%)), m. rectus femoris averaged 46.3% (peak 93.7% (79.1-99.9%)). There was smaller activity in the m. biceps femoris at 22.6% (peak 40.1% just before impact) and m. gluteus maximus at 10.2% (peak 27.1% just before impact) during the same period. In a period of knee extension the activity of the m. vastus lateralis was 81.7% (peak 101.6% (91.6-112.3%)) (Dörge et al., 1999). The net muscle torques about the hip and knee were positive during almost the entire time. EMG peaks for the iliopsoas and rectus femoris muscles coincided with the peak net muscle torque about the hip joint. Following the peak net muscle torque about the hip joint, there was an observed smaller peak net muscle torque around the knee joint. This peak coincided with the EMG peak from the rectus femoris and with an increase in activity from the vastus lateralis. A decrease, followed by another increase in net muscle torques at the hip and knee joint respectively was then observed, almost repeating the prior peak muscle torque pattern. The second torque pattern was thought to be due to a decrease in the activity of the biceps femoris. A rapid decrease in net muscle torque just before impact followed and was thought to be due to an increased activation of the biceps femoris and gluteus maximus. However, there was only a slight torque reversal around the hip just before impact, with angular deceleration of the thigh failing to increase the angular velocity of the shank (work -3.57 to 0.0%). Therefore no positive work on the shank was observed from a deceleration of the thigh. The positive work on the shank originated from the net extensor torque about the knee joint and the torque produced by the centripetal force (circular movement) of the thigh. The hip flexor muscles, including the m. iliopsoas, were activated even during the deceleration of the thigh, and as concluded it thus indicates the importance of maintaining angular velocity of the thigh during the motion, and therefore performing work on the shank (Dörge et al., 1999).

Another study by Manolopoulos et al. (2006) looked specifically at EMG activity of the rectus femoris (RF), vastus medialis (VM) and the long head of the biceps femoris (BF) of the kicking leg, and the rectus femoris, biceps femoris and medial head of the gastrocnemius of the support leg of amateur players performing a soccer instep kick. Similar to Orchard et al. (1999), but in contrast to Dörge et al. (1999), the EMG measurements were normalised by dividing the data by the maximum EMG of each muscle during each kick. Participants were divided into two groups, with one group to act as the control group (n = 10) and the other an experimental group which was given a training program (n = 10). The pre training results from the kicking leg of the experimental group are presented next. EMG activity was recorded during three phases. These results were recorded from the start of the movement to the contact of the support leg on the ground (RF 47.8 ± 17.4%, BF 38.9 ± 23.9%, VM 33.1 ± 13.7%), from ground contact of the support leg until the smallest knee angle of the kicking leg (RF 85.5 ± 20.5%, BF 40.1 ± 20.3%, VM 66.9 ± 16.5%), and from the smallest angle of the kicking leg until ball contact (RF 59.1 ± 27.5%, BF 54.1 ± 27.2%, VM 54.4 ± 14.0%). These RF values were slightly more (12.8% more), whilst the BF was much higher (31.5% more) than the pre-impact Australian Football kicking values reported by Dörge et al. (1999). Results reported by Manolopoulos et al. (2006) indicated that the activation patterns of the muscles examined were not significantly affected by the training program. The exception was the vastus medialis which displayed significantly higher activity in the latter stage of the kick for the experimental group (before 54.4 ± 14.0%, after 70.8 ± 15.6%). This indicates that higher force may be produced during this phase for the experimental group.

However, as the authors point out, the contribution of the vastus medialis to knee extension muscle torque is unclear as it is only a component of the knee extensor muscle group. Another possible limitation of the study was the EMG normalisation technique used. Training effects on EMG data may affect the magnitude of the reference value and the value during the kick, therefore possibly masking the true effects of the training program (Manolopoulos et al., 2006). Other limitations in the reporting of EMG values is that inaccurate positioning of electrodes can lead to cross contamination of results and the number of muscles investigated is limited by the equipment and the number of channels available (Baczkowski, Marks, Silberstein & Schneider-Kolsky, 2006).

Due to differences in the recording of kick durations, it is difficult to compare Australian Football and soccer EMG data. However, it is clear that both the quadriceps and hamstrings are active during kicking, with the quadriceps being more dominant.

### 2.3. Fatigue and Sports Skills

Fatigue has been reported to be detrimental to performance (Kellis et al., 2006) and increases injury risk (Gleeson, Reilly, Mercer, Rakowski & Rees, 1998). Altered technique under fatigue has also been reported in several sports skills including landing (Coventry, O'Connor, Hart, Earl & Ebersole, 2006; Madigan & Pidcoe, 2003) and running (Derrick, Dereu, & Mclean, 2002). There is no singular definition of muscular fatigue that is commonly used in fatigue research. Neuromuscular fatigue has been defined as "an inability of a muscle or group of muscles to sustain the required or expected force" (Bigland-Richie & Woods, 1984), or even "any reduction in the force generating capacity of the total neuromuscular system regardless of the force required in any given situation" (Bigland-Richie & Woods, 1984).

### 2.3.1 Central versus Peripheral Fatigue

During physical activity, in many cases the cause of failure to continue has been determined to be central, while in other cases the cause of failure has been determined to be peripheral (MacIntosh & Allen, 2000). Central fatigue causes a failure of the activation of the motor neural pathways. Activation of sufficient numbers of motor units is unable to be achieved to permit continued exercise at the desired intensity (MacIntosh & Allen, 2000). In many cases, however, the cause of the inability to continue physical activity can be localized to changes occurring in the muscle involved, rather than a central fatiguing mechanism (MacIntosh & Allen, 2000). Peripheral fatigue has been shown to result from either failure of the conduction of motor neuron action potential, failure of neuromuscular junction transmission, failure of muscle fibre action potential generation and propagation, or failure of calcium release within the fibre, calcium combining with the troponin, or even impaired cross-bridge interaction (Nigg, MacIntosh & Mester, 2000). Along with central and peripheral fatigue, Avela and Komi (1998) concluded that decreased muscle performance is partly due to an impaired ability to make use of stiffness-related elastic energy. The process of muscular fatigue involves both central and peripheral control systems, both of which provide time-related changes in levels of recruitment and firing rate of motor units (Nigg et al., 2000).

### 2.3.2 Fatiguing Protocols

It is difficult to compare fatigue-based data due to the abundance of different fatigue protocols that have been implemented in skill-based research. Bigland-Richie and Woods (1984) stated that fatigue can be induced isometrically by sustained maximal isometric contractions and dynamically by bicycle pedalling and bench stepping.

Gollhofer, Komi, Miyashita and Aura (1987) induced fatigue to the upper extremity by repeated landings and push-offs with the hands whilst lying on an incline movable bench. The results suggest that a repeated stretch-shorten cycle induces fatigue and that the effects on the muscles mechanical behaviour are very similar to those induced by either concentric or isometric fatigue contractions (Gollhofer et al., 1987). Local muscular fatigue has also been attempted to be induced through central fatigue protocols. Bigland-Richie & Woods (1984) found that central fatigue does not necessarily limit force generation by limb muscles during intermittent, sub-maximal contractions lasting up to 20min. Non-fatigued muscles have also been shown to compensate for fatigued muscles. This was the case found by Nyland, Shapiro, Caborn, Nitz & Malone (1997), who found that the non-fatigued tibialis anterior muscle appeared to compensate for both the fatigued quadriceps femoris and hamstring muscle groups.

#### 2.3.2.1 Measuring Muscular Fatigue

In addition to different means of inducing fatigue, fatigue has also been quantified in many different ways. Muscular fatigue can be measured in terms of reduced force or work generating capacity, suppression of motor neuron discharge from changes such as a shift in the EMG power spectrum, slowing of muscle contractile speed and muscle conduction velocity, and the accumulation of lactate and other metabolites (Bigland-Richie & Woods, 1984; Nyland, Shapiro, Stine, Horn & Ireland, 1994). The Integrated EMG (IEMG)/force relationship is not perfectly linear. However, Bigland-Richie & Woods (1984) stated that it appears to be unique and repeatable for each muscle. Therefore it was concluded that the IEMG, when expressed as percentage of maximal contraction, provides a relatively accurate index of the degree of muscle excitation by the central nervous system (Bigland-Richie & Woods, 1984). EMG has been used to measure fatigue in the soleus (SOL) and vastus medialis (VM) during drop jumps after a marathon (Avela & Komi, 1998). The repeated long term stretch-shortening cycle (SSC) caused a pre-activation decrease in the SOL of 26.6% and in the VM of 38.7%. During the eccentric phases, the SOL showed a 25.2% decreased EMG activity, while the VM decreased activity by 27.3% (Avela & Komi, 1998).

Fatigue has also been quantified by measuring changes in performance measures. Kellis et al. (2006) used an increase in sprint times as one indicator of fatigue. Dynamic fatigue during a lifting task has been documented as a reduction in lifting power and was seen as 31% decrease from non-fatigued power output (Sparto, Parnianpour, Reinsel & Simon, 1997). Horita, Komi, Nicol & Kyrolainen (1999) also quantified fatigue using power as a measure. Drop jumps were performed before and after a sub-maximal stretch-shorten cycle, to exhaustion, on a special sledge apparatus. On average, exhaustion occurred within 3min, and knee joint positive peak power decreased by 19% from pre to post-fatigue measures. After a similar fatigue protocol, Horita, Komi, Hamalainen & Avela (2003), found that the contribution of the knee joint peak power decreased both in the eccentric and concentric (standing) phase of a drop jump. In contrast, during a follow-up period, both ankle and hip joint contribution increased.

Coventry et al. (2006) also used a dynamic measure to quantify fatigue in a drop landings study. Throughout a fatigue landing protocol, subjects were instructed to perform a maximal countermovement jump (CMJ) on a force plate, using their preferred leg. CMJ power output results indicated that the protocol induced fatigue (first cycle $14.98 \pm 3.22$W kg$^{-1}$, last cycle $9.9 \pm 2.76$W kg$^{-1}$, $P = 0.005$). Net joint work decreased at all joints (first cycle: Hip $0.80 \pm 0.38$J kg$^{-1}$, Knee $0.98 \pm 0.31$J kg$^{-1}$, Ankle 0.40 ±

0.25J $kg^{-1}$; last cycle: Hip 0.55 ± 0.16J $kg^{-1}$, Knee 0.40 ± 0.25J $kg^{-1}$, Ankle 0.72±0.25J $kg^{-1}$), but the decrease was significant at the knee ($P = 0.002$) and ankle ($P = 0.005$), indicating greatest fatigue at these joints. Hoffman, Nusse & Kang (2003) also used CMJ's and squat jumps (SJ) to analyse changes in maximal power performance before, immediately after, and 24 hours after a soccer match. No significant difference was found in CMJ or SJ peak power when compared before (CMJ ≈ 3100W, SJ ≈ 3200W) and after (CMJ ≈ 2950W, SJ ≈ 3250W) the match for starters. Although the authors hypothesised that there would be a decrease after the game, this did not eventuate and was thought to be due to many of the starters being substituted at the start of the second half and therefore recovering before the post-game testing.

EMG has also been used as a fatigue measure. In a study that compared root mean square (RMS) values for running over a treadmill-simulated soccer match, Rahnama, Reilly & Lees (2004) found that the RMS values were greater pre-game than post-game and increased with an increase in running speed ($6km \cdot h^{-1}$ to $21km \cdot h^{-1}$) for the rectus femoris, biceps femoris and tibialis anterior, whilst the RMS value only significantly increased with an increase in running speed for the gastrocnemius. As EMG activity was greater before the simulated game, the authors concluded that fatigue had an effect on muscle activity, and is likely to be the cause of reduced activity and work rate in a soccer match (Rahnama, Reilly & Lees, 2004). No kicks were analysed in this study.

Muscular fatigue has been investigated in depth. However, much of the research is inconsistent in terms of definitions, techniques for inducing muscular fatigue, and measures of muscular fatigue. Sufficient muscular fatigue protocols have been shown to cause a decrease in the muscle's ability to produce force.

### 2.4. Fatigue and Kicking

Research points to a relationship between muscle strength and performance, as muscles are directly responsible for increasing the speed of the foot during kicking (Lees & Nolan, 1998). It is therefore logical to assume that any activity that decreases the active muscles strength will affect kicking technique. Tourny-Chollet, Leroy, Delaue & Beuret-Blanquart (2003) reported that the higher concentric strength recorded on an isokinetic dynamometer by soccer players, as opposed to sedentary subjects, is thought to be highly correlated with ball kicking speed. When comparing kick distance and knee extensor strength on an isokinetic muscle function dynamometer at an angular speed of $3.6 rad \cdot s^{-1} \cdot$, Cabri et al. (1988) found a high correlation ($r = 0.74$). They also found a significant relationship between kick distance and hip flexor strength ($r = 0.56$) (Lees & Nolan, 1998). Manolopoulos et al. (2006) also found that a combined strength and kicking coordination program caused a significant increase in ball speed, an important indicator of a successful soccer kick. As the strength relates to kicking performance, and tired muscles lose their ability to generate strength, it is important to investigate how fatigue can affect kicking performance. However, in relation to many sports that involve kicking, there has been limited research on how fatigue affects the skill, or may increase the chance of injury.

#### 2.4.1 Fatigue and Kicking in Australian Football

Australian Football is a physically demanding sport. It is played on a ground with an area far exceeding that of any of the other football codes (e.g. ground area between 14000 and 19000 $m^2$ compared with between 6000 and 8000$m^2$ for soccer and rugby codes) (Ball, 2006). Australian Football is also played for a longer duration than other codes, with the average game taking approximately 120min as compared to 93min in soccer (Ball, 2006).

Further, Australian Football has a very intermittent nature with GPS technology showing that on average players cover 12.5km of distance during a game, have an average speed of 6.78km·hr$^{-1}$, (7.31km·hr$^{-1}$ for midfielders), and spend one third of their playing time in speed zones above 8km·hr$^{-1}$. Players have also been found to surge above 18km·hr$^{-1}$ on average 90.09 times per game for total time of almost 6min, equating to an average of 4s per sprint over 18km·hr$^{-1}$ (Wisbey & Montgomery, 2007).

Given the high physical demands on Australian Football players it is logical to assume that they would operate under some form of fatigue throughout a game and thus possibly be more susceptible to injury. Andrews, Dawson & Stewart (2005) concluded that elite Australian Footballer's hamstring/quadricep torque ratios reduce after acute running fatigue. Although kicking was not tested, this was proposed to increase the chance of hamstring injury. Baczkowski et al. (2006) established that the rectus femoris is significantly activated during a drop punt kick and the Australian Football kicking motion places very high strains on the muscles of the upper thighs and legs, placing players at risk of injury (Baczkowski et al., 2006). The study looked at muscle activity and kicking using magnetic resonance imaging (MRI) and found that the signal intensity of all of the 14 leg muscles tested changed after 100 maximal kicks. This change was observed most prominently in the adductor longus and tensor fascia latae muscles (49.4 ± 9% and 45.5 ± 7.9% respectively, $P < 0.05$). Injuries to the quadriceps of the kicking leg have been shown to be almost certainly increased by kicking a football (Orchard et al., 1999).

In spite of the injuries associated with kicking, the influence of fatigue on technique and that Australian Football is played for long durations and at relatively high intensities, there have been no published studies examining kicking technique changes under fatigue in Australian Football.

### 2.4.2 Fatigue and Kicking in Soccer

There has, however, been some research done on the effects of fatigue on kicking in soccer. This research has been limited as in a paper titled 'Fatigue in soccer: A brief review', Mohr, Krustrup & Bangsbo (2005) did not even report any kicking data. A few fatigue kicking research studies have centred around the biomechanics of the soccer instep kick and how improvements in technique can create a better chance for success in a soccer game situation, or how improved technique may limit the players susceptibility to injury. In a soccer match players can cover 8 to 12km per game (Greig, 2006), and travel in speed zones above 16km·hr$^{-1}$ for averages of only 2.5s (Bangsbo, Norregaard & Thorso, 1994). Fatigue or reduced performance has been shown to occur after short-term intense periods of activity, in the initial phase of the second half and towards the end of a match (Mohr et al., 2005). Injury risk has been shown to be highest in the first and last 15min of a soccer match, reflecting the intense opening of a game and the possible effects of fatigue late in the game (Rahnama, Reilly & Lees, 2002). Rahnama et al. (2003) showed that late in a game, players' leg muscle strength decreases due to fatigue. In turn this was proposed to affect kicking technique and leave players more susceptible to injury. This was supported by Apriantono, Nunome, Ikegami & Sano (2006), who found 3D kinetic and kinematic differences in maximal instep soccer kicking technique before and after a fatigue protocol.

#### 2.4.2.1 Soccer Non Match-Specific Fatigue Protocols

Many previous studies examining fatigue and technique change in sports have failed to perform a game-specific fatiguing protocol. For example Apriantono et al. (2006) elicited a fatigue state by using knee extension and flexion exercises. This ignored the musculature at the hip, where the kicking motion is initiated and the majority of the muscular force is developed (Dörge et al., 1999). Apriantono et al. (2006) used a two link kinetic chain model composed of the thigh and lower leg to analyse the effect of muscle fatigue on instep kicking. Examining three dimensional kinetics and kinematics, Apriantono et al. (2006), found technical changes in the maximal instep soccer kick before and after a fatigue protocol. Apriantono et al. (2006), showed that a repeated loaded knee extension and flexion fatigue protocol on a weight-training machine caused decreased muscle moments (peak net moment of shank: non-fatigue 89 ± 16N·m, fatigue 84 ± 15N·m, $P < 0.05$; peak muscle moment of knee joint: non-fatigue 128 ± 20N·m, fatigue 108 ± 17N·m, $P < 0.01$) and interactive moments (maximal interactive moment of knee joint: non-fatigue 58 ± 25N·m, fatigue 30 ± 12N·m, $P < 0.01$) during the kick. This resulted in a decrease in the peak velocity of the shank swing (non-fatigue 37.1 ± 3.4rad·s$^{-1}$, fatigue 35.7 ± 2.4rad·s$^{-1}$, $P < 0.05$), and maximal toe linear velocity (non-fatigue 27.1 ± 1.2m·s$^{-1}$, 26.0 ± 1.3m·s$^{-1}$, $P < 0.01$). The authors suggested that this decreased leg swing velocity caused poorer ball contact, which in turn led to significantly slower ball velocity (non-fatigue 28.4 ± 1.6m·s$^{-1}$, 26.8 ± 1.1m·s$^{-1}$, $P < 0.01$). As ball velocity correlates with the distance the ball travels (Ball, 2008), these results indicate that fatigue will affect kicking distance. It was also observed that immediately before ball impact the eccentric action of the knee flexors (thought to be a safety mechanism to prevent over extension of the knee joint) was less evident, therefore possibly increasing the kicker's susceptibility to injury.

A limitation of the Apriantono et al. (2006) study was that the fatigue protocol used was not representative of the intensity, duration and various actions performed in a soccer match. The use of the weight training machine did not require any movement at the hip, thereby negating the work by the hip flexors; other than the rectus femoris which is also used to extend the knee. The hip flexor has been shown to be a major influence in force production during kicking (Dörge et al., 1999). Other fatigue-based soccer studies have also failed to utilise a fatiguing protocol that is specific to the sport. Lees & Davies (1988) found decreased coordination between the upper and lower leg during kicking after a 6min step test, whilst Lyons, Al-Nakeer & Nevill, (2006) found that performance on the modified Loughborough Soccer Passing Test decreased (rest score 39.84 ± 2.81, 90% localised muscle fatigue score 44.32 ± 2.40) after a high-intensity 1min bout of alternate split squats.

#### 2.4.2.1 Soccer Match-Specific Fatigue Protocols

In contrast to these short-term non match-specific fatigue protocols, some studies have attempted to replicate match-induced fatigue by either using a treadmill or ground-based running protocol. Rahnama et al. (2003) tested quadricep and hamstring muscle strength on an isokinetic dynamometer prior to, at the half way point, and after a 90min soccer-specific intermittent exercise protocol performed on a treadmill. Intensities elicited walking, jogging, running and sprinting, as observed in a soccer match. The authors showed that late in a game, as players get tired their leg muscle strength decreases (shown as significant reductions in peak torques for both hamstrings and quadriceps at several angular velocities, $P < 0.001$) as does the hamstrings:quadriceps ratio (ratio decreased by 3.6, 9.7 and 6.2% at testing speeds of 1.05, 2.09 and 5.23rad$\cdot$s$^{-1}$) due to fatigue. The results show a decrease in both quadricep and hamstrings strength, but this decrease was more prominent in the hamstrings, leaving the quadriceps to become more dominant (greater quadricep dominance has also been found for high level soccer players as opposed to sedentary individuals (Tourney-Chollet et al., 2003). As the eccentric action of the knee flexors just prior to impact has also been shown to decrease with fatigue (Apriantono et al., 2006), the fatigued kicking technique may not slow down knee extension as much, and therefore leave players more susceptible to injury. A similar fatigue protocol was also used by Rahnama, Lees & Reilly (2005) to test the EMG activity of selected lower limb muscles at various intensities before, during and after fatigue. The subsequent decrease in RMS value of EMG activity (pre-exercise, half-time, and post-exercise) of the rectus femoris ($P < 0.05$), biceps femoris ($P < 0.01$) and tibialis anterior ($P < 0.05$) was thought to be an indicator of fatigue and decreased strength during prolonged exercise. A significant effect was not found for the gastrocnemius. The authors also pointed out due to reduced muscle strength, represented by decreased RMS signals, greater levels of muscle activation would be needed to maintain performance.

Gleeson et al., (1998) also attempted to use a variety of endurance-based fatiguing protocols designed to simulate the physiological demands of soccer match-play and training to test the effects on leg strength, electromechanical delay and knee laxity. The four different protocols used are summarised in Table 4. Each of these protocols produced different results, however it was suggested that the prolonged intermittent high-intensity shuttle run (PHISR) trial was the best representative of the physiological stresses experienced by soccer players during match play. This conclusion was based on similarities between the protocol and game-based physiological data such as heart rate and blood lactate.

Table 4 - Fatigue protocols used by Gleeson et al. (1998)

| Fatigue protocol | Description |
|---|---|
| 1) High intensity shuttle run | A prolonged intermittent high-intensity shuttle run (PHISR) simulating the 90min of a soccer game broken into observed work-to-rest intervals and activity modes (total distance of 9600m consisting of 12 by 200m cycles of activity, each comprising 60m walking (1.54m·s-1), 15m sprinting (5m deceleration and 5m recovery walk), 60m jogging (55% $VO_{2max}$), and 60m running (95% $VO_{2max}$)) |
| 2) Shuttle run | Subjects completed a total distance of 9600m in four sections of 2400m at 70% $VO_{2max}$ (SR) |
| 3) Treadmill run | Treadmill run of a total distance of 9600m in four sections of 2400m at 70% $VO_{2max}$ (TR) |
| 4) Control condition | No exercise (CC) |

Peak torque was found to significantly decrease in the PHISR, SR and TR trials for both knee flexion and extension movements. This decrease in strength was greater in the knee flexors than the extensors (Gleeson et al., 1998). As previously reported, a decreased ability of the knee extensors to produce force on an isokinetic dynamometer after fatigue was also reported by Rahnama et al. (2003) and Apriantono et al. (2006). Gleeson et al. (1998) also did not analyse kicking technique.

Kellis et al. (2006) did test how the biomechanics of the maximal instep soccer kick changed during a 90min soccer-specific intermittent exercise protocol, performed on a 20m turf surface. Although the protocol included varied intensities, all running was in a straight line. Kicks were performed before, during and after the protocol. Physiological markers such as blood lactate concentrations (before 1.44 ± 0.49mmol/L, middle 5.27 ± 0.93mmol/L, after 6.24 ± 1.20mmol/L, $P < 0.01$) and $NH_3$ (ammonia) (before 124.16 ± 11.35µmol/L, middle 140.09 ± 11.17µmol/L, after 148.70 ± 10.12µmol/L, $P < 0.01$) concentrations, and significant increases in 15m sprint times were found at the third and fourth section when compared with section one of the protocol (section 1 ≈ 2.5 ± 0.4m·s$^{-1}$, section 3 ≈ 2.75 ± 0.75m·s$^{-1}$, section 4 ≈ 2.9 ± 0.3m·s$^{-1}$, $P < 0.01$) indicated that the protocol caused musculature fatigue. Ground reaction force s were not significantly influenced by fatigue. The fatigue protocol caused a significant decline in ball speed (pre 24.69m·s$^{-1}$, post 21.78m·s$^{-1}$, $P < 0.01$), ball:foot speed ratio (pre 1.4 ± 0.12, post 1.33 ± 0.18, $P < 0.01$), angular velocity of the shank (pre ≈ 1800 ± 600°·s$^{-1}$, middle ≈ 1550 ± 500°·s$^{-1}$, post ≈ 1600 ± 500°·s$^{-1}$, $P < 0.01$) and angular position of the ankle (pre 144.4 ± 12.93°, middle 131.7 ± 15.85°, post 129.3 ± 12.99°, $P < 0.01$). Kellis et al. (2006) reported this was associated with a significant decline during the support phase of the net moment ($N_m$) applied on the shank (pre 231.89 ± 81.30, post 184.54 ± 92.79, $P < 0.01$) and moment because of muscle force acting on the shank ($M_m$) (pre 114.91 ± 48.17, post 78.73 ± 46.40, $P < 0.01$). The authors suggested the decline in ball speed and angular velocity of the shank was due to the reduced strength exerted by the knee musculature at 'critical' times. As the thigh velocity stayed constant and shank velocity significantly decreased due to the net moment applied on the shank decreasing, this alteration in the proximal to distal pattern is similar to that found by Coventry et al. (2006), who found a redistribution of energy absorption from the ankle to the larger proximal muscles that cross the hip during fatigued landings. Coventry et al. (2006) found that net work at the hip significantly increased ($P = 0.031$), work at the knee only slightly decreased ($P = 0.473$), whilst work at the ankle decreased considerably ($P < 0.0001$) (first cycle: Hip -0.20 ± 0.19J kg$^{-1}$, Knee -0.97 ± 0.43J kg$^{-1}$, Ankle -1.14 ± 0.25J kg$^{-1}$; last cycle: Hip -0.44

± 0.36J $kg^{-1}$, Knee -0.85 ± 0.40J $kg^{-1}$, Ankle -0.87 ± 0.24J $kg^{-1}$). As the protocol was shown to induce lower extremity fatigue, these results indicate a redistribution of energy absorption (negative work) from the muscles that cross the ankle to the larger possibly more fatigue-resistant muscles that cross the hip, during a landing. A similar higher reliance on the more fatigue-resistant muscle groups higher in the kinetic chain appears to be a possible coping mechanism also found in kicking under fatigue.

Although there have been several studies that have looked at the effect of fatigue on leg strength, muscle activation or soccer kicking technique, it is clear that only limited comparisons can be made between these studies due to the vast array of fatigue protocols that have been implemented. Many of these studies made little attempt to utilise a fatigue protocol that simulated a match scenario. Although Rahnama et al. (2003), Rahnama et al. (2005), Gleeson et al. (1998) and Kellis et al. (2006) all attempted to use soccer specific protocols, they all failed to incorporate the many changes of direction, jumping, tackling and kicking motions used in a game. These studies also failed to use elite soccer players as their participants, therefore limiting the implications of the research to junior and amateur soccer players. It is also difficult to compare results from soccer based research to Australian Football due to the inherent differences in the games and the kicking technique.

### 2.5. Summary and Recommendations for Future Research

Fatigue has been shown to decrease performance and increase injury risk in other sports and activities, but this has not been evaluated in relation to Australian Football kicking technique. Given the longer timeframes, larger grounds and longer average sprint times, examination of the influence of fatigue in Australian Football kicking is essential to improve performance and decrease injury risk. Identification of the changes in technique and muscle function due to fatigue can lead to better conditioning programmes and identification of optimal techniques that limit the effects of fatigue.  Further, the results can provide useful information to be incorporated into assessment of the two major injury mechanisms in elite Australian Football: hamstring strains and osteitis pubis.

The three proposed studies three-dimensionally analyse the mechanics of the Australian Football kicking technique before, during and after both short-term and long-term Australian Football specific fatigue protocols.  Study 1 focusses on kinematics after a short-term protocol, Study 2 on kinematics after a long-term protocol and Study 3 on kinetics after a long-term protocol.  Elite, sub-elite and junior Australian Football players were analysed.  It was expected that participants would display changes in their kicking technique post-fatigue.  These differences were thought to show up in changes in foot speed and shank angular velocity just before ball contact, and a possible redistribution of work to utilize the larger hip flexors in a fatigued state.  Due to their higher levels of Australian Football specific training, it was thought that these differences would be less pronounced in the elite group.

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# Chapter 3

## Study 1

## 3. Kinematic Effects of a Short-Term Fatigue Protocol on Punt-Kicking Performance

* This article has been accepted for Publication:

Coventry, E., Ball, K., Parrington, L., Aughey, R. & McKenna, M. (2015). Kinematic effects of a short-term fatigue protocol on punt-kicking performance, *Journal of Sports Sciences, DOI*: 10.1080/02640414.2014.1003582.

### 3.1 Abstract

The punt kick is a fundamental skill used in several team sports, however there has been a lack of research on how fatigue affects its technique. The purpose of this study was to determine the effects of short-term fatigue on punt kicking performance. Eight elite and sub-elite Australian Football players performed maximal drop punt kicks on their preferred leg prior to, during and after a match-specific fatigue protocol. Optotrak Certus collected kinematic data from kick foot toe-off until ball contact. Repeated-measures ANOVA showed a significant increase in 20m sprint times after each short-term protocol, indicating fatigue. Foot speed did not significantly change with fatigue, however increases in the range of motion at the pelvis and kicking thigh, along with increases in kicking thigh angular velocity occurred. For the support leg, maximum knee flexion angular velocity increased while there was greater flexion found at the knee and hip, and greater range of motion at the knee. Players are able to make kinematic adaptations in order to maintain foot speed whilst punting for maximal distance after short-term efforts.

**Keywords:** biomechanics, drop punt, technique, Australian football

### 3.2 Introduction

The punt kick is a fundamental skill used in Australian Football, and is also used in Gaelic football, American football, the rugby codes and association football. The general kicking technique consists of the coordination of multiple segments in a proximal to distal sequence in a kinematic chain (Dörge et al., 1999). The kicking motion is initiated at the larger proximal muscles around the hip and proceeds down the chain to the more distal foot segment for high speed at ball impact. In Australian Football, kicking is the most prevalent method of passing between players, with effective long kicking having been found to be significantly related to success (Forbes, 2003). Specifically, greater kicking distances have been associated with more passing options and more shots at goal being taken from further out (Ball, 2008).

Technical elements have been found to be important for punt kicking, particularly in distance kicking among elite Australian Football players. Ball (2013) reported preferred leg foot speeds ($22.4 \pm 0.7 m \cdot s^{-1}$) to be larger than non-preferred leg foot speeds ($19.1 \pm 1.0 m \cdot s^{-1}$) when punting for maximal distance. In an early study on elite Australian Football players, Macmillan (1975) reported foot speeds of 23.3 to $23.7 m \cdot s^{-1}$ when subjects kicked for distance (average distance 47.4m). Ball (2008) reported that foot speed ($26.4 \pm 1.2 m \cdot s^{-1}$) was the major contributor to kicking the ball further, with larger foot speeds being associated with longer distances ($r = 0.68$ with a likely range of $r = 0.51$ to 0.81, $P < 0.01$). Foot speed has therefore been shown as an important performance indicator for distance punt kicking.

Fatigue has been shown to be detrimental to the performance of sports skills generally (Voloshin, Mizrahi, Verbitsky & Isakov, 1998; Verbitsky, Mizrahi, Voloshin, Treiger & Isakov, 1998; Coventry, O'Connor, Hart, Earl & Ebersole, 2006) and kicking technique specifically (Kellis, Katis & Vrabas, 2006; Apriantono, Nunome, Ikegami & Sano, 2006). To date changes in technique due to fatigue have been examined in soccer kicking and have mostly centred on long-term exercise, yielded conflicting findings (Apriantono et al., 2006; Kellis et al., 2006; Rahnama, Reilly, Lees & Graham-Smith, 2003). Rahnama et al. (2003) and Apriantono et al. (2006) proposed that that long-term fatigue protocols were detrimental to kicking technique, however, Lyons, Al-Nakeer & Nevill (2006) found an improvement in performance under fatigue after a moderate-intensity short-term fatigue protocol. Participants performed a soccer passing test after three conditions: rest, 70% (moderate-intensity) and 90% (high-intensity) of maximal repetitions in one minute. All parameters including scores, number of passing errors and least number of combined penalties improved after the moderate-intensity localised muscular fatigue conditions and decreased after the high-intensity conditions. The authors suggested the possibility of there being an optimal level of exercise-induced arousal at a moderate intensity that also caused deterioration in performance at a higher intensity.

There have been no published studies looking at the effects of either short-term or long-term fatigue on punt kick technique. Fatigue has been described in skill performance research as a reduction in maximal force, power, muscle strength or coordination due to sustained exercise (Mohr, Krustrup & Bangsbo, 2002) or immediate effort (Mohr, Krustrup & Bangsbo, 2005), and has been associated with a decline in performance (Kellis et al., 2006). In Australian Football, GPS technology has shown that players run above 18km·h$^{-1}$ on average 90.09 times per game for total time of almost 6min. This equates to an average of 4s per sprint over 18km·h$^{-1}$ (Wisbey & Montgomery, 2007). The speed of the game has also increased over recent times, with the mean speed of players being highest in the first few minutes of a quarter with a greater number of high intensity efforts being performed by players who are interchanged more often (Gray & Jenkins, 2010). Due to the influence of fatigue on technique, and the fact that Australian Football is played for long durations and at relatively high intensities, it might be expected that players experience some fatigue throughout a game and that kicking technique would change as a result of this. To date all punt kicking research has been performed on players in a pre-fatigued state. The findings of the previous punt kicking studies might therefore be limited if changes in technique occur under fatigue. It is important to understand what these possible technical changes in punt kicking may be after exercise and if these changes result in performance factors changing.

The aim of this study was to examine if short-term fatigue affects maximal drop punt kicking performance (foot speed) and kinematics.

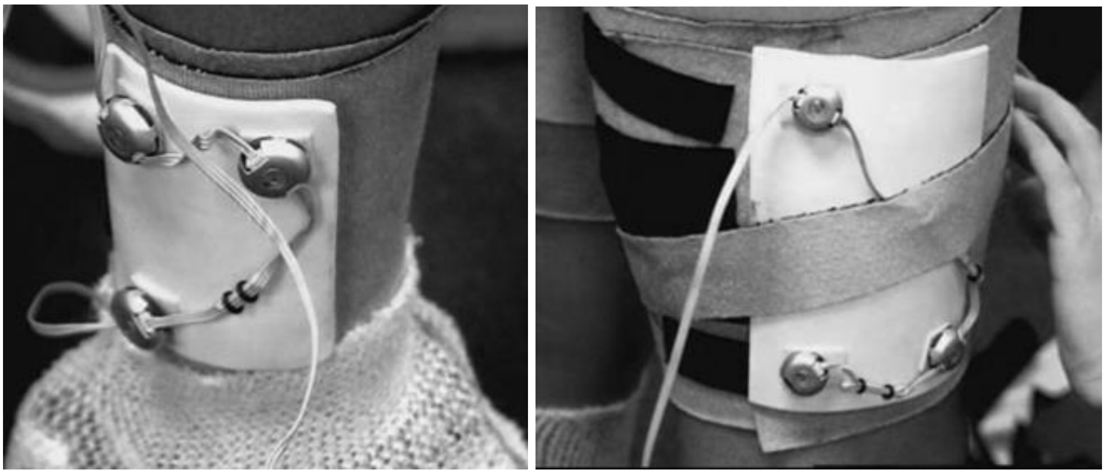
## 3.3 Methods

### *3.3.1 Participants*

Eight elite and sub-elite Australian Football players (age 19.75 ± 0.89years, height 185.25 ± 8.38cm, body mass 81.5 ± 8.59kg) were recruited for this study. All participants reported they were injury free and were engaged in full training with their club at the time of testing. Informed consent was obtained before data collection and ethical approval for the study was obtained from the University's human ethics committee.

### *3.3.2 Procedures*

Participants had clusters of three light emitting diodes (non-collinear iRED markers) placed on rigid moulds positioned laterally and distally on the thigh and shank (Figure 1). A pelvis cluster was placed in line with both posterior superior iliac spines (PSISs) such that the mid-point of the top two markers of the pelvis clusters was situated at the sacrum landmark. A trunk cluster was positioned at C7 and an individual foot marker was placed at the head of the fifth metatarsal of the kick foot. Anatomical landmarks were virtually stored using a digitising probe (Northern Digital Inc., NDI, Ontario, Canada) in the experimental set up procedure (First Principles, NDI). This process required each anatomical landmark to be manually palpated. These virtual landmarks were then used to create the anatomical frame of each segment and allowed estimation of the internal joint centres within Visual3D (C-Motion) and is functionally similar to the processes described by Cappozzo, Cantini, Della Croce & Leardini (1995). These modelling procedures have been used previously in Australian Football biomechanics studies (Parrington, Ball & MacMahon, 2012; Ball, 2011).



**(a)** **(b)**

**Figure 1: Clusters of light emitting diodes on kick leg shank (a) and thigh (b)**

### *3.3.3 Warm-up*

Participants performed a standardized warm up, consisting of jogging on a treadmill for 10min and stretching the muscles to be used in the kicking movement (hamstrings, quadriceps, calves, hip flexors). Participants then performed 20 practice kicks, building up to maximal effort. Following this, participants walked through the fatigue protocol course, and then moved through it again at 75% of the required intensity.

### *3.3.4 Protocol*

Following the warm-up, each participant performed three maximal distance kicks into a net using their preferred leg. These kicks were recorded and the kick with the highest foot speed was selected as the 'pre kick' for analysis (pre). Participants then underwent a short-term game-specific fatigue cycle, adapted from Coutts & Duffield (2008) (Figure 2). Each fatigue cycle included a 20m sprint at the start and end with timing gates recording the sprint time to indicate fatigue. Sprint times have been used previously as a fatigue indicator in soccer (Kellis et al., 2006). Each participant completed the fatigue cycle two times in succession, with a maximal kick performed immediately following the end of the cycle on the preferred (post-1, post-2) and non-preferred leg (Figure 3). Only preferred leg kicks were used for analysis. Non-preferred leg kicks were included to assist in keeping the protocol game specific. The first sprint time in fatigue cycle-1 was used as the pre-sprint as it was performed at the start of the cycle, with the second sprint of fatigue cycle-1 and the second sprint of fatigue cycle-2 being used as post-1 and post-2 sprint respectively as these sprints were performed towards the end of each cycle. Originally seventeen participants completed at least one trial, however, only eight were analysed for all three kicking trials due to technical issues. All statistical analysis was done on these eight participants throughout.

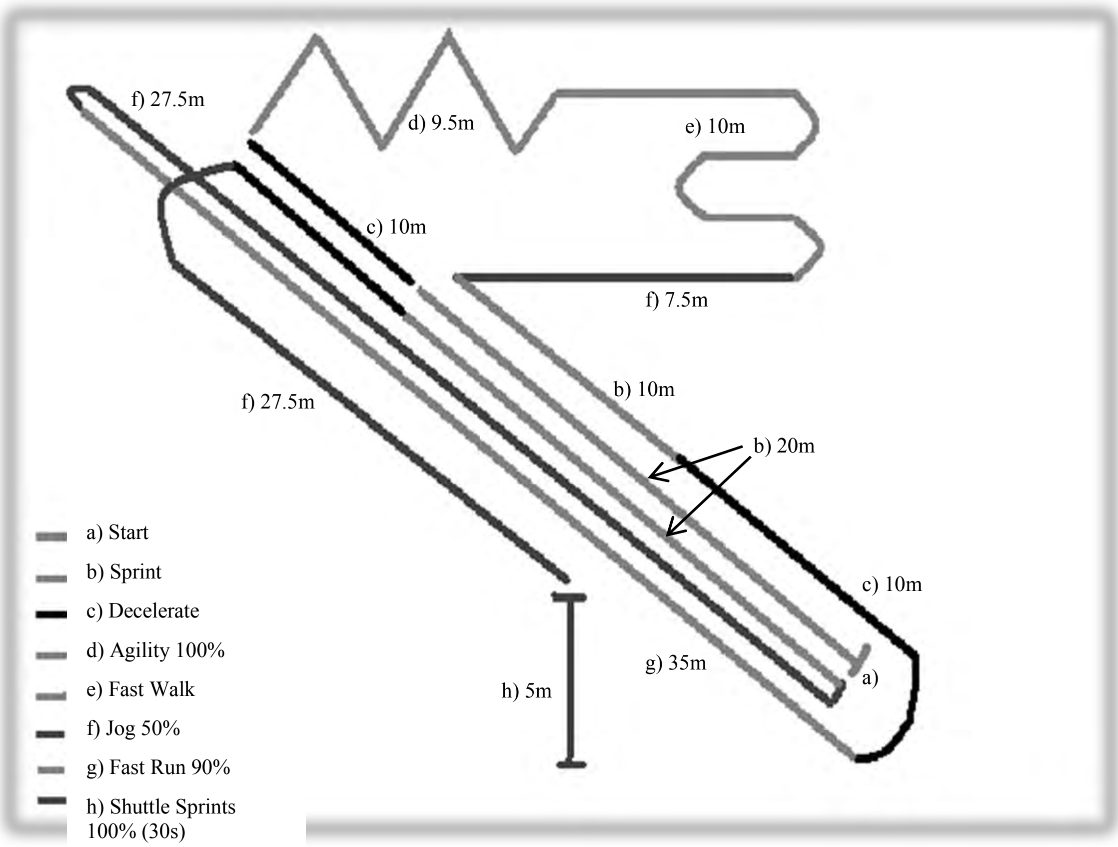



**Figure 2: Short-term fatigue protocol**

Markers attached

↓

Warm-up and familiarisation

↓

3 Pre Kicks

↓

Fatigue cycle 1

↓

Post kick 1

↓

Fatigue cycle 2

↓

Post kick 2

**Figure 3: Outline of experimental procedure**

An Optotrak Certus 3D motion analysis system (Northern Digital Incorporated, Ontario, Canada) operating at 100 Hz captured 3D coordinate data of each kick. Data were exported to Visual3D software (C-motion Inc, Germantown, MD) and were smoothed (Butterworth, cut-off frequency = 12Hz, based on spectral and residual analyses of the signal, on visual inspection of the resulting time-series curves and on previous literature, e.g. Ball, 2011). Kicks were analysed from kick foot toe-off until ball contact. Ball contact was identified using video images of the kick (200Hz), which were linked to the data collection via a pulsed light in the field of view of the video.

The pulsed light (2Hz) also produced a square wave, which was passed to the Optotrak system so that the instant of each pulse was known. Then, using the time between the closest pulse and ball contact as identified on video, this timing could be used to locate ball contact in the 3D data. In all cases, the peak linear velocity of the kicking foot toe (fifth metatarsal), corresponded with ball contact from video data. Data from the instant before ball contact onwards was removed to avoid issues of distorted velocity calculations and smoothing through impact (Knudson & Bahamonde, 2001). This data were then padded from the instant before ball contact forwards with 30 points (reflected) in Visual 3D, smoothed using a Butterworth 4$^{th}$ order digital filter, then the 30 reflected points were removed so that data up to the instant before ball contact only remained. Anatomical landmarks at the hip, knee and ankle were digitised to create the anatomical frame of each segment, and allow the estimation of internal joint centres (Calibrated Anatomical Systems Technique, Cappozzo, Catani, Della Croce, & Leardini, 1995). These modelling procedures have been used previously in Australian Football biomechanics studies of kicking (Coventry, Ball, Parrington, Taylor, Aughey & McKenna, 2011; Ball, 2011) and handballing (Parrington et al., 2012). Parameters were chosen based on previous punt kicking research and were calculated in the same way (Ball, 2011). The three-point central difference method was used to calculate linear foot velocity and angular velocities of the pelvis, hip, thigh, knee, and shank from smoothed displacement data. Joint angles were calculated as anatomical angles. The pelvis was used as the coordinate system for the hip, while the knee axis was measured as a 3D angle between thigh and shank. The pelvis, thigh and shank angles were calculated in relation to the global axis, which was aligned with the kicking action (i.e. the Y-axis was parallel to the direct of the kick, X-axis perpendicular to the line of kick, Z-axis vertical).

### *3.3.5 Statistical Analysis*

Means, standard deviations and confidence intervals were recorded for kick leg linear foot speed and lower body kinematics at ball contact as well as maxima, minima and range of motion for the kick leg and support leg. Repeated measures ANOVAs were performed in SPSS 20 to evaluate the difference between sprint times and the influence fatigue had on each variable. Significance was set at $P < .05$ and effect sizes (partial $\eta^2$) were calculated for comparison. Cohen (1992) suggested effect sizes for various indexes, including $\eta^2$ (small = .0099, medium=.0588, large=.1379). However, when the degrees-of-freedom of the numerator exceeds 1, as it did with each variable in this study, eta-squared is compared to R-squared (Levine & Hullett, 2002). So adapting Cohen's (1992) thresholds, equivalent classification for effect sizes were used as the square root of these thresholds (.01 is a small effect, 0.09 a medium effect and 0.25 a large effect) (Pierce, Block & Aguinis, 2004).

Post hoc analysis was performed on all significant variables. Maximum errors were calculated for each variable (based on 100Hz vs 500Hz data from a previous study in the lab) and those no longer significant with maximum possible errors were not included for discussion. Least-significant-difference multiple comparison procedure (Rahnama et al., 2003), were used to determine the specific differences between each fatigue cycle data. Correlation coefficients (r) were also calculated to evaluate the relationship between foot speed and each significant dependent variable to determine if the relationship changed under fatigue. Those that were higher than the critical value of 0.707 ($df = 6$, $P = 0.05$) were included in the discussion (Bluman, 2004).

### 3.4 Results

Table 1 shows sprint times, linear foot speed at ball contact, kick time and other kicking leg kinematics for the pre, post-1 and post-2 fatigue conditions. Sprint times significantly increased across the three trials ($P < 0.01$). Linear foot speed displayed a large, non-significant effect, but the trend was towards an increase across the three trials. Thigh sagittal plane angular velocity at ball contact significantly increased between post-1 and post-2 trails ($P < 0.05$), displaying its highest value for the post-2 trial. Thigh and pelvis sagittal plane range of motion increased from pre to post-1, with the thigh continuing to increase from post-1 to post-2, however the pelvis range of motion for post-2 was slightly lower than that from post-1. These increases were significant between pre and post-1 ($P = 0.01$), pre and post-2 for the thigh ($P = 0.028$), and between pre and post-1 for the pelvis ($P = 0.01$). Pelvis ($P < 0.05$) frontal plane range of motion increased significantly between the pre and post-1 trial. Minimum knee angle (flexion) increased across each trial, with a significant increase between pre and post-2 trials ($P = 0.02$). Maximum thigh sagittal plane angular velocity significantly increased from pre to post-1 ($P = 0.01$). Table 2 shows correlations (r) between linear foot speed at ball contact and sprint times, kick time and other kicking leg kinematics for the pre and two fatigue conditions. The r-value for the post-2 maximal thigh angular velocity and foot speed was greater than the critical value. Maximum thigh frontal plane angular velocity and hip adduction angular velocity increased. These increases were significant at the thigh between post-1 and post-2 trials ($P = 0.04$) and pre and post-2 trials ($P = 0.03$). Kick time also increased from pre to post-fatigue kicks, significantly between pre and post-1 trials ($P = 0.01$) and pre and post-2 trials ($P = 0.01$).  Time series data for pelvis, hip and knee angle and angular velocities are displayed in Figure 4.

**Table I. Statistically significant ANOVA results for kick leg variables at ball contact (BC), maximums, minimums and ranges of motion (ROM), as well as kick time and 20m sprint times. Significant post hoc results are indicated between pre and post-1 (*), post-1 and post-2 (**) and pre and post-2 (***) trials. Upper and lower confidence intervals are also included.**

| KICK LEG | partial $\eta^2$ | pre mean ± s | pre 95% Confidence limit Upper | pre Lower | post-1 mean ± s | post-1 95% Confidence limit Upper | post-1 Lower | post-2 mean ± s | post-2 95% Confidence limit Upper | post-2 Lower |
|---|---|---|---|---|---|---|---|---|---|---|
| Foot Speed at BC ($m \cdot s^{-1}$) | 0.436 | 19.7 ± 2.0 | 21.3 | 18.1 | 20.3 ± 1.7 | 21.6 | 18.9 | 20.5 ± 1.4 | 21.7 | 19.4 |
| ***Sagittal Plane*** | | | | | | | | | | |
| Thigh Angular Velocity at BC ($° \cdot s^{-1}$) | 0.369 | 69 ± 71 | 118 | 20 | 51 ± 56 ** | 99 | 16 | 118 ± 53 | 155 | 81 |
| Thigh - Maximum Angular Velocity ($° \cdot s^{-1}$) | 0.422 | 742± 89 * | 803 | 680 | 796 ± 111 | 873 | 719 | 791 ± 90 | 854 | 729 |
| Thigh ROM (°) | 0.473 | 84 ± 5 * | 88 | 81 | 88 ± 5 | 92 | 85 | 89 ± 5 *** | 93 | 86 |
| Pelvis ROM (°) | 0.430 | 51 ± 8 * | 56 | 44 | 57 ± 10 | 64 | 50 | 55 ± 10 | 62 | 48 |
| ***Frontal Plane*** | | | | | | | | | | |
| Pelvis ROM (°) | 0.399 | 6.1 ± 1.7 * | 7.4 | 4.9 | 11.9 ± 5.4 | 16 | 8 | 9.9 ± 5.0 | 14 | 6 |
| Thigh - Maximum Angular Velocity ($° \cdot s^{-1}$) | 0.494 | 76± 77 | 133 | 19 | 92 ± 62 ** | 138 | 45 | 127 ± 40 *** | 156 | 97 |
| ***Flexion/Extension*** | | | | | | | | | | |
| Knee - Minimum Angle (flexion) (°) | 0.396 | -116 ± 6 | -111 | -120 | -121 ± 10 | -114 | -128 | -122 ± 7 *** | -118 | -127 |
| ***Abduction/Adduction*** | | | | | | | | | | |
| Hip – Maximum Angular Velocity (adduction) ($° \cdot s^{-1}$) | 0.404 | 182 ± 116 | 268 | 97 | 242 ± 96 | 313 | 170 | 276 ± 120 | 366 | 187 |
| Kick Time (s) | 0.500 | 0.19 ± 0.03 * | 0.21 | 0.17 | 0.21 ± 0.03 | 0.23 | 0.19 | 0.22 ± 0.04 *** | 0.24 | 0.19 |
| Sprint times (s) | 0.739 | 3.28 ± 0.11 * | 3.36 | 3.21 | 3.44 ± 0.16 ** | 3.55 | 3.33 | 3.53 ± 0.23 *** | 3.69 | 3.37 |

**Table II. Correlations (r) between foot speed and significant kick leg dependent variables at ball contact (BC), maximums, minimums and ranges of motion (ROM), as well as kick time and 20m sprint times.**

| | | | |
|---|---|---|---|
| **KICK LEG** | | | |
| ***Sagittal Plane*** | | | |
| Thigh Angular Velocity at BC (°·$s^{-1}$) | -0.47 | -0.24 | -0.12 |
| Thigh - Maximum Angular Velocity (°·$s^{-1}$) | 0.59 | 0.63 | 0.71 |
| Thigh ROM (°) | 0.21 | 0.46 | 0.55 |
| Pelvis ROM (°) | 0.46 | 0.38 | 0.30 |
| ***Frontal Plane*** | | | |
| Pelvis ROM (°) | 0.42 | 0.39 | 0.56 |
| Thigh - Maximum Angular Velocity (°·$s^{-1}$) | -0.45 | -0.53 | -0.26 |
| ***Flexion/Extension*** | | | |
| Knee - Minimum Angle (flexion) (°) | -0.30 | -0.18 | -0.20 |
| ***Abduction/Adduction*** | | | |
| Hip – Maximum Angular Velocity (adduction) (°·$s^{-1}$) | -0.17 | 0.47 | 0.34 |
| Kick Time (s) | -0.28 | -0.82 | -0.50 |
| Sprint times (s) | -0.47 | -0.67 | -0.42 |

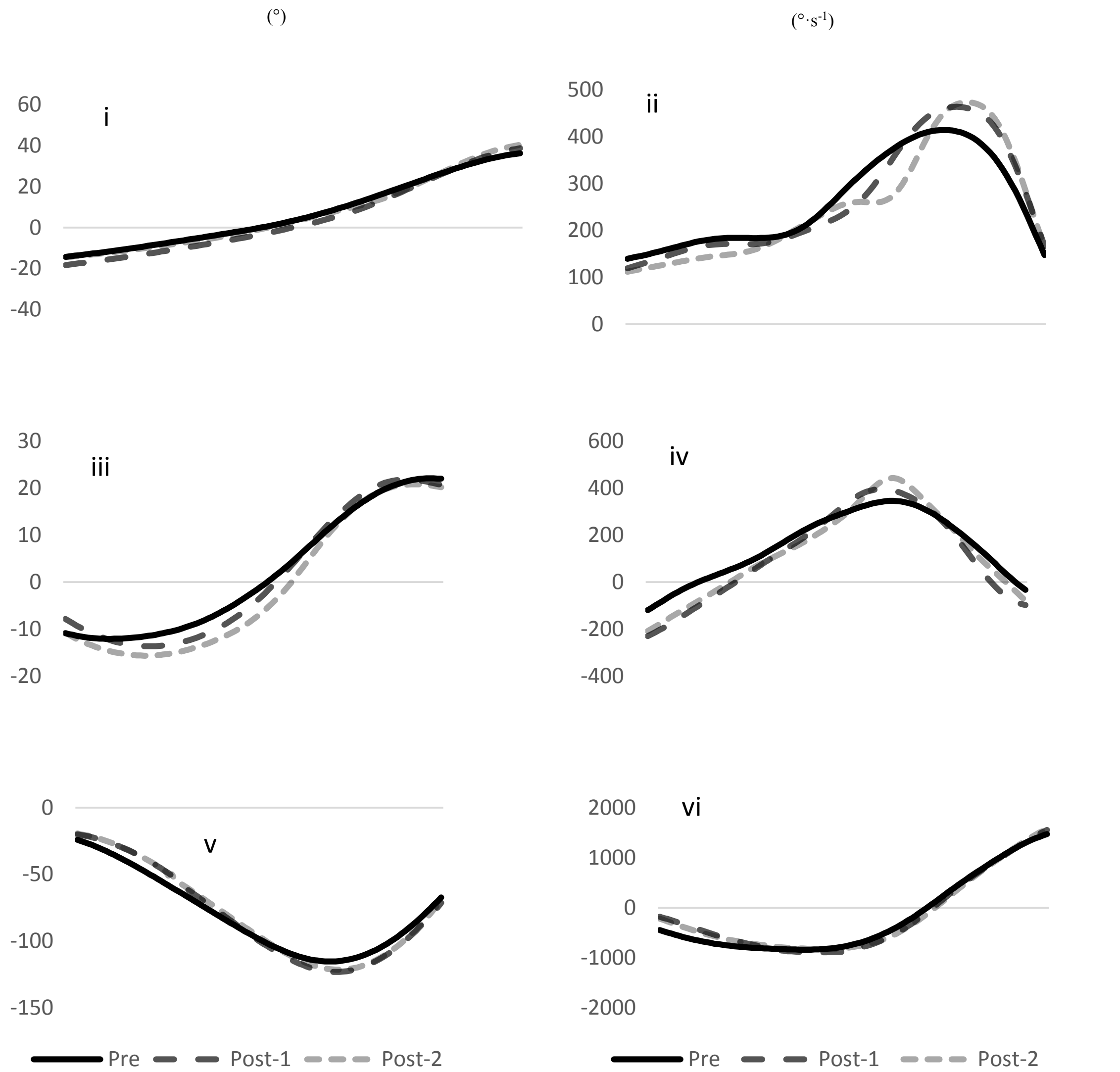



**Figure 4: Time series changes of mean sagittal plane pelvis angles (i) and angular velocities (ii) including flexion (+) and extension (-), hip angles (iii) and angular velocities (iv) including flexion (+) and extension (-) and knee angle (v) and angular velocities (vi) including flexion (-) and extension (+) from toe-off to ball contact. Data has been normalised to 101 data points.**

Table 3 shows support leg kinematics for the pre and two fatigue conditions. Knee angle (flexion) at ball contact increased significantly between the pre and post-1 trials ($P < 0.01$), and between pre and post-2 trials ($P < 0.01$). Hip range of motion (flexion/extension) showed a similar trend, however a significant increase was only found between pre and post-1 trials ($P = 0.02$). Knee maximum angle (flexion) ($P < 0.01$) and minimum angle (flexion) ($P < 0.01$) also increased significantly between the pre and post-1 trials. There was a significant decrease in maximum knee angle (flexion) between the post-1 and post-2 trials ($P = 0.03$), and a significant increase in minimum knee angle (flexion) between pre and post-1 ($P < 0.01$) trials. Maximum hip angle (flexion) significantly increased between pre and post-1 trials ($P = 0.01$). Maximum knee angular velocity (extension) showed a similar trend with there being a significant increase between pre and post-1 trials ($P = 0.02$), however a significant increase was also found between pre and post-2 trials ($P = 0.01$). Table 4 shows correlations (r) between linear foot speed at ball contact and support leg kinematics for the pre and two fatigue conditions.

**Table III. Statistically significant ANOVA results of all support leg variables at ball contact (BC), maximums and ranges of motion (ROM). Significant post hoc results are indicated between pre and post-1 (*), post-1 and post-2 (**) and pre and post-2 (***) trials. Upper (Up) and lower (Low) confidence (Conf) intervals are also included.**

| SUPPORT LEG | partial $\eta^2$ | pre mean ± s | 95% Conf limit Up | Low | post-1 mean ± s | 95% Conf limit Up | Low | post-2 mean ± s | 95% Conf limit Up | Low |
|---|---|---|---|---|---|---|---|---|---|---|
| ***Flexion/ Extension*** | | | | | | | | | | |
| Knee Angle at BC (flexion) (°) | 0.461 | -39 ± 9 * | -33 | -45 | -45 ± 8 | -39 | -50 | -44 ± 9 *** | -38 | -51 |
| Hip ROM (°) | 0.484 | 56 ± 10 * | 63 | 49 | 66 ± 9 | 73 | 60 | 62 ± 10 | 68 | 55 |
| Knee - Maximum Angle (flexion) (°) | 0.578 | -17 ± 5 * | -14 | -20 | -22 ± 5 ** | -18 | -25 | -18 ± 5 | -14 | -21 |
| - Minimum Angle (flexion) (°) | 0.605 | -43 ± 7 * | -39 | -48 | -50 ± 7 | -45 | -55 | -49 ± 7 *** | -45 | -54 |
| Hip - Maximum Angle (flexion) (°) | 0.470 | 54 ± 8 * | 60 | 49 | 62 ± 8 | 67 | 56 | 56 ± 10 | 63 | 49 |
| Knee - Maximum Angular Velocity (extension) ($°\cdot s^{-1}$) | 0.517 | 220 ± 116 * | 305 | 134 | 431 ± 115 | 517 | 346 | 411 ± 177*** | 543 | 280 |

**Table IV. Correlations (r) between foot speed and significant support leg dependent variables at ball contact (BC), maximums and ranges of motion (ROM).**

| SUPPORT LEG | | | |
|---|---|---|---|
| ***Flexion/Extension*** | | | |
| Knee Angle at BC (flexion) (°) | 0.05 | -0.43 | 0.03 |
| Hip ROM (°) | 0.61 | 0.11 | 0.37 |
| Knee - Maximum Angle (flexion) (°) | 0.13 | 0.27 | -0.06 |
| - Minimum Angle (flexion) (°) | 0.14 | 0.05 | 0.23 |
| Hip - Maximum Angle (flexion) (°) | 0.14 | -0.24 | 0.02 |
| Knee - Maximum Angular Velocity (extension) ($°\cdot s^{-1}$) | 0.69 | -0.13 | 0.56 |

### 3.5 Discussion

Sprint times progressively significantly increased with fatigue, indicating that the short-term protocol did cause fatigue. Time series data for the hip and knee (Figure 4) were similar in shape to those reported in previous Australian Football kicking research (Ball, 2011; Dichiera, Webster, Kuilboer, Morris, Bach & Feller, 2006). Range of motion and angular velocities increased after the fatigue protocol. Thigh and pelvis range of motion in the sagittal plane and pelvis range of motion in the frontal plane all significantly increased from pre to post-1 conditions, with thigh sagittal plane range of motion also significantly increasing from pre to post-2 conditions. Bazett-Jones, Winchester & McBride (2005) found that after 3 by 3 sets of leg press at 90% maximum, participants displayed a significant increase in lower body joint range of motion, even though there was a significant decline in rate of force production and no change in peak force for isometric squat trials.  The increase in thigh and pelvis sagittal plane range of motion, frontal plane pelvis range of motion, along with the greater minimum knee angle (greater knee flexion) found in the current study could account for the lack of decrease in foot speed.  As absolute kick time significantly increased with fatigue, there is the possibility that a slower kick may give an opponent more time block or interfere with the outcome of the kick in a match situation.  Within-match analysis to determine the overall effect, if any, of kick time increase would be a useful future direction for research.  Post hoc analysis showed that kick time to have a significant relationship with foot speed in the post-1 trials, meaning participants moved their limbs through greater range of motion over a longer period of time, to the point where foot speed did not slow down significantly.  This greater range of motion was also supported by increased maximal thigh frontal plane angular velocity and hip angular velocity (adduction), and increased maximal thigh sagittal plane angular velocity, with post hoc analysis revealing maximal thigh sagittal plane angular velocity having a significant relationship with foot speed in the post-2 trials.  Therefore the importance of the thigh's relationship with foot speed increases as fatigue related to the short-term protocol increases.

In study on the effect of activity on a soccer passing test, McMorris & Rayment (2007) found that a 100m sprint actually resulted in an increase in the speed of movement, as determined by the number of passes.  The number of passes returned to near resting measure after three 100 m sprints.  The authors proposed that the increase in the performance after one sprint could have induced an increase in physiological arousal, and therefore improved speed of performance, however, three bouts led to an over arousal and a subsequent return to performance similar to those found following rest.  Although outside the scope of the current study, the current protocol involved only two short bouts of activity, and the improved speed of movement at the hip and thigh could possibly be due to an increase in physiological arousal.

Changes were also found for support leg kinematics after the short-term fatigue protocol. A more flexed support knee angle at ball contact, as indicated by a significantly greater negative support knee angles (flexion) between pre and post-1 and between pre and post-2 trials, coupled with significantly greater negative maximum and minimum support knee angles (flexion) between pre and post-1 trials following the short-term fatigue protocol indicated that the knee was more flexed through the kick phase when players were under short-term fatigue after the first protocol. Greater maximal support hip angles (flexion) (before the support leg was planted) and greater support hip range of motion (flexion/extension) was also found following fatigue cycle-1. Under short-term fatigue the support leg collapsed more at the hip and knee, possibly not allowing as much drive to the kick after short-term fatigue. Previous research has shown the support limb to display inferior thigh strength and proprioception when compared to the kicking limb during single-limb landing (Ross, Guskiewicz, Prentice, Schneider & Yu, 2004), and may be the reason for why the support leg showed a tendency to collapse more under the weight of the body with fatigue. As the support leg has been reported as being essential to resist the large external force to stabilise the body and to transfer momentum to the thigh (Inoue, Nunome, Sterzing, Shinkai & Ikegami, 2012) it appears as though the more collapsed support leg, as found after the fatigue cycles, should have had a detrimental effect on thigh or hip (Nunome & Ikegami, 2005) movement. Interestingly, in the current study maximal thigh angular velocity and thigh angular velocity at ball contact actually increased after the fatigue cycles, however, kinetics were not measured to determine if positive moments were initiated at the support hip and knee, which has been reported to increase lower leg angular velocity (Nunome & Ikegami, 2005).

Maximal support knee angular velocity (extension), which indicates support knee extension speed at kicking foot toe-off (before the support leg was planted), also significantly increased with fatigue. This increased speed of movement could also relate to the previously discussed possibility of an increase in physiological arousal (McMorris & Rayment, 2007), although not tested in this study, possibly causing the increase in support knee extension speed before the support leg plant. However, this improvement could not continue under the weight of the body as in the stance phase the hip and knee flexed more with short-term fatigue.

While the difference between pre and post-fatigue foot speed was not significant, a large effect existed, and interestingly foot speed increased under short-term fatigue. Foot speed failing to decrease under fatigue is inherently counterintuitive, and in contrast to findings from Kellis et al. (2006) for soccer players performing a maximal instep kick after a 90min intermittent exercise protocol. Kellis et al. (2006) had their players complete a total of 9600m, separated into 12 by 200m of different intensity running, as opposed to the current study which only had two short-term bursts of varied intensity movement, so this might have influenced the different findings. Other studies that have looked at the effects of moderate-volume endurance on the performance of skills and have found non-significant changes in the countermovement jump and maximal instep soccer kick (Juarez, Lopez de Subijana, Mallo & Navarro, 2011). Bullock, Panchuk, Broatch, Christian & Stepto (2012) actually reported improvements in technical skill performance after a 45min soccer-specific exercise program as did Lyons et al. (2006) after a one minute bout of moderate intensity squats.

The findings of the current study align with the lack of skill deterioration found by Lyons' et al. (2006) and Bullock et al. (2012) and give support to the possibility of there being an optimal amount of fatigue that may limit initial decreases in skill outcome.

Given these results it appears as though players may be able to continue to successfully develop foot speed in kicking a drop punt for distance in a match after short-term efforts by making movement adaptations such as increasing the range of motion of the kick thigh and pelvis, and increasing angular velocity at the thigh and hip. More research with larger numbers of players is needed to explore the effects of short-term high-intensity fatigue on sports specific skills. Future research should be conducted with a higher sample rate. The 100Hz capture was a limitation of the current study and was a consequence of the Optotrak system being unable to capture at a faster rate due to the number or markers used. To further assess the appropriateness of the sample rate the authors compared a 100Hz capture to a 500Hz capture and found that maximum error ranges for the parameters measured were low. Further, given game time for team sports is between 30-120 min, longer term fatigue protocols should be examined to determine if technical changes occur over longer periods of time as found with long-term fatigue studies in other tasks. Varied arousal levels should also be tested to determine their influence, if any, on foot speed. Research into the kinetics of the kicking motion under fatigue should also be undertaken to determine what causes these changes in kinematics.

### 3.6 Conclusions

A game specific short-term fatigue protocol affected kicking mechanics but not performance as measured by foot speed.  Contrary to some long-term fatiguing studies, it appears as though participants can make adjustments to their technique to avoid a loss in performance, as indicated by their ability to maintain foot speed in the current study, after a short-term fatigue protocol.   These adjustments were made in the form of increases in kicking leg pelvis sagittal and frontal plane, and kicking thigh sagittal plane range of motion, increased minimum knee angles (flexion), and increases in thigh sagittal and frontal plane and hip velocities (adduction), with the relationship particularly evident at the thigh.  Support knee velocity (extension) also increased with short-term fatigue, whilst support leg flexion and range of motion decreased, showing that this could not be sustained under the weight of the body.

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# Chapter 4

## Study 2

## 4. Kinematic Effects of a Long-Term Fatigue Protocol on Punt-Kicking in Australian Football Players

### 4.1 Abstract

Most kicking studies have examined non-fatigued kick technique, however research indicates that kicking in most team sports is performed under some level of fatigue. This study examined the effects of fatigue on punt kicking kinematics by comparing technique between pre-fatigued and fatigued states, and progressively within the fatigued state. Ten junior male Australian Football players performed maximal kicks prior to and immediately after each of three 10.77min cycles of a game-like running fatigue protocol that included six individualized speeds (maximal sprint, fast run, run, jog, walk, stand) on a non-motorized treadmill. Fifty-six parameters were calculated from VICON Nexus (250 Hz) three-dimensional coordinates, then reduced to eight using factor analysis. Repeated-measures ANOVA was used to identify if changes occurred between: 1. pre-fatigue and fatigued kicks, and 2. kicks performed during the fatigue protocol, with Holms correction used to adjust the alpha-level. Sprint variables declined and overall work decreased across all three cycles, indicating that fatigue (defined as a significant reduction in performance) occurred both compared to the pre-fatigued state, and progressively during each cycle. Compared to pre-fatigue kicks, foot speed was significantly lower in kicks performed after the first two fatigue cycles. Further a different movement strategy was evident with maximal thigh sagittal plane angular velocity and hip flexion at ball contact increasing, and the thigh positioned more vertically at ball contact. Kick kinematics also changed between the fatigue cycles. Later in the protocol, performance improved, and the direction of the changes in the significant parameters (other than hip flexion at ball contact), changed. Fatigue influences kicking performance and technique but longer term changes need to be further revaluated.

**Keywords:** Biomechanics, technique, drop punt, kick

### 4.2 Introduction

In Australian Football the drop punt is the primary kicking technique used due to its accuracy and the ease of marking for the receiver (Ball, 2008; Orchard, Walt, McIntosh & Garlick, 1999). The ability of the individual players to perform the drop punt kick successfully is vital to their team's success (Forbes, 2003). Any factors that increase the kicker's ability to launch the ball longer should be enhanced, whilst any factors that decrease their ability to kick the ball a maximal distance or increase the chance of injury should be minimised.

While there have been soccer-based studies that have looked at fatigue (Kellis, Katis & Vrabas, 2006; Apriantono, Nunome, Ikegami & Sano, 2006; Lees & Davies, 1988), there has not been any research on fatigue and Australian Football skills. Australian Football is a physically demanding sport (Aughey, 2010). It is played on a ground with an area far exceeding that of any of the other football codes (e.g. ground area between 14000 and 19000m$^2$ compared with between 6000 and 8000m$^2$ for soccer and rugby codes) (Ball, 2006). Australian Football is also played for a longer duration than other codes, with the average game taking approximately 120min as compared to 93min in soccer (Ball, 2006). Further, Australian Football players on average cover 12.5km of distance during a game, have an average speed of 6.8km·h$^{-1}$, (7.3km·h$^{-1}$ for midfielders), and spend one third of their playing time in speed zones above 8 km·h$^{-1}$ (Wisbey & Montgomery, 2007). Players have also been found to run at speeds above 18km·h$^{-1}$ on average 90.09 times per game for total time of almost 6min, equating to an average of 4s per sprint over 18km·h$^{-1}$ (Wisbey & Montgomery, 2007). Given these physical demands of Australian Football, coupled with kicking placing high strains on the kick leg (Baczkowski, Marks, Silberstein & Schneider-Kolsky, 2006), and the injury link found between quadriceps injuries and kicking (Orchard et al., 1999), an understanding of kicking technique under fatigue would seem to be important. While the literature examining the punt kick has examined distance and accuracy factors (Dicheria, Webster, Kuilboer, Morris, Bach & Feller, 2006; Ball, 2008; Ball, 2011), this has been performed on pre-fatigued kicks so if changes in technique under fatigue exist, different performance factors might also exist for the kick.

Fatigue has been found to be detrimental to performance (Kellis et al., 2006) or to increase injury risk (Gleeson, Reilly, Mercer, Rakowski & Rees, 1998) during and after match specific fatigue protocols. Rahnama, Reilly, Lees & Graham-Smith (2003) measured quadricep and hamstring muscle strength on an isokinetic dynamometer prior to, at the half way point and after a soccer match-specific protocol. The authors reported that players' leg muscle strength progressively decreased in a game, due to fatigue. In turn this long-term fatigue was proposed to affect kicking technique and leave players more susceptible to injury. Gleeson et al., (1998) was more specific in finding that peak torque was found to significantly decrease in the prolonged intermittent high-intensity shuttle run trials for both knee flexion and extension movements. This decrease in strength was greater in the knee flexors than the extensors. Greig (2009) found that during an intermittent soccer match specific treadmill protocol, knee joint kinematics as measured during a cutting maneuver, changed in the form of decreased flexion at touchdown, and changes in knee valgus and varus alignments, which the author proposed to have implications for increased injury incidence.

Changes due to fatigue have also been found in technique. Kellis et al., (2006) reported changes in soccer kicking technique after a match-specific fatigue protocol. Players performed kicks before, during and after the protocol, producing a significant decline in foot speed (pre 17.64m$\cdot$s$^{-1}$, post 16.38m$\cdot$s$^{-1}$, $P$ < 0.01), ball speed (pre

24.7m·s$^{-1}$, post 21.8m·s$^{-1}$, $P < 0.01$), ball:foot speed ratio (pre 1.40 ± 0.12, post 1.33 ± 0.18, $P < 0.01$), angular velocity of the shank (pre ≈ 1800 ± 600°·s$^{-1}$, post ≈ 1600 ± 450°·s$^{-1}$, $P < 0.01$. Note: means and standard deviations have been approximated from the figures presented in this paper as no values were reported in text form) and angular displacement of the ankle (Pre 144 ± 13°, Post 129 ± 13°, $P < 0.01$). The authors suggested that the decline in ball speed and angular velocity of the shank was due to the reduced strength exerted by the knee musculature at 'critical' times.

These studies, however, are soccer specific. Some fundamental differences exist between soccer kicking and the punt kick that mean these findings might not generalize. The punt kick involves releasing the ball from the hand prior to kicking and in the case of Australian and American football and the rugby codes, ball shape differences (spherical compared to ovoid) means that ball orientation becomes a factor (Ball, 2013a). With the addition of different game demands (Ball, 2006; Wisbey & Montgomery, 2007) it is necessary to re-evaluate these factors specific to punt kicking.

Another limitation of research examining the effects of fatigue on kicking is the use of a large range of fatiguing protocols. The specificity of the protocol has been shown to have an influence on changes in skill performance and it is important to use a protocol that is sport-specific and replicates match-like conditions (Chavez, Knudson, Harter & McCurdy, 2013). Using a non-match specific protocol with an isokinetic dynamometer, Apriantono et al. (2006) found a decrease in peak angular velocity of the shank (pre 37.1 ± 3.4rad·s$^{-1}$, post 35.7 ± 2.4rad·s$^{-1}$, $P < 0.05$), and maximal toe linear velocity (pre 27.1 ± 1.2m·s$^{-1}$, post 26.0 ± 1.3m·s$^{-1}$, $P < 0.01$) during instep kicking after an exhaustive repeated loaded knee extension and flexion fatigue protocol. As foot velocity has been shown to correlate with the distance the ball travels (Ball, 2008), these results indicate that a long-term exhaustive localized fatigue protocol could negatively affect kicking distance. While a strength of this study was the ability to carefully control the amount of work performed in the fatiguing protocol, the knee extensor machine used would have fatigued the rectus femorus but not the illiopsoas hip flexor, found to generate the majority of the muscular force in kicking (Dörge et al., 1999). So while useful information was reported in this study from a carefully controlled loading of the kick leg, this needs to be extended to include more game-specific protocols.

Focusing more on the influence of specific protocols on leg strength, electromechanical delay and knee laxity, Gleeson et al., (1998) used a variety of endurance-based fatiguing protocols designed to simulate the physiological demands of soccer match-play and training. The authors concluded that the prolonged intermittent high-intensity shuttle run trial was most representative of the physiological stresses experienced by soccer players during match play. This trial simulated the 90min of a soccer game broken into observed work-to-rest intervals and activity modes. The total distance of 9600m consisted of 12 by 200 m cycles of activity, each comprising 60m walking ($1.54 m\cdot s^{-1}$), 15m sprinting (5m deceleration and 5m recovery walk), 60m jogging (55% $\cdot VO_{2max}$), and 60m running (95% $\cdot VO_{2max}$). Based on heart rate, blood lactate concentrations and activity profiles, the prolonged intermittent high intensity shuttle run trials were deemed to better represent a soccer match than steady state running (corresponding to 70% $\cdot VO_{2max}$), and a control condition during which no exercise was performed. Kellis et al., (2006) also implemented a 90min soccer-specific intermittent exercise protocol, and performed it on a 20m turf surface, whilst Rahnama et al. (2003) and Greig (2009) used motorised treadmills to perform their 90min soccer-specific intermittent exercise protocols. As each of these fatigue protocols were intermittent and based on match-specific movement patterns, the results are likely to have higher validity for soccer than steady state or non-match specific protocols.

The aim of this study was to examine the effects of a long-term game-specific fatigue protocol on maximal drop punt kicking kinematics in Australian Football by comparing kicking technique between pre-fatigued and fatigued states, and progressively within the fatigued state. The questions addressed were 1. Do changes in kicking kinematics occur after 10, 20, and 30min of game-specific running and 2. Are kinematics affected progressively with increases in fatigue. Changes were evaluated in two sections: between a non-fatigued trail and three post-fatigue trials, and between the three post-fatigue trials.

## 4.3 Methods

### *4.3.1 Participants*

Ten male Associated Public Schools first team representative (age 16.5 ± 0.9years; height 179.7 ± 5.7cm, mass 70.3 ± 7.7kg) Australian Football players were recruited for this study. All participants reported they were free from any injury that may have impaired their ability to kick or exert themselves maximally during the protocol. The parents/guardians of each participant provided written informed consent allowing their sons to take part in the study. University Ethics Committee approval was obtained for this study.

### *4.3.2 Procedures*

All procedures were performed at the University Sports Biomechanics Laboratory. Twenty-eight reflective markers (14mm in diameter) were attached to body landmarks; spinous processes of the 7th cervical and the 10th thoracic vertebrae, xiphoid process of the sternum, where the clavicles meet the sternum, acromio-clavicular joints, anterior superior iliac spines, posterior superior iliac spines, a cluster of three markers on the lateral mid-section of each thigh and anterior lower/mid-section of each shank, the heads of the first and fifth metatarsals and calcaneous of each foot. A static calibration was then performed and anatomical landmarks at the hip, knee and ankle were digitised to create the anatomical frame of each segment, and allow the estimation of internal joint centres (Calibrated Anatomical Systems Technique, Cappozzo, Catani, Della Croce & Leardini, 1995).

### *4.3.3 Warm-up*

Participants performed a standardized warm-up on a non-motorised treadmill (NMT; Woodway Force, Waukesha, WI, USA) for 10min, attempting to move at six different intensities (stand $0 m\cdot s^{-1}$, walk $1.2 m\cdot s^{-1}$, jog $2.1 m\cdot s^{-1}$, run $2.7 m\cdot s^{-1}$, fast run $3.9 m\cdot s^{-1}$ and sprint $6.0 m\cdot s^{-1}$) to simulate an Australian Football match. Participants followed a red line on a monitor that varied its position on the screen when the intensity changed. The warm-up served several purposes; to get the participants warm, to familiarise them with the NMT and the varied intensities and to determine the individuals maximum sprint speed.

Participants then performed dynamic stretches of the muscles to be used in the kicking movement (hamstrings, quadriceps, calfs, hip flexors). Following this, 12 warm-up kicks were performed outside on an oval with each leg (two at 15m, two at 25m and two at 35m). Participants then moved back inside to the testing facility and performed a further four slow approach kicks (three on their preferred leg, one on their non-preferred leg) and four fast approach (three preferred, one non-preferred) kicks to further familiarise themselves with the laboratory environment.

### *4.3.4 Protocol*

Participants were asked to perform three maximal kicks, with the trial with the highest foot speed being selected as the pre kick. Participants then had their hip markers removed, as they interfered with the safety harness on the NMT, and moved back to the NMT to begin the fatigue protocol. The NMT protocol was modified from previous team sport-based research (Sirotic & Coutts, 2007) and made more specific to reflect movement intensities of elite Australian Football (Coutts, Quinn., Hocking, Castagna & Rampinini, 2010; Brewer, Dawson, Heasman, Stewart & Cormack, 2010) (Figure 1). An advantage of a treadmill protocol over a free running protocol is that the activity profile of match-play can better replicated (Greig, 2009; Greig & Siegler, 2009). Drust, Reilly and Cable (2000b) reported that a treadmill, particularly a NMT, has the ability to control experimental conditions and permits a more accurate measurement of running performance. A motorized treadmill requires maximal accelerations to be set between transitions from speeds, such as the maximal $2m \cdot s^2$ used by Greig (2009) and Greig, McNaughton & Lovell (2006). Thus if a participant was accelerating from a stationary position to a maximal sprint of $6m \cdot s^{-1}$ (as was the case with some participants in this study), it would take 3s for the participant to reach maximal speed. Therefore a NMT treadmill was chosen for the study as it has the benefits of almost instantaneous changes in speed (Drust, Cable & Reilly, 2000a; Drust, Reilly & Cable, 2000b), and allows any decline in power output to be detected with the onset of fatigue (Drust, Reilly & Cable, 2000b). A NMT was therefore thought to be more representative of match-like accelerations. Three maximum sprint speeds were then performed, with the intensity of each of the six criterion speeds being adjusted based on each participants highest maximal sprint speed ($5.48 \pm 0.24 m \cdot s^{-1}$). A maximal sprint was represented by 100%, 65% = fast run, 45% = run, 35% = jog, 20% = walk, 0% = standing. Each criterion speed was represented by a red line on the screen and the participant had to keep their movement line (green line) as close to as possible to this red line. As the criterion speed increased the red line would move higher on the screen, indicating to the participant to increase the rate of running on the NMT in order to move the green line higher to match it. The opposite would occur if a decrease in criterion speed was required.

Three fatigue cycles were performed with the duration of each fatigue cycle being 10.77min. This time of each cycle represented approximately one third of a quarter (Heasman, Dawson, Berry & Stewart, 2008) and was performed three times in the protocol, therefore total running time of the protocol represented approximately one quarter of a match. Having three cycles also allowed three preferred foot kicks to be recorded during the protocol which is a reasonable representation of what players would usually perform in a quarter (Johnston, Watsford, Pine, Spurrs, Murphy & Pruyn, 2011). The total of six kicks per protocol (including the three non-preferred kicks included to help elicit fatigue) would be at the upper end, but not unreasonable, of what players perform in a quarter. Each cycle included four 6s sprints with 14s of standing in between each one. These were performed at the start and end of each cycle and were used to assist in inducing fatigue as well as a measure of fatigue (Sirotic & Coutts, 2007; Serpiello, McKenna, Stepto, Bishop & Aughey, 2011). The two other sprints included in the cycle were performed for 3s each, Fast Runs = 4s, Run = 6s, Jog = 8s, Walk = 8s and Stand = 8s (Figure 1).

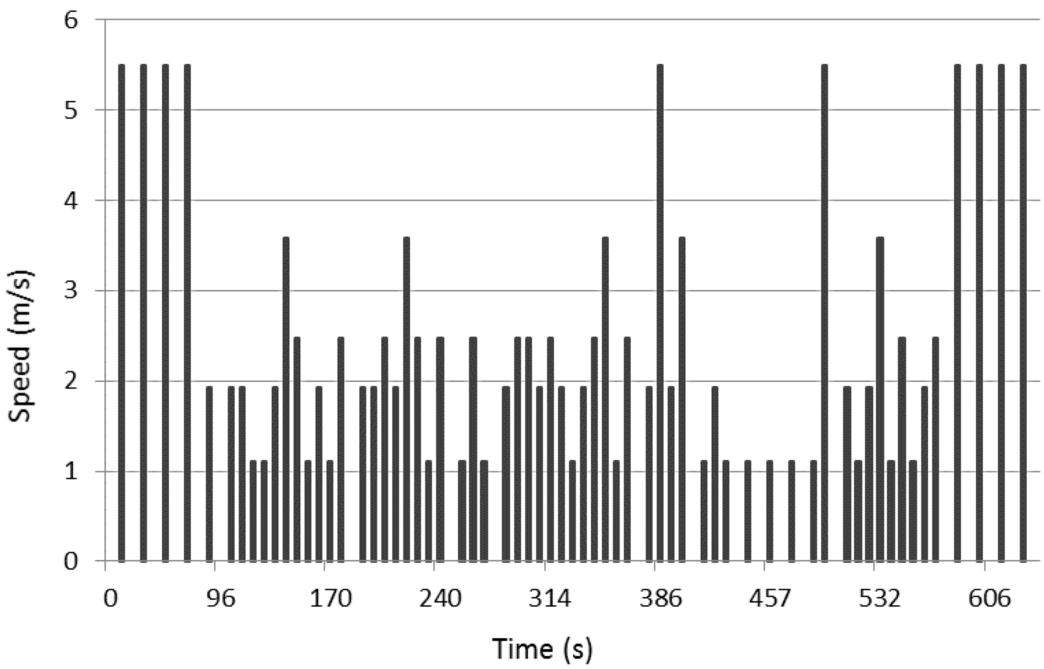


**Figure 1: 10.77 minute varied intensity fatigue cycle profile for a participant with a maximal speed of 5.5m·s$^{-1}$**

After each cycle the participant stepped off of the treadmill, had their hip markers quickly reattached to the previously marked point then they ran to the start of their kick run up (approximately 10m) and kicked a Sherrin football (Sherrin, Australia; official ball in the Australian Football League (AFL) competition, inflated within the AFL specified pressure range of 67-75 psi) for maximal distance first with their preferred then non-preferred legs. The use of both kick legs served to increase the game-specific nature of the task as kicks with both legs are performed but analysis was restricted to the preferred leg only. A static calibration was then performed to be used in analysis of that kick. After this, the hip markers were removed again before immediately beginning another cycle on the NMT. Each participant performed three cycles with the preferred and non-preferred leg at the end of each of these for a total of six kicks across the full sequence (Figure 2).

3 Pre Kicks

↓

Fatigue Cycle 1

↓

Fatigue Kicks 1

↓

Fatigue Cycle 2

↓

Fatigue Kicks 2

↓

Fatigue Cycle 3

↓

Fatigue Kicks 3

**Figure 2: Sequence of Testing**

Each preferred leg kick was recorded using a three dimensional motion-capture system (VICON Motion Systems, Oxford Metrics Ltd., Oxford, UK). Ten cameras (operating at 250 Hz) were calibrated about the kicking runway within an accuracy of 1mm. Interpolation was conducted using VICON spline fill (Reid, Whiteside & Elliott, 2011) for a maximum of five data points. Data were exported to Visual3D software (C-motion Inc, Germantown, MD), smoothed (Butterworth, cut-off frequency = 8Hz, based on spectral and residual analyses of the signal, previous research, e.g. Ball, 2008, and on visual inspection of velocity curves) and analysed from kick foot toe-off until ball contact. To avoid issues of distorted velocity calculations due to smoothing through impact (Knudson & Bahamonde, 2001; Nunome, Ikegami, Kozakai, Apriantono & Sano, 2006; Ball, 2008), data from the instant before ball contact onwards was removed. This pre-impact data were then padded with 30 points from the instant before ball contact in Visual 3D, smoothed using a Butterworth $4^{th}$ order digital filter, then the 30 reflected points were removed so that data to the instant before ball contact only remained. Using this smoothed data, knee (angle between the thigh and shank segments, flexion/extension) and hip (angle between pelvis and thigh segments, flexion/extension, adduction/abduction) joint angles and angular velocities were calculated using local axes. Knee and hip extension angles were represented by 0°. The pelvis, thigh and shank segments were also quantified using the global axis (y-axis aligned with the line of the kick) and both angular displacement and velocity also calculated for these segments. From these time series data, segment (pelvis, thigh and shank) and joint (hip and knee) angle and angular velocity values at ball contact, segment and joint ranges of motion, segment and joint angular velocity maxima and time of maxima were quantified. These parameters were chosen based on previous Australian Football kicking research (Ball, 2008; Ball, 2011), however, the parameters in the current study were expanded to include frontal plane segmental and hip joint angles and transverse plane pelvis angles. Total kick time from kick foot toe-off until ball contact and support knee angle at support heel strike (Ball, 2013b) was also measured. Foot speed was calculated using the marker on the head of the fifth metatarsal as used in previous kicking research (Ball, 2011). All linear and angular velocities were calculated using the three-point central differences method (Nakamura, 1993).

#### *4.3.5 Statistical Analysis*

Group means and standard deviations were recorded for preferred kick leg linear foot speed, the performance measure, and lower body kinematics at ball contact as well as maxima and range of motion. To determine if there was significant difference in mean and peak sprint velocities and mean and peak sprint powers (Serpiello et al., 2011) between the first sprint in the first fatigue cycle and the last sprint in the third fatigue, paired *t* tests were performed in Microsoft Excel 2010. To evaluate the difference between total work performed during each fatigue protocol (to indicate overall fatigue) repeated measures ANOVAs were then performed in SPSS 20. In total, 56 kicking parameters were initially measured. The number of parameters was then reduced using the method employed by Ball (2008) which used a combination of principal components, cross correlations, and theoretical assessment to identify factors among parameters. Principal components analysis was performed using SPSS 20. The Kaiser-Meyer-Olkin measure of sampling adequacy of < 0.06, varimax rotation, and a cut-off of 0.56 for parameter inclusion in a factor ($P < 0.01$) was used. The number of factors chosen was based on an eigen-value greater than one. Groupings with two very large (> 0.70) or three large (> 0.60) loadings were considered to indicate factors (Ball, 2008).

One parameter was chosen from each in order to represent that factor, with the decision being based on a combination of significant findings in previous Australian Football kicking studies, coaching recommendations and theoretical assessment (Ball, 2008). Repeated measures ANOVAs were then performed in SPSS 20 to evaluate the influence fatigue had on each of the kicking variables and on the performance measure, linear foot speed. Significance was set at $P < 0.05$ with a Holm-Bonferroni correction applied post hoc. Briefly this correction involves first performing the analysis then ordering *P*-values for each comparison from smallest (strongest) to largest. The test with the smallest probability is Bonferroni corrected for a family of the number of tests (*C*). If the first test is significant then the second smallest *P*-value is then Bonferroni corrected and adjusted based on the number of tests minus 1 (*C*–1). As soon as a test becomes non-significant the procedure stops. Using the Bonferroni correction with Holm's approach, the corrected *P*-value for the *i*th-test is calculated as $(C - i + 1) \times P$ (Abdi, 2010). Knudson (2009) proposed the use of the Holm's procedure in sports biomechanics research in order to control for the inflation of Type I errors using $P < 0.05$ for multiple comparisons. It also offsets the possibility of generating type 2 errors when using a Bonferroni correction alone. Effect sizes (partial $\eta^2$) were also calculated for comparison. Effect sizes for various indexes, including $\eta^2$ (small = .0099, medium = .0588, large = .1379) have been suggested in previous research (Cohen, 1992). However, when the degrees of freedom (df) of the numerator exceeds 1, as it did with each variable in this study, eta-squared is compared to *R*-squared (Levine & Hullett, 2002). So adapting Cohen's (1992) thresholds, equivalent classification for effect sizes were used as the square root of these thresholds (.01 is a small effect, 0.09 a medium effect and 0.25 a large effect) (Pierce, Block & Aguinis, 2004). Where appropriate, measured parameters that produced large effect sizes were included in discussion to support the significant results and aid in discussion of the explorative data, noting that these would need further research with larger N to clarify. Generally for each variable, df were whole numbers (eg. 3 and 24) but, if sphericity was not satisfied, then adjustment was made through Greenhouse-Geisser.

Post hoc analysis was performed on all significant main effects. Least significant difference (LSD) multiple comparison procedure (Rahnama et al., 2003), were used to determine the specific differences between each fatigue cycle data.

### 4.4 Results

Each of the fatigue related sprint variables significantly decreased between the first sprint of the first fatigue cycle and the last sprint of the last fatigue cycle (Table 1) (mean velocity, $P = 0.02$; peak velocity, $P = 0.01$; mean power, $P = 0.0001$; peak power, $P = 0.03$). Total work during the protocol also decreased ($P = 0.0005$), with post hoc analysis revealing this differences to be significant across all three fatigue cycles (first to second cycle, $P = 0.002$; second to third cycles, $P = 0.03$; first to third trial, $P < 0.001$).

**Table I. Paired t test results for the first sprint and last sprint of each cycle and ANOVA results for total work throughout each cycle. All variables were significantly different.**

| | Cycle | First Sprint | Last Sprint |
|---|---|---|---|
| **Mean Velocity (m·s$^{-1}$)** | 1 | 4.64 (0.18) | 4.29 (0.32) |
| | 2 | 4.59 (0.29) | 4.05 (0.42) |
| | 3 | 4.37 (0.45) | 4.08 (0.59) |
| **Peak Velocity (m·s$^{-1}$)** | 1 | 5.51 (0.22) | 5.07 (0.36) |
| | 2 | 5.43 (0.33) | 4.85 (0.46) |
| | 3 | 5.28 (0.64) | 4.99 (0.63) |
| **Mean Power (W)** | | | |
| | 1 | 696 (119) | 565 (77) |
| | 2 | 620 (139) | 498 (90) |
| | 3 | 565 (155) | 501 (118) |
| **Peak Power (W)** | 1 | 2362 (970) | 1926 (507) |
| | 2 | 1880 (419) | 1667 (422) |
| | 3 | 1620 (402) | 1553 (428) |

| | | Whole Cycle |
|---|---|---|
| **Total Work (kj)** | 1 | 87.31 (11.62) |
| | 2 | 79.94 (9.79) |
| | 3 | 75.48 (12.80) |

The results of the factor analysis with each parameter within the factor it loaded most strongly with, the parameter chosen for further analysis from each factor and the reasoning behind each decision is presented in Figure 3. Initially, scree plots and Eigen values indicated 10 factors existed among the data collected. However, factors nine and 10 did not meet the criteria for consideration as a factor (no very large or large factor loadings) and so were eliminated from the analysis.

| Parameter/Factor | Parameter chosen to represent factor | Reason for choice |
|---|---|---|
| Shank ROM (sagittal)<br>Knee ROM (flexion/extension)<br>Thigh ROM (sagittal)<br>Pelvis ROM (sagittal)<br>Thigh Angular Velocity Maximum (sagittal)<br>Pelvis Angular Velocity Maximum (sagittal)<br>Knee Angular Velocity Minimum Time (sagittal)<br>Hip Angular Velocity Maximum Time (flexion)<br>Pelvis Angle at BC (transverse)<br>Pelvis ROM (transverse)<br>Pelvis Angular Velocity Maximum (transverse)<br>Support Hip ROM (flexion/extension)<br>Support Hip Angular Velocity Maximum<br>Kick Time | Thigh Angular Velocity Maximum (sagittal) | Significant in Baker & Ball, 1996. |
| Shank Angular Velocity at BC (sagittal)<br>Knee Angular Velocity at BC (extension)<br>Thigh Angular Velocity at BC (sagittal)<br>Hip Angular Velocity at BC (flexion)<br>Pelvis Angular Velocity at BC (sagittal)<br>Hip Angular Velocity Maximum (flexion)<br>Pelvis Angular Velocity Maximum Time (sagittal)<br>Support Hip Angular Velocity at BC (flexion/extension)<br>Support Knee ROM (flexion/extension)<br>Thigh Angular Velocity at BC (frontal)<br>Hip Angular Velocity (abduction/adduction)<br>Thigh Angular Velocity Maximum (frontal)<br>Hip Angular Velocity maximum (abduction/adduction)<br>Support Hip Angular Velocity (abduction/adduction)<br>Support Hip Angular Velocity maximum | Knee Angular Velocity at BC (extension | Significant in Macmillan, 1976; Ball, 2008; |

| Parameters | Selected parameter | Rationale |
|---|---|---|
| Pelvis Angular Velocity at BC (transverse)<br>Thigh Angle at BC (frontal)<br>Hip Angle at BC (abduction)<br>Shank Angular Velocity at BC (frontal)<br>Shank ROM (frontal)<br>Thigh ROM (frontal) | Thigh Angle at BC | None of these parameters have been significant in the research to select in this factor, therefore it is important to look at frontal data and the thigh, as thigh sagittal angles were discussed in Baker & Ball, 1996. |
| Hip ROM (flexion/extension)<br>Support Knee Angle at BC (flexion/extension)<br>Pelvis Angle at BC (frontal)<br>Hip ROM (abduction/adduction)<br>Pelvis Angular Velocity Maximum (frontal)<br>Support Hip Angle (abduction/adduction)<br>Support Hip ROM (abduction/adduction) | Hip ROM (flexion/ extension) | Significant in Ball, 2011. Coaching recommendation to maximise hip ROM in Parkin & Smith, 1984. |
| Hip Angle at BC (flexion)<br>Pelvis Angle BC (sagittal)<br>Support Hip Angle at BC (flexion/extension)<br>Support Knee Angular Velocity at BC (flexion/extension)<br>Shank Angle at BC (frontal) | Hip Angle at BC (flexion) | Significant in Ball, 2008; Dichiera et al., |
| Knee Angle at BC (flexion)<br>Thigh Angle at BC (sagittal)<br>Support Knee Angle at Support Heel Strike | Knee Angle at BC | Coaching recommendation in Baker & Ball, |
| Pelvis Angular Velocity (frontal)<br>Pelvis ROM (frontal)<br>Shank Angular Velocity maximum (frontal) | Pelvis ROM (frontal) | None of these parameters have been significant in the research to select in this factor therefore, it is important to look at the pelvis, as pelvis sagittal ROM has been discussed as important (Dichiera et al.,2006; |
| Shank Angle at BC (sagittal)<br>Pelvis Angular Velocity Maximum Time (transverse)<br>Support Knee Angular Velocity Maximum | Shank Angle at BC | Reported in Baker & Ball, 1996; Ball, 2011. |

**Figure 3. Factor analysis of parameters used to describe the maximal Australian Football punt kick. BC = ball contact, ROM = range of motion.**

Significant main effects were found for foot speed, hip flexion angle at ball contact, maximal thigh sagittal plane angular velocity and thigh frontal plane angle at ball contact. Linear foot speed, the performance measure, significantly changed (pre 21.1 ± 1.6m·s$^{-1}$, post-1 20.1 ± 1.1m·s$^{-1}$, post-2 19.7 ± 1.1m·s$^{-1}$, post-3 20.8 ± 1.1m·s$^{-1}$, *P* = 0.01), with post hoc analysis indicating a significant decrease between pre and post-1 (*P* = 0.01) and pre and post-2 (*P* = 0.04) trials. Within the fatigue cycles, foot speed did not differ between post-1 and post-2 trials, but was significantly larger for post-3 compared to post-2 (*P* = 0.02). Holm's corrected significantly different parameters are displayed in Table 2. Hip flexion angle at ball contact significantly increased between pre and post-3 (*P* = 0.004) and within the fatigue cycles it continually increased, significantly between post-1 and post-3 (*P* = 0.002) trials. Maximal thigh sagittal plane angular velocity significantly increased between pre and post-1 (*P* = 0.004) trials. Within the fatigue cycles, it significantly decreased between post-1 and post-2 (*P* = 0.006) and post-1 and post-3 (*P* = 0.021) trials. Thigh frontal plane angle at ball contact decreased from pre to post-1 (*P* = 0.011) and pre to post-2 (*P* = 0.004) trials, while within the fatigue cycles, it increased from post-1 to post-3 trials (*P* = 0.028).

**Table II. Holm-Bonferroni corrected ANOVA results for kick leg parameters. * = Significantly different. Positive joint or segment values represent flexion or adduction, negative values represent extension or abduction. BC = ball contact, ROM = range of motion.**

| KICK LEG | **Pre** mean ± s | **post-1** mean ± s | **post-2** mean ± s | **post-3** mean ± s | **partial** $\eta^2$ | ***P* valve** | **Holm-Bonferroni corrected *P* value** |
|---|---|---|---|---|---|---|---|
| * Hip Angle at BC (flexion) (°) | 21.6 ± 6.8 | 21.7 ± 7.6 | 23.7 ± 7.1 | 25.6 ± 8.1 | 0.419 | 0.004 | 0.028 |
| Knee Angle at BC (flexion) (°) | 47.7 ± 4.7 | 47.1 ± 5.6 | 47.7 ±5.6 | 50.7 ± 5.6 | 0.170 | 0.162 | 0.324 |
| Hip ROM (flexion/extension) (°) | 38 ± 3.9 | 38.9 ± 3.7 | 39.6 ± 4.3 | 40.2 ± 4.3 | 0.139 | 0.300 | 0.324 |
| Knee Angular Velocity at BC (extension) (°·s⁻¹) | 1645 ± 164 | 1615 ± 128 | 1538 ± 153 | 1557 ± 100 | 0.285 | 0.026 | 0.130 |
| ***Sagittal Plane*** | | | | | | | |
| * Thigh Maximum Angular Velocity (°·s⁻¹) | 804 ± 62 | 851 ± 58 | 816 ± 52 | 817 ± 57 | 0.349 | 0.008 | 0.048 |
| Shank Angle at BC (°) | 5.2 ± 3.6 | 7.8 ± 4.2 | 7.9 ± 5 | 4.5 ± 6.4 | 0.224 | 0.072 | 0.216 |
| ***Frontal Plane*** | | | | | | | |
| * Thigh Angle at BC (°) | -14.5 ± 4.5 | -8.9 ± 3.7 | -8.7 ± 3.9 | -11.8 ± 3.8 | 0.446 | 0.001 | 0.008 |
| Pelvis ROM (°) | 16.5 ± 3.1 | 13.3± 4.5 | 12.9 ± 4.2 | 16.6 ± 4.8 | 0.329 | 0.027 | 0.130 |

### 4.5 Discussion

Sprint values decreased from the first to last sprint and overall work decreased across all three cycles. This indicated that fatigue was occurring during each fatigue cycle leading up to the kick performed immediately after the each cycle was completed. It also indicated this fatigue was accumulating, as overall work reduced progressively from the first to third cycle.

Changes with fatigue are discussed in two separate sections. The first focusses on changes between the non-fatigued trial (pre) and any of the three fatigue trials (post-1, post-2 or post-3). The second section of the discussion looks at the changes during fatigue that occur between any of the three fatigue trials (post-1, post-2 or post-3).

#### *4.5.1 Changes from Pre to Post-Fatigue*

Between the pre-trial and at least one of the fatigue trials, significant changes were found for four parameters, including the performance measure, foot speed, and at the thigh and hip.

Foot speed at ball contact decreased with fatigue, with significantly lower speeds evident in post-1 and post-2 kicks and a lower value in post-3 kicks, although this was not significant. Similar detriments in performance with fatigue have been found in soccer-based studies. Kellis et al. (2006) reported a significant decrease in foot velocity after a 90min intermittent exercise protocol, equating to 7.1%, while Apriantono et al. (2006) found a 4.1% decrease in maximal toe linear velocity after an exhaustive repeated loaded knee extension and flexion fatigue protocol. The current study also found significant decreases that were between the ranges found in the soccer studies for pre and post-1 trials (4.7%) and between the pre and post-2 trials (6.4%), whilst there was a non-significant 1.5% decrease between the pre and post-3 trials.

Changes in technique were also evident from pre to post-fatigue trials. Maximal thigh sagittal plane angular velocity was significantly larger than pre-fatigue values for the post-1 kick, while shank angular velocity did not change. This points to the possibility of there being a redistribution of work performed with fatigue, with a greater reliance on the thigh to develop foot speed. A similar change in patterning, where higher angular velocity of the upper leg and lack of change in lower leg velocity values when fatigued was also found in soccer (Lees & Davies, 1988). Their study utilised a relatively short term 6min step test, therefore the similar changes found in the current study may be due to it being early in the protocol, as there was a little over ten minutes of activity that separated the pre and post-1 kick trials. Although higher angular velocities of the upper leg were recorded, Lees & Davies (1988) found no change in foot speed at ball contact and pointed to the possibility of a lack of coordination between the upper and lower leg affecting the transfer of energy between thigh and shank. A similar mechanism may be at play in the current study, and possibility even more pronounced, as this also coincided with a decrease in foot speed at ball contact. Therefore, movement more distally was affected to an even greater degree, possibly due to a similar lack of coordination reported by Lees & Davies (1988). Although not a study on fatigue, Ball (2008) reported a large negative association between knee angular velocity and thigh angular velocity at ball contact ($r = -0.90$, $P < 0.001$), suggesting some players used a thigh strategy (higher thigh angular velocity and relatively lower knee angular velocity) and others a knee strategy (higher knee angular velocity and lower thigh angular velocity) to gain greatest ball distance. It appears as though after the first fatigue cycle in the current study the participants may be adopting a greater ‘thigh strategy’ as they become fatigued. Subject numbers were too low to evaluate this relationship in this study but a useful future direction for this work would be to examine if this shift occurs for both strategies and to what amount.

Thigh angular velocity increased after the first fatigue cycle and shank angular velocity did not change. A similar finding of increased importance on the more proximal segments or joints after fatigue was also found after fatigued drop landings (Coventry, O’Connor, Hart, Earl & Ebersole, 2006). The authors reported a redistribution of energy absorption (negative work) from the muscles that cross the ankle to the larger possibly more fatigue resistant muscles that cross the hip during drop landings after an exhaustive one legged squat protocol (first cycle: Hip -0.20 ± 0.2 J $kg^{-1}$, Knee -0.97 ± 0.4 J $kg^{-1}$, Ankle -1.14 ± 0.3 J $kg^{-1}$; last cycle: Hip -0.44 ± 0.4 J $kg^{-1}$, Knee -0.85 ± 0.4 J $kg^{-1}$, Ankle -0.87 ± 0.2 J $kg^{-1}$). It is possible that a similar coping strategy is at play in the current study, as thigh angular velocity increased the first fatigue cycle and shank angular velocity did not change, however kinetics were not measured. Kinetic analysis should be undertaken in future research to determine if a similar pattern is found for fatigued punt kicking.

Soccer kicking research has also reported a decline in performance for kicking with fatigue, suggesting it was due to the reduced strength exerted by the knee musculature at ‘critical’ times (Kellis et al., 2006). This was based on the finding that the angular velocity of the shank decreased with fatigue after a soccer-specific protocol. Using the same theory, given that thigh angular velocity increased in the current study, it appears as though in Australian Football kicking the hip musculature may have been important for improving the movement of the thigh between pre and post-1 trials, pointing to an increased importance on the hip under fatigue, as found for drop landing (Coventry et al., 2006).

Further supporting the increased importance of the hip with fatigue, hip flexion at ball contact increased between pre and post-3 trials. This might have contributed to the increase in foot speed, as being more flexed at impact may allow the participant to 'put more hip' into the kick, a coaching recommendation deemed as important for Australian Football punt kicking (Parkin & Smith, 1984). Post hoc correlation showed an increased relationship with hip flexion at ball contact and foot speed (pre r = -0.04, post-1 r = -0.14, post-2 r = -0.34, post-3 r = 0.49) during the post-3 kick. From a more theoretical perspective it might have provided a greater distance through which the foot had a force applied to it and so increased work on the foot and subsequent velocity at ball contact. However, in a study on looking at leg presses at 90% maximum, Bazett-Jones, Winchester and McBride (2005) found that after 3 by 3 sets, participants displayed a significant increase in lower body joint range of motion, even though there was a significant decline in rate of force production and no change in peak force for isometric squat trials. Therefore, the increased hip flexion at ball contact between the pre and the post-trials in the current study may not have had a great effect on performance as foot speed did not change significantly between pre and post-3 trials.

Changes between pre and post-fatigue kicks were also found in the frontal plane, with the thigh angles at ball contact becoming more vertical between the pre and post-1, and between the pre and post-2 trials. There has been limited kinematic frontal plane research on kicking, and that that has been undertaken has looked at hip adduction. Hip Angle at ball contact (abduction) was part of the same factor as frontal plane thigh angles at ball contact in the current study and wasn't chosen for further analysis but the hip angle was less abducted during the same kick trials. Katis & Kellis (2011) also found that a reduced foot speed was associated with decreased hip frontal plane rotations in the latter part of soccer instep kick. In the current study, as participants were instructed to kick for distance, and more skilled kickers have been found to display greater hip abduction/adduction range of motion and rotation range of motion in maximal soccer kicking (Shan & Westerhoff, 2005), it appears as though participants were less able to swing the leg around more horizontally in the frontal plane to create a wider arc to assist with increasing foot speed after early fatigue cycles. This materialised itself in a more vertical leg at ball contact in post-1 and post-2 fatigue trials in the current study.

### *4.5.2 Changes During Fatigue*

Changes in technique and performance were also found between the three post-trials. Hip angle (flexion) at ball contact, after being significantly more flexed from pre to post-1 trials, continued to flex more, between post-1 and post-3 trials, whilst the other three significant variables changed direction. Foot speed at ball contact increased between post-2 and post-3 trials, maximal thigh sagittal plane angular velocity decreased between post-1 and post-2 and between post-1 and post-3 trials, and thigh frontal plane angle at ball contact increased between post-1 and post-3 trials, indicating that the kick thigh moved through a more horizontal plane (wider) in the last trial.

The increase in foot speed after the final cycle was unexpected and did not support the majority of previous research. It was not due to a 'thigh strategy' as maximal sagittal plane thigh angular velocity also decreased between post-1 and post-3 cycles, and did not change significantly between post-2 and post-3 trials.

Both hip angle and thigh frontal plane angle were significantly different in the post-3 kick compared to post-1 which might have contributed to the increase in foot speed in the last kick. Considering first the thigh frontal plane angle change, the post-3 value was 33% larger than post-1 ($P = 0.028$) and 36% larger than post-2, although this was not significant ($P = 0.063$). This suggested that players were positioning their thigh at a greater angle to the horizontal. This might indicate players were leaning further to the side, extending the thigh more laterally at ball contact or a combination of both. As hip abduction at ball contact was also in the same factor as thigh frontal plane angle, it is likely due to extending the thigh more laterally. From a theoretical perspective this position would allow for the kick leg to be extended further, providing a longer lever, while avoiding the kick foot toe striking the ground. However, this was not supported by knee extension data, which indicated the knee was more flexed at the point of ball contact for post-3 compared to post-1 and post-2 (Table 1). Therefore, the larger frontal plane thigh angle is possibly a result of a greater range of motion through which the leg is taken through during the forward swing, a factor found to be associated with greater foot speed in soccer (Katis & Kellis, 2011). To further cloud the reason for this finding, the correlation between foot speed and thigh frontal plane angle at ball contact became more negative, indicating that a larger thigh frontal plane angle was actually associated with slower foot speeds (post-2 r = -0.19, post-3 r = -0.49).

The influence of increased flexion of the hip at ball contact to foot speed provided clearer evidence. Hip flexion at ball contact increased by 18% between post-1 and post-3 trials ($P = 0.002$), and non-significantly increased by 8% between post-2 and post-3 trials ($P = 0.18$). As stated previously, the strongest correlation between hip flexion at ball contact and foot speed was for the post-3 trails (r = 0.49), which was an increase in strength and change in direction from the pre (r = -0.04), post-1 (r = -0.14) and post-2 trials (r = -0.34). It therefore appears that the influence of hip flexion at ball contact on performance increased as the protocol progressed into the post-3 trial, and may account for why post-3 foot speed increased as compared to post-2 foot speed. Again, theoretically this might provide a greater distance through which foot can have force applied to it and subsequently increase its speed. Hip range of motion was also at its largest during the post-3 trials.

After several trials, participants appeared to be able to learn to adapt to the fatigue by changing their technique at the hip in order to improve their performance at the foot. Hip flexion at ball contact increased and thigh frontal plane angle widened after the last cycle, and shank or knee parameters did not change. A similar finding of an initial decrease in performance followed by an improvement in performance later in a fatigue protocol has also been found during a soccer fatigue protocol (Ferraz, van den Tillar & Marques, 2012). Ten participants, repeating a fatigue circuit, then kicking for maximal power five times, found soccer ball velocity decreased after circuit one, but increased after circuit three, and again after circuit five compared to circuit two. Similar to the current study, there were not progressive directional changes, and an initial decrease in performance was followed by improvement in performance in the later stages of the protocol. The authors suggested the general governor model might be responsible, where participants may have subconsciously paced themselves and kept a security reserve for an “end spurt” (Millett, 2011). Ferraz et al. (2012), considered that their participants may have tapped in to this security reserve knowing they were nearing the end of the protocol. While this possible influence cannot be evaluated in the current study, participants in the current study were also aware of the end point of the protocol, and a similar motivation may have been at play. Future research should control for the potential for participant pacing by not having obvious finishing times to determine if this is a factor in improved punt kicking performance later in a fatigue protocol. Further research into the effects of long term fatigue on kicking kinetics is also needed to determine what causes these changes in kinematics.

### 4.6 Conclusions

Drop punt kicking technique changed following a long-term fatigue protocol. Changes were found in the performance measure foot speed, and at the thigh and hip. Compared to pre-fatigued kicking, foot speed decreased, thigh frontal plane angle at ball contact became more vertical, maximal thigh angular velocity increased and the hip became more flexed at ball contact. Participants appeared to attempt to minimise this decrease in performance through increasing maximal thigh sagittal plane angular velocity and hip flexion at ball contact. Kicking hip flexion continued to increase throughout the protocol. Changes also existed within the fatigue trials. Between the post-fatigue trials a change of strategy became apparent, with the initial more vertical, faster kicking thigh slowing down and increasing its angle later in the protocol as indicated by a decrease in maximal thigh sagittal plane angular velocity and increasing thigh frontal plane angles at ball contact. This coincided with an increase in foot speed between the last two trials. Participants appeared to be able to learn to adapt to the fatigue by changing their technique after several trials.

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# Chapter 5

## Study 3

## 5. Kinetic Effects of a Long-Term Fatigue Protocol on Punt-Kicking in Australian Football Players

### 5.1 Abstract

Changes to the kinematics of kicking technique under fatigue have been found and to better understand the underlying mechanics of these changes, the next stage of this research needs to examine the kinetics of the kick. The purpose of this study was to examine the effects of a long-term game-specific fatigue protocol on maximal drop punt kicking kinetics. Ten junior male Australian Footballers performed maximal kicks prior to and immediately following three 10.77min cycles of a game-like fatigue protocol that included maximal sprinting, fast running, running, jogging, walking and standing on a non-motorized treadmill. Three-dimensional data were obtained using VICON (250Hz) from kick foot toe-off until ball contact with kinetics of the kick leg calculated using inverse dynamics. Sprint times increased and overall work significantly decreased between the pre-test and fatigue tests as well as progressively during each cycle. Between pre and post-fatigue cycles, performance (foot speed) declined likely due to a decrease in the maximal knee extension moment. A greater reliance on the hip to perform the kicks later in the protocol was also indicated as the decrease in maximal moments was more prominent at the knee. The increase in foot speed between the second and final cycles could not be explained by kick leg kinetics. Fatigue influences kicking performance, kinetics, but longer term changes need to be researched more.

**Keywords:** Biomechanics, technique, drop punt, kick

### 5.2 Introduction

The punt kick is a fundamental skill used in Australian Football. Research suggests a proximal-to-distal sequence of segment motions in kicking, with muscle activation being a crucial factor in the accelerating and decelerating of segments (Nunome, Ikegami, Kozakai, Apriantono & Sano, 2006; Orchard, Walt, McIntosh & Garlick, 1999). Muscles have been reported as being directly responsible for increasing the speed of the foot during kicking (Lees & Nolan, 1998). Manolopoulos, Papadopoulos & Kellis (2006) found that a combined strength and kicking coordination program caused a significant increase in ball speed, an important indicator of a successful soccer kick.

There has only been limited work examining kinetics of the punt kick. In a study produced for the Australian Football League Research and Development Board, Orchard, McIntosh, Landeo, Savage & Beatty (2003) discussed kinetic data when reporting the implications for quadricep strain injuries when kicking in Australian Football, but failed to include quantitative values. The results showed that greatest peak moment and power values are achieved at the hip, followed by knee. Putnam (1983) also found this to be the case when reporting on the interaction between segments during the punt kicking motion.

The drop punt kicking motion in Australian Football has been reported to place very high strains on the muscles of the upper thighs and legs, not only possibly decreasing performance, but also placing players at risk of injury (Baczkowski, Marks, Silberstein & Schneider-Kolsky, 2006). Injuries to the quadriceps of the kicking leg have been shown to be almost certainly increase by kicking a football (Orchard et al., 1999). Baczkowski et al. (2006) established that the rectus femoris is significantly activated during a drop punt kick. Dawson, Andrews and Stewart (2004) concluded that in elite Australian Footballers, hamstring/quadricep moment ratios reduce after acute running fatigue. Although kicking was not tested, this was proposed to increase the chance of hamstring injury. It is therefore important to determine if these changes in muscle activation under fatigue have an influence on kicking mechanics.

Peak moment has been used in research as a measure of strength (Rahnama, Reilly, Lees & Graham-Smith, 2003). Soccer kicking research has shown that peak joint moments are highest at the hip, followed by the knee, and lowest at the ankle. Hip flexion moment data has been reported to range between 309N.m (Nunome et al., 2006) and 194N.m (Luhtanen, 1988). Knee extension moment data has ranged between 161N.m (Dörge et al., 1999) and ≈ 68N.m (Roberts et al., 1974). These differences in values have been mainly due to methodological issues such as the reporting of either average or instantaneous values, two versus three-dimensional models, and differences in data processing, particularly at impact (Kellis & Katis, 2007). There has been limited research on hip abduction/adduction and internal/external moments, however Kawamoto, Miyagi, Ohashi & Fukashiro (2007) reported experienced side-foot kicking soccer players to display 168 ± 20N.m of hip flexion, 100 ± 39N.m of hip adduction, 41 ± 9N.m of hip external rotation, 32 ± 7N.m of knee extension, and 10 ±1N.m of ankle dorsiflexion. The authors also reported skilled soccer players performing a place kick to display average peak hip muscle moments of 271.3Nm and average peak knee muscle moments of 161.0Nm.

Given that peak moments are a measure of strength and it is reported in several soccer kicking studies due to its importance, it stands to reason that any factors, such as fatigue, that may reduce peak moments, will in turn affect the performance of the kick. In the only published study on the effect of fatigue on Australian Football kicking, Coventry, Ball, Parrington, Aughey & McKenna (2015) found that foot speed (pre 19.7 ± 2m·s$^{-1}$, post-2 20.5 ± 1.4m·s$^{-1}$), the performance measure did not significantly change with fatigue. Increases in the range of motion at the pelvis (pre 51 ± 8°, post-1 57 ± 10°), kicking thigh (pre 84 ± 5°, post-1 88 ± 5°, post-2 89 ± 5°) and shank (pre 87 ± 13°, post-2 97 ± 7°), along with increases in kicking thigh angular velocity (maximum pre 742 ± 89°·s$^{-1}$, post-1 796 ± 111°·s$^{-1}$; at ball contact post-1 51 ± 56°·s$^{-1}$, post-2 118 ± 53°·s$^{-1}$) were also reported. The study required participants to kick before and after a first and second short-term bout of intermittent activity simulating a section of a game. The authors concluded that contrary to some long-term fatiguing studies, that have produced detriments in performance, participants appeared to make adjustments to their technique to avoid a loss in performance. In addition to not focusing on the effects of long-term fatigue, the study did not report kinetic data.

There has been more extensive research done on the effects of fatigue on soccer kicking. Fatigue or reduced performance has been shown to occur towards the end of a match (Mohr, Krustrup & Bangsbo, 2005). Injury risk has been shown to be highest in the first and last 15min of a soccer match, reflecting the intense opening of a game and the possible effects of fatigue late in the game (Rahnama, Reilly & Lees, 2002). Rahnama et al. (2003) showed that late in a game, as players get tired their leg muscle strength decreases (shown as significant reductions in peak moments for both hamstrings and quadriceps at several angular velocities, $P < 0.001$) as does the hamstrings:quadriceps ratio (ratio decreased by 3.6, 9.7 and 6.2% at testing speeds of 1.05, 2.09 and 5.23rad·s$^{-1}$) due to fatigue. Rahnama et al. (2003) tested quadricep and hamstring muscle strength on an isokinetic dynamometer prior to, at the half way point and after a 90min soccer-specific intermittent exercise protocol performed on a treadmill. Intensities elicited walking, jogging, running and sprinting, as observed in a soccer match. The results show a decrease in both quadricep and hamstrings strength, but this decrease was more prominent in the hamstrings, leaving the quadriceps to become more dominant (greater quadricep dominance has also been found for high level soccer players as opposed to sedentary individuals; Tourney-Chollet, Leroy, Delarue & Beuset-Blanquart, 2003). A similar fatigue protocol was also used by Rahnama, Lees & Reilly (2005) to test the electromyographic (EMG) activity of selected lower limb muscles at various intensities before, during and after fatigue. The subsequent decrease in RMS value of EMG activity (pre-exercise, half-time, and post-exercise) of the rectus femoris ($P < 0.05$), biceps femoris ($P < 0.01$) and tibialis anterior ($P < 0.05$) was thought to be an indicator of fatigue and decreased strength during prolonged exercise. A significant effect was not found for the gastrocnemius. The authors also pointed out that due to reduced muscle strength, represented by decreased RMS signals, greater levels of muscle activation would be needed to maintain performance. This was not observed in Rahnama et al.'s, (2005) study, suggesting that players were possibly making some other compensations such as switching activity to other muscle groups to accommodate the required work load.

Gleeson, Reilly, Mercer, Rakowski & Rees (1998) also attempted to use a variety of endurance-based fatiguing protocols designed to simulate the physiological demands of soccer match-play and training to test the effects on leg strength, electromechanical delay and knee laxity. Peak moments were found to significantly decrease in several trials and was greater in the knee flexors compared to the extensors (Gleeson et al., 1998). Kicking technique was not analysed in either of these studies.

Kellis, Katis & Vrabas (2006) used a 90min intermittent exercise protocol to test the effect of long-term fatigue on the maximal instep kick. Kicks were performed before, during and after the protocol. The fatigue protocol caused a significant decline in ball speed (pre 24.7m·s$^{-1}$, post 21.8m·s$^{-1}$, $P < 0.01$), angular velocity of the shank (pre ≈ 1800 ± 600°·s$^{-1}$, middle ≈ 1550 ± 500°·s$^{-1}$, post ≈ 1600 ± 500°·s$^{-1}$, $P < 0.01$) and angular position of the ankle (pre 144 ± 13°, middle 132 ± 16°, post 129 ± 13°, $P < 0.01$). Kellis et al. (2006) reported this was associated with a significant decline during the support phase of the net moment ($N_m$) applied on the shank (pre 232 ± 81, post 185 ± 93, $P < 0.01$) and moment because of muscle force acting on the shank ($M_m$) (pre 115 ± 48, post 79 ± 46, $P < 0.01$). The authors suggested the decline in ball speed and angular velocity of the shank was due to the reduced strength exerted by the knee musculature at 'critical' times. The thigh velocity stayed constant and shank velocity significantly decreased due to the net moment applied on the shank decreasing. This alteration in the proximal to distal pattern is similar to that reported by Coventry, O'Connor, Hart, Earl & Ebersole (2006), who found a redistribution of energy absorption from the ankle to the larger proximal muscles that cross the hip during fatigued landings.

Despite the fact that Australian Football is played on a ground with an area far exceeding that of any of the other football codes, is played for a longer duration than other codes (Ball, 2006), and on average players cover more distance than soccer players (Wisbey & Montgomery, 2007; Greig, 2006), there has been a lack of research as to how fatigue influences kicking kinetics in Australian Football. The aims of this study were to examine the effects of a long-term game-specific fatigue protocol on maximal drop punt kicking kinetics in Australian Football by comparing kicking technique between pre-fatigued and fatigued states, and progressively within the fatigued state. The questions addressed were 1. Do changes in kicking kinetics occur between the pre-fatigued and fatigued state and 2. Are kinetics affected progressively with increases in fatigue by examining kicking after 10, 20 and 30min of game-specific running. Changes were evaluated in two sections: between a non-fatigued trial and three post-fatigue trials, and between the three post-fatigue trials.

## 5.3 Methods

**A note for the examiners: this study was performed using data from the same testing session as in Study 2 with the differences only in analysis procedures examining kinetics rather than kinematics. However, angular velocities data are also included to assist in interpreting the kinetics. This inclusion had no influence on the statistical procedures and significant variables found. As both studies have been submitted for review in journals, wording differs between this Study and Study 2 given it would infringe copyright to have the same text and figures. There are some additions (e.g. Figures 1 and 2, and Table 1) included for the convenience of the reader and these additions have been noted.**

### *5.3.1 Participants*

Ten male Australian Football players who represented an Associated Public Schools first team (age 16.5 ± 0.9years; height 179.7 ± 5.66cm, mass 70.25 ± 7.66kg) participated in this study. Each of the participants reported they were free from any injury that may have limited the ability to perform maximally or kick during testing. Written informed consent was provided by the parents/guardians of each participant to allow their son to take part in the study. Approval for this study was obtained by the University Ethics Committee.

### *5.3.2 Procedures*

Procedures were performed at the University Sports Biomechanics Laboratory and involved the attachment of twenty-eight reflective markers (14mm in diameter) to body landmarks; the heads of the first and fifth metatarsals and calcaneous of each foot,  a cluster of three on the lateral mid-section of each thigh and anterior, the anterior superior iliac spines, posterior superior iliac spines, lower/mid-section of each shank, acromio-clavicular joints, where the clavicles meet the sternum, the xiphoid process of the sternum and the spinous processes of the 7th cervical and the 10th thoracic vertebrae.  In addition to the tracking markers, anatomical landmarks at the hip, knee and ankle were digitised after a static calibration to create the anatomical frame of each segment, and allow the estimation of internal joint centres (Calibrated Anatomical Systems Technique, Cappozzo, Catani, Della Croce, & Leardini, 1995).

### *5.3.3 Warm-up*

Participants performed a standardized warm up that simulated a 10min section of an Australian Football match on a non-motorised treadmill (Woodway Force, Waukesha, WI, USA), attempting to move at six different intensities (stand $0 m \cdot s^{-1}$, walk $1.2 m \cdot s^{-1}$, jog $2.1 m \cdot s^{-1}$, run $2.7 m \cdot s^{-1}$, fast run $3.9 m \cdot s^{-1}$ and sprint $6.0 m \cdot s^{-1}$).  A monitor displayed a red line that varied its position on the screen when the intensity changed.  This approach was chosen as in addition to getting the participants physically ready for the study, the warm-up also allowed them to familiarise themselves with the non-motorised treadmill and the varied intensities and to determine the individual's maximum sprint speed.

Following the treadmill section of the warm-up, participants performed dynamic stretches of the muscles to be used in the kicking movement (hamstrings, quadriceps, calfs, hip flexors), and then undertook 12 warm-up kicks. These kicks were performed outside on an oval with both the preferred and non-preferred legs (two at 15m, two at 25m and two at 35m). After the outside kicks, the participants then moved back inside to the testing facility and performed an additional four slow approach kicks (three on their preferred leg, one on their non-preferred leg) and four fast approach (three preferred, one non-preferred) in order to further familiarise themselves with the laboratory environment.

### *5.3.4 Protocol*

Participants performed three maximal kicks from inside the lab kicking out onto an oval through a large open doorway, with the trial with the highest foot speed being selected as the pre-kick. Following the pre-kicks, participants had their hip markers removed, as they interfered with the safety harness on the non-motorised treadmill, and moved back onto the non-motorised treadmill to begin the fatigue protocol. The non-motorised treadmill protocol was modified from previous team sport-based research (Sirotic & Coutts, 2007) to more specifically reflect the movement intensities of elite Australian Football (Coutts, Quinn, Hocking, Castagna. & Rampinini, 2010; Brewer Dawson, Heasman, Stewart & Cormack, 2010) (Figure 1). A treadmill, as opposed to free running, was chosen for the protocol as the activity profile of match-play can be better replicated (Greig, 2009; Greig & Siegler, 2009). Specifically, a non-motorised treadmill was chosen over a motorized treadmill, as motorized treadmills require maximal accelerations to be set between transitions from speeds (Greig, McNaughton & Lovell, 2006; Greig, 2009). A non-motorised treadmill has the benefits of almost instantaneous accelerations and decelerations (Drust, Cable & Reilly, 2000) and was thought to therefore be more representative of match-like accelerations.

To permit the speeds for each of the six levels of the protocol to be set, three maximum sprints were performed, with the intensity of each of the six speeds being adjusted based on each participants highest maximal sprint speed ($5.48 \pm 0.24 m \cdot s^{-1}$). Standing was represented by 0%, 20% = walk, 35% = jog, 45% = run, 65% = fast run, and 100% represented a maximal sprint. Each of these speeds was represented on the monitor by a red line that the participant had to keep their movement line (green line) as close to as possible. The faster the speed required, the higher the red line would move on the screen, indicating to the participant to increase the speed of running on the non-motorised treadmill in order to move the green line higher to match it. A required decrease in speed was represented by a lower red line and the participant had to move slower in order to match it with their green line.

Each fatigue cycle lasted 10.77min, with three fatigue cycles being performed by each participant, with the total running time of the protocol representing approximately one quarter of a match (Heasman, Dawson, Berry & Stewart, 2008). Breaking the protocol into three cycles also allowed three preferred foot kicks to be recorded during the protocol. Three kicks a quarter is a reasonable representation of what players would usually perform in elite Australian Football (Johnston, Watsford, Pine, Spurrs, Murphy & Pruyn, 2011). Including the extra three non-preferred kicks (included in the protocol to help elicit fatigue), the total of six kicks per protocol would be at the upper end, but not unreasonable, of what players perform in a quarter. Each cycle also included four 6s sprints with 14s of standing in between each one. These were used to assist in inducing fatigue, as well as a measure of fatigue, and were performed at the start and end of each cycle (Sirotic & Coutts, 2007; Serpiello, McKenna, Stepto, Bishop & Aughey, 2011). Each cycle also included: two other sprints for 3s each, Fast Runs = 4s, Run = 6s, Jog = 8s, Walk = 8s and Stand = 8s (Figure 1).

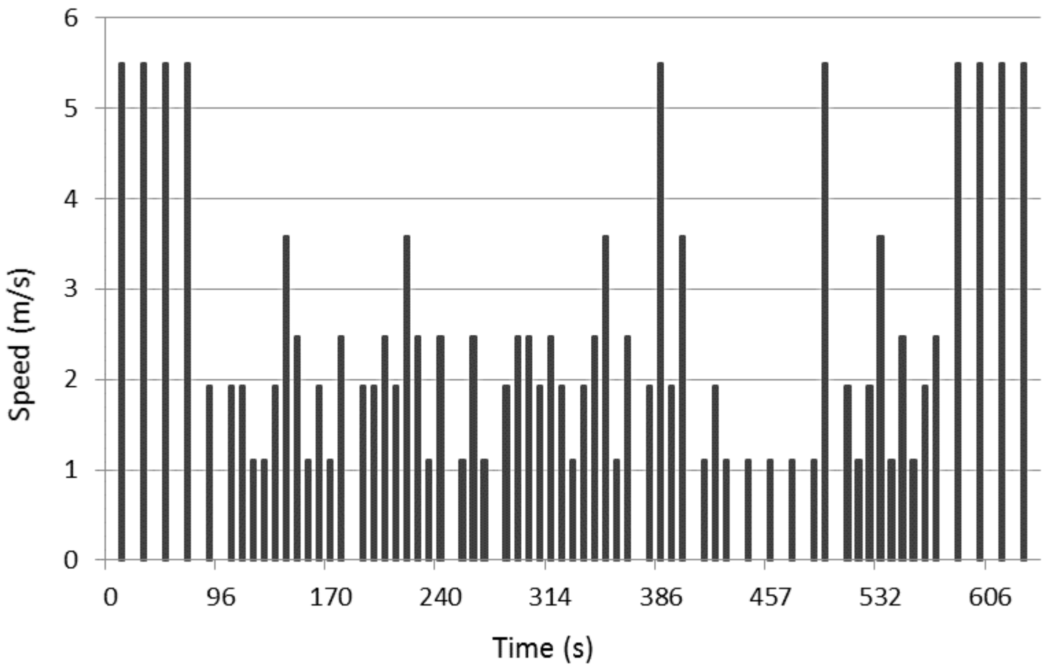



**Figure 1: 10.77min varied intensity fatigue cycle profile for a participant with a maximal speed of 5.5m·s$^{-1}$** (repeated from study 2 for the convenience of the reader)

After each cycle the participant moved off of the treadmill and had their hip markers quickly reattached to the previously marked point. They then ran to the start of their kick run-up and kicked a Sherrin football (Sherrin, Australia; official ball of the Australian Football League (AFL) competition, inflated within the AFL specified pressure range of 67-75 psi) for maximal distance first with their preferred leg, then with their non-preferred leg. In case the hip markers were not reattached in the exact location as previously, a static calibration was then performed. The hip markers were then removed again before the participant immediately began another cycle on the non-motorised treadmill.  Each participant performed three cycles, with a preferred and non-preferred leg kick at the end of each of the cycles, for a total of six kicks across the full sequence, with only preferred leg kicks being analyzed (Figure 2).

3 Pre Kicks

↓

Fatigue Cycle 1

↓

Fatigue Kicks 1

↓

Fatigue Cycle 2

↓

Fatigue Kicks 2

↓

Fatigue Cycle 3

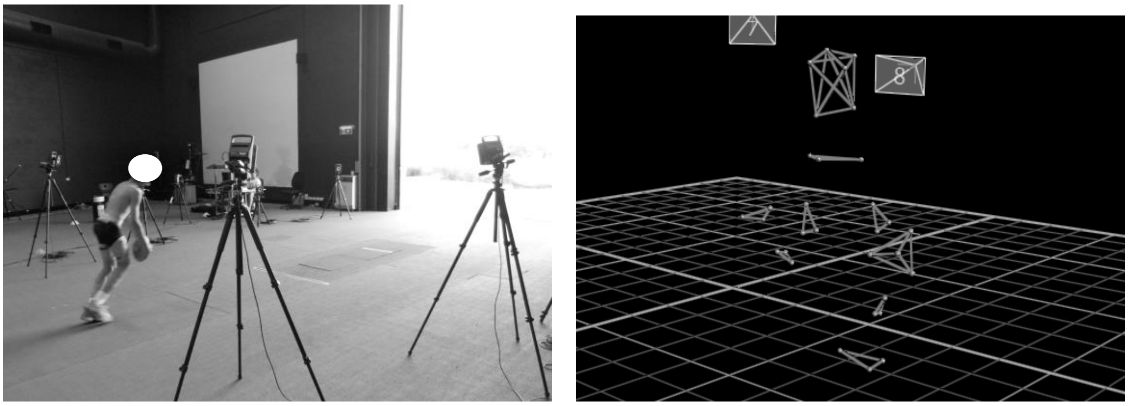
↓

Fatigue Kicks 3

**Figure 2: Sequence of Testing** (repeated from study 2 for the convenience of the reader)

A three-dimensional motion-capture system (VICON Motion Systems, Oxford Metrics Ltd., Oxford, UK) was used to record each preferred leg kick (Figure 3). Ten cameras (250Hz) were calibrated about the kicking runway within an accuracy of 1mm. Markers were tracked to include the phase from kick foot toe-off until the instant before ball contact. Once collected, data were identified, interpolated for a maximum of five data points, using VICON spline fill (Reid, Whiteside & Elliott, 2011) then exported to Visual 3D software (C-motion Inc, Germantown, MD) for data analysis. Data were smoothed (Butterworth, cut-off frequency = 8Hz, based on spectral and residual analyses of the signal, previous research, e.g. Ball, 2008, and on visual inspection of velocity curves) and analysed from kick foot toe-off until ball contact. To avoid issues of distorted velocity calculations and smoothing through impact, data from the instant before ball contact onwards was removed (Knudson & Bahamonde, 2001; Nunome, Asai, Ikegami & Sakurai, 2002) and then padded. Padding was undertaken from the instant before ball contact forwards with 30 points (reflected) in Visual 3D, then smoothed using a Butterworth 4$^{th}$ order digital filter, then the 30 reflected points were removed so that only data up to the instant before ball contact remained.

Using this smoothed data, knee (angle between the thigh and shank segments, flexion/extension) and hip (angle between pelvis and thigh segments, flexion/extension, adduction/abduction) joint angular velocities were calculated using local axes. Kinetic parameters quantified included maximal hip (flexion/extension and abduction/adduction) and maximal knee (flexion/extension) moments and powers. Joint parameters were chosen based on previous kicking research (Kawamoto et al., 2007; Nunome et al., 2002). Hip and knee joint moments were calculated using inverse dynamics (Winter, 2005; Kawamoto et al., 2007) in Visual 3D. The head of the fifth metatarsal was used to calculate foot speed (Ball, 2011). The three-point central differences method (Nakamura, 1993) was used to calculate all linear and angular velocities.  In total, nine parameters were measured consisting of maximal hip flexion and adduction angular velocity, moment and power and maximal knee extension angular velocity, moment and power. Linear foot speed was also calculated as the performance measure.



**(a)** **(b)**

**Figure 3:  Participant kicking out maximally to an open field (a).  Three-dimensional reconstruction of participant on motion-capture system (VICON Motion Systems, Oxford Metrics Ltd., Oxford, UK) (b)**

### *5.3.5 Statistical Analysis*

Means and standard deviations were recorded for preferred kick leg linear foot speed, maximal hip (flexion/extension, abduction/adduction) and maximum knee (flexion/extension) angular velocities, moments and powers.  (Angular velocities were analysed in Study 2 of this thesis, but were also used here to assist in interpretation of moment and power data).  Paired *t* tests were performed in Microsoft Excel 2010 to determine if there was significant difference in mean and peak sprint velocities and mean and peak sprint powers (Serpiello et al., 2011) between the first sprint in the first fatigue cycle and the last sprint in the third fatigue cycle.  Repeated measures ANOVAs were then performed in SPSS 20 to evaluate the difference between total work performed during each fatigue protocol (to indicate overall fatigue) and the influence fatigue had on each of the nine kicking variables and on the performance measure, linear foot speed.  Significance was set at $P < .05$ and Holm's correction was performed, involving ordering *P*-values for each comparison from smallest (strongest) to largest.  The test with the smallest probability, the strongest test, is Bonferroni corrected for a family of the number of tests (*C*).  A second test on the next smallest *P*-value is then Bonferroni corrected, if the original strongest test was found to be significant, and is adjusted based on the number of tests minus 1 ($C$–1).  The procedure stops as soon as a test becomes non-significant.  The corrected *P*-value for the *i*th-test is calculated as $(C - i + 1) \times P$ by using the Bonferroni correction with Holm's approach, (Abdi, 2010).  The Holm's procedure has been proposed to control the inflation of Type I errors in sports biomechanics research using $P < 0.05$ for multiple comparisons, while also offsetting the possibility of generating type 2 errors when using a Bonferroni correction alone (Knudson, 2009).  Effect sizes (partial $\eta^2$) were calculated for comparison and discussion.  Cohen (1992) suggested effect sizes for various indexes, including $\eta^2$ (small = .0099, medium = .0588, large = .1379), however, when the degrees-of-freedom of the numerator exceeds 1, as it did with the variables in this study, eta-squared is compared to R-squared (Levine & Hullett, 2002).  Therefore, adapting Cohen's (1992) thresholds, equivalent classification for effect sizes were used as the square root of these thresholds (.01 is a small effect, 0.09 a medium effect and 0.25 a large effect) (Pierce, Block & Aguinis, 2004).  Generally for each variable, degrees-of-freedom were found to be whole numbers (eg. 3 and 24) but, if sphericity was not satisfied, then adjustment was made through Greenhouse-Geisser.

Post hoc analysis was performed on all significant main effects, with least significant difference (LSD) multiple comparison procedure (Rahnama et al., 2003), being used to determine the specific differences between each fatigue cycle data.

### 5.4 Results

Sprint variables significantly decreased between the first sprint of the first fatigue cycle (so effectively the pre-fatigue state) and the last sprint of the last fatigue cycle (mean velocity $P = 0.02$, peak velocity $P = 0.01$, mean power $P = 0.0001$, peak power $P = 0.03$) (Table 1). There was also a significant decrease in total work during the protocol also ($P = 0.0005$), that was significant across all three fatigue cycles when analysed post hoc (first to second cycle $P = 0.002$, second to third cycles $P = 0.03$, first to third cycle $P < 0.001$).

**Table I. Paired t-test results for the first sprint and last sprint of each cycle and ANOVA results for total work throughout each cycle. All variables were significantly different (**repeated from study 2 for the convenience of the reader)

| | Cycle | First Sprint | Last Sprint |
|---|---|---|---|
| **Mean Velocity (m·s$^{-1}$)** | 1 | 4.64 (0.18) | 4.29 (0.32) |
| | 2 | 4.59 (0.29) | 4.05 (0.42) |
| | 3 | 4.37 (0.45) | 4.08 (0.59) |
| **Peak Velocity (m·s$^{-1}$)** | 1 | 5.51 (0.22) | 5.07 (0.36) |
| | 2 | 5.43 (0.33) | 4.85 (0.46) |
| | 3 | 5.28 (0.64) | 4.99 (0.63) |
| **Mean Power (W)** | | | |
| | 1 | 696 (119) | 565 (77) |
| | 2 | 620 (139) | 498 (90) |
| | 3 | 565 (155) | 501 (118) |
| **Peak Power (W)** | 1 | 2362 (970) | 1926 (507) |
| | 2 | 1880 (419) | 1667 (422) |
| | 3 | 1620 (402) | 1553 (428) |

| | | Whole Cycle |
|---|---|---|
| **Total Work (kj)** | 1 | 87.31 (11.62) |
| | 2 | 79.94 (9.79) |
| | 3 | 75.48 (12.80) |

Linear foot speed, the performance measure, significantly changed (pre 21.1 ± 1.6m·s$^{-1}$, post-1 20.1 ± 1.1m·s$^{-1}$, post-2 19.7 ± 1.1m·s$^{-1}$, post-3 20.8 ± 1.1m·s$^{-1}$, $P$ = 0.01), with post hoc analysis indicating a significant decrease between pre and post-1 ($P$ = 0.01) and pre and post-2 (*P* = 0.04) trials. Within the fatigue cycles, foot speed did not differ between post-1 and post-2 trials, but was significantly larger for post-3 compared to post-2 (*P* = 0.02).

Maximal knee extension moment significantly decreased between pre and post-1 (*P* = 0.025), pre and post-2 (*P* = 0.004) and pre and post-3 (*P* = 0.026) trials. Maximal knee angular velocity and power did not significantly change during the protocol, however maximal knee angular velocity (extension) displayed a large effect size, with values decreasing across trials (Table 2, Figure 4). Repeating from methods, Holm-Bonferroni corrections were made including all new data (ie both knee and hip parameters) as this was the appropriate method to use. The data has been presented in separate tables here for ease of reading and should not be interpreted as separately corrected analyses.

**Table II. ANOVA results for kicking knee velocity, moments and power. Variables that were statistically significant are marked (*) next to their label (eg. * Knee - Maximum Moment (N·m)). Positive knee joint velocities and moments represent extension.**

| | **pre** mean ± s | **post-1** mean ± s | **post-2** mean ± s | **post-3** mean ± s | **partial $\eta^2$** | ***P* value** | **Holm-Bonferroni corrected *P* value** |
|---|---|---|---|---|---|---|---|
| Knee - Maximum Angular Velocity (°·s⁻¹) (extension) | 1658 ± 168 | 1640 ± 125 | 1576 ± 140 | 1574 ± 114 | 0.36 | 0.011 | 0.088 |
| * Knee - Maximum Moment (N·m) (extension) | 80 ± 19 | 71 ± 17 | 68 ± 19 | 70 ± 14 | 0.40 | 0.003 | 0.027 |
| Knee - Maximum Power (W) (extension) | 178 ± 91 | 156 ± 80 | 155 ± 76 | 150 ± 58 | 0.15 | 0.245 | 0.424 |

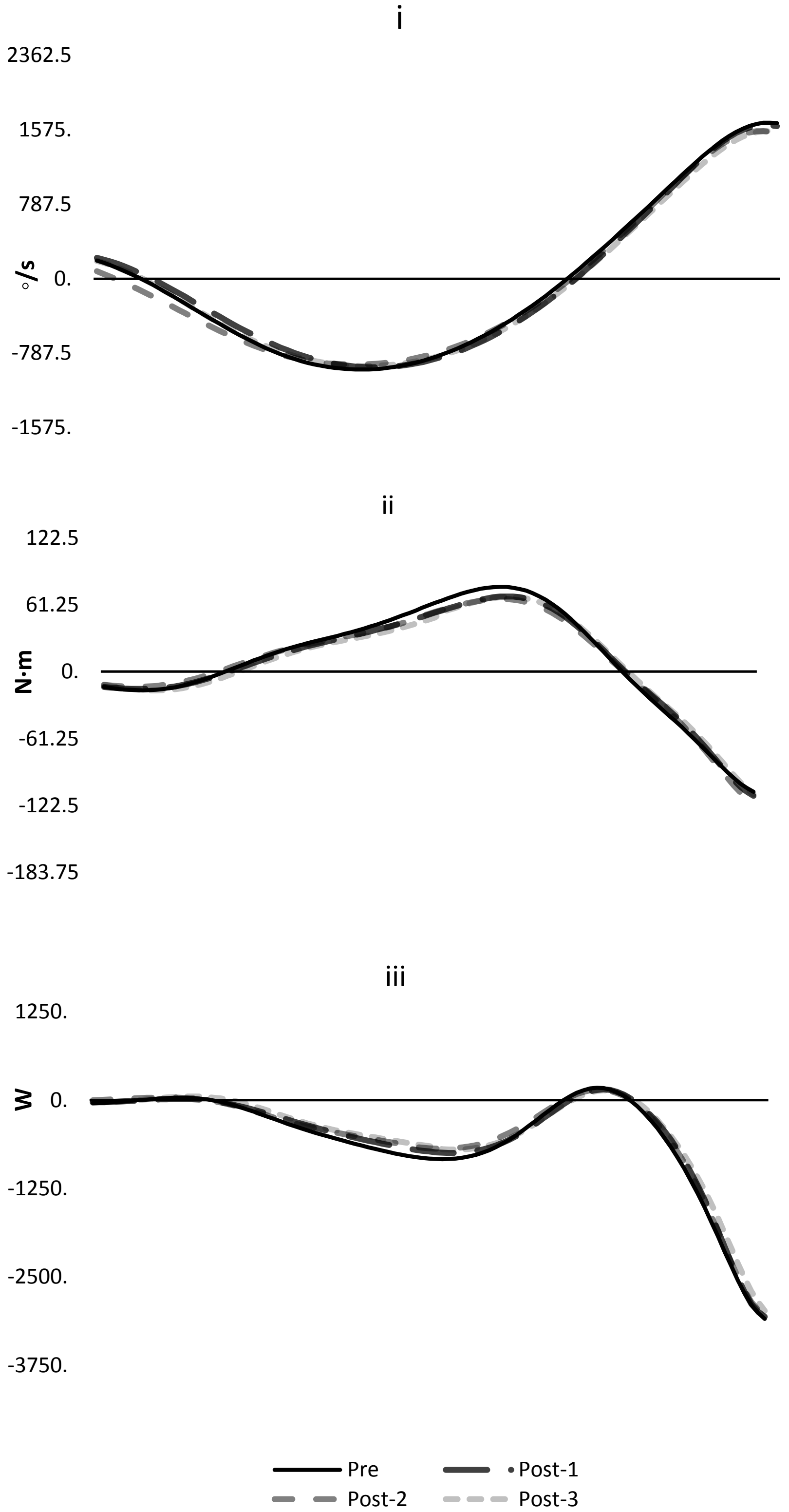



**Figure 4: Ensemble averaged time series data normalised between kick foot toe-off and ball contact for: (i) mean knee angular velocities, (ii) mean knee moments, and (iii) mean knee powers. Extension is positive for all figures.**

Maximal hip flexion moment and maximal hip adduction moments did not significantly change between pre and post kicks, nor within the fatigue kicks themselves, however there was a large effect size for the maximal hip flexion moment, with values decreasing across trials. Maximal hip flexion power and maximal hip adduction power did not significantly change between pre and post kicks, nor within the fatigue kicks themselves, though there was a large effect size for maximal hip flexion power (Table 3, Figures 5 and 6).

**Table III. ANOVA results for kicking hip variables. Positive hip joint velocities and moments represent flexion or adduction, negative hip joints velocities represent extension or abduction.**

| | **pre mean ± s** | **post-1 mean ± s** | **post-2 mean ± s** | **post-3 mean ± s** | **partial $\eta^2$** | ***P* value** | **Holm-Bonferroni corrected *P* value** |
|---|---|---|---|---|---|---|---|
| Hip - Maximum Angular Velocity (°·s⁻¹) (flexion) | 406 ± 58 | 423 ± 54 | 430 ± 63 | 408 ± 57 | 0.17 | 0.212 | 0.424 |
| Hip - Maximum Angular Velocity (°·s⁻¹) (adduction) | 228 ± 60 | 244 ± 80 | 192 ± 45 | 259 ± 86 | 0.25 | 0.049 | 0.252 |
| Hip - Maximum Moment (N·m) (flexion) | 229 ± 46 | 224 ± 48 | 203 ± 54 | 212 ± 46 | 0.36 | 0.026 | 0.182 |
| Hip - Maximum Moment (N·m) (adduction) | 58 ± 19 | 56 ± 15 | 57 ± 19 | 61 ± 20 | 0.06 | 0.064 | 0.256 |
| Hip - Maximum Power (W) (flexion) | 1416 ± 439 | 1369 ± 447 | 1315 ± 425 | 1319 ± 385 | 0.26 | 0.042 | 0.252 |
| Hip - Maximum Power (adduction) (W) | 64 ± 28 | 73 ± 30 | 70 ± 30 | 61 ± 28 | 0.18 | 0.067 | 0.256 |

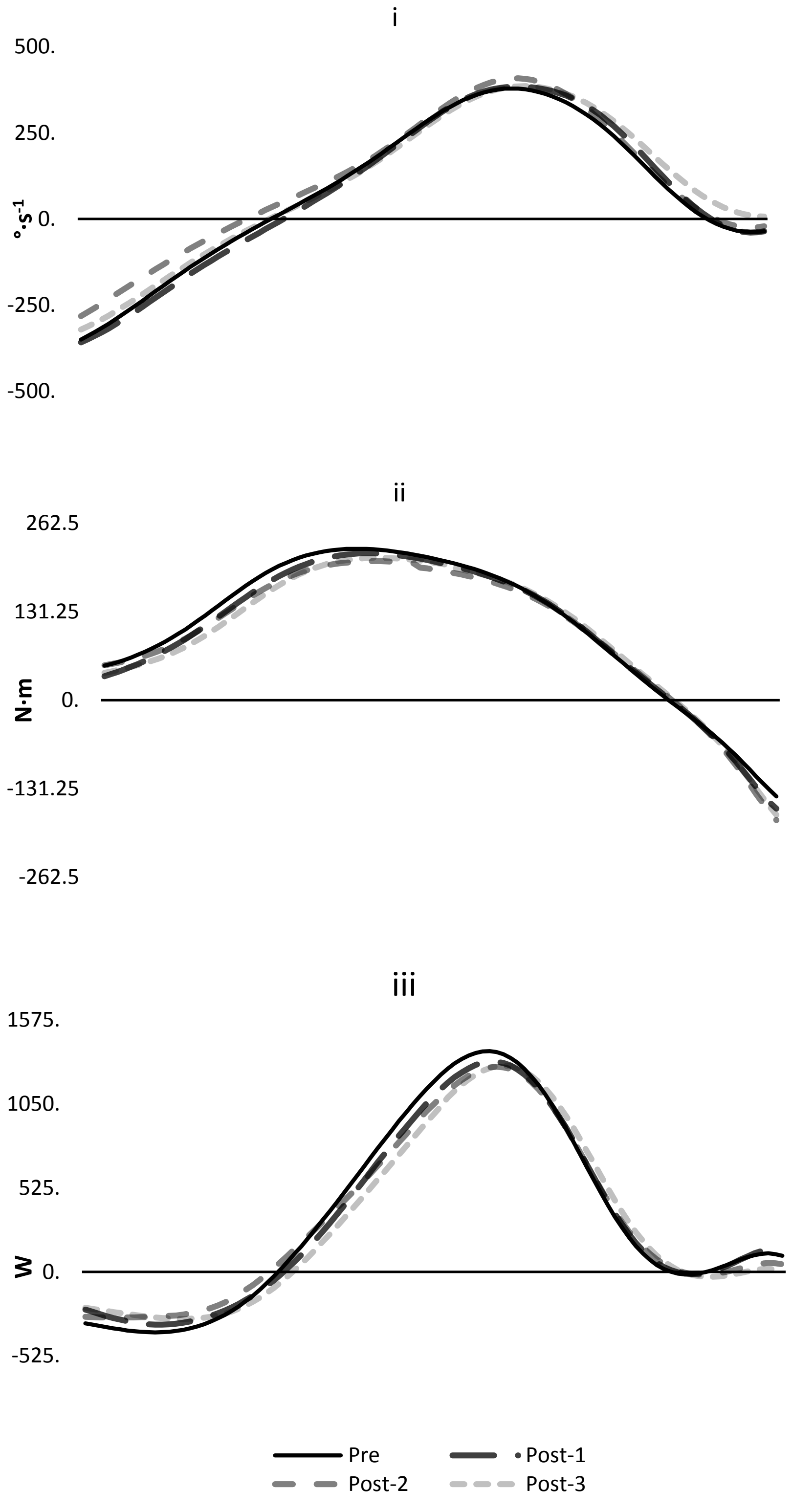



**Figure 5: Ensemble averaged time series data normalised between kick foot toe-off and ball contact for: (i) mean hip angular velocities, (ii) mean hip moments, and (iii) mean hip powers. Flexion is positive and extension is negative for all figures.**

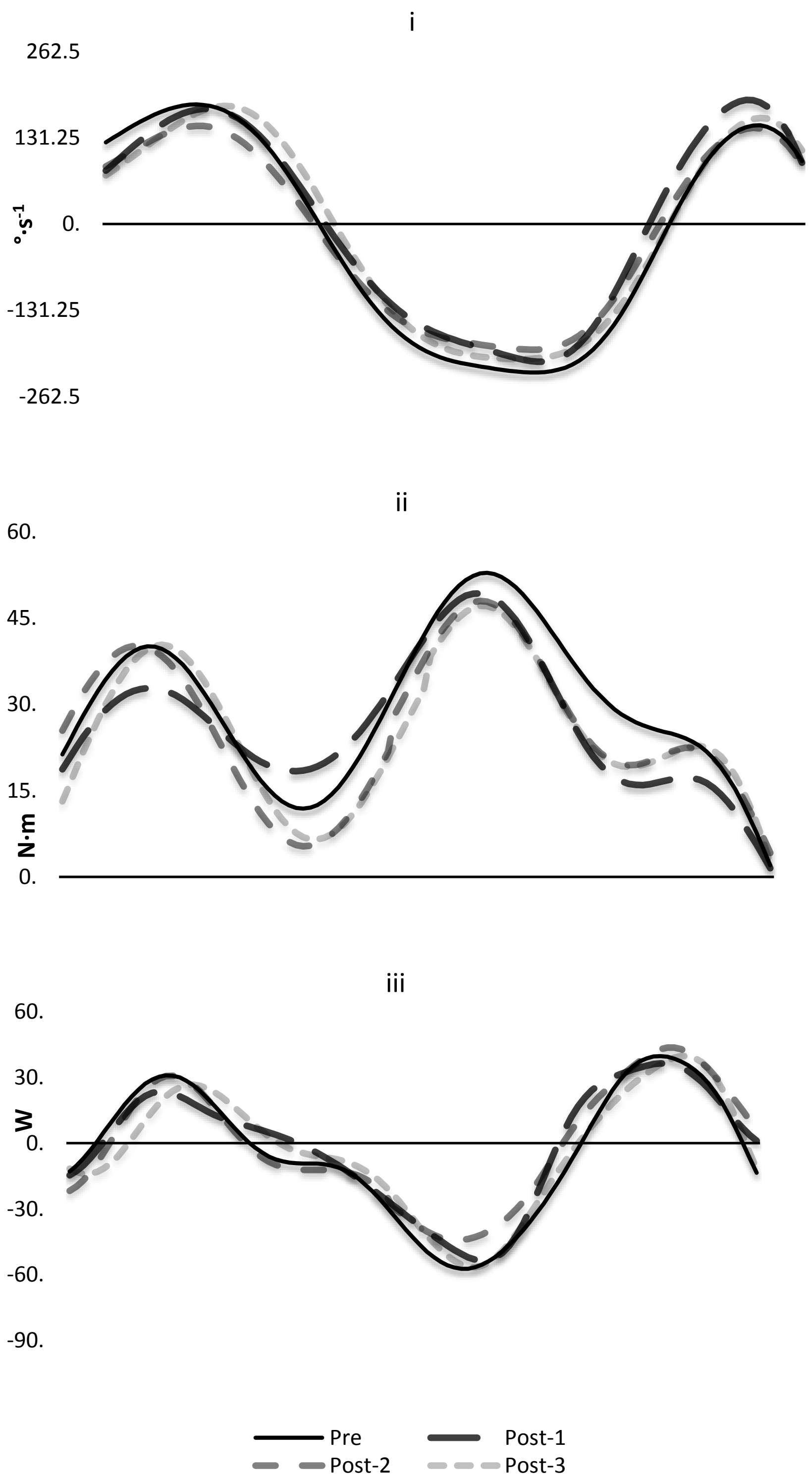



**Figure 6: Ensemble averaged time series data normalised between kick foot toe-off and ball contact for: (i) mean hip angular velocities, (ii) mean hip moments, and (iii) mean hip powers. Adduction is positive and abduction is negative for all figures.**

### 5.5 Discussion

Overall patterns of joint angular velocities and moments for the knee and hip did not change noticeably under fatigue based on the qualitative assessment of curves. The patterns of joint angular velocities and moments for the knee (Figure 4) and hip (Figures 5 and 6) were similar for pre and post fatigue kicks. The knee moment at kick foot toe-off started in slight flexion (negative) and moved into extension (positive), continuing to increase to approximately 80N·m (pre-kick) before declining and crossing zero approximately .04s before ball contact. Prior to ball contact a negative moment existed that coincided with maximal knee extension velocity of approximately $1600°·s^{-1}$, and negative knee extension power of approximately -3000W. The hip flexion/extension moment curve started in flexion (positive) and continued to its peak of around 200N·m before declining and crossing the zero approximately .025s before ball contact. Peak hip flexion power of approximately 1300W (pre) was reached approximately .04s later than the peak hip flexion moment and slightly before the peak hip flexion velocity of slightly above 400N·m. At ball contact an extension (negative) moment existed which coincided with a hip angular velocity and power of slightly above $0°·s^{-1}$ and 0W respectively. Ensemble averages are presented and account for why curve data slightly under represent tabled values. Slight individual differences did exist but curve shapes were similar for all participants.

The shape of the flexion/extension time series curves of joint moments were similar to those reported by Kawamoto et al. (2007) and Nunome et al. (2002) for the soccer side-foot kick. They were also similar in shape to those reported by Orchard et al. (2003) for a set kick in Australian Football, except that the authors reported the moment began at toe-off as an extensor moment briefly (rather than as a flexor moment found in the current study), before moving into flexion then extension, then finishing in flexion, as was found in the current study. The authors also found that the timing of the peak moments appeared later for the hip and earlier for the knee. In fact the knee moment peaked before the hip moment, as opposed to the current study where the hip moment peaked before the knee moment. This could be due to Orchard et al. (2003) using six elite level players, as opposed to the juniors used in the current study, and the possibility of the kick not being maximal as there was no description of the length or effort requested for the kick. Putnam (1983) reported a similar shaped knee moment to the current study for the punt kick, but a distinctive double hump in the hip flexion moment which was not present in either the current study or the results reported by Orchard et al. (2003). Furthermore, in contrast to the current study and that by Orchard et al. (2003), Putnam (1983), reported that the hip moment finished in flexion, even though the thigh was accelerating in the negative direction. Putnam (1983) thought this to be due to the influence of the shank rotating very rapidly. As the author did not describe the participant group's age or skill level or whether smoothing had been performed through impact or not, these variables may have accounted for the variation from the current study.

The shape of the adduction/abduction time series curves of joint moments in the current study was similar to a previous study and differed slightly to another. Nunome et al. (2002) reported a similar multiple hump curve, predominantly adducting at the hip as was found in the current study, for both maximal side-foot and instep soccer kicks to a target 11m away. Kawomoto et al. (2007) reported a similarly predominantly adducting hip, but with no double hump. The lack of a double hump may be due to the use of adult participants, as opposed to the junior participant groups used in the current study and by Nunome et al. (2002), and the slight differences in the nature of the kick given that participants used a side-foot kick only and were instructed to kick along the ground towards a target 8m away in a lab environment.

Pre-fatigue foot speeds at ball contact were similar to those found for juniors ($21.3 \pm 1.3 m \cdot s^{-1}$, Ball, Smith & MacMahon, 2010) and lower than the ranges found for elite players ($26.4 \pm 1.2 m \cdot s^{-1}$, Ball, 2008; 23.3 to $23.7 m \cdot s^{-1}$; Macmillan, 1975) in previous Australian Football research. The magnitude of the pre-fatigue maximal flexion/extension moments at both the knee and hip in the current study (knee 80 ± 19N·m, hip 229 ± 46N·m) were similar to those reported by Nunome et al. (2002) for the soccer side-foot kick (knee 80 ± 7N·m, hip 231 ± 38N·m). Maximal pre-fatigue hip adduction moments (58 ± 19N·m) were, however, smaller than those found by Nunome et al. (2002) (side foot 129 ± 23N·m, instep 115 ± 17N·m) and Kawamoto et al. (2007) (100 ±39 N·m), coinciding with the smaller hip adduction velocities found in the current study ($228 \pm 60^{\circ} \cdot s^{-1}$; Kawamoto et al, 2007, $315 \pm 103^{\circ} \cdot s^{-1}$). This result seems logical as the Australian Football punt kicking action is more planar in line with the direction of the kick in nature than the side-foot or instep soccer kicks (Hancock & Ball, 2008), therefore having less reliance on hip adduction. Abduction/adduction moments have not been reported in the literature for Australian Football punt kicking.

Fatigue was indicated to occur during each fatigue cycle leading up to each kick and was also accumulative as sprint values decreased from the first to last sprint and overall work decreased across all three cycles. Changes with fatigue are discussed in two separate sections: 1) Changes between the non-fatigued trial (pre) and any of the three fatigue trials (post-1, post-2 or post-3), and 2) Changes during fatigue that occur between any of the three fatigue trials (post-1, post-2 or post-3).

*5.5.1 Changes from Pre to Post-Fatigue*

Between the pre-trial and at least one of the fatigue trials, significant changes were found in the performance measure, foot speed, and at the knee. There was a decrease in foot speed between pre and post-1, and pre and post-2 trials. The decrease in foot speed with long term fatigue found in the current study is consistent with results found by Lees & Davies (1988) and Kellis et al. (2006) for soccer kicking. A decrease in maximal knee extension moment between pre and post-1, pre and post-2 trials and pre and post-3 trials was also found. Large effect sizes (used to discuss possible trends that require more research with greater participant numbers) indicated that maximal knee extension velocity and maximal hip flexion moment and power trended to decrease, between pre and post-2 trials and pre and post-3 trials and maximal hip adduction velocity did not change between pre and any of the post-fatigue cycles.

It appears as though the musculature assisting in extending the knee was less able to assist in accelerating the foot. Between pre and post-1, post-2 and post-3 trials there was a decrease in the maximal knee extension moments. A decrease in maximal knee moments with fatigue has also been found by Apriantono, Nunome, Ikegami & Sano (2006) in the maximal instep soccer kick before and after a repeated loaded knee extension and flexion fatigue protocol on a weight-training machine. The authors found a 15.2% peak muscle moment of knee joint (non-fatigue 127.8 ± 20.2N·m, fatigue 108.4 ± 17.1N·m, $P < 0.01$) during the kick, as compared to the decreases in the current study (pre to post-1 = 11.3%, pre to post-2 = 15%, pre to post-3 = 12.5%). They also reported a 4.1% decrease in maximal toe linear velocity (non-fatigue 27.1 ± 1.2m·s$^{-1}$, 26.0 ± 1.3m·s$^{-1}$, $P < 0.01$), as compared to the decreases (pre to post-1 = 4.7%, pre to post-2 =

6.6%, pre to post-3 = 1.4%) in the current study.  Comparisons with Apriantono et al. (2006) and the current study are somewhat limited due to the different kicking styles and fatigue protocols, but the overall patterns are similar.

There appears to be a greater reliance on the hip to assist generating foot speed as kickers progressed through the protocol.  This is evident due to the significant decrease in the maximal extension moments, but the absence of a significant decrease in the hip flexion moment (although large effect sizes did indicate a trend towards a decrease maximal hip flexion moment between pre and post-fatigue cycles).  Given these changes were greater at the knee, there was therefore an increased reliance on the hip when fatigued.  Large effect sizes also indicated that knee extension angular velocity continued to trend towards decreasing between post-1 and post-2 trials, while maximal hip flexion velocity did not differ significantly.  Post hoc calculations revealed maximal hip/knee angular velocity ratios increased significantly at $P = 0.021$ (pre 0.24, post-1 0.25, post-2 0.27, post-3 0.26).  Post hoc hip/knee maximal flexion/extension moment calculations revealed an increased reliance on the hip moment later in the protocol (pre 2.94, post-1 3.24, post-2 3.09, post-3 3.08).  Although not significant, there was a medium effect ($\eta^2 = .191$).  These results indicate that participants were moving towards adopting a greater 'hip strategy' later in the protocol.

A greater reliance on more proximal joints when fatigued has also found in other research.  When studying  drop landings after an exhaustive one-legged squatting protocol, Coventry et al. (2006) reported that net work at the hip (first cycle: -0.20 ± 0.19J $kg^{-1}$, last cycle: -0.44 ± 0.36J $kg^{-1}$) actually significantly increased, while work at knee did not change (first cycle: -0.97 ± 0.43J $kg^{-1}$, last cycle: -0.85 ± 0.40J $kg^{-1}$).  A significant decrease in work at the ankle was also reported (first cycle: -1.14 ± 0.25J $kg^{-1}$, last cycle: -0.87 ± 0.24J $kg^{-1}$).  It was concluded that participants redistributed the energy absorption from landings to the larger, possibly more fatigue resistant, muscles that crossed the hip. However, more work with larger subject numbers would be required to determine if this change in strategy exists.

Some fatigued-kicking research has also indicated a greater reliance or more proximal segments or joints. In a recently published paper, Coventry et al. (2015) found that a short-term Australian Football specific fatigue protocol did not change performance but several kicking leg parameters such as range of motion at the pelvis and kicking thigh, and thigh angular velocity improved. The authors reported that the changes were more evident at the thigh than the shank. In a study focusing on soccer kicking segmental changes after a match specific fatigue protocol, Kellis et al. (2006), found a significant decline in the angular velocity of the shank during soccer kicking (pre ≈ 1800 ± 600°·$s^{-1}$, middle ≈ 1550 ± 500°·$s^{-1}$, post ≈ 1600 ± 500°·$s^{-1}$, $P < 0.01$). This was associated with a significant decline during the support phase of the net moment applied on the shank (pre 231.89 ± 81.30, post 184.54 ± 92.79, $P < 0.01$) and moment because of muscle force acting on the shank (pre 114.91 ± 48.17, post 78.73 ± 46.40, $P < 0.01$). As the thigh velocity stayed constant and shank velocity significantly decreased due to the net moment applied on the shank decreasing, this alteration in the proximal to distal pattern is similar to that found by Coventry et al. (2006) and in the current study.

### *5.5.2 Changes During Fatigue*

Between the three fatigue trial kicks, changes in moments and powers at the knee and hip were evident but were not progressive or linear. Maximal knee extension moment did not change. Maximal hip flexion moment and power did not change between the fatigue cycles, while large effect sizes indicated a trend towards a continued decrease in maximal knee extension moment between post-1 and post-3 trials, and an increase in maximal hip adduction velocity between post-2 and post-3 trials. This indicated the changes are more complex than simply reducing with progressive fatigue.

Foot speed increased between the last two cycles, however, peak moment and power data did not provide a clear indication of the cause. Maximal hip adduction moment and velocity was at its highest in the post-3 kick, and a large effect size indicated a trend towards an increase in maximal hip adduction velocity between the post-2 and post-3 trials. Future research should include more participants to determine if this trend would become significant. Post hoc testing also revealed a change in direction and an increase in correlation between foot speed and maximal hip angular velocity between post-2 ($r = -0.23$) and post-3 ($r = 0.55$) trials, and a change in direction and an increase in correlation between foot speed and maximal hip flexion power between post-2 ($r = -0.33$) and post-3 ($r = 0.39$) trials. This indicated that the hip played an important role in relation to increasing foot speed after the post-3 fatigue cycle. The hip therefore may be important in maintaining, or in this case improving, performance when participants are fatigued late in a quarter.

While not explained by increases in maximal joint moments or velocities, the kicker appeared able to adapt technique, or possibly effort, late in the fatigue protocol to improve performance. In a study looking at the effect of fatigue on ball velocity in soccer kicking, Ferraz, van den Tillar & Marques (2012) reported that participants showed a decrease in ball velocity after initial fatigue cycles, followed by an increase in ball velocity after late fatigue cycles. Joint or segmental mechanics were not measured. The authors proposed that the non-linear changes were possibly due to players being more highly motivated due to it being the last fatigue trial of the protocol, although none of them reported this to be the case, and them having subconsciously paced themselves and subsequently having a "security reserve" to tap into as a final "end spurt" (Millett, 2011). This may have also been the case in the current study and future research should control for the possibility of subconscious participant pacing by utilizing non-evident finishing times. The use of elite level participants should also be tested to determine if these changes also exist in elite athletes.

### 5.6 Conclusions

Drop punt kicking technique changed following a long-term fatigue protocol. Changes were found in the performance measure foot speed, and at the knee. Foot speed and maximal knee extension moment decreased between the pre and post-fatigue trials, indicating that the musculature used to assist in extending the knee was less able to contribute to accelerating the foot. As changes between pre and post-trials were greatest at the knee, this gives rise to there being a greater reliance on the hip to perform kicks when fatigued. Between the post-fatigue trials a change of strategy became apparent, with foot speed increasing and maximal knee extension moment not changing. After an initial decrease in performance, participants were able to improve their performance after several protocols, even though they did not make significant late changes to their technique.

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# Chapter 6

# 6. General Discussion

Given the different nature of the fatigue protocols, it is interesting to look at how the overall results were similar and how they differed. Performance, as measured by foot speed, after short-term fatigue (Study 1) was maintained, and a large effect size indicated a trend towards improving. Long-term fatigue (Study 2 and Study 3) caused an initial decrease in performance, however, late in the protocol foot speed increased between cycles. The results show that participants were able to make adjustments in their mechanics in order to attempt to maintain performance whilst under both short and long-term fatigue.

## 6.1. Methodological Issues

Pre-fatigue data from each participant was compared to their own fatigued data, and therefore the data compared within each study is highly valid. However, making direct comparisons across the studies should be done with caution due to differences in participant groups, statistical designs, fatigue protocols and the motion capture systems used. Some methodological issues need to be taken into account when comparing data, particularly between the short-term fatigue study (Study 1) and the long-term fatigues studies (Study 2 and Study 3), and to other research. The following section discusses the differences in the methods used between the studies and the implications for comparisons between the results.

### 6.1.1 Non-Motorised Treadmill versus Motorised Treadmill versus Overground Running

Advantages and disadvantages exist with different methods used to induce match specific fatigue. Further to discussion in the long-term kinematics paper (Study 2) (Chapter 4, page113), using a treadmill also allows the researcher to control the velocity and distance the participants travel. It has been utilised in other fatigue studies such as by Rahnama, Reilly, Lees & Graham-Smith (2003) and Greig (2009). These studies, however, used a motorised treadmill which as reported does not allow for rapid, naturally occurring, changes in acceleration. An important component of the long-term kinematic (Study 2) and the long-term kinetic protocol (Study 3) was the use of a non-motorised treadmill (NMT). As reported a NMT treadmill was chosen for the long-term studies as it has the benefits of almost instantaneous changes in speed (Drust, Cable & Reilly, 2000a, Drust, Reilly & Cable, 2000b), and allows any decline in power output to be detected with the onset of fatigue (Drust, Reilly & Cable, 2000b). The fatigue protocol run on a NMT in the long-term studies is therefore thought to be a more valid protocol as it allows for more 'natural' changes in acceleration and thus better represents what players do in a match than a motorized treadmill protocol.

As the belt harness used was required to be fastened where the hip markers are placed, there was an issue with hip marker placement when using the NMT treadmill. This required a static capture after each kick and the markers to be taken off quickly before each fatigue cycle began, then the markers needed to be put back on after the cycle and before the kick. Although this time was minimal, roughly 45s total which included 20 to 25s of standing and 20 to 25s of walking/jogging in getting off the treadmill and moving to the start point and taking the kick, the lag time may have allowed for some recovery from fatigue. Research has found that whilst some recovery is present in the first 30s after a long-term protocol, participants can still remain significantly fatigued, as measured by force, 15min after the cessation of exercise (Baker, Kostov, Miller & Weiner, 1993). Baker et al. (1993) found a 35 ± 3.1% decrease in maximal voluntary contraction force immediately following a short-duration exercise (SDE) two minute sustained protocol and a 42 ± 3.3% decrease immediately after a long-duration exercise (LDE) 15 to 20min fatigue protocol. The authors reported the recovery (increase in force) to be much slower for the LDE (15.3 ± 4.2%) than the SDE (40 ± 4.2%) over the first minute after the cessation of the protocols. Thus in the current long-term fatigue studies the recovery should have been minimal as there was only 20 to 25s of non-activity. The 20 to 25s of lag time between the end of the protocol and the kick was also the case for every kick performed, and as the protocol induced accumulative fatigue, as indicated by the significant decrease in total work (-13.5%) from cycle-1 to cycle-3 and decreases in first sprint cycle-1 mean power and first sprint cycle-3 mean power (-28%), the effect of the recovery from this short resting timeframe should have been minimal.

An overground running protocol is the most ecologically valid protocol. In the only study that looked at kicking mechanics after a fatigue protocol, Kellis, Katis & Vrabas (2006) implemented a 90min soccer-specific intermittent exercise protocol performed on a 20m turf surface. The disadvantage of an overground protocol is that there is less researcher control over the intensity of the protocol and it does not allow a decline in power output to be detected with the onset of fatigue (Drust, Reilly & Cable, 2000b). For this reason it was not used for the long-term studies. An overground running protocol was, however, the preferred fatigue inducer of fatigue for the short-term study so as to simulate a short burst of match specific activity before kicking. It was thought not only important to have participants accelerate and decelerate, but also to get them to change direction, something that could not be done on a treadmill. Timing the 20m sprint incorporated into the protocol was a means of tracking fatigue (Kellis et al., 2006) without adding any performance measures which may add additional fatigue and thus affect results.

### 6.1.2 Use of a Single Recorded Kick after Fatigue Cycles

The use of a single kick per cycle per leg during fatigue protocols was selected as the best approach for the short-term and long-term fatigue studies. Research examining kicking under fatigue has recorded up to three kicks (Apriantono, Nunome, Ikegami & Sano, 2006). The advantage of this method is it might improve obtaining a ‘typical’ kick for each player, although there has been no work examining how many kicks are required to attain a stable mean performance as used in some other sports (e.g. golf; Ball & Best, 2007). However, a number of disadvantages exist with this multiple-kick method. First, recovery can occur as there is more time spent between fatiguing activities so it might be expected that the third kick will be performed in a more recovered state (acknowledging that the kick itself can contribute to fatigue). Second, the feedback from performance on kick one can be used to adjust for kick two and kick two to adjust for kick three, potentially contaminating the data and introducing a confounding factor to the testing. Third, testing becomes less ecologically valid as the likelihood of a player performing three maximal kicks in rapid succession is extremely remote and the total number of kicks performed would have been substantially larger than in games (e.g. nine kicks for the long-term protocol in a quarter when the average for an AFL game is approximately three). Finally, specific to study one, it was important to obtain a kick immediately on completion of the fatigue protocol in an attempt to gain information on that specific game situation where a kick is made immediately at the end of a high intensity bout of exercise.

Research has also shown that maximal kicking tasks have found to be reliable (Markovic, Dizdar & Jaric, 2006) with 2 to 3% variation in intra-individual evaluation for single trials. Based on these considerations, the single kick methodology was chosen as the better approach for this thesis.

### 6.1.3 Junior versus Senior Participants

Given the design for each of the three studies was comparing the non-fatigued kicks of participants within a group to their own fatigued kicks, the results are valid for each of the studies individually. However, the use of two different participant groups between Study 1 and Studies 2 and 3 makes it difficult for results to be compared between the short-term and long-term studies. The short-term fatigue protocol was undertaken on seventeen elite and sub-elite Australian Football players (age 19.75 ± 0.89years, height 185.25 ± 8.38cm, body mass 81.5 ± 8.59kg). These participants were recruited as they play in the highest level competition and best represent an elite group. The long-term protocol was a much longer in duration and was therefore more difficult to recruit elite adult performers as participants. Ten male Associated Public Schools first team representative (age 16.5 ± 0.9years; height 179.7 ± 5.66cm, mass 70.25 ± 7.66kg) Australian Football players were recruited for this study as they were still first-grade footballers and they were able to commit to working towards physical exhaustion during the protocol. The elite players were not able to make this commitment. The lack of a drop in performance (foot speed) in the short-term study (Study 1) as compared to the decrease in performance found in the long-term studies (Study 2 and Study 3) may be attributed to the protocols used and the changes in technique discussed in each study. However, it could also be influenced by the skill level and experience of the participant group. The older more elite participant group used in Study 1 may have coped with fatigue better than the less experienced participant group from Studies 2 and 3. The issue of comparing results between different participant groups also occurs when making comparisons to other research. Most other fatigued kicking research has also focussed on sub-elite performers (Kellis et al., 2006; Nunome, Ikegami, Kozakai, Apriantono & Sano, 2006; Nunome, Asai, Ikegami & Sakurai, 2002) and juniors (Nunome et al., 2006; Nunome et al., 2002), therefore allowing for somewhat valid comparisons, taking into account the different styles of kicking used in soccer and the different fatigue protocols. However, it would be useful in future studies to examine the elite population for long-term fatigue protocols, as it would be to examine sub-elite and amateur players in both short-term and long-term conditions.

### 6.1.4 Optotrak versus Vicon Motion Capture Systems

The Optotrak motion capture system was used for the short-term fatigue study as it was the best system available at the time of testing. It was pilot tested and appeared able to withstand the rigours of an intermittent high-intensity fatigue protocol and kicking. This also appeared the case for much of the testing as eight participants produced full data sets of a pre and two post-fatigue cycle kicks. There were, however, nine participants whose data was not fully collected or was eliminated from the analysis due to possible recovery before the kick was taken. This was due to either cables between markers and the central connecting box, which was located on the players, becoming dislodged (requiring re-calibration which allowed for player recovery) or the inability to 'reconnect' the Optotrak system with the data collecting computer (the cable connecting the computer to the box located on the player represented a safety risk so was disconnected while the fatigue protocol was performed then reconnected).

Given the issues related to the possible cessation of data collection mid-protocol due to cable dislodgement, it was decided to use the cable-less Vicon system that had become available for the long-term protocol testing. Therefore, during the long-term fatigue studies there were no issues with cable connections as the Vicon system is a reflective marker system that does not require cables on the participant. The system was able to produce a higher number of valid data sets than the Optotrak system used for the short-term fatigue study.

### 6.1.5 Sample Rates: 100hz for the Short-Term Study versus 250hz for the Long-Term Studies

The use of two different systems between studies that could sample at different rates also warrants further discussion. The Optotrak system, used for the short-term study, was limited in its sample rate based on the number of markers required to be used to accurately measure kicking. Given the system and the number of markers used, that led to 100Hz being the rate for the short-term study. A sample rate of 250Hz was possible for the long-term studies as a Vicon system became available for use.

The 100Hz sample rate for the short-term study was lower than was originally desired, however, it was the maximum at which the Optotrak system could operate. The Optotrak system sample rate is related to the number of markers (4600 divided by the number of markers plus 2) and as initial data collection was planned for upper and lower body mechanics, 100 Hz was the highest sample rate possible. The low sample rate was the reason for not performing kinetic analyses in Study 1. To ensure the kinematic results would be valid at 100Hz, prior to testing, kicking data obtained at 500Hz, were resampled at 250Hz, 125Hz, 100Hz and 50Hz for five kickers performing maximal kicks. Using the resampled data, foot speeds were within 2% of values obtained from the 'gold standard' 500Hz for 100Hz re-sampled data. Based on this finding, as well as, importantly, the fact that the study compared pre and post-fatigue kicking parameters using the same Optotrak system (so while values might have been slightly underestimated, this would be the case for all trials so the comparisons remain valid) and given similar rates have been used in previous kicking studies (100Hz, Linthorne & Patel, 2011; 120Hz, Kellis et al., 2006), a 100Hz capture was decided to still be an appropriate methodology. This study had been accepted for publication (Coventry, E., Ball, K., Parrington, L., Aughey, R. & McKenna, M. (2015). Kinematic effects of a short-term fatigue protocol on punt-kicking performance, *Journal of Sports Sciences, DOI*: 10.1080/02640414.2014.1003582).

### 6.1.6 Differences in Statistical Designs

All three studies looked at the effect of fatigue, over time, on kicking. It was therefore decided to use a repeated measures ANOVA design in order to determine what these changes may have been.

Given that the short-term study (Study 1) was the first conducted, and there had not been any previous published data on the effect of fatigue on punt kicking, it was decided to be explorative in the data collection and analysis. Many variables were looked at and significance was set at $P < 0.05$, based on previous kicking research, with effect sizes also calculated to aid in discussion. Post hoc analysis was also used to determine where these changes occurred throughout the protocol. Correlations with foot speed and significant variables was also undertaken to determine if any relationships existed between the variable and the performance measure at any stage throughout the protocol. Corrections were also made for maximum possible error, with variables that displayed potential error in calculations being discarded (Appendix 1).

The long-term kinematics study (Study 2), utilised some of the information gathered from Study 1 in order to assist in lowering the number of parameters examined in statistical analysis. A factor analysis was therefore performed on all of the kinematic variables, with groupings being made and one parameter, based on previous punt kicking research, coaching recommendations and on study one results, was selected to represent each factor. This design had been used in previous punt kicking research (Ball, 2008). Significance was again set at $P < 0.05$. After factors were identified, a repeated measures ANOVA was performed with Holm-Bonferroni correction, in order to assist in controlling possible error. Effect sizes (partial $\eta^2$) were also calculated for comparison. Again, post hoc analysis was also used to determine where these changes occurred throughout the protocol.

In the long-term kinetics study (Study 3) a simpler design was used due to the lower number of parameters not requiring any reduction. A repeated measures ANOVA was again performed with Holm-Bonferroni correction in order to assist in controlling possible error. Effect sizes (partial $\eta^2$) were also calculated for comparison and discussion. Post hoc analysis was used again to determine where these changes occurred throughout the protocol.

Overall the statistical design used in the three studies had some implications. The use of Holm-Bonferroni corrected $P$ values has been proposed to be control for Type I errors in sports biomechanics research and also better offsets the possibility of generating Type II errors than using Bonferroni correction alone (Knudson, 2009). This correction decreased the number of significant variables as compared to if no correction was implemented. The reporting of effect sizes was therefore also incorporated into the statistical designs in order to support the significant data and aid in discussion of the explorative data, noting that future research would need a larger N to clarify non-significant data that displayed large effect sizes.

### 6.1.7 Impact: Ball Contact

The portion of the kick to analyse was also an important consideration. Some previous kicking research has looked at three phases: backswing, leg-cocking and leg-acceleration (Nunome et al., 2002; Kawamoto, Miyagi, Ohaski & Fukashiro, 2007), while other research has looked at the phase from kicking foot toe-off to ball contact or the instant just before ball contact (Ball, 2008; Ball, 2011; Dörge, Bull-Andersen, Sorensen & Simonsen, 2002, Kellis et al., 2006; Kawamoto et al., 2007). The latter was the method implemented in all three studies as it was the method validated and used by most studies and allowed for comparison with previous Australian Football kicking research (Ball, 2008; Ball, 2011).

Another important consideration was what to do about the values at ball contact (Appendix 2: Impact Research). As previously stated, most studies analyse the kick only up until the point just prior to ball contact (Ball, 2008; Ball, 2011; Dörge et al., 1999; Kellis et al., 2006; Kawamoto et al., 2007). In these cases velocity measures were one time interval back from actual ball contact and this was not considered an issue. As such, the ball contact data in Study 1 and Study 2 were also analysed in this manner. Study 3, however, focussed on kinetics and using this method would cause torque measures to be two to three intervals back. The kinetic analysis therefore focussed on maximal moments, as have been reported in previous kinetic kicking research (Nunome et al., 2002; Kawamato et al., 2007).

### 6.2 Other Limitations of Studies

There were some limitations associated with both the short-term and long-term fatigue studies. Prior to the commencement of the studies, participant numbers were calculated from statistical power analyses and using effect sizes from pilot testing carried out to assess changes due to fatigue in the means of the performance measure (foot velocity). As no fatigued kicking research had been done with Australian Football, pilot testing gave the best indication of the sample size required for each level of athlete. Eight participants were recommended from pilot research. As another approximation, calculations based on research by Greig, McNaughton & Lovell (2006) and Apriantono et al. (2006), revealed seven participants per group as the number of participants to be used to find significant differences in soccer kicking fatigue research. Although sample size estimation, based on previous research and pilot testing, points to participant numbers for each study being valid, higher participant numbers would be desirable. Some interesting findings came from the current studies, such as participants did not significantly change their foot speed after short-term fatigue cycles, however, they appeared to be increasing their foot speed as was indicated by a high effect size (partial $\eta^2 = 0.436$, Pre $19.7 \pm 2.0 m \cdot s^{-1}$, post-1 $20.3 \pm 1.7 m \cdot s^{-1}$, post-2 $20.5 \pm 1.4 m \cdot s^{-1}$). Future short-term fatigue kicking research should be done with larger subject numbers to assess if participants improve performance or not.

### 6.3 Future Research Directions

More research with larger numbers of players is needed to explore the effects of both short-term high-intensity fatigue and long-term fatigue on sports specific skills.

Higher sample rates should also be used and should be consistent, along with participant groups, across both short and long-term fatigue studies. This would allow for greater validity in comparing the kicking results from a short-term fatigue protocol to the kicking changes from a long-term fatigue protocol.

Given game time for team sports is between 30 to 120min, longer-term fatigue protocols should be examined to determine if technical changes occur over longer periods of time as found with long-term fatigue studies in other tasks. As the results from the long-term study were variable, it would be interesting to see if they 'levelled out' in an even longer protocol.

Varied arousal levels should also be tested to determine their influence on foot speed and kicking mechanics. In a study looking at the effect of fatigue on ball speed in soccer kicking non-linear changes were proposed to possibly be due to players being more highly motivated late in the protocol and having subconsciously paced themselves for a final "end spurt" (Ferraz, van den Tillar & Marques, 2012; Millett, 2011). If there is an influence, then future research would need to put in measures to control for arousal levels during testing, such as incorporating non-evident finishing times.

More kinetic focussed punt kicking research should also be undertaken. In a fatigued drop landings study, Coventry, O'Connor, Hart, Earl & Ebersole (2006) found a redistribution of energy absorption (negative work) from the muscles that cross the ankle to the larger possibly more fatigue resistant muscles that cross the hip. It is possible that a similar coping strategy was at play after initial fatiguing cycles in the current studies, however kinetics were not measured in the short-term study. As Study 3 was the first punt kicking kinetic study, more kinetic analysis should be undertaken in future research to determine if a similar pattern is found for fatigued punt kicking, particularly after short-term fatigue and with elite adult participants.

### 6.4 Coaching Recommendations

Technical changes occurred after the short-term fatigue protocol and they have implications for the performance and training of the maximal punt kick. It has been reported that kicking practice tends to take place in blocks immediately after the warm-up and before other drills such as match simulations (Ball, 2012). The results of the three studies show that both long-term and short-term fatigue affects kicking mechanics differently at different stages. It is therefore important that coaches look to incorporate maximal kicking practice into drills throughout training sessions in order to give the players experience in kicking under different levels of fatigue. Kicking should also be practised after short bursts of match-type intensity running and towards the end of sessions where players would presumably be performing under more accumulated long-term fatigue. This would better allow players to practise their maximal kicking technique under match-like conditions.

The increased influence of the hip in the maximal kicking motion following both the short and long-term protocols has direct relevance for strength and technique training. The importance of the thigh was evidenced in the short-term protocol by increased segmental velocities at the thigh. In the long-term protocol the importance of the hip and thigh was shown by an increase maximal thigh angular velocity and the hip becoming more flexed at ball contact, as compared to pre fatigue trials. No kinematic changes were found at the knee, however the maximal knee moment decreased (Study 3) as compared to pre-fatigue trials. It appears as though the larger muscles of the hip and thigh are important in the fatigued kicking motion. Possibly the smaller, more distal muscles, decrease their contribution and these higher chain muscle groups compensate by maintaining their contribution and thus produce a greater kinematic influence on the post-fatigue kick. A similar distal to proximal redistribution of work to the musculature that crosses the hip was found by Coventry et al. (2006) for drop landings. This was also supported by the long-term kinetic data as the knee maximal moments decreased. A large effect size pointed to a possible trend towards the hip adducting faster in kicks later in the protocol, which coincided with a late increase in foot speed. It is therefore important that fitness staff and coaches work with their players on incorporating a program that both works on speed and power of the hip flexors and adductors, and increases the muscular endurance of the knee extensors. Future research into fatigued kicking mechanics post such a program would be interesting to see if participants were better able to maintain performance, and if they relied more on improvements in hip velocity or on a smaller detriment to knee extension velocity.

Range of motion also appears to have an influence on kicking performance. The adaptations made during the short-term fatigue protocol (Study 1) involved an increase in the range of motion at thigh and pelvis. This change coincided with large a large effect size indicating a trend towards increased foot speed. In the long-term studies there were no significant changes in range of motion, however a large effect size indicated a decrease in pelvis range of motion between pre and early post-fatigue trials, which corresponded with a decrease in foot speed, and an increase in pelvis range of motion for the post-3 trials, which corresponded with a significant increase in foot speed. Coaches should therefore be working on the dynamic flexibility of their players in order improve range of motion. Previous research has found a moderate association between hip flexibility and hip angles during kicking (Young, Clothier, Otago, Bruce & Liddell, 2003). However, a study on the influence of static stretching on kicking range of motion and foot speed found no increase in flexibility and subsequently no increase in kicking range of motion and foot speed (Young et al., 2003). It is therefore important that coaches focus on dynamic stretching as this form of stretching has been found to improve dynamic hip range of motion more than static stretching during soccer instep kicking (Amiri-Khorasani, Abu Osman & Yusof, 2011). Before kicking, players should make sure they are thoroughly warmed up and have been through several range of motion dynamic stretches, such as leg swings in both the frontal and sagittal planes. This will not only assist in preventing muscular strain type injuries but with repeated practise, flexibility and range of motion should begin to increase.

### 6.5 References


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# Chapter 7

## 7. Conclusions

Fatigue causes changes in Australian Football maximal punt kicking mechanics. These changes in kicking technique vary in conjunction with either short-term or long-term fatigue.

Study 1 looked at how short-term fatigue, simulating a burst of activity in a match, affected kicking mechanics and found that performance was maintained due to increases in ranges of motion at the thigh and pelvis, and increases in kicking leg segmental angular velocities. This relationship was particularly evident at the thigh. Support knee extension velocity also increased, while support leg flexion and range of motion decreased however, showing that this could not be sustained under the weight of the body.

Study 2 focussed on how long-term fatigue, accumulated throughout a match, affected kicking kinematics. Changes were found in the performance measure foot speed, and at the thigh and hip. Foot speed decreased, thigh frontal plane angle at ball contact became more vertical, maximal thigh angular velocity increased and the hip became more flexed at ball contact when fatigued kicks were compared to pre-fatigued kicks. The increase in maximal thigh sagittal plane angular velocity and hip flexion at ball contact appeared to be an attempt by participants to minimise the decrease in performance. Throughout the protocol kicking hip flexion continued to increase. Within the fatigue trails changes also existed, with a change in strategy becoming apparent. The initial more vertical, faster kicking thigh slowed down and increased its frontal plane angle later in the protocol, coinciding with an increase in foot speed between the last two trials. After several trials it appeared as though participants were able to learn to adapt to the fatigue by changing their technique.

Study 3 concentrated on the kinetic kicking changes throughout a long-term protocol. Between pre and post-fatigue trials, foot speed and maximal knee extension moment decreased, indicating that the musculature used to assist in extending the knee was less able to contribute to accelerating the foot. As these changes were greater at the knee than the hip, this gives rise to there being a greater reliance on the hip to perform kicks when fatigued. As found in study 2, a change of strategy became apparent between the post-fatigue trails. Foot speed increased, while maximal knee extension moment did not change. Participants were able to improve their performance late in the protocol, even though they did not make significant late changes to their technique.

As hypothesised, fatigue, both short-term and long-term, caused changes in kicking mechanics. Under short-term fatigue, from a high intensity protocol, participants were able to maintain performance through increasing segmental ranges of motion and velocities, particularly at the thigh. When participants were exposed to a more progressive long-term fatigue protocol, as hypothesised, they initially decreased their kicking performance. This decrease in performance was due to a decrease in knee extension moment but was minimised through increased velocity and angles higher up the chain at the thigh and hip. Performance then improved later in the protocol due to the kicking thigh widening its frontal plane angle and flexing more at the hip.

In all three studies participants were able to make adaptations in order to attempt to maintain performance and, as hypothesised, these changes tended to be to utilise the hip and thigh more in order to compensate for the more fatigued musculature lower in the chain. It is therefore important that coaches incorporate training programs that focus on improving the endurance of the knee extensor musculature or the power of the hip flexors and adductors in order to assist in maintaining maximal kicking performance later in a match.  Maximal kicking practice should also be undertaken at varying times in training so players can work on their kicking mechanics under different levels of fatigue.

# Appendices

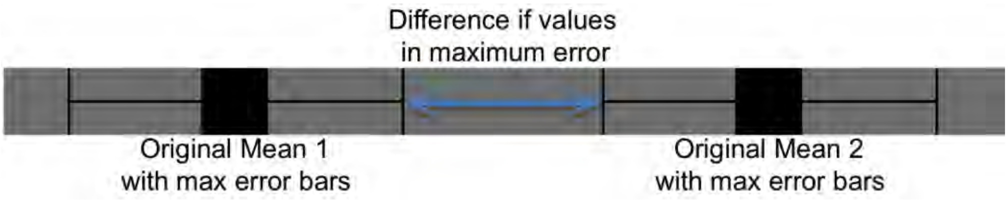
# Appendix 1

Table I. Differences between groups if measures in maximal error due to sample rate Significant post hoc results only [pre and post-1 (*), post-1 and post-2 (**) and pre and post-2 (***)]

| | PRE | Post1 | Post2 | | |
|---|---|---|---|---|---|
| **KICK LEG** | **mean ± s** | **mean ± s** | **mean ± s** | **% error** | **Group mean values adjusted to maximum error (* means still significant)** |
| Foot Speed at BC (m·s$^{-1}$) | 19.7 ± 2.0 | 20.3 ± 1.7 | 20.5 ± 1.4 | 2% | |
| | | | | | |
| ***Sagittal Plane*** | | | | | |
| Thigh Angular Velocity at BC (°·s$^{-1}$) | | 51 ± 56 ** | 118 ± 53 | 10% | 56 v 106* |
| Thigh - Maximum Angular Velocity (°·s$^{-1}$) | 742± 89 * | 796 ± 111 | | 1% | 749 v 783* |
| Shank ROM (°) | 87 ± 13 | | 97 ± 7 *** | 16% | 101 v 82 (potential problem) |
| Thigh ROM (°) | 84 ± 5 * | 88 ± 5 | 89 ± 5 *** | 1% | 84.8 v 87.1* and 88.1* |
| Pelvis ROM (°) | 51 ± 8 * | 57 ± 10 | | 0.6% | 51.3 v 56.7* |
| | | | | | |
| ***Frontal Plane*** | | | | | |
| Thigh ROM (°) | 10.3 ± 3.6 * | 13.2 ± 5.0 | | 16% | 11.9 v 11.1(potential problem) |
| Pelvis ROM (°) | 6.1 ± 1.7 * | 11.9 ± 5.4 | | 1.6% | 6.2 v 11.7* |
| Thigh - Maximum Angular Velocity (°·s$^{-1}$) | 76± 77 | 92 ± 62 ** | 127 ± 40 *** | 4% | 79 v 88 and 122* |
| | | | | | |
| ***Flexion/Extension*** | | | | | |
| Knee - Minimum Angle (flexion) (°) | -116 ± 6 | | -122 ± 7 *** | 0.6% | 117 v 121* |
| | | | | | |
| ***Abduction/Adduction*** | | | | | |
| Hip – Maximum Angular Velocity (adduction) (°·s$^{-1}$) | 182 ± 116 | 242 ± 96 | 276 ± 120 | 2% | 187 v 247 and 270 * |
| | | | | | |
| Kick Time (s) | 0.19 ± 0.03 * | 0.21 ± 0.03 | 0.22 ± 0.04 *** | 1% | .20 v .20* and .21* |
| Sprint times (s) | 3.28 ± 0.11 * | 3.44 ± 0.16 ** | 3.53 ± 0.23 *** | N/A | |

**Percent error** calculated by first finding the maximum difference in the final five frames of 500 Hz data (so the range of possible values that could be obtained using

100Hz) then expressing this in terms of the group mean.




**Group mean values adjusted to maximum error** = using the maximum possible error, group means are adjusted to identify if the error might influence the result. For example for Thigh Angular Velocity, an error of 10% might have existed due to the use of 100 Hz compared to 500 Hz data. This 10% was added to the Post 1 group mean value (51 degrees/s becomes 56 degrees/s) and subtracted from Post2 (118 degrees/s becomes 106 degrees/s) indicating that even with this error, group means are still substantially different. The t-test was also repeated using the 'maximum error' mean and the original standard deviations to see if the comparison remained significant. Of note here is that this analysis has been performed using the 'worst case scenario' where mean 1 is in maximum error towards mean 2 and vice versa. The true error will be lower as the sampling issue will generate a random and not systematic error so these results have likely increased type 1 errors.

# Appendix 2

# Impact Research

## How previous studies have dealt with 'impact'?

**<u>KEY</u>**

No Impact adjustments

Padded

| Author (Sport) | Method | Filter/cut-off |
|---|---|---|
| Dorge et al (1999) - Soccer | - (400Hz capture)<br>Kinematics<br>- Angular and linear velocities and accelerations were derived by finite difference computation from filtered displacement data<br>Kinetics<br>- A classical inverse dynamics approach (Winter, 1990), as well as velocity dependent equations (Putnam, 1993) were used to calculate torques on the thigh and shank | Displacement data were filtered using a digital forth-order Butterworth low-pass filter with 0° phase lag (6-10Hz cut-off |

| | | |
|---|---|---|
| | - Analysed up until BC. No mention of anything done to account for BC | from residual analysis) |
| Kellis et al (2006) | - (120Hz capture)<br>- Ball impact point was specified with each data set<br>- "The curves were then smoothed in order to obtain a more close fit of the raw data curves over a specified small interval (around impact) of the sequence. Adjustment of the curves was achieved by permitting higher frequency variations in raw values. This resulted in smooth curves that more closely fit the change in the raw data curves because of ball impact".<br>No mention of anything else done to account for BC | Displacement -time data from the start of the movement to BC were filtered using a forth-order (low-pass) Butterworth filter with zero phase lag |
| Kawamoto et al (2007) - Soccer | - (200Hz capture)<br>Kinematics<br>- Captured motion data were reconstructed into three- dimensional coordinates by the direct linear transformation (DLT) method<br>- Data were interpolated using splines if the time series had any gaps<br>- A relatively high frequency (20Hz) was selected as the cut-off frequency of the Butterworth-type | Butterworth-type digital low-pass filter (20hz cut-off) |

| | | |
|---|---|---|
| | digital low-pass filter. This was to minimise any distortion of the kinematic data around impact<br>- Segmental angular velocities were calculated based on Winter<br>- Segmental angular accelerations were calculated as the first time-derivatives of the angular velocities<br>Kinetics<br>- Joint torques were calculated through inverse dynamics<br><br>**Did not look at impact**<br>*Joint angles, angular velocities, and torques were calculated from TO to* ***10ms before impact****.*<br>- *Resultant velocity of the kicking foot immediately before BC was calculated as the first derivative of its non-filtered displacement during 20ms before BC*<br>- *Resultant velocity of the ball after BC was calculated as the first derivative of its non-filtered displacement during 20ms after BC* | |
| Luhtanen (1988) – Soccer | Kinematics and kinetics | Linear and angular kinematic data were |

| | | |
|---|---|---|
| | | smoothed by the digital filtering method (Winter et al., 1974) |
| Bisseling et al (2006) – Landing | - (200Hz capture)<br>To improve the assessment of knee moment during the impact phase of landing after a jump, the SM (standard inverse dynamic method) using low-pass filtering at 20Hz (SM20) was compared with SM100, low pass filtered at 100Hz, and with the AM (Accelerometer based method), both accelerometer output and required kinematic data filtered at 100Hz.<br>- The real segmental accelerations contained frequencies well above 20Hz<br>- Filtering accelerations at 20Hz suppressed high-frequency components at impact<br>- to calculate truthful knee moments at impact it is recommended to use the same cut-off frequencies and same filter technique for both kinematic and force plate data<br>A cutoff frequency of 20Hz was considered sensible in the view of findings with SM100 for landing | |
| | - | |

| | | |
|---|---|---|
| Reid et al (2007) – Wheelchair tennis serve | - (250Hz Capture)<br>- Kinetics<br>- Inverse dynamics<br>- Up until impact, then looked at follow-through .004s post impact (no curves published) | |
| | - | |
| Ball (2008) - Football | - (500 Hz capture)<br>Kinematics<br>- From kicking foot toe off until instant before ball contact<br>- "To avoid measurement issues that exist when analysing kinematic data across impacts (Knudson and Bahamonde, 2001), no evaluation of the impact phase was performed. The last frame analysed (ie. The instant before ball contact) is referred to as ball contact for this paper"<br>- "Digitized XY coordinates were transferred to excel. Data were padded with 50 points at the start and end of the digitized sequence to avoid smoothing endpoint problems (50 frames from toe-off were mirrored and added to the start of the sequence, while the 50 frames before ball contact were mirrored and added to the end of the sequence). This number of padded points was higher than that used in literature (eg 15 points for | Butterworth digital filter (cut-offs between 8Hz and 12Hz). Cutt-offs determined based on combination of residual analysis, visual inspection of raw and smoothed curves, and observation of the influence of |

| | | |
|---|---|---|
| | moment data: Nunome, Lake, Grorgakis and Stergioulas2006) but visual inspection of the raw smoothed data in this study indicated 50 was appropriate".<br>- velocities calculated using three-point central difference method | different cut-offs on parameter values (Ball, Best, Wrigley 2001) |
| Ball (2001) - Football | See Ball 2008<br>Kinematics<br>- (200 Hz capture)<br>- Kick leg toe-off until instant before contact<br>- 50 padded points in excel before smoothing<br>- velocities calculated using three-point central difference method | Butterworth digital forth-order filter (12Hz cut-off) |
| Iino and Kojima (2011) – Table tennis | - 200Hz Capture<br>- Kinetics of upper limbs<br>- Joint forces and torques through inverse dynamics<br>- Rate of Work (joint) = Torque * angular velocity<br>- Rate of Work (segment) = Force * velocity<br>- No mention of impact – probably due to minor acceleration changes due to low mass of ball | Coordinate data smoothed with forth order Butterworth zero-phase lag digital low pass filter (5.8 to 14Hz cut-off |

| | | |
|---|---|---|
| | | – residual analysis) |
| Nunome et al (2006) - Soccer | Moments<br>- computed from unsmoothed coordinates until 3 frames before impact (allows appropriate second derivatives to be obtained without any influence of BC using central differentiation)<br>- non-smoothed moment data then extrapolated for 15 points (including 3 points) using a polynomial regression (the additional 12 data points avoided the end point distortion produced by filtering artefacts)<br>- moments were then extrapolated using the **first-order** polynomial regression<br>Angular velocities<br>- extrapolated using the **second-order** polynomial regression<br>The polynomial regressions were carefully defined for each single data set to resemble its final change<br>- the final 8-12 data points were used to determine each polynomial regression after extensive experimentation with all the signals available in the study (200Hz capture) | After the extrapolations, all parameters were digitally smoothed by a forth-order Butterworth filter at **12.5Hz** then the extrapolated region after the moment of BC was removed |

| | | |
|---|---|---|
| Apriantono et al (2006) - Soccer | See Nunome (2006)<br>- …However, the final 25-35 data points were used to determine each polynomial regression after extensive experimentation with all the signals available in this study (500Hz capture) | See Nunome (2006) |
| Dorge et al (2002) – Soccer | - (400Hz capture)<br>- The ends of the displacement signal were extrapolated by reflection in both the x- and y-directions, so that the slopes of the original and extrapolated sequence were matched at the end point<br>- After filtering the extrapolated signals were removed<br>- Optimal cut-off frequencies (6-10Hz) were determined by residual analysis<br>- From the filtered displacement signal, angular and linear velocities and accelerations were derived by finite difference computation<br>- Muscle moments about the hip and knee and the motion dependent joint reaction forces acting as moments on the shank were determined using inverse dynamics starting at the open end, the ankle | Displacement data from TO to BC were filtered using a Butterworth low-pass filter with 0° phase lag |
| Reid et al (2012) – | - (500 Hz Capture) | Low pass cut-off 17Hz |

| | | |
|---|---|---|
| Tennis serve | - 2nd order polynomial proved to be the least erroneous extrapolation technique (displacement and vel)<br>- Quintic spline filter was the most appropriate filter<br>- The previously performed "smoothing through impact" method, using the quintic spline filter, underestimated the racket velocity (9.1%) at impact | (determined by residual analysis) |
| Knudson et al (2001) – Tennis forehand | - Position and velocity<br>- Smoothing through impact created distortions of the position signal up to 100ms before impact and resulted in 3.2% underestimation of wrist angle and 67.9% underestimation of angular velocity at impact<br>Linear and polynomial extrapolation conditions smoothed with all techniques provided lower root mean squared errors than the smoothing-through-impact condition, with discrete wrist positions at impact within 1.1% of the criterion data | |

# Appendix 3

## Original Candidature Proposal

Evan Coventry

# Biomechanical Considerations of the effect of Fatigue on Kicking in Australian Rules Football

First Review of proposed research for the degree

**Doctor of Philosophy**

Supervisors:

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## Introduction

Australian Rules Football (ARF) is a physically demanding sport. It is played on a ground with an area far exceeding that of any of the other football codes (e.g. ground area between 14000 and 19000 $m^2$ compared with between 6000 and 8000 $m^2$ for soccer and rugby codes) (Ball, 2006). Australian rules football (AFL) is also played for a longer duration than other codes, with the average game taking approximately 120 minutes as compared to 93 minutes in soccer (Ball, 2006). Further, ARF has a very intermittent nature with GPS technology showing that on average players cover 12.5km of distance during a game, have an average speed of 6.78km/hr, (7.31km/hr for midfielders), and spend one third of their playing time in speed zones above 8km/hr. Players have also been found to surge above 18km/hr on average 90.09 times per game for total time of almost 6 minutes, equating to an average of 4 s per sprint over 18km/hr (Wisbey & Montgomery, 2007). This differs from soccer in which players cover 8-12km per game (Greig, 2006), and travel in speed zones above 16km/hr for averages of only 2.5 s (Bangsbo, 1994).

Fatigue has been reported to be detrimental to performance (Kellis *et al*., 2006) and increases injury risk (Gleeson *et al*., 1998). In soccer, Rahnama *et al*., (2003) showed that late in a game, players' leg muscle strength decreases due to fatigue. In turn this was proposed to affect kicking technique and leave players more susceptible to injury. This was supported by Apriantono *et al.* (2006), who found 3D kinetic and kinematic differences in maximal instep soccer kicking technique before and after a fatigue protocol. Altered technique under fatigue has also been reported in other sports skills such as landing (Coventry *et al*., 2006; Madigan and Pidcoe, 2003) and running (Derrick *et al.*, 2002).

In spite of the influence of fatigue on technique and that ARF is played for long durations and at relatively high intensities, there have been no studies examining technique change under fatigue in ARF. Further, many previous studies examining fatigue and technique change in other sports have not performed a game-specific fatiguing protocol. For example Apriantono *et al.* (2006) elicited a fatigue state by using knee extension and flexion exercises. This ignored the musculature at the hip, where the kicking motion is initiated and the majority of the muscular force is developed (Dorge *et al*, 1999).

The aims of this study will be to evaluate the effects of fatigue on the kinematics and kinetics of ARF kicking among elite, sub-elite and junior ARF players using both short term and long term AFL specific fatigue protocols that simulate an Australian Rules Football match.

**Contribution to Knowledge**

This will be the first study to examine the effect of fatigue on kinetics and kinematics of the drop punt in ARF. This study will use a validated ARF-specific fatiguing protocol . It will build on the knowledge of how fatigue affects kicking technique, but will have specific relevance to ARF. As fatigue has been shown to affect kicking technique in soccer (Apriantono *et al*., 2006) and has been touted as a factor in increasing the chance of injury late in a game (Hawkins, 2001), this study will also provide essential information in assessing the negative performance and injury consequences that fatigue may have on ARF players.

**Statement of Significance**

Fatigue has been shown to decrease performance and increase injury risk in other sports and activities, but this has not been evaluated in ARF. Given the longer timeframes, larger grounds and longer average sprint times, examination of the influence of fatigue in ARF is essential to improve performance and decrease injury risk. Identification of the changes in technique and muscle function due to fatigue can lead to better conditioning programmes and identification of optimal techniques that limit the effects of fatigue. Further, the results can provide useful information to be incorporated into assessment of the two major injury mechanisms in AFL: hamstring strains and osteitis pubis. This is an area of great interest to a number of ARF stakeholders, specifically the sports triangle (VU, The Western Bulldogs AFL team, the Western Jets under 18s, and Victoria University sponsored schools (Keilor College, Maribyrnong College).

**Literature Review**

Kicking is a fundamental skill in ARF. It is the most prevalent method of passing between players and the only method of scoring a goal. Effective kicking is also significantly related to success (Forbes, 2003).

The general kicking technique consists of the coordination of multiple segments in a proximal to distal sequence in a kinematic chain (Dorge *et al.*, 1999). The kicking motion is initiated at the larger proximal muscles around the hip and proceeds down the chain to the more distal foot segment for high speed at ball impact. In ARF, the drop punt is the primary kicking technique used (Orchard *et al.*, 1999). Figure 1 shows the drop punt sequence. During the early phases of a drop punt most of the work is performed eccentrically by the proximal muscle groups which transfer momentum to the distal segments just prior to ball contact (Orchard *et al.*, 1999).

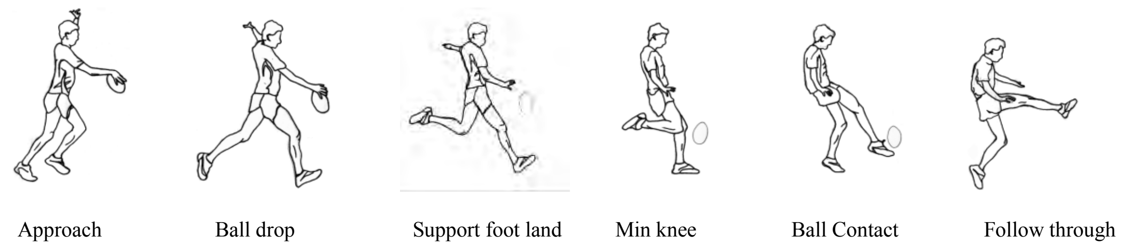


Figure 1: The Drop Punt Sequence (from Ball, 2008)

In spite of the importance of kicking in ARF, there has been little research examining the technique of kicking. In one of the only studies on ARF kicking technique, Ball (in press), found that when kicking for distance, foot speed was the major contributor to kicking the ball further and that maximum hip linear velocity in the last stride before ball contact and shank angular velocity accounted for the majority of the variance in foot speed. Foot speed and quality of contact between the foot and ball has also been proposed to be crucial when kicking for accuracy in ARF (Cameron and Adams, 2003).

No study has examined the effect of fatigue on kinetics and kinematics of the drop punt in ARF. Most fatigue kicking research has centred around the biomechanics of the soccer in-step kick and how improvements in technique can create a better chance for success in a soccer game situation, or how improved technique may limit the players susceptibility to injury. Rahnama *et al*., (2003) showed that late in a game, as players get tired their leg muscle strength decreases due to fatigue and this is thought to affect kicking technique and leave players more susceptible to injury. Apriantono *et al*., (2006) used a two link kinetic chain model composed of the thigh and lower leg to analyse the effect of muscle fatigue on instep kicking. Examining three dimensional kinetics and kinematics, Apriantono *et al*. (2006), found technical changes in the maximal instep soccer kick before and after a fatigue protocol. Apriantono *et al*. (2006), showed that a repeated loaded knee extension and flexion fatigue protocol on a weight-training machine caused decreased muscle moments and interactive moments during the kick resulting in a decrease in the velocity of the leg swing. Apriantono *et al*. (2006) suggested that this decreased leg swing velocity caused poorer ball contact, which in turn led to significantly slower ball velocity. As ball velocity correlates with the distance the ball travels (Ball, 2008), these results indicate that fatigue will affect kicking distance. It was also observed that immediately before ball impact the eccentric action of the knee flexors (thought to be a safety mechanism to prevent over extension of the knee joint) was less evident, therefore possibly increasing the kicker's susceptibility to injury.

A limitation of the Apriantono *et al*. (2006) study was that the fatigue protocol used was not representative of the intensity, duration and various actions performed in a soccer match. The use of the weight training machine did not require any movement at the hip, thereby negating the work by the hip flexors; other than the rectus femoris which is also used to extend the knee. The hip flexor has been shown to be a major influence in force production during kicking (Dorge *et al*., 1999). As such, the generalisability of the Apriantono *et al*. (2006) findings to soccer remains questionable. Other fatigue based soccer studies have also failed to utilise a fatiguing protocol that is specific to the sport. Lees and Davis (1987) found decreased coordination between the upper and lower leg during kicking after a six minute step test, while Lyons *et al*. (2006) found that performance on the modified Loughborough Soccer Passing Test decreased after a high intensity one minute bout of alternate split squats.

Some studies have attempted to replicate match induced fatigue by either using a treadmill or an exercise protocol. Rahnama *et al.*, (2003) tested quadricep and hamstring muscle strength on an isokinetic dynamometer prior to, at the half way point and after a 90-minute soccer specific intermittent exercise protocol performed on a treadmill. Intensities elicited walking, jogging, running and sprinting, as observed in a soccer match. A similar fatigue protocol was also used by Rahnama *et al*., (2005) to test the electromyographic (EMG) activity of selected lower limb muscles at various intensities before, during and after fatigue. The subsequent decrease in EMG activity was thought to be an indicator of fatigue and decreased strength during prolonged exercise.

Gleeson *et al.*, (1998) also attempted to use a variety of endurance based fatiguing protocols designed to simulate the physiological demands of soccer match-play and training to test the effects on leg strength, electromechanical delay and knee laxity. The four different protocols used are summarised in Table 1. Each of these protocols produced different results, however it was suggested that the prolonged intermittent high intensity shuttle run (PHISR) trial was the best representative of the physiological stresses experienced by soccer players during match play. This conclusion was based on similarities between the protocol and game-based physiological data such as heart rate and blood lactate.

Table 1 - Fatigue protocols used by Gleeson *et al.* (1998)

| Fatigue protocol | Description |
|---|---|
| 1) High intensity shuttle run | A prolonged intermittent high intensity shuttle run (PHISR) simulating the 90 minutes of a soccer game broken into observed work-to-rest intervals and activity modes (total distance of 9600m consisting of 12*200m cycles of activity, each comprising 60m walking (1.54m.s-1), 15m sprinting (5m deceleration and 5m recovery walk), 60m jogging (55% VO2 max), and 60m running (95% Vo2 max)) |
| 2) Shuttle run | Subjects completed a total distance of 9600m in four sections of 2400m at 70% VO2 max |
| 3) Treadmill run | Treadmill run of a total distance of 9600m in four sections of 2400m at 70% VO2 max |
| 4) Control condition | No exercise |

Kellis *et al*., (2006) also used a 90 minute intermittent exercise protocol to test the effect of soccer-specific fatigue on the biomechanics of the maximal instep kick. Kicks were performed before, during and after the protocol. Physiological markers such as blood lactate concentrations and $NH_3$ (ammonia) concentrations indicated that the protocol caused musculature fatigue. This fatigue caused a significant decline in ball speed and angular velocity of the shank and knee. Kellis *et al.* (2006) reported this was associated with a significant decline of the net moment applied on the shank and suggested it was due to the reduced strength exerted by the knee musculature at ‘critical’ times.

Although there have been several studies that have looked at the effect of fatigue on leg strength, muscle activation or soccer kicking technique, it is clear that only limited comparisons can be made between these studies due to vast array of fatigue protocols that have been implemented. Many of these studies made little attempt to utilise a fatigue protocol that simulated a match scenario. Although Rahnama *et al*. (2003), Rahnama *et al*. (2005), Gleeson *et al.* (1998), and Kellis *et al*. (2006) all attempted to use soccer specific protocols, they all failed to incorporate the many changes of direction, jumping, tackling and kicking motions used in a game. These studies also failed to use elite soccer players as their participants, therefore limiting the implications of the research to junior and amateur soccer players. It is also difficult to compare results from soccer based research to ARF due to the inherent differences in the games and the kicking technique.

The proposed study will three dimensionally analyse the kinetics and kinematics of the ARF kicking technique before and after a short term and long term ARF specific fatigue protocol. Elite, sub elite and junior ARF players will be analysed and compared. It is expected that participants will display changes in their kicking technique post fatigue. These differences may show up in changes in foot speed and shank angular velocity just before ball contact, and a possible redistribution of work to utilize the larger hip flexors in a fatigued state. Due to their higher levels of ARF specific training, it is thought that these differences will be less pronounced in the elite group.

**Research Design**

General Aim - To examine three dimensional kinematics and kinetics of ARF kicking pre and post fatigue.

Study 1 will three dimensionally analyse the pre fatigue kinetics and kinematics of the ARF kicking technique.

Study 2 will compare the pre fatigue ARF kicking technique to the kicking technique after an ARF-specific short term fatigue protocol.

Study 3 will compare the pre fatigue ARF kicking technique to the kicking technique after an ARF-specific long term fatigue protocol.

Methods

Elite, sub elite and junior ARF players will be recruited for this study. Participant numbers will be calculated from statistical power analyses and using effect sizes from pilot testing carried out to assess changes due to fatigue in the means of performance measures (velocity of foot and velocity of ball). As no fatigued kicking research has been done with ARF, pilot testing will give the best indication of the sample size required for each level of athlete. As an approximation based on research by Greig (2006) and Apriantono et al. (2006), 7 subjects per group was the number of participants used to find significant differences in soccer kicking fatigue research. Participants will be screened for injury and will sign consent forms before taking part in the study. The participants will be tested in the Victoria University Biomechanics lab, Basement level (Room B30) 300 Flinders St, Melbourne. They will perform a standardized warm up which will consist of riding an exercise bike for 10mins and stretching the muscles to be used in the movement (hamstring, quadriceps, calf, hip flexor).

Study 1 will be used to identify important pre fatigue kinetic and kinematic parameters in kicking for distance. Three dimensional (3D) data will be collected (a progression from two dimensional data obtained by Ball, 2008). Participants will perform up to 10 self-paced practice drop punt kicks on their preferred foot in the lab environment. The number of trials will be based on pilot testing to find where mean performance measures (the velocity of the foot and the velocity of the ball) stabilize. Participants will be instructed to kick for maximal distance.

Study 2 will evaluate how the important technical parameters identified from Study 1 alter under short term fatigue. Study 2 will use existing global positioning satellite (GPS) data on ARF movement obtained from the Western Bulldogs, VFL and elite junior footballers, in conjunction with pilot testing, to formulate a specific short term fatigue protocol for each level of participant. Each protocol will include a range of agility, tackling and jumping movements. Immediately after the protocol the participant will perform three kicks for maximal distance, on their preferred leg, with an attempt made to capture at least two clean force plate strikes with the support foot (Illich, 2004). In addition fatigue markers will be used to assess fatigue immediately after the third kick. Fatigue markers will include power generation from a one legged jump off a force platform and the timing of a 20m sprint. Physiological and psychological markers such as heart rate, blood lactate, ADD plasma potassium and rating of perceived exertion (RPE) indicators of workrate and a means of explaining the fatigue. Electromyography (EMG) median frequency of major thigh and leg muscles during the kick will also be measured to indicate central fatigue and activation (see Table 3 for a complete outline).

Study 3 will evaluate how the important parameters identified from Study 1 may alter under long term fatigue. Study 3 will use existing GPS data on ARF movement obtained from the Western Bulldogs, VFL and elite junior footballers, in conjunction with pilot testing, to formulate a specific long term fatigue protocol for each level of participant. Each protocol will be treadmill based and reflect the duration and changes of intensity in an entire game at each level of ARF. Three maximal drop punt kicks will be measured every five minutes throughout the protocol. In addition physiological and mechanical fatigue markers will be used to assess fatigue immediately after the third kick in each kick set throughout the protocol.

Data Collection

For all studies each kick will be measured from kick foot toe off until ball contact (Ball, 2008). An Optotrak Certus 3D motion analysis system (Northern Digital Incorporated, Ontario, Canada) will be used to obtain 3D coordinates of the kicking leg, pelvis and trunk. Joint and segment velocities, joint ranges of motion, segment angles and timing variables will be derived from the recorded data. Ball speed immediately after the ball leaves the foot will be analysed from high speed video, with the video footage being digitised using Silicon Coach Analysis tools (used by Ball, 2008). All procedures are non- invasive and standard for the collection of biomechanical data and have been used in the Victoria University biomechanics laboratory. Forces and moments will be measured in the non kicking leg using an AMTI force plate (AMTI LG6-4, 1200 mm x 600 mm). Force and moment data collected during each kick will be passed through an AMTI amplifier (AMTI SGA6-4 attached to the LG6-4 force plate) set at a maximum gain of 4000. The data will then pass through a 24.3 Hz low pass filter and be sampled by an

AMLAB 16-bit data acquisition system (AMLAB Technologies, Sydney, Australia) at 1000Hz.

In study 1, means and standard deviations will be measured for the parameters listed in Table 2. A factor analysis will be applied to the parameters to reduce the number of parameters used in subsequent statistical analysis. As used by Ball *et al.* (2003), the factor analysis will be used to reduce the number of parameters and not to find the end result. Therefore large subject numbers for each parameter will not be an issue required to be considered. Regression and correlation analyses will then be performed on this reduced number of parameters to examine relationships between kicking performance (foot speed and ball speed) and technical parameters. This method was used on two dimensional data by Ball (2008).

Table 2 - Study 1 starting parameters

| Parameter | Definition | Use in previous study |
|---|---|---|
| Ball Speed (m/s) | Averaged of five frames from immediately after the ball has left the foot | |
| *At Ball Contact* | | |
| Foot Velocity ($m.s^{-1}$) | Midpoint between ankle and toe (approx centr of ball contact on foot) | (Ball, 2008) |
| Foot to Ball Distance (m) | The horizontal distance from the heel of the support foot to the ball centre | (Ball, 2008) |
| Ball Height (m) | The vertical distance from the base of the support foot to the ball centre | (Ball, 2008) |
| Knee Angle ( $^o$ ) | Angle between the thigh and shank | (Ball, 2008) |
| Knee Angular Velocity ( $^o.s^{-1}$) | Angular velocity of the knee | (Ball, 2008) |
| Pelvic Tilt ( $^o$ ) | Range of motion (3D angle) | (Illich, 2004) |
| Pelvic Rotation ( $^o$ ) | Range of motion (3D angle) | (Illich, 2004) |
| Hip Linear Velocity ($m.s^{-1}$) | Linear velocity of the kick leg hip | (Ball, 2008) |
| Thigh Angle ( $^o$ ) | Angle between the thigh, defined by the hip and knee digitized points, and the horizontal | (Ball, 2008) |
| Thigh Angular Velocity ( $^o.s^{-1}$) | Angular velocity of the thigh segment | (Ball, 2008) |
| Shank Angle ( $^o$ ) | Angle between the shank, defined by the knee and ankle digitized points, and the horizontal | (Ball, 2008) |

| | | |
|---|---|---|
| Shank Angular Velocity ( $^{o}.s^{-1}$) | Angular velocity of the shank segment | (Ball, 2008) |
| *Maxima and minima* | | |
| Minimum Knee Angle ( $^{o}$ ) | | (Ball, 2008) |
| Maximum Knee Angular Velocity($^{o}.s^{-1}$) | | (Ball, 2008) |
| Minimum Knee FlexExt Moment (N.m) | Net effect of forces acting on the ankle joint * the distance of the line of action to the joint centre - Minimal muscle torque acting on join | (Illich, 2004) |
| Maximum Knee FlexExt Moment (N.m) | Maximal muscle torque acting on joint | (Illich, 2004) |
| Range of Knee FlexExt Moment (N.m) | Range of muscle torque acting on joint | (Illich, 2004) |
| Minimum Knee Power (W) | Indicates absorption/generation of mechanical energy at the joint (the rate of doing work, P=w/t) - Joint moment * joint ang vel | (Illich, 2004; Coventry, 2006) |
| Maximum Knee Power (W) | | (Coventry, 2006 |
| Range of Knee Power (W) | | (Coventry, 2006 |
| Net Knee Work (J) | Muscle force generation in relation to length change - Integrated Joint power curve to give net value of energy absorption/generation | (Coventry, 2006 |
| Maximum Hip Angle ( $^{o}$ ) | | (Ball, 2008) |
| Maximum Hip Linear Velocity ($m.s^{-1}$) | | (Ball, 2008) |

| | | |
|---|---|---|
| Lateral hip displacement of the support limb relative to the support foot (cm) | | (Greig, 2006) |
| Lateral hip displacement angle (°) | | (Greig, 2006) |
| lateral hip rotation ( ° ) | | (Greig, 2006) |
| Minimum Hip FlexExt Moment (N.m) | Net effect of forces acting on the ankle joint * the distance of the line of action to the joint centre - Minimal muscle torque acting on join | (Illich, 2004) |
| Maximum Hip FlexExt Moment (N.m) | Maximal muscle torque acting on joint | (Illich, 2004) |
| Range of Hip FlexExt Moment (N.m) | Range of muscle torque acting on joint | (Illich, 2004) |
| Minimum Hip Power (W) | Indicates absorption/generation of mechanical energy at the joint (the rate of doing work, P=w/t) - Joint moment * joint ang vel | (Illich, 2004) |
| Maximum Hip Power (W) | | (Illich, 2004) |
| Range of Hip Power (W) | | (Illich, 2004) |
| Net Hip Work (J) | Muscle force generation in relation to length change - Integrated Joint power curve to give net value of energy absorption/generation | (Coventry, 2006 |
| Maximum Thigh Angular Velocity ( $^{o}.s^{-1}$) | | (Ball, 2008) |

| | | |
|---|---|---|
| Maximum Shank Angular Velocity ( $^{o}$.s$^{-1}$) | | (Ball, 2008) |
| Minimum Ankle Angle ( $^{o}$ ) | | |
| Maximum Ankle Angular Velocity ( $^{o}$.s$^{-1}$) | | |
| Minimum Ankle FlexExt Moment (N.m) | Net effect of forces acting on the ankle joint * the distance of the line of action to the joint centre - Minimal muscle torque acting on join | (Illich, 2004) |
| Maximum Ankle FlexExt Moment (N.m) | Maximal muscle torque acting on joint | (Illich, 2004) |
| Range of Ankle FlexExt Moment (N.m) | Range of muscle torque acting on joint | (Illich, 2004) |
| Minimum Ankle Power (W) | Indicates absorption/generation of mechanical energy at the joint (the rate of doing work, P=w/t) - Joint moment * joint ang vel | (Illich, 2004) |
| Maximum Ankle Power (W | | (Illich, 2004) |
| Range of Ankle Power (W) | | (Illich, 2004) |
| Net Ankle Work (J) | Muscle force generation in relation to length change - Integrated Joint power curve to give net value of energy absorption/generation | (Coventry, 2006 |
| Last Step Distance (m) | Distance between the toe of the kick foot whe in contact with the ground to the toe of th support foot when in contact with the ground | (Ball, 2008; Greig, 2006) |
| Ball Drop Height (m) | Vertical distance from wrist of the ball drop hand to the ground (the ball was partially | (Ball, 2008) |

obscured by the hand so wrist rather than ball

height was used for this parameter)

Study 2 and 3 will use the technical parameters identified as important to foot and ball speed from study 1, as well as selected parameters that have been found to change under fatigue in soccer kicking (e.g. pelvic motion, Greig, 2006). Fatigue indicators (table 3) will also be measured to indicate the level of fatigue of the participant.

Table 3 - Fatigue markers and descriptors measured immediately after the third kick in study 2 and 3

| **Fatigue Marker** | **Definition/Description** | |
|---|---|---|
| Power generation from a one legged jump off a force platform (W) | | (Coventry, 2006) |
| Timing of 20m sprint (sec) | | |
| **Descriptor of Fatigue / Workrate indicator** | **Definition/Description** | |
| HR (bpm) | Heart Rate monitored continuously at 5 second intervals using short range radio telemetry (PolarTeam System, Polar Electro, Kempele, Finland) | (Greig, 2006) |
| Blood Lactate Concentration ($mmol \cdot l^{-1}$) | Finger tip puncture | (Greig, 2006) |
| ADD plasma potassium | | (Aughey, 2005) |
| EMG (rectus femoris, biceps femoris of kicking leg) | total iEMG, median frequency and peak EMG | (Greig, 2006) |
| RPE | Rating of Perceived Exertion on a 6-20 point scale | (Coventry, 2006; Greig, 2006) |

Data Analysis

Quantitative data will be summarized statistically using means and standard deviations. A factor analysis, as used by Ball (2008) will be applied to the starting parameters in study 1 to reduce the number of parameters used in subsequent statistical analysis. One parameter will be chosen from each factor based on three levels of decision making - the parameter that most represents that factor, importance of a parameter in previous research and on theoretical bases. These parameters will then be used to compare to the performance measures (velocity of foot and velocity of ball) after a short term fatigue protocol in study 2 and a long term fatigue protocol in study 3. T-tests will be used to assess changes due to short term fatigue in study 2. ANOVAs with repeated measures will then be used to assess changes in each variable as fatigue progresses throughout study 3.

**Timeline (in 6 month block)**

| | Feb-07 | Aug-07 | Feb-08 | Aug-08 | Feb-09 | Aug-09 | Feb-10 | Aug-10 | Feb-11 | Aug-11 | Feb-12 | Aug-12 | Feb-13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Prepare Candidature Application | ■ | ■ | ■ | | | | | | | | | | |
| Study 1: Developing ARF specific fatigue protocol. Participant recruitment & testing | ■ | ■ | ■ | | | | | | | | | | |
| Validating ARF specific fatigue protocol | | ■ | ■ | ■ | ■ | ■ | | | | | | | |
| Paper and thesis writing | | | | ■ | ■ | ■ | ■ | | | | | | |
| Study 2: Examining pre-fatigue technique descriptively: Participant recruitment & testing | | | | ■ | ■ | ■ | | | | | | | |
| Analysis | | | | ■ | ■ | ■ | ■ | | | | | | |
| Paper and thesis writing | | | | | ■ | ■ | ■ | ■ | | | | | |
| Study 3: Examine technique changes due to fatigue. Participant recruitment & testing | | | | | ■ | ■ | ■ | | | | | | |
| Analysis | | | | ■ | ■ | ■ | ■ | ■ | ■ | | | | |
| Paper and thesis writing | | | | | | | ■ | ■ | ■ | ■ | | | |
| Thesis writing | | | | | | | | | | ■ | ■ | ■ | |
| Submit thesis | | | | | | | | | | | | ■ | ■ |

**Budget $4500**

Optotrak leads (to be used with Optotrak to obtain 3D data) $1000

EMG equipment (electrodes and leads to be used to assess fatigue in muscles) $500

Parking/travel (50 subjects @$17 for parking, travel between campuses) $1000

Transport of equipment (between Footscray and City campuses) $500

Footballs x 3 (for use in kicking testing) $300

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