

Research article

Relationship between Leg Mass, Leg Composition and Foot Velocity on Kicking Accuracy in Australian Football

Nicolas H. Hart^{1,2}✉, Jodie L. Cochrane³, Tania Spiteri⁴, Sophia Nimphius³ and Robert U. Newton¹

¹ Exercise Medicine Research Institute, Edith Cowan University, Perth, W.A., Australia; ² Fremantle Dockers Football Club, Perth, W.A., Australia; ³ Centre for Exercise and Sport Science Research, Edith Cowan University, Perth, W.A., Australia; ⁴ School of Health Science, University of Notre Dame, Perth, W.A., Australia

Abstract

Kicking a ball accurately over a desired distance to an intended target is arguably the most important skill to acquire in Australian Football. Therefore, understanding the potential mechanisms which underpin kicking accuracy is warranted. The aim of this study was to examine the relationship between leg mass, leg composition and foot velocity on kicking accuracy in Australian Football. Thirty-one Australian Footballers ($n = 31$; age: 22.1 ± 2.8 years; height: 1.81 ± 0.07 m; weight: 85.1 ± 13.0 kg; BMI: 25.9 ± 3.2) each performed ten drop punt kicks over twenty metres to a player target. Athletes were separated into accurate ($n = 15$) and inaccurate ($n = 16$) kicking groups. Leg mass characteristics were assessed using whole body DXA scans. Foot velocity was determined using a ten-camera optoelectronic, three-dimensional motion capture system. Interactions between leg mass and foot velocity evident within accurate kickers only ($r = -0.670$ to -0.701). Relative lean mass was positively correlated with kicking accuracy ($r = 0.631$), while no relationship between foot velocity and kicking accuracy was evident in isolation ($r = -0.047$ to -0.083). Given the evident importance of lean mass, and its interaction with foot velocity for accurate kickers; future research should explore speed-accuracy, impulse-variability, limb co-ordination and foot-ball interaction constructs in kicking using controlled with-in subject studies to examine the effects of resistance training and skill acquisition programs on the development of kicking accuracy.

Key words: muscle, impulse, relative, variability, coordination.

Introduction

Football sports require a combination of speed and accuracy in various forms in order to generate a successful performance; however the act of kicking a ball accurately to a specified target is arguably the most important skill to master (Ball, 2007b). A footballer who is able to deliver a ball accurately over greater maximal and sub-maximal distances is a critical asset to their team (Ball, 2008; Young and Rath, 2011; Young et al., 2010), particularly as the effectiveness of the kicking skill can often differentiate between winning or losing a competitive match (Ball, 2007a; Dichiera et al., 2006). Despite the importance of kicking accuracy in sport, there is limited research focusing on ways to describe, develop and improve this technical characteristic (Dichiera et al., 2006; Young et al., 2010).

Previous research has identified a variety of ways to enhance kicking distance (Baktash et al., 2009; Ball,

2007a; 2008; Young and Rath, 2011), principally focusing attention towards optimising foot velocity as a descriptor for subsequent ball velocity (Ball, 2008; Kellis and Katis, 2007; Lees and Nolan, 1998; Levanon and Dapena, 1998). However, foot velocity might not resonate strongly with kicking accuracy. In particular, resultant ball velocity is the product of applied angular impulse and transferred angular momentum (Baktash et al., 2009; Sterzing and Hennig, 2008); and while foot velocity is an influential characteristic of kicking behaviour, it does not wholly represent the complexity of the kicking action. Specifically, it fails to address the fundamental description of angular momentum which requires the consideration of both the quantity and distribution of lower limb mass, in addition to the angular foot velocity produced at ball impact (Andersen et al., 1999; Baktash et al., 2009; Lees and Nolan, 1998).

Modifying kicking behaviour to enhance performance can be achieved by adjusting the speed (angular velocity) at which the lower limb travels, or alternatively by adjusting the striking mass (rotational inertia) of the limb (Ball, 2008; Kellis and Katis, 2007; Young and Rath, 2011), through combinations of context-specific technique training and physical conditioning programs. While increasing the velocity of the kicking limb might improve kicking distance, there is a potential conflict with kicking accuracy due to an anticipated speed-accuracy trade-off (Beilock et al., 2008; Magill, 2008; Nagengast et al., 2011), prompting a possible decrease in movement precision at higher limb velocities (Dean and Maloney, 2007; Urbin et al., 2011). Instead, a plausible solution may involve the manipulation of striking mass achievable through training intervention, as this should allow an equivalent distance to be achieved at a reduced angular velocity (Young and Rath, 2011), effectively shifting the speed-accuracy continuum towards greater accuracy without compromising achievable distance.

A paucity of research exists investigating the potential relationship between the technical and temporal strategy of accurate and inaccurate kickers in response to the physical parameters modifiable by athletic conditioning. Indeed, increasing scientific understanding of those mechanisms which underpin accurate performance will inevitably improve the quality of coaching, physical conditioning and acquisition strategies, with the aim to enhance athletic performance. In particular, adjusting the quality (composition) and quantity (amount) of lower limb mass through a targeted strength training interven-

tion may have a profound impact on an athlete's kicking action and technical proficiency. The purpose of this paper was to investigate the relationship between leg mass, leg composition and foot velocity on kicking accuracy outcomes for accurate and inaccurate kickers in Australian Football, as a hypothesis-generating study (Bishop, 2008) for future intervention-based, longitudinal research investigations.

Methods

Participants

Thirty-one Australian footballers (age: 22.1 ± 2.8 years; mass: 85.1 ± 13.0 kg; height: 1.81 ± 0.07 m; BMI: 25.9 ± 3.2 ; playing experience: 8.4 ± 2.3 years) were recruited from the Western Australian Football League (WAFL) for participation in this study. All athletes were part of the same football team and same developmental zone; and therefore received a similar prescription of kicking practice during structured training and skills sessions for at least five years prior to the current study, with two consecutive years of experience at their current playing level. Athletes were also required to have no injuries or contraindications at the time of testing; and were not permitted to perform any strenuous exercise or lower body resistance training within 48 hours of their assigned testing session. All athletes were notified of the potential risks involved, and provided written informed consent for participation. Ethics clearance was provided by the University's Human Research Ethics Committee.

Experimental design

This study utilised an acute, between-groups, cross-sectional design, consisting of a single testing session. Anthropometric measures including height, weight, joint breadths and limb lengths were performed; followed by an assessment of whole-body composition and lower body segmental mass characteristics (lean, fat, total) of the kicking and support limbs using Dual-energy X-ray Absorptiometry (DXA; Hologic Discovery A, Waltham, WA). Athletes were taken through a general dynamic warm-up, prior to a sport-specific warm-up (kicking over variable distances), designed to stabilise their kicking performance (Amiri-Khorasani et al., 2010). The kicking protocol, consisting of ten drop punt kicks over 20 metres, was then completed. Athletes were required to wear their club issued football shorts; were provided with indoor football shoes (Nike5 Bomba, Nike Inc, USA); and were

thoroughly familiarised with all testing procedures prior to assessment. Following the assessment and analysis of their kicking performance, subjects were subsequently assigned to accurate ($n = 15$) and inaccurate ($n = 16$) groups for further analysis (Table 1), in accordance with accuracy determination criteria (Hart et al, 2013; 2014).

Anthropometry

Stature was recorded to the nearest 0.1 cm using a wall-mounted stadiometer (Model 222, Seca, Hamburg, DE), with body mass recorded to the nearest 0.1 kg using an electronic weighing scale (AE Adams CPW Plus-200, Adam Equipment Inc., CT, USA). Length of the kicking leg was assessed using a retractable measuring tape (Model 4414, Tech-Med Services, NY, USA), from the greater trochanter of the femur to the lateral malleolus of the fibula, and was recorded to the nearest 0.1 cm. Joint breadths of the elbow (medial to lateral epicondyles of the humerus), wrist (ulna to radial styloid processes), knee (medial to lateral epicondyles of femur) and ankle (medial to lateral malleoli) were also measured. Stature, kicking leg length and joint breadth measures were performed three times for each participant, with the average of each variable retained for analysis. All measures were reliably performed by the same accredited exercise scientist ($CV \leq 0.19\%$; $ICC \geq 0.997$).

Dual-energy X-ray Absorptiometry

Whole-body scans were performed using DXA (QDR-1500, Hologic Discovery A, Waltham, MA). Athletes assumed a stationary, supine position on the scanning bed with both arms pronated by their side (Figure 1). To ensure consistent and reproducible subject positioning, the same DXA operator manually assisted all subjects to straighten their head, torso and pelvis; internally rotate and fixate their legs and feet at 45° ; and position their arms next to the body within the DXA scanning zone. This has produced a scan/re-scan coefficient of variation below 1% in our laboratory (Hart et al., 2015; Hart et al., 2014; Hart et al., 2013). Using the in-built scan analysis software (Version 12.4; QDR for Windows, Hologic, Waltham, MA), the whole body model (Hologic, 2004) was applied to the scan image, separating the body into axial and appendicular sections to determine whole body composition and segmental composition of the kicking and support legs. Composite mass was categorised into fat mass (g), lean mass (g) and total mass (g) values for each sub-region across all scans and subjects. Relative lean

Table 1. Subject characteristics for accurate ($n=15$) and inaccurate ($n=16$) kickers. Values are expressed as mean (\pm SD).

Subject Characteristics	Accurate	Inaccurate	Effect (d)
Age (yrs)	21.7 (3.3)	23.1 (1.9) *	.52 ^d
Height (m)	1.82 (0.07)	1.81 (7.3)	.13
Weight (kg)	80.6 (8.0)	89.4 (15.2)	.72 ^c
Kicking Leg Length (cm)	87.3 (3.3)	85.7 (3.6)	.46 ^d
Body Mass Index (BMI)	24.4 (1.5)	27.3 (3.8) **	1.00 ^c
Total Body Fat (%)	11.1 (2.0)	17.4 (5.2) **	1.60 ^b
Playing Experience (yrs)	8.2 (2.7)	8.5 (2.3)	.08
Kicking Efficiency (%)	91.3 (11.3)	57.5 (16.4) **	2.40 ^a

Playing experience = total playing experience in years; Sig. = significance level; Effect = effect size; ** = statistical significance ($\alpha \leq 0.01$); * = statistical significance ($\alpha \leq 0.05$); a = very large effect ($d \geq 2.0$); b = large effect ($d \geq 1.2$); c = moderate effect ($d \geq 0.6$); d = small effect ($d \geq 0.2$).

mass for each limb was calculated by dividing the amount segmental mass (g) by total body mass (g).



Figure 1. Subject positioning for use during whole-body DXA scans, with the head, neck and torso positioned parallel to the long-axis of the scan bed; the shoulders and pelvis positioned perpendicular to the long-axis of the scan bed; arms pronated by the side; and legs internally rotated to 45° and fixated together to minimise incidental movement.

Vicon motion capture

Three-dimensional motion analysis of the kicking action was assessed using a ten-camera optoelectronic device (ViconMX, Vicon, Oxford, UK), sampling at 250 Hz. A total of 39 retroreflective markers were positioned on subjects over pre-determined anatomical landmarks in accordance with the Vicon Plug-in Gait model (Besier et al., 2001; Spiteri et al., 2014) to capture movement patterns produced. A series of anthropometric measures were taken and used in the model, including joint breadths of the both elbows, wrists, knees and ankles; as well as leg length of both lower limbs. Retroreflective markers were positioned on the athlete prior to their sports-specific kicking based warm-up to allow adequate familiarisation of kicking with markers attached. Prior to data collection, a static calibration for each athlete was performed to locate anatomical landmarks and define segment and joint coordinate systems within the kinematic model. Official

trials were recorded using the inbuilt data acquisition software (ViconNEXUS, 1.7.1; Vicon, Oxford, UK) through a custom pipeline to obtain filtered marker trajectories using a zero-lag fourth order 18 Hz, low-pass Butterworth filter (Besier et al., 2001; Spiteri et al., 2014).

Kicking protocol

Kicking technique was assessed using the drop punt kick, performed with an Australian football (450g, Sherrin, Victoria, AU) inflated to official air pressure specifications (67 – 75 kPa) (Ball, 2008), using an electronic air pump (Air Erupt, Volcano, Taiwan). Athletes were required to produce a total of ten drop punt kicks to a stationary human (player) target situated 20 metres from the centre of the kicking zone with the intention to deliver the ball as accurately as possible to the specified target (Figure 2). An obstacle representing an opposite player (base-to-head height: 6 ft; base-to-hand height: 7 ft) was positioned between the kicker and the target to control for minimum kicking trajectory. Prior to commencing the kicking assessment, subjects completed a series of mechanically specific warm-up sets (5 drop punt kicks over 20m, 30m and 40m respectively). The ten official (20m) drop punt trials were then completed with a one minute recovery provided between each kick. For the trial to be considered successful, the athlete had to produce a straight approach consisting of at least two steps prior to planting their foot within the assigned kicking zone. Any trials that did not meet this criterion were considered invalid, and a repeat kicking trial subsequently provided until ten successful kicks were produced.

Accuracy analysis

Kicking accuracy was assessed using a customised numerical scoring system (Hart et al., 2014; Hart et al., 2013). All kicks were visually graded immediately following each trial by the lead researcher; the human target (receiving the ball) and a research assistant. All assigned scores were recorded and visually confirmed using a two-dimensional digital video camera (MV710I PAL, Canon, NSW, AU). The scoring system for each kick spanned from 1 (accurate), 2 (moderate) and 3 (inaccurate), and

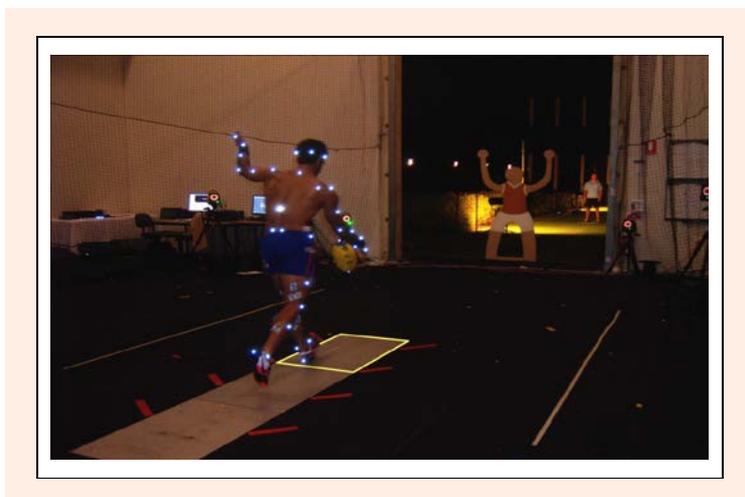


Figure 2. The kicking protocol set-up, with the athlete performing the drop punt, over an obstacle (height: 6 ft), to a stationary human target 20 meters from the kicking zone (outlined, dimensions: 1.0m x 0.7m).

was judged by the location of ball delivery to the target (Table 2). Following ten successful kicks, each athlete's scores were summated, with total scores ranging between 10 to 30 points. Athletes were classified as either accurate (10 – 18 points) or inaccurate (19 – 30 points), resulting in fifteen accurate kickers, and sixteen inaccurate kickers. Kicking efficiency was subsequently determined by calculating the percentage of accurate trials produced within the ten trial quota.

Table 2. Accuracy grading and determination criteria for human target kicking outcomes.

Assigned Score	Description of Ball Delivery to Target
1 (Accurate)	The ball is delivered directly to the target, between the waist and head of the receiving player.
	The target should not reach or jump in any direction from their stationary position for this score to be awarded.
2 (Moderate)	The ball slightly deviates from the target, though not excessively (within the targets reach).
	The target may take one step or reach in any direction; jump directly upwards; or kneel down from their stationary position for this score to be awarded. No combined "step and reach" or "jump and reach" are allowed.
3 (Inaccurate)	The ball misses the target by any margin beyond the limits seen within the 'Accurate' or 'Moderate' grading criteria.
	If the target needs to step and reach; jump and reach; or take more than one step to receive the ball, or, if the ball misses the target zone all together; it is awarded an inaccurate score.

Statistical analysis

Independent t-tests was used to determine whether significant differences were evident between subject characteristics, kicking leg mass components, and peak foot velocity produced by accurate and inaccurate kickers. Statistical significance was set at an alpha level of $p \leq 0.05$. The magnitude of differences between groups was determined using Cohen's d effect size statistic, classified in accordance with Hopkins (2002): $d \geq 0.2$ is small; $d \geq 0.6$ is moderate; $d \geq 1.2$ is large; $d \geq 2.0$ is very large and $d \geq 4.0$ is nearly perfect. Pearson's product moment (PPM)

correlation coefficient (r) was calculated to determine the strength of relationship between leg mass variables to peak angular foot velocities; leg mass variables to kicking accuracy scores; and peak angular foot velocities to kicking accuracy scores. The strength of relationship was classified in accordance with Hopkins (2002): $r \geq 0.3$ is moderate; $r \geq 0.5$ is strong; $r \geq 0.7$ is very strong; $r \geq 0.9$ is nearly perfect; and $r \geq 1.0$ is perfect. All statistical computations were performed using a statistical analysis program (SPSS, Version 17.0; Chicago, IL).

Results

Accurate kickers were younger ($p = 0.040$; $d = 0.52$) and lighter ($p = 0.055$; $d = 0.72$) than their inaccurate counterparts, with a small effect evident for kicking leg length ($p = 0.434$; $d = 0.46$). Accurate kickers also exhibited significantly lower total body fat and significantly lower BMI with a moderate-to-large effect ($p \leq 0.009$; $d \geq 1.00$). Despite similar total playing experience and exposure to sport-specific development ($p = 0.812$; $d = 0.08$), accurate kickers were ~34% more accurate, with significantly greater kicking efficiency with very large effect ($p = 0.001$; $d = 2.40$), attributable – in part – to established differences in the quality and quantity of tissue mass and composition.

Leg mass characteristics of accurate and inaccurate kickers are provided in Table 3. No significant differences between accurate and inaccurate kickers were evident for absolute lean mass and absolute total mass of the kicking leg ($p \leq 0.843$; $d \geq 0.07$). However, accurate kickers did contain significantly lower absolute fat mass ($p = 0.001$; $d = 1.39$). A greater relationship between composite mass and kicking accuracy was observed when expressed relative to body mass. Relative lean mass was significantly higher ($p = 0.001$; $d = 1.46$), and relative fat mass was significantly lower ($p = 0.001$; $d = 1.50$) in accurate kickers. Furthermore, a strong positive correlation was evident between kicking accuracy and relative lean mass within the kicking leg ($r = 0.631$), with strong negative correlations shown between both absolute and relative quantities of fat mass within the kicking leg ($r = -0.568$ to -0.582).

Relationships between peak foot velocity, absolute lean mass and absolute total mass of the kicking leg for accurate kickers and inaccurate kickers are presented in Figure 3. Interestingly, absolute total mass of the kicking leg produced a very strong negative correlation with peak foot velocity in the accurate group only ($r = -0.701$), with

Table 3. Leg mass characteristics of the kicking limb for accurate and inaccurate kickers (expressed in absolute and relative (to body mass) quantities). Values are expressed as mean (\pm SD).

		Accurate	Inaccurate	Effect (d)
Absolute Mass	Lean (g)	11913 (1170)	11806 (1720)	.07
	Fat (g)	1764 (483)	3017 (1179) **	1.39 ^b
	Total (g)	14281 (1496)	15461 (2567)	.56 ^d
Relative Mass	Lean (g)	14.8 (.7)	13.4 (1.1) **	1.46 ^b
	Fat (g)	2.2 (.5)	3.4 (1.0) **	1.50 ^b
	Total (g)	17.7 (.5)	17.5 (.8)	.30 ^d

Playing experience = total playing experience in years; Sig. = significance level; Effect = effect size; PPM = correlation coefficient between mass and kicking accuracy; ** = statistical significance ($\alpha \leq 0.01$); * = statistical significance ($\alpha \leq 0.05$); a = very large effect ($d \geq 2.0$); b = large effect ($d \geq 1.2$); c = moderate effect ($d \geq 0.6$); d = small effect ($d \geq 0.2$).

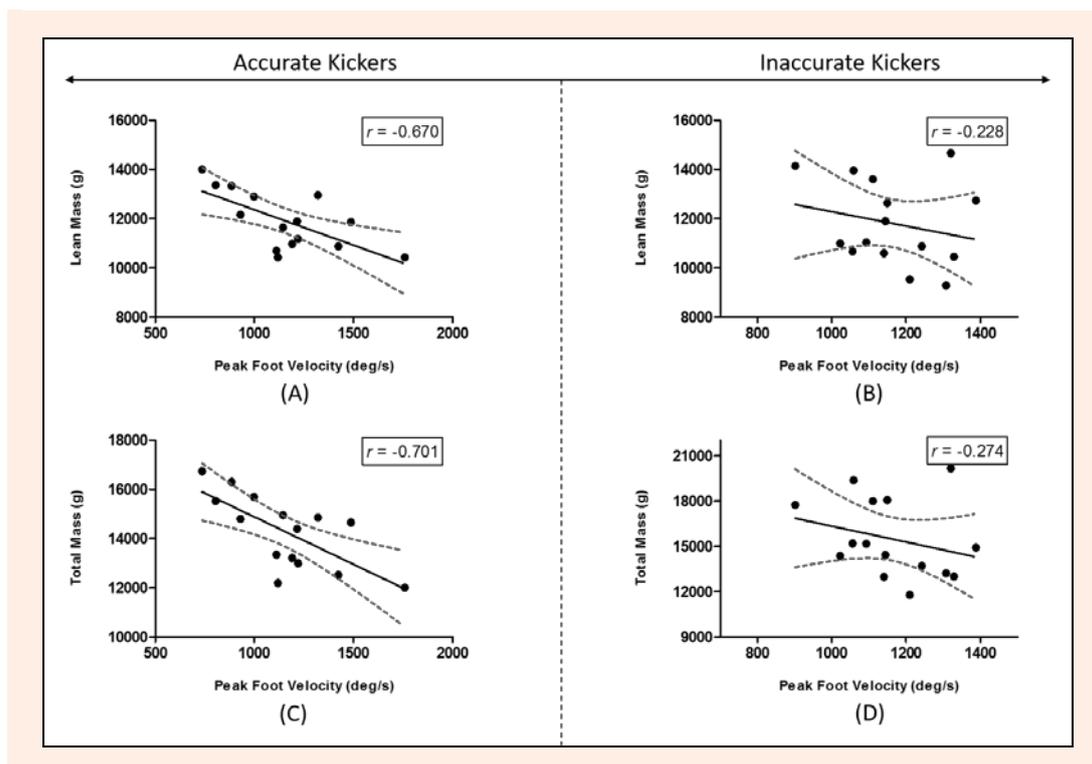


Figure 3. Relationship between peak foot velocity (deg/s) and mass components of the kicking limb (with 95% confidence intervals). Specifically (A) lean mass of accurate kickers, (B) lean mass of inaccurate kickers, (C) total mass of accurate kickers, and (D) total mass of inaccurate kickers.

no notable correlation evident within the inaccurate group ($r = -0.274$). Similarly, absolute lean mass of the kicking leg produced a very strong negative correlation with peak foot velocity in the accurate kickers only ($r = -0.670$), with no notable correlation evident for inaccurate kickers ($r = -0.228$). Interpretively, as lean mass and total mass increases, accurate kickers are able to proportionately reduce peak foot velocity when kicking over a submaximal distance. In comparison, inaccurate kickers do not appear to regulate peak foot velocity to compensate for changes in their limb mass. No significant correlations were apparent between relative lean mass or relative total mass in the kicking leg and subsequent peak foot velocity ($r = -0.199 - 0.284$), however, this seems inconsequential given there were also no significant correlations were between foot velocity and kicking accuracy (accurate: $r = -0.035$; inaccurate: $r = -0.083$), as illustrated in Figure 4. Instead, strong positive and strong negative relationships for relative lean mass ($r = 0.631$) and relative fat mass ($r = -0.570$) with kicking accuracy were observed (Figure 4).

Discussion

Kicking a ball accurately over a desired distance to an intended target is arguably the most important skill to acquire in football sports, therefore understanding the potential mechanisms which underpin kicking accuracy is critical. The purpose of this study was to investigate the influence and interrelationships of leg mass, composition and foot velocity on kicking accuracy outcomes between accurate and inaccurate kickers in Australian Football. The results of this study demonstrated no interaction

between peak foot velocity and kicking accuracy between-subjects; as accurate kickers with various limb mass characteristics produced vastly different angular foot velocities, ranging between 750 and 1750 degrees per second. Instead, accurate kickers contained significantly greater quantities of relative lean mass and significantly lower quantities of relative fat mass in their kicking leg, which might explain their ability to mediate and control foot velocity production in accordance with heightened limb co-ordination and control; providing accurate kickers with a greater opportunity to strike the ball in the right place, at the right time and in the right direction (Urbin et al., 2011).

The absence of a relationship between limb velocity and target accuracy in the current study may be due to the between-subjects design utilised; however these results are also in agreement with recent literature investigating similar multi-joint dynamic, asymmetrical motor skills which utilised with-in subject study designs, including the tennis serve and ground-stroke (Cauraugh et al., 1990; Landlinger et al., 2012), fast-bowling in cricket (Phillips et al. 2012), and shooting in handball (Van den Tillar and Ettema, 2003), finding no significant correlations with speed of movement and subsequent accuracy within skilled athletes. A potential explanation might include the quantity and structure of training provided to experienced athletes, who are specifically trained to perform accurately at high speeds (Wagner et al., 2012); therefore, speed of movement may not be a performance restriction in expert, elite performers (Nagengast et al., 2011; Phillips et al., 2012). Instead, other factors might be more influential within these populations, including mental strategy, movement variability, limb strength, and

striking mass (Chelly et al., 2010; Janelle, 2002; Manolopoulos et al., 2006; Schorer et al., 2007; Wilson et al., 2008); which are factors modifiable through training interventions and may assist with improving kicking accuracy.

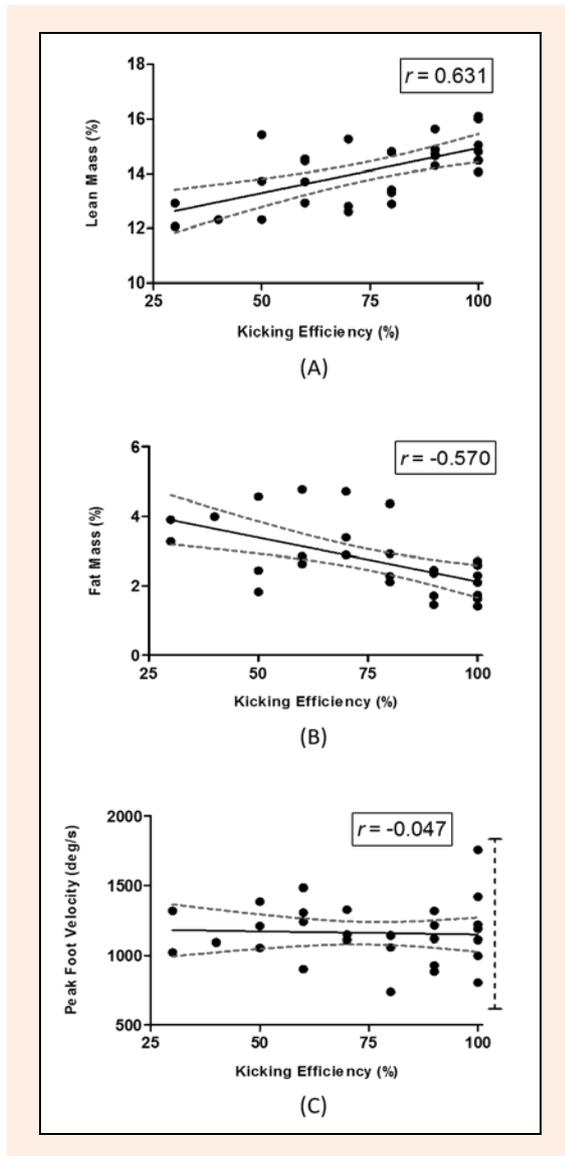


Figure 4. Relationship between kicking accuracy (reported as a percentage, i.e. kicking efficiency) and (A) relative lean mass, (B) relative fat mass, (C) peak foot velocity (with 95% confidence intervals); Dashed vertical line (C) highlights the variety of velocities used by accurate kickers (100% efficiency).

Previous research investigating the interaction between movement speed and target accuracy have primarily assessed the speed of movement as an isolated entity, without equal consideration for the striking mass characteristics or proportionate muscular impulses required to produce the movement (Schmidt and Lee, 2005; Urbin et al., 2011). In Australian Football, the desired ball velocity required to reach an intended target cannot be wholly explained by foot velocity or lower limb mass in isolation. Rather, it is the controlled co-contribution of these two characteristics which appears to discriminate between the

accurate and inaccurate performer, evidenced by the very strong inverse relationship within the accurate kicking group of this study. The ability of accurate kickers to readily mediate foot velocity as a product of their striking mass seems to suggest an element of superior spatial and temporal control often seen within expert performers (Cameron and Adams, 2003; Davids et al., 2000; Wilson et al., 2008; Williams and Ericsson, 2005). While expert and novice performers both exhibit higher levels of movement variability during motor performance; expert performers display an active and deliberate functional variability, whereas novice performers demonstrate a circumstantial random variability (Schorer et al., 2007; Wagner et al., 2012). Since foot velocity is a volatile kinematic characteristic in kicking, and lean mass is a stable and trainable component of the lower limbs; increasing the functional (lean) mass of the kicking leg may provide a practical solution to increase accuracy outcomes, potentially creating greater functional variability and system flexibility within an athlete in order to appropriately mediate foot velocity.

Impulse-variability theory might provide a better mechanistic explanation towards distinguishing between accurate and inaccurate kickers in football sports (Urbin et al., 2011). In particular, the expected inverse relationship between movement speed and target accuracy (the speed-accuracy phenomenon) still requires the same magnitude of muscular impulse to develop and transfer an equivalent angular momentum to the ball. This required impulse might be the critical component in accurate performance, as temporal and spatial components of limb behaviour (velocity, trajectory and distance) are a result of the magnitude and duration of muscular torques acting on the joint (Magill, 2008; Urbin et al., 2011). Specifically, reducing the relative muscular impulses required to produce the kicking action (i.e. through increasing relative lean mass) may improve kicking accuracy through greater limb control, potentially improving the compensatory movement variability of an athlete, increasing their ability to resist undesired perturbations at a proportionately reduced volitional effort (Cameron and Adams, 2003; Phillips et al., 2012; Wagner et al., 2012; Wilson et al., 2008). The results of this study appear to indirectly support this notion, with accurate kickers illustrating significantly greater relative lean mass, and significantly lower relative fat mass within their lower limbs, producing considerable correlations with kicking accuracy outcomes.

Foot-ball interaction is another consideration for kicking accuracy that may be influenced by differences in kicking leg mass, composition and foot velocity between footballers. In particular, the coefficient of restitution (a measure of impact elasticity and momentum transfer in striking tasks) is influenced by the stiffness of the kicking foot at impact (Cameron and Adams, 2003; Young and Rath, 2011). While impact specific parameters between the foot and ball were not directly measured in this study, the higher relative lean mass and lower relative fat mass in the kicking leg of accurate kickers may describe a more stable and rigid surface at ball impact (Hart et al., 2013; 2014). Indeed, kicking accuracy may be jeopardised if there is a subsequent loss of limb control due to insuffi-

cient muscular activation, co-contraction and strength. Greater relative lean mass may ultimately provide greater limb co-ordination during the kicking action (impulse-variability) and greater limb control during foot-ball interaction (coefficient of restitution). While these hypotheses are of interest, it is recognised that leg mass, composition and foot velocity represent only few of many determinants of kicking accuracy. Specifically, the current study did not assess full-body kinematic, kinetic or muscle activation profiles which may provide a more thorough overview of kicking accuracy; and total training history was not recorded. Regardless, this hypothesis-generating study provides a suitable premise for future research to directly explore speed-accuracy and impulse-variability constructs using controlled, with-in subject studies involving resistance training and/or skill acquisition programs.

Conclusion

Potential relationships between technical and temporal strategies of accurate and inaccurate kickers in response to the physical parameters modifiable by athletic conditioning were explored in this study. Ball velocity was unable to be explained by either foot velocity or leg mass in isolation; rather, it was the co-contribution of these characteristics which were the discriminatory factors between accurate and inaccurate kickers. As temporal and spatial components of kicking limb behaviour (velocity, trajectory, and distance) are a result of the magnitude and duration of muscular impulses acting on the joints, greater relative lean mass may afford accurate kickers with improved limb control in response to reduced volitional effort and lower relative impulses to generate kicking limb velocity.

Practitioners wishing to consider interventions to improve kicking accuracy and distance concomitantly are encouraged to improve relative lower-body lean mass through strength and conditioning interventions. Future research should focus on exploring impulse-variability as an underpinning mechanism to produce accurate performances in sports requiring rapid ball striking; particularly as investigations concerning speed-accuracy and impulse-variability relationships within familiar, asymmetrical, dynamic (acyclic) movement tasks remains limited; particularly in striking-based activities or sports.

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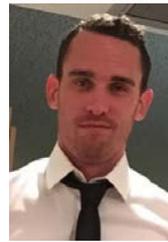
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Key points

- Accurate kickers expressed a very strong inverse relationship between leg mass and foot velocity. Inaccurate kickers were unable to replicate this, with greater volatility in their performance, indicating an ability of accurate kickers to mediate foot velocity to compensate for leg mass in order to deliver the ball over the required distance.
- Accurate kickers exhibited larger quantities of relative lean mass and lower quantities of relative fat mass in their kicking leg. Higher relative lean mass reduces the relative muscular impulses required to produce a given action, allowing greater limb control with proportionately reduced volitional effort.
- Kicking accuracy was unable to be explained by either foot velocity or leg mass in isolation; rather, it was the co-contribution and interrelation of these characteristics which were the discriminatory factors between accurate and inaccurate kickers.

AUTHOR BIOGRAPHY



Nicolas H. HART

Employment

Research Fellow, Exercise Oncology

Degree

PhD, AES, CSCS, ESSAM.

Research interests

Exercise as medicine; Exercise oncology; Injury prevention; Musculoskeletal screening, training and adaptation; Bone strength and disease.

E-mail: n.hart@ecu.edu.au



Sophia NIMPHIUS

Employment

Senior Lecturer, Strength and Conditioning.

Degree

PhD, CSCS*D.

Research interests

Profiling and long-term training adaptations of youth and elite athletes; Measurement and development of strength and power; Gender differences in athletic performance.

E-mail: s.nimphius@ecu.edu.au



Tania SPITERI

Employment

Lecturer, Motor Control

Degree

PhD, AES, ESSAM

Research interests

Agility, Change of direction, Athlete profiling; Skill acquisition; Gender differences in athletic performance; Strength and power development.

E-mail: tania.spiteri@nd.edu.au



Jodie COCHRANE

Employment

Senior Lecturer, Biomechanics

Degree

PhD

Research interests

Sports biomechanics; Neuromuscular training and injury prevention

E-mail: j.wilkie@ecu.edu.au



Robert NEWTON

Employment

Foundation Professor, Exercise and Sport Science.

Degree

PhD, CSCS*D, AEP, FESSA, FNCSA.

Research interests

Muscular strength and power; athletic profiling and long-term monitoring; Exercise as medicine; Exercise oncology.

E-mail: r.newton@ecu.edu.au

✉ Dr. Nicolas H. Hart

Exercise Medicine Research Institute, Edith Cowan University, 270 Joondalup Drive, Joondalup, Perth, Western Australia, Australia – 6027