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Is there a sweet spot on the foot in Australian football drop punt kicking?

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ABSTRACT

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

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KEYWORDS
Kicking accuracy; successful kicking; punt kicking; soccer kicking; impact location

Introduction

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

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

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

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

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

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

Methods

Task, data collection and analysis

After gaining informed consent approved by the university human research ethics committee, ten players between the age of 20 to 28 years old with various expertise playing Australian Football (amateur through to elite competition) were recruited for the study (Table 1). Each player performed 30 drop punt kicks toward a target 30 meters in distance with a standard Australian Football ball (Sherrin Match Ball; size = 5; mass = 0.455 kg; inflation = 69 kPa) in a laboratory setting that featured an athletics track surface. This kicking task simulated kicking to a fellow team member on the field. The total number of kicks analysed varied between each player due to the foot and/or ball not remaining in the calibrated volume throughout the duration of foot-ball impact (Table 1). Despite this, a broad range of kick outcomes (i.e., kicks that went to the left and right of the target, and hit the target) were captured, enabling an intra-individual analysis to be performed.

Table 1. Characteristics of individual players.

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

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

A six degrees of freedom model comprising the shank, foot and ball was created for each player. During a static trial, the distal, proximal and centroid positions of the shank and foot were obtained from reflective markers attached to the lateral and medial epicondyles of the knee, the lateral and medial ankle malleolus, and the head of the fifth (lateral aspect) and first (medial aspect) metatarsals. Additional reflective markers were attached to the most dorsal aspect of the foot at the head of the metatarsals and at the malleolus to generate the surface location of the foot relative to the foot segment for calculation of impact point (discussed below). The centroid position and three radii of the ball (Figure 1(b); r_x, r_y, r_z) were determined from markers attached at both ends of the long axis and two short axes. These key anatomical landmarks were projected from tracking markers that remained on the players during the kicking trials. The shank and foot were each represented by five spherical reflective markers 13 mm in diameter, fixed to the limb using rigid strapping tape. Tracking markers on the ball consisted of flat rectangular pieces of reflective tape (2.5 x 2.5 cm) with an 8mm black circular sticker attached to the middle. Spherical markers could not be attached to the ball during kicking trials as their presence would impede the player's ability to hold the ball as it is dropped, possibly contact the ball during impact, and influence ball flight.

Data of each kicking trial were measured at 4,000 Hz from 20 frames before to 20 frames after visually identified ball contact and release, respectively. Markers were tracked in ProAnalyst software (Xcitex Inc., USA) and three-dimensional

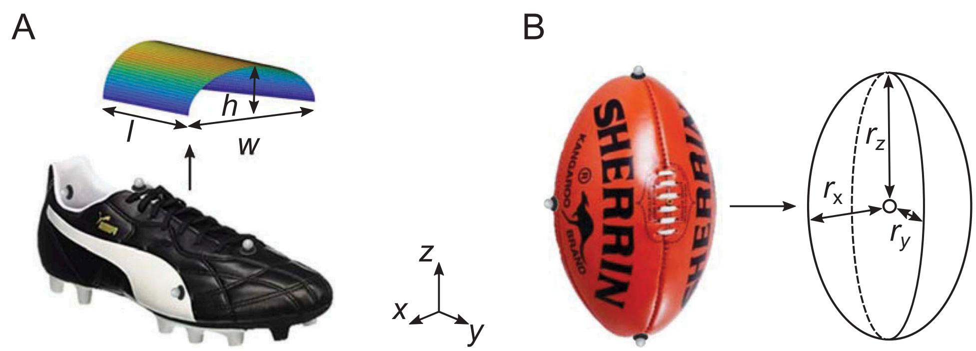

Figure 1. (a) the grid representing the anterior aspect of the foot. (b) the model of the ball shell. Approximate locations of static markers are attached to the foot.

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

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

Calculation of impact point

A novel method was developed to calculate the impact location on the foot at the instant of ball contact by modelling the foot and ball as rigid bodies within Matlab software (R2016b, The Mathworks, Inc.). The anterior surface of the foot was modelled as a semi-elliptical cylinder (Figure 1(a); Equations 1–4) and the ball an ellipsoid (Figure 1(b); Equation 5). Both models were shells projected from their centroid position based on their geometric properties derived during the static capture. The anterior surface of the foot was constructed as a 200 x 200-point grid of X-Y-Z coordinates. The size of this grid was dependent upon individual player characteristics (the width and height of the foot at the malleolus and head of metatarsals, and overall foot length). Between each kick there were two variables that distinguished the impact location; relative foot-ball orientation and relative foot-ball displacement. Therefore, the grid was rotated and translated to the relative orientation and position of the foot and ball. To identify the intersecting point on the foot and the ball, each position of the grid was entered into the equation of the ball (Equation 5; Figure 1), which solved the depth of the point relative to its shell. Any point on the shell yielded a value of 1, a point that was in the shell yielded a value of < 1, and a point with a value > 1 was outside the shell. The impact location on the foot was assumed to yield the smallest value from the entire grid. From identifying the X-Y-Z coordinate of impact location, the impact location across the medial-lateral and proximal-distal direction was calculated as the distance from the foot centre.

$$x_l = \frac{w_l}{2}\cos\emptyset \qquad (1)$$

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

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

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

$$y_l = h_l \sin\emptyset \qquad (3)$$

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

$$h_l = \frac{(h_p - h_d)}{l} \cdot h_l + h_d \qquad (4)$$

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

$$\frac{{x_l}^2}{{r_x}^2} + \frac{{y_l}^2}{{r_y}^2} + \frac{l^2}{{r_z}^2} = d \qquad (5)$$

Where r_x = the short radius of the ball; r_y = the short radius of the ball (note: $r_x = r_y$); r_z = the long radius of the ball; d = the depth of the coordinate relative to the ball shell (see Figure 1).

Statistical analysis

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

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

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

The sweet spot location on the foot for each of the kicking measures were also identified by interpreting the coefficients of the regression equations. The sweet spot is the impact location that delivers maximum performance for the respective measure. Maximum performance for azimuth ball flight angle was 0°, and we identified the impact location on the foot from the regression equation that yielded a ball flight angle of 0° (Figure 3). For ankle plantar/dorsal flexion during impact, because it has been established reducing ankle motion is beneficial to performance, we set the sweet spot at a change in ankle angle of 0°, and identified the impact location across the proximal-distal direction of the foot that corresponded to this point, as indicated from the regression equation. Foot-ball speed ratio, coefficient of restitution and effective mass are all scalar values, and increasing them is considered beneficial to performance as they will all increase ball velocity. Therefore, the sweet spot location for these measures is found at the highest point, which, can only be identified from the turning point in the quadratic equation (see Figure 4 as an example). No turning point in the quadratic equations (the maximum performance for the given measure) were identified in the range of data for some individuals, therefore, no sweet spot was identified for that individual. Statistical confidence on these locations were determined from 90% confidence intervals, calculated from the standard error of the coefficients.

Results

Validation of impact location measurement

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

The distribution of impact locations between kicks

All players produced a normal distribution of impact locations across both the medial-lateral and proximal-distal directions of the foot, evidenced by the non-significant ($p > 0.05$) results of the Shapiro-Wilk tests and visual inspection of the histograms. The mean impact location across the medial-lateral direction was identified to be on the medial side of the foot for all players, whereas the mean impact locations across the proximal-distal direction varied to be either proximally or distally from the foot centre between players (Table 2; Figure 2 for Player 4).

The relationship between impact location with kick outcome

A positive linear relationship existed for nine players between medial-lateral impact location with ball azimuth flight angle. The sweet spot, the impact location that delivered an azimuth ball flight of 0°, occurred on the medial aspect of the foot for all players (Table 3; Figure 3 for Player 8). The direction of the relationship meant that impact locations to the lateral side of this sweet spot resulted in an azimuth ball flight in the lateral direction.

A positive linear relationship was identified in all players between proximal-distal impact location with ankle plantar/dorsal flexion (Table 4). The sweet spot, the location that produced a change in ankle angle of 0°, varied between

Table 2. The mean and standard deviations of impact locations across the medial-lateral and proximal-distal directions of the foot, measured from the foot centre. Positive values represent the lateral and distal direction of the foot.

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

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

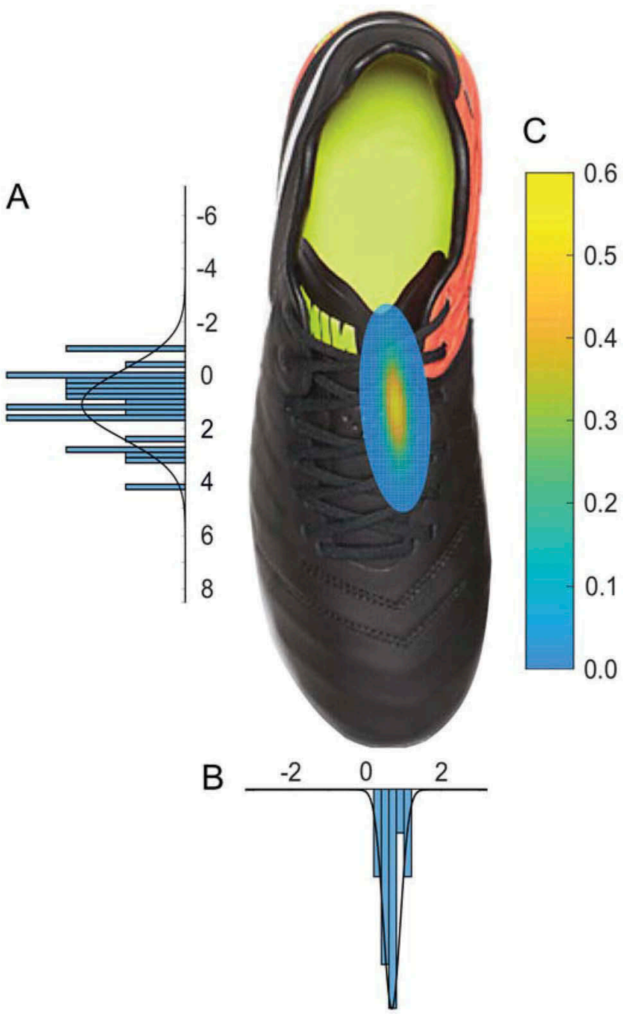

Figure 2. The impact location for Player 4. (a) Histogram of impact location across the proximal-distal impact location (cm from foot centre of mass). (b) Histogram of impact location across the medial-lateral impact location (cm from foot centre of mass). The bivariate distribution plot has been superimposed onto the foot, and the scale (c) represents the relative distribution.

players to occur on either proximally or distally from the foot centre. As players impacted the ball at a location distally from the sweet spot, the magnitude of plantarflexion increased.

Quadratic relationships between proximal-distal impact location and foot-ball speed ratio and a sweet spot location were identified in four players (Table 6; Figure 4 for Player 4). When players impacted the ball either side from the sweet spot location, foot-ball speed ratio decreased. Negative linear relationships were identified between proximal-distal impact location and foot-ball speed ratio in Player 2 and Player 7. A positive linear relationship existed between proximal-distal impact location and foot-ball speed ratio for Player 3.

Five players displayed a linear relationship between proximal-distal impact location and effective mass that was negative in direction for all (Table 5). Three players displayed a quadratic relationship, and a sweet spot could be identified in each (Figure 4 for Player 4).

Quadratic relationships and a sweet spot location were identified between proximal-distal impact location with coefficient of restitution for five players (Table 7; Figure 4 for Player 4). A positive linear relationship was in one player, Player 5.

Discussion

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

Did players target a specific location on their foot?

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

Medial-lateral impact location

The medial-lateral impact location influenced azimuth ball flight angle. Nine of ten players produced a linear relationship between medial-lateral impact location with azimuth ball flight angle (Table 3), supporting the findings of Peacock and Ball (2017) who also identified this pattern in their analysis with a mechanical kicking machine analysing the drop punt

Table 3. Relationship between medial-lateral impact location and azimuth ball flight angle.

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

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

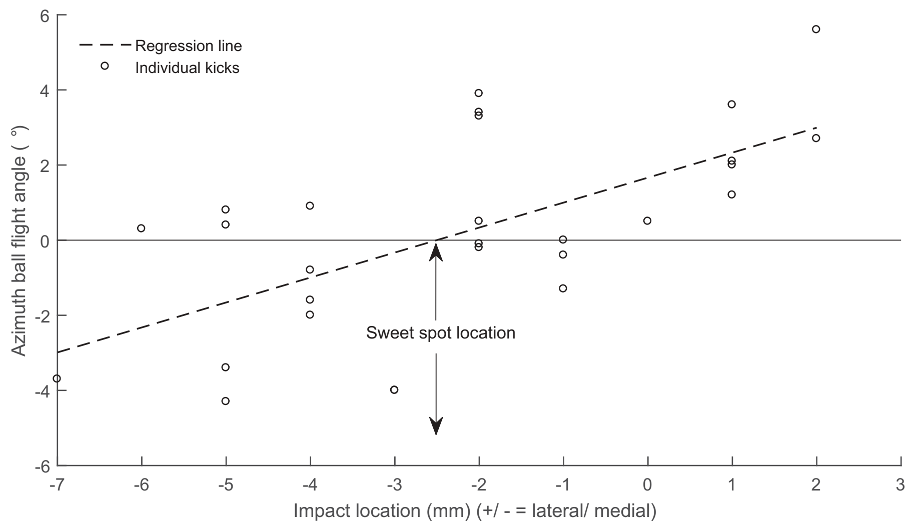

Figure 3. The relationship between medial-lateral impact location and azimuth ball flight angle for Player 8. The sweet spot location (the point on the horizontal axis) can be identified by identifying the azimuth ball flight angle (vertical axis at 0°) from the regression line. Positive values represent the lateral direction from foot centre (impact location) and ball flight trajectory (azimuth ball flight angle).

Table 4. Relationship between proximal-distal impact location and change in ankle plantar/dorsal flexion.

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

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

kick. As discussed by Peacock and Ball (2017), the oblique impact theory indicates the angle of the intersecting surfaces influences the angle of trajectory. Across the medial-lateral dimension of the foot, the surface angle of the foot changes substantially, where azimuth ball flight trajectory will be 0° at the impact location where the medial-lateral surface angle is perpendicular to the direction of the target. For all players, this location was on the medial aspect of the foot due to its asymmetrical shape, as found by Peacock and Ball (2017) on their mechanical kicking machine. Because the surface angle of the foot changes substantially across the medial-lateral dimension, the impact location across the medial-lateral direction on the foot is a key variable toward azimuth ball flight angle.

Proximal-distal impact location

The proximal-distal impact location influenced ankle plantar/dorsal flexion during foot-ball impact (Table 4). A linear relationship was identified for all players between impact location with ankle plantar/dorsal flexion, where impacting the ball distally from this location corresponded to an increased ankle

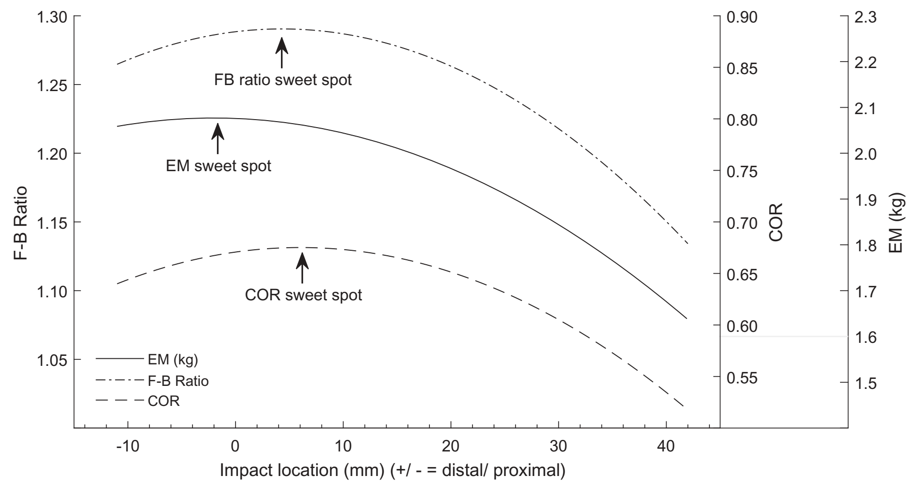

Figure 4. The proximal-distal (P-D) sweet spot locations for Player 4, as identified by the quadratic regressions between impact location and foot-ball speed ratio (FB Ratio), coefficient of restitution (COR), and effective mass (EM).

Table 5. Relationship between proximal-distal impact location and foot-ball speed ratio.

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

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

plantarflexion. Because ankle motion during foot-ball impact is passive (Nunome et al., 2006; Peacock & Ball, 2018a, 2018b; Shinkai et al., 2009), the resulting ankle motion is largely dependent upon the torque applied to the ankle joint. Between kicks in the present study, the average force applied to the foot changed minimally because the kick distance was constant (impact force associated with kick distance; (Peacock et al., 2017)). Therefore, the resulting torque applied about the ankle was mostly dependent upon the moment arm, which is the distance between the proximal-distal impact location and the ankle joint. Thus, the proximal-distal impact location is an influential characteristic to ankle plantar/dorsal flexion during impact, in addition to the starting angle of the ankle (Peacock et al., 2017) and the stiffness of the ankle joint (Ball, Smith, & MacMahon, 2010; Peacock & Ball, 2018b).

Impact location influenced foot-ball speed ratio in most players and a location that produced the greatest impact efficiency was identified in four players (Table 5). Foot-ball speed ratio has been used previously to describe the efficiency of energy transferred from foot to ball (Ball et al., 2010; Peacock et al., 2017; Shinkai et al., 2013; Smith, Ball, & MacMahon, 2009), and we identified in players an impact location that produced the highest impact efficiency, as quantified by foot-ball speed ratio. Further, we identified three players produced linear relationship with foot-ball speed ratio, meaning impact efficiency was influenced by the impact location in these players as well. These results suggest the impact location across the proximal-distal direction was influential to energy transfer.

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

It could not be clearly identified how impact location influenced impact efficiency in human kickers. In the present analysis, coefficient of restitution and effective mass were both associated with proximal-distal impact location between players (Tables 6 and 7). In their analysis with a mechanical kicking machine, Peacock and Ball (2018b) found distal impact locations decreased ball velocity. This decrease in ball velocity was due to decreases in coefficient of restitution as the greater magnitude of ankle plantarflexion at the end of impact with distal impact locations meant more elastic energy was stored in the spring mechanism (that represented the muscle tendon unit) and was not transferred to ball velocity. Conversely, increases to joint stiffness, which also decreased ankle plantarflexion and increased ball velocity, increased effective mass and had no effect on coefficient of restitution as less of the kinetic energy from the shank could be transferred to the ball via the ankle joint. This mechanical modelling suggested different strategies to reduce ankle plantarflexion influenced impact efficiency through different mechanisms. Specifically, proximal impact locations influence impact efficiency through coefficient of restitution and not effective mass. In this analysis with human kickers, however, it could not be clearly seen that impact location influenced coefficient of restitution and not effective mass, as identified in the mechanical kicking machine.

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

Important to note, muscle activation of the ankle dorsal flexors still appears to be important toward producing high impact efficiency and ball velocity. Because the muscles can act as a brake during muscle lengthening (Dickinson et al., 2000; Williams, Regnier, Daniel, & McCulloch, 2012), the foot does not rotate freely around the bottom of the shank. This

Table 6. Relationship between proximal-distal impact location and effective mass.

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

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

Table 7. The relationship between proximal-distal impact location and coefficient of restitution.

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

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

introduces some component of the shank toward the collision. Therefore, while no studied has determined the efficaciousness, these results support previous suggestions that players could perform strength training of the ankle musculature to improve impact efficiency (Ball et al., 2010; Peacock & Ball, 2018a, 2018b).

Is there a sweet spot on the foot?

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

Conclusion

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

Disclosure statement

No potential conflict of interest was reported by the authors.

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