The approach towards the ball, rather than the physical characteristics of the kicker, limits accurate rugby place kicking range

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Abstract

The aim of this study was to understand how a place kicker's range is limited by their approach to the ball and their physical characteristics. Thirty-three kickers performed maximal place kicks and vertical jumps in a laboratory. Whole-body motion and ground reaction forces during the approach phase of the kicks, jump performance and anthropometric measurements of those whose predicted *maximum distance* was limited by range (n = 17) rather than accuracy were analysed. Principal component analysis (PCA) reduced the number of variables considered before stepwise regression analyses assessed variance in place kick *maximum distance* and associated criteria. Four components, explaining 94% of the variance in *maximum distance*, were extracted from the PCA: width of approach, anterior-posterior body position, centre-of-mass height and lower limb strength. Lower limb strength was a significant predictor of both kicking foot velocity ($R^2 = 0.55$, $p = 0.001$) and ball velocity magnitude ($R^2 = 0.57$, $p < 0.001$). However, *maximum distance* was determined by body position during the approach (antero-posterior position, $R^2 = 0.52$, $p = 0.001$ and centre-of-mass height, $R^2 = 0.12$, $p = 0.049$). This highlights the importance of considering three-dimensional motion of the kicker alongside their physical capabilities to understand place kicking range.

Keywords: anthropometrics, ground reaction forces, kinematic, lower-body, strength

Introduction

Place kicks (conversions and penalties) contributed 45% of all points scored in international matches over a 10-year period (Quarrie & Hopkins, 2015). Understanding how successful place kicking is achieved is therefore desirable in order to improve the likelihood of team success. To-date the majority of research has focussed on the kicking phase (from the top of the backswing to ball contact) and has concentrated on the motion of the kicking leg, identifying hip flexion and knee extension motion as key determinants of foot and ball velocity (Atack et al., 2019b; Padulo et al., 2013; Sinclair et al., 2014; Sinclair et al., 2017; Zhang et al., 2011) and kick accuracy (Atack et al., 2019b; Sinclair et al., 2017), as well understanding the influence of the kicking foot swing plane on kick accuracy (Bezodis et al., 2019). Motion of the torso has been found to influence both ball velocity, through greater longitudinal trunk and pelvis rotations (Atack et al. 2019b; Bezodis et al., 2007; Green et al., 2016) and kick accuracy, with a greater pelvis-trunk separation and longitudinal trunk rotation considered detrimental to performance (Atack et al., 2019b; Hébert-Losier et al., 2020). The non-kicking-side arm also rotates across the body during the downswing to counteract the angular momentum of the kicking leg and maintain a more accurate kick (Bezodis et al., 2007).

The movement of the kicker prior to the kicking phase has received limited attention within the literature despite the importance placed on it by coaches (Bezodis & Winter, 2014). Place kickers adopt an angled approach to the ball of 34 ± 6° (Bezodis et al., 2017), consistent with soccer instep kicking (Lees et al., 2009), and position their support foot ~0.30 m lateral to, and ~0.10 m behind, the ball (Bezodis et al., 2017; Cockroft & van den Heever, 2016). This support foot position has demonstrated relatively low inter- and intra-kicker variation in place kicking (Bezodis et al., 2017; Cockroft & van den Heever, 2016) and despite it being the base of support, about which the kicking leg swings, even extreme (± 0.30 m) manipulations in this position had no effect on ball velocity (Baktash et al., 2009). These findings are supported by experimental manipulations to approach angle in soccer instep kicking, which revealed minimal effects on both ball velocity and accuracy (Kellis et al., 2004; Isokawa & Lees, 1988; Scurr & Hall, 2009).

Evidence from soccer instep and Australian Rules punt kicking has, however, identified a positive association between approach velocity and the kicking foot and ball velocities achieved (Andersen & Dörge, 2011 and Ball, 2008). It has been suggested that a faster approach may enable a longer final step (Ball, 2008), and thus a longer flight time to achieve greater kicking leg retraction at the top of the backswing and subsequently a longer kicking foot path towards ball contact (De Witt, 2002). Furthermore, if the length of the final step and position of the kicking foot at the top of the backswing enable a faster kicking foot velocity, it is also important to consider the anthropometric characteristics (e.g. lower limb lengths) of the kicker given the inherent influence they may have.

A second advantage that a fast approach may provide a kicker is the ability to transfer the forward whole-body momentum to angular momentum of the kicking leg, as demonstrated in soccer instep kicking (Potthast et al, 2010). Decelerating this forward momentum, through exertion of large posterior ground reaction forces (GRFs) by the support leg, will enable a kicker to transfer this forward velocity to the kicking leg and also to reduce their centre of mass (CM) velocity at ball contact (BC), where a faster velocity has previously been found to negatively affect within-kicker place kick performance (Hébert-Losier et al., 2020). The efficacy of the kicker to halt this forward momentum may be determined by the strength capabilities of their lower limbs. Although currently unexplored in rugby kicking, previous research investigating the relationship between lower limb strength and kicking velocity in soccer is inconclusive (e.g. Cabri et al. (1988) found a strong positive relationship, Saliba & Hrysomalis (2001) non-significant weak-moderate relationships and Cometti et al. (2001) an unclear relationship), likely due to the common use of isokinetic tests which do not reflect the specific demands of the kicking action (Rodriguez-Lorenzo et al., 2016). Maximal jump tests have also produced conflicting relationships with ball velocity in soccer kicks (three studies identifying a significant relationship and four a non-significant relationship; Rodriguez-Lorenzo et al., 2016), potentially due to the unclear familiarisation procedures employed and the varied experience of players assessed.

Although there is limited research into how a rugby kicker’s approach to the ball may affect place kicking, evidence from other football codes has highlighted how motion during the approach phase can influence ball velocity and thus kick range, and how other factors such as strength and anthropometrics may interact with this. Given the importance placed on the approach phase by coaches, as well as the influence of place kicking success on rugby match outcome, it is crucial to identify practically meaningful aspects that coaches may be able to address in order to improve place kicking range. Therefore, the aim of this study is to understand how a place kicker’s approach to the ball affects their performance, and whether physical characteristics influence this.

Methods

Participants

Thirty-three male competitive rugby players (mean ± SD: age = 22 ± 4 years, mass = 86.2 ± 8.8 kg, height = 1.82 ± 0.06 m), proficient at place kicking and playing at levels ranging from amateur to senior international, provided written informed consent to participate in this study.

The study was approved by the local university research ethics committee prior to testing (reference number: SMEC_2012-13_001).

Procedures

All data for each participant were collected in a single testing session, in an indoor laboratory. The order of the procedures was consistent across all participants in that anthropometric data were collected first, then place kicking trials were undertaken, and finally vertical jump tests were conducted. Sufficient, self-selected rest was provided to participants throughout, and they refrained from strenuous physical activity in the 24 hours prior to testing.

Anthropometric Measurements

Standing heights were measured using a stadiometer, and mass and leg length (average height of both greater trochanter motion capture markers) were measured during a standing trial on a force platform (9287BA, Kistler, Switzerland; 960 Hz). A Casio EX-FH20 digital camera was used to obtain images (2592 × 3456 pixels) of the participants standing upright in the frontal plane and left and right views of the sagittal plane within a planar six-point calibration frame. Specific anatomical landmarks were digitised (Gittoes et al., 2009) on two separate occasions using Motus (v.9, Vicon, Oxford, UK) and average coordinates of each landmark were reconstructed using 2D Direct Linear Transformation (Abdel-Aziz & Karara, 1971). These data were input to Yeadon's (1990) mathematical model to produce individual-specific segment masses and lengths for the torso, thigh and shank. An average of both limbs was calculated, and segmental lengths were expressed as a percentage of height.

Place Kicking Analysis

Following a self-directed warm-up and familiarisation, participants performed a minimum of five place kicks, as if from their maximum range, towards a vertical target (representative of the centre of the goal posts) suspended in a net, 2 m away. Participants wore their own moulded boots and used their preferred kicking tee. Eighty retro-reflective markers (25 mm diameter) were positioned on anatomical landmarks, a headband, wristbands and rigid clusters to define a 14-segment kinematic model during a static trial (described in Atack et al., 2019b and detailed in Supplementary Tables 1 and 2). Fifty-four of these markers remained on the participant during the kicking trials (tracked by a Vicon© MX3 system, 240 Hz) along with six circular markers attached to the ball (Gilbert Virtuo, size 5). GRF underneath the support foot was synchronously recorded (960 Hz) using a Kistler 9287BA force platform.

Marker trajectories were labelled using Nexus v1.8.3 and the .c3d files were exported for processing in Visual 3D (v. 5.0, C-Motion, USA). All trials were cropped one frame pre-BC, identified by the kicking toe marker reaching peak anterior velocity (Shinkai et al., 2009), and marker data were low-pass filtered at 18 Hz using a fourth-order Butterworth filter with endpoints padded (20-point reflection). The raw GRF data were filtered at 125 Hz, with cut-off frequencies identified through residual analysis (Winter, 2009). Segmental kinematics were reconstructed using an Inverse Kinematics global optimisation approach (Lu & O'Connor, 1999) with three rotational degrees of freedom at all joints.

To reduce the dataset and ensure technique characteristics that are practically meaningful to coaches were identified from the data, three key events which align with instants in the movement often focussed on by coaches (Bezodis et al., 2017) were identified from the processed data: kicking foot take-off (KFO), the frame in which the kicking foot toe marker was more than 0.10 m above the ground (Lees et al., 2009) following its final ground contact. Support foot contact (SFC), the frame in which the recorded vertical GRF data first increased, and subsequently remained above, 10 N. Top of the backswing (TB), the frame where the kicking foot CM reached its highest vertical position.

The participants' whole-body CM location was calculated and CM displacement and velocity time-histories were determined. The whole-body CM position (relative to the ball) and velocity at KFO, SFC and at the instant prior to BC (hereafter, identified as BC) were extracted. The 3D displacement of the kicking foot CM at TB relative to the ball CM on the tee was determined. Similarly, the 3D position and velocity of the kicking foot at BC was also measured, and the latter enabled the horizontal and vertical planar angles of the kicking foot path to be determined at BC. The distance between the support foot CM at SFC and the ball CM was also calculated. The length of the final step towards the ball was calculated as the resultant displacement between the kicking foot CM in the frame prior to KFO and the support foot CM at SFC, and the angle of this vector relative to the global antero-posterior axis was calculated. All calculated position and displacement variables were normalised to leg length.

The recorded GRF data were normalised to body weight (Hof, 1996) before peak values and their timings were extracted. Net impulse was calculated in the three principal directions through integration (trapezium rule) and divided by mass to calculate the deceleration of the whole-body CM in each direction between SFC and BC. Total horizontal deceleration was also calculated.

To determine the performance of each kick, an aerodynamic model of rugby ball flight was used to obtain the predicted *maximum distance* (Atack et al., 2019a) using the measured initial ball kinematics. The trial in which the participant achieved the greatest predicted *maximum distance* was used for subsequent analysis. The reason for failure of that kick from any greater distance was also identified as either "inaccurate" (would have passed outside the goalposts) or "lacking range" (would have dropped below crossbar height).

Vertical Jump Tests

After the kicking trials, participants performed six maximal vertical jumps on the force platform. These jumps comprised two squat jumps (SJs), two countermovement jumps (CMJs) and two drop jumps from a 30 cm box (DJs). All jumps were performed with arms folded across the chest. The vertical force data were exported and analysed in Matlab (v.7.12.0, The MathWorks Ltd., USA). Jump heights were calculated from flight times using a 10 N threshold (integration of force data was not possible as not all participants were static prior to initiating the jump, but all maintained extended legs in-flight and landed in this position). The trial where the greatest height was achieved for each jump type was selected for further analysis. Peak propulsive force was normalised to body weight. Reactive strength index (RSI) was calculated for the DJ (Flanagan & Comyns, 2008), modified RSI (RSImod) was calculated for the CMJ (Ebben & Petushek, 2010), and the Eccentric Utilisation Ratio (EUR) was calculated by dividing the CMJ height by SJ height.

Statistical Analysis

Given the aim of this study, the data from the participants whose kicks were deemed to be "lacking range" (n = 17) were retained for further analysis. Participants whose best kick was "inaccurate" were excluded so that this analysis focussed on the movements that limited the range of straight kicks. First, Pearson correlation coefficients were used to assess the relationships between kick performance measures. *Maximum distance* was deemed the primary criterion variable as it encompasses both the distance and accuracy requirements of place kicking. However, as many previous studies have used other measures of performance, such as ball velocity post-contact and kicking foot velocity at BC, it was important to understand the relationships between these variables. Correlation coefficient thresholds were defined as follows: $r < 0.1$ trivial, $0.1 \leq r < 0.3$ small, $0.3 \leq r < 0.5$ moderate and $r \geq 0.5$ strong (Cohen, 1988); whilst $p < 0.05$ indicated a significant correlation.

As multiple constructs (namely technique characteristics, strength capabilities and anthropometric parameters) each containing numerous variables were investigated, principal component analysis (PCA) was used to reduce the number of variables analysed (as previously performed by Ball, 2008 and Colyer et al., 2017). To ensure the PCA had sufficient power despite the inevitable small sample size associated with collecting data in specialist sport contexts, an initial selection of variables to be included was undertaken. Following Hair et al.'s (2009) recommendation, first, the variables were assessed based on their association with the criterion performance measure of *maximum distance* and any variables with strong significant correlations were extracted. Subsequently only variables that were deemed to be independent of the others were selected for inclusion (e.g. if all individual components and the composite variable were identified, the composite was selected but if only individual components were identified these were used for subsequent analysis).

All variables selected for inclusion in the PCA were then transformed into z-scores to standardise scaling for analysis in SPSS Statistics (v.24; IBM Corp, Armonk, NY). The Bartlett test of sphericity and Kaiser-Meyer-Olkin measure of sampling adequacy were used to confirm the suitability of the dataset for PCA. An initial solution was computed with the optimum number of components identified when the Cumulative Initial Eigenvalues totalled more than 90% (Jolliffe, 2002). An orthogonal varimax rotation was used to simplify the structure. A significant loading was identified if more than ± 0.7 loading was seen on a single component, and any variables which were loaded across multiple components were eliminated. Labels were assigned to describe each component, reflecting all of the variables with significant loading.

The variable demonstrating the strongest relationship to each component was considered to represent the broad component and used as a predictor variable in a stepwise multiple regression analysis to determine place kick performance. Initially, *maximum distance* was used as the criterion for the regression before it was repeated using the other performance components that were strongly correlated to *maximum distance* to identify how these variables also related to the ball launch velocity attained as well as the foot velocity at BC. The Durbin-Watson statistic assessed autocorrelation, and the consistency of the residuals were evaluated using the Breusch-Pagan and Koenker homoscedasticity tests (Breusch & Pagan, 1979; Koenker & Bassett, 1982) and standard normality tests. Entered variables remained in the regression model if they elicited a significant R^2 change ($p < 0.05$).

A *K*-fold leave-one-out cross-validation method was used to assess the stability of the predictive regression models. The standard error of measurement (SEM) was calculated between the performance variables predicted by the cross-validation and the measured values, and correlations between the two datasets were analysed, with the R^2 value compared to the initial model.

Results

Bivariate correlations to assess the relationship of performance components with maximum distance

The 17 analysed kicks had a *maximum distance* of 37.19 ± 7.48 m (range = 21.8-53.3 m). Analysis of the initial in-flight ball kinematics and the kicking foot kinematics at BC revealed strong, significant correlations between a number of variables and the *maximum distance* of the kicks (Table 1). Resultant ball launch and kicking foot velocity showed the strongest correlations with *maximum distance* (both $r = 0.81$), whilst components of these (antero-posterior and vertical ball velocity, and medio-lateral and antero-posterior foot velocity) were also strongly correlated ($r = 0.80$, 0.63, 0.79 and 0.60 respectively). Therefore, the two resultant velocities and the lateral direction of the kicking foot velocity vector in the horizontal plane at BC (hereafter termed 'lateral direction of the kicking foot'; $r = 0.69$) were identified as the variables which best determined the *maximum distance* of the kicks and were subsequently used as additional dependent variables in the regression analyses.

Table 1. The measured initial ball flight and the kicking foot kinematic variables at ball contact, and their respective Pearson correlation coefficients (± 95% CL) with the *maximum distance* of the kick.

	mean ± sd	**Relationship with *maximum distance***	
		r (± 95% CL)	*p* value
Ball Flight Kinematics			
Resultant launch velocity (m/s)	26.05 ± 3.49	**0.81** (0.53 – 0.93)	**<0.001**
Lateral velocity component (m/s)	0.38 ± 0.88	-0.22 (-0.62 – 0.28)	0.391
Anterior velocity component (m/s)	21.99 ± 3.35	**0.80** (0.51 – 0.92)	**<0.001**
Vertical velocity component (m/s)	13.86 + 1.75	**0.63** (0.21 – 0.85)	**0.006**
End-over-end angular velocity (°/s)	2173 ± 985	0.27 (-0.24 – 0.65)	0.297
Yaw angular velocity (°/s)	-9 ± 520	-0.18 (-0.59 – 0.32)	0.500
Longitudinal angular velocity (°/s)	305 ± 270	-0.44 (-0.75 – 0.05)	0.080
Lateral launch direction (°)	1 ± 3	-0.33 (-0.69 – 0.17)	0.196
Vertical launch direction (°)	32 ± 3	-0.38 (-0.72 – 0.12)	0.131
Kicking Foot CM Kinematics at Ball Contact			
Resultant velocity (m/s)	19.46 ± 1.82	**0.81** (0.52 – 0.92)	**<0.001**
Lateral velocity magnitude (m/s)	7.67 ± 2.18	**0.79** (0.40 – 0.91)	**<0.001**
Anterior velocity magnitude (m/s)	17.61 ± 1.43	**0.60** (0.16 – 0.83)	**0.012**
Vertical velocity magnitude (m/s)	-2.37 ± 0.89	-0.22 (-0.62 – 0.28)	0.392
Lateral direction (°)	23 ±6	**0.69** (0.31 – 0.87)	**0.002**
Vertical direction (°)	-8 ± 3	-0.11 (-0.55 – 0.38)	0.673

Bivariate correlations to assess the relationship of technique characteristics, strength capabilities and anthropometric parameters with maximum distance

A large number of strong, significant correlations were also identified between *maximum distance* and variables which described the kickers' approach to the ball (CM kinematics, Figure 1; final step kinematics, Figure 2), the position of the kicking foot at TB (Figure 3) and the jump performance measures (Figure 4). However, no strong correlations were observed with the GRFs exerted under the support foot during the place kicks (Figure 5) or the kickers' anthropometric characteristics (Figure 6). Fifteen variables (those in bold in Figures 1-6) were entered into the PCA as they were all strongly correlated with *maximum distance* and were deemed independent of each other.

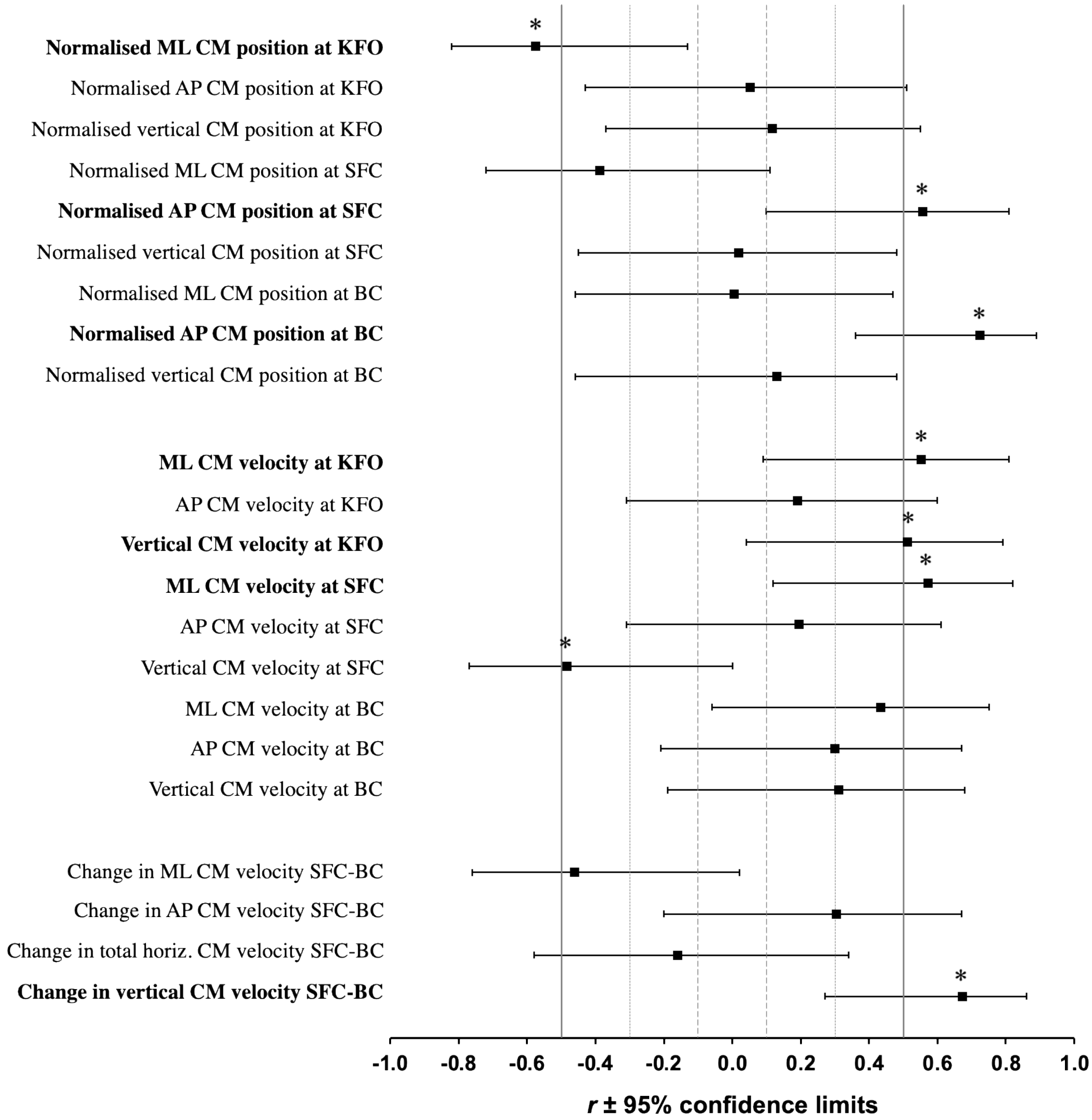

Figure 1. Pearson correlation coefficients (± 95% CL) between *maximum distance* and centre of mass kinematics prior to ball contact. Negative coefficients for the medio-lateral positions represent being to the left of the ball. Solid grey vertical lines indicate a strong correlation (r = 0.5), dotted lines a moderate correlation (r = 0.3) and dashed lines a weak correlation (r = 0.1). * denotes a significant correlation ($p < 0.05$). Abbreviations: ML, medio-lateral; AP, antero-posterior; CM, centre of mass; KFO, kicking foot take-off; SFC, support foot contact; BC, ball contact.

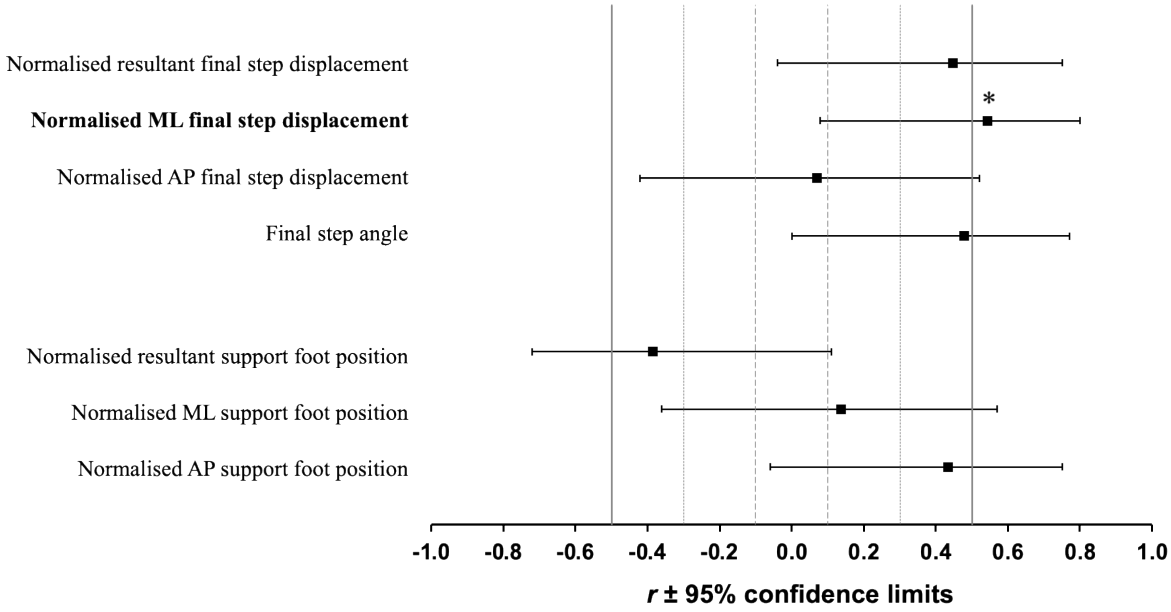

Figure 2. Pearson correlation coefficients (± 95% CL) between *maximum distance* and normalised final step kinematic variables. Negative coefficients for the medio-lateral positions represent being to the left of the ball. Solid grey vertical lines indicate a strong correlation ($r = 0.5$), dotted lines a moderate correlation ($r = 0.3$) and dashed lines a weak correlation ($r = 0.1$). * denotes a significant correlation ($p < 0.05$). Abbreviations: ML, medio-lateral; AP, antero-posterior.

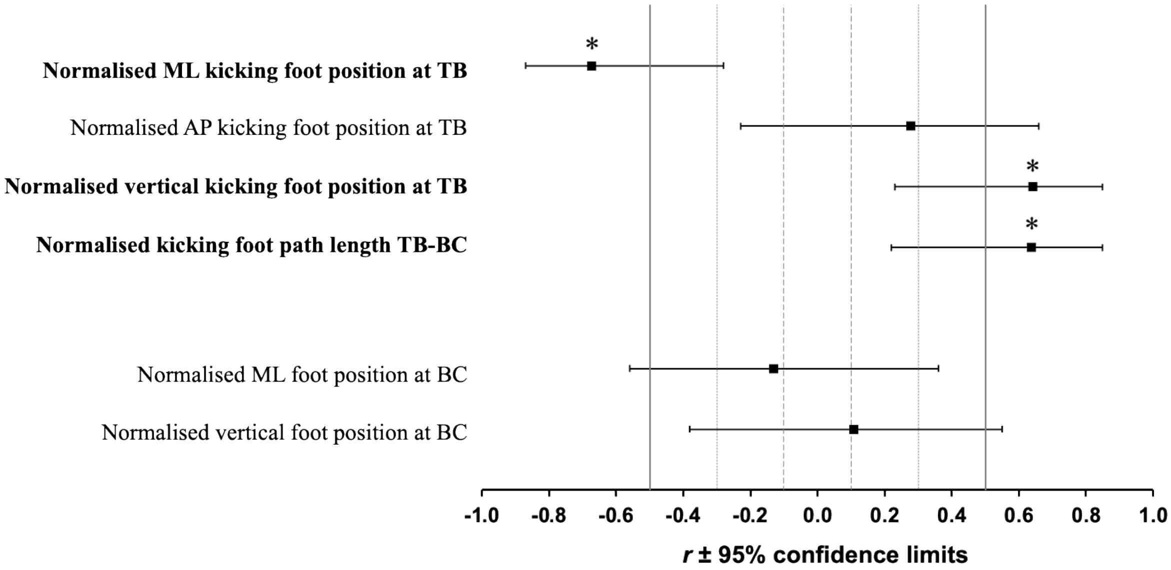

Figure 3. Pearson correlation coefficients (± 95% CL) between *maximum distance* and kicking foot kinematics during the downswing. Negative coefficients for the medio-lateral positions represent being to the left of the ball. Solid grey vertical lines indicate a strong correlation ($r = 0.5$), dotted lines a moderate correlation ($r = 0.3$) and dashed lines a weak correlation ($r = 0.1$). * denotes a significant correlation ($p < 0.05$). Abbreviations: ML, medio-lateral; AP, antero-posterior; TB, top of the backswing; BC, ball contact.

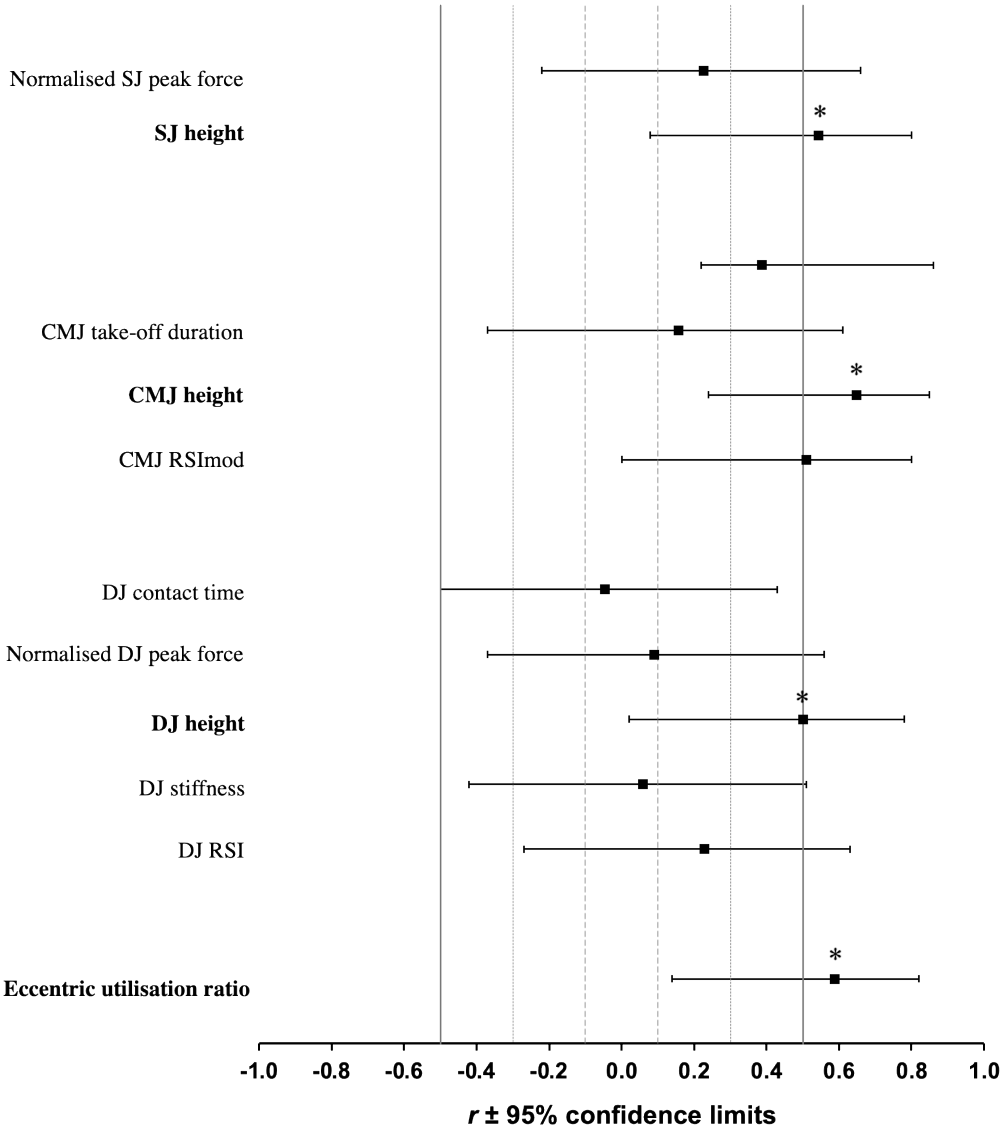

Figure 4. Pearson correlation coefficients (± 95% CL) between *maximum distance* and jump performance characteristics. Negative coefficients for the medio-lateral positions represent being to the left of the ball. Solid grey vertical lines indicate a strong correlation ($r = 0.5$), dotted lines a moderate correlation ($r = 0.3$) and dashed lines a weak correlation ($r = 0.1$). * denotes a significant correlation ($p < 0.05$). Abbreviations: SJ, squat jump; CMJ, countermovement jump; DJ, drop jump; RSI, reactive strength index.

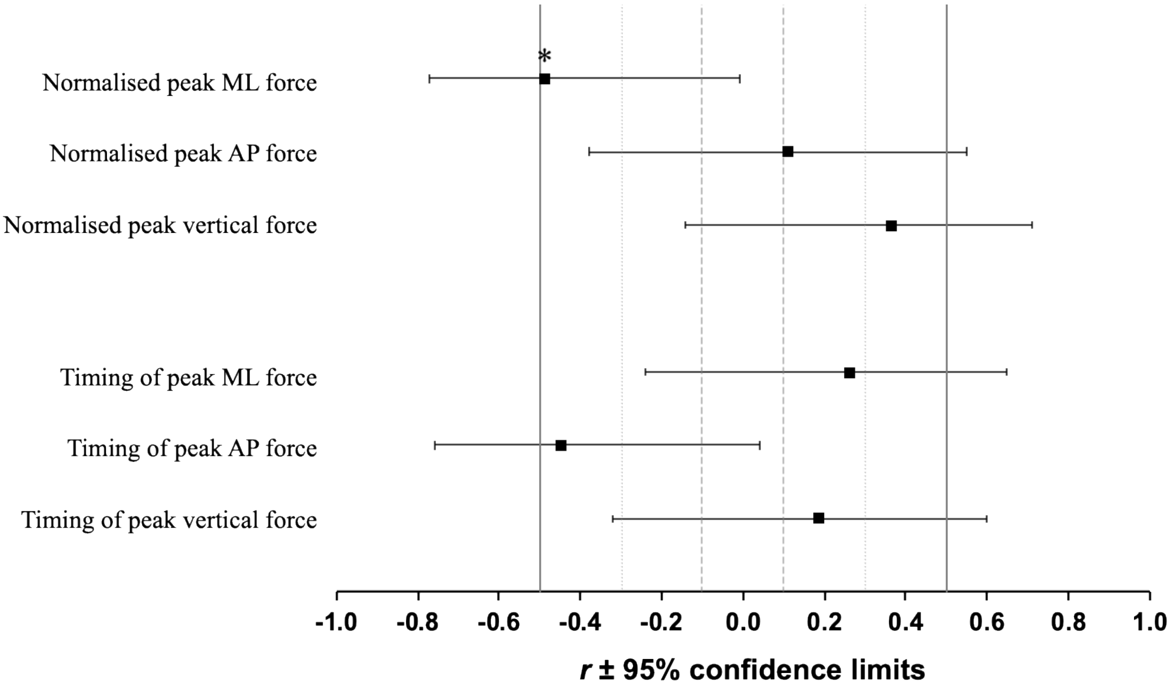

Figure 5. Pearson correlation coefficients (± 95% CL) between *maximum distance* and ground reaction forces exerted underneath the support foot. Negative coefficients for the medio-lateral positions represent being to the left of the ball. Solid grey vertical lines indicate a strong correlation ($r = 0.5$), dotted lines a moderate correlation ($r = 0.3$) and dashed lines a weak correlation ($r = 0.1$). * denotes a significant correlation ($p < 0.05$). Abbreviations: ML, medio-lateral; AP, antero-posterior.

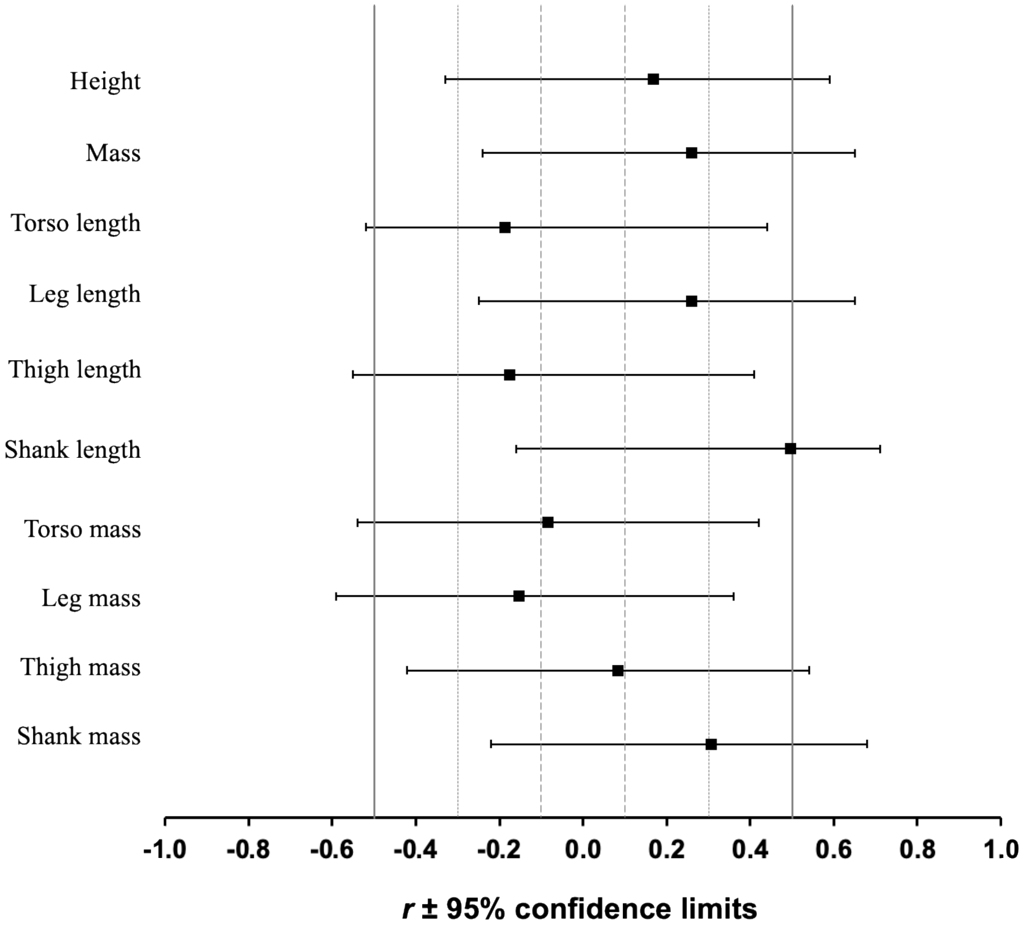

Figure 6. Pearson correlation coefficients (± 95% CL) between *maximum distance* and anthropometric characteristics of the kickers. Negative coefficients for the medio-lateral positions represent being to the left of the ball. Solid grey vertical lines indicate a strong correlation ($r = 0.5$), dotted lines a moderate correlation ($r = 0.3$) and dashed lines a weak correlation ($r = 0.1$). * denotes a significant correlation ($p < 0.05$).

Components and loading of variables derived from PCA

Following the first iteration of the PCA, three variables (change in vertical CM velocity from SFC to BC, kicking foot path length from TB to BC and EUR) were cross-loaded across multiple components and thus eliminated prior to re-running the analysis. The variables included in the second iteration met all conditions (each had a significant loading on a single component) and the Kaiser-Meyer-Olkin measure of sampling adequacy (0.700) and the Bartlett's test of sphericity ($p < 0.001$) confirmed that the data were appropriate for the analysis. Four components were extracted from the PCA (Table 2), explaining 94% of the variance in the data. The components were interpreted to represent: 1, width of approach; 2, anterior-posterior body position; 3, CM height; 4, lower limb strength.

Table 2. Components identified from the Principal Component Analysis and the corresponding loading of each variable to the components.

	Component			
	1	**2**	**3**	**4**
ML CM position at KFO	**-0.923**	-0.165	-0.170	-0.186
ML CM velocity at KFO	**0.916**	0.208	-0.066	0.292
ML CM velocity at SFC	**0.898**	0.211	-0.091	0.314
ML kicking foot position at TB	**-0.874**	-0.311	-0.302	-0.169
ML final step displacement	**0.909**	0.186	0.203	0.230
AP CM position at SFC	0.522	**0.795**	0.054	-0.139
AP CM position at BC	0.203	**0.913**	0.145	0.255
Vertical CM velocity at KFO	-0.044	0.035	**0.876**	0.386
Vertical kicking foot position at TB	0.475	0.290	**0.703**	0.279
CMJ Height	0.310	0.171	0.289	**0.870**
SJ Height	0.191	0.096	0.208	**0.934**
DJ Height	0.298	-0.018	0.208	**0.869**

Abbreviations: ML, medio-lateral; AP, antero-posterior; CM, centre of mass; KFO, kicking foot take-off; SFC, support foot contact; TB, top of the backswing; BC, ball contact; CMJ, countermovement jump; SJ, squat jump. Variable names in bold (with values shaded) used to represent the individual components in the multiple regression analysis.

Stepwise regression analyses to determine the predictors of place kick performance

The variables with the greatest loading to each component (shaded values in Table 2) were medio-lateral CM position at KFO (1), antero-posterior CM position at BC (2), vertical CM velocity at KFO (3) and SJ height (4). When entered into a stepwise multiple regression model, two of these (antero-posterior CM position at BC and vertical CM velocity at KFO) were found to explain 64% of the total variance in the *maximum distance* of the place kicks (Table 3). The same four predictor variables were entered into separate stepwise multiple regression models to predict resultant ball launch velocity, resultant kicking foot velocity and lateral direction of the kicking foot at BC as these represent the performance criteria that were strongly associated with *maximum distance*. These further the understanding of how performance was achieved and were able to explain 71%, 55% and 71% of the total variance in the respective dependent variables (Table 3).

Table 3. Results and validation data for the stepwise multiple regression models to estimate the *maximum distance* of the place kicks and other associated performance criteria.

	Regression equation components			Variance explained (R^2, *p value*)		Model assessment statistics				
									K-fold validation	
Dependent Variable	Independent variable 1 (unstandardised ß coefficient)	Independent variable 2 (unstandardised ß coefficient)	Constant	Independent variable 1	Independent variable 2	Durbin-Watson statistic	Breusch-Pagan (*p* value)	Koenker (*p* value)	Correlation of predicted values and measured (R^2, *p* value)	SEM
Maximum distance	AP CM position at BC (0.449)	vertical CM velocity at KFO (13.149)	42.294	0.52 $p = 0.001$	0.12 $p = 0.049$	1.972	0.524	0.426	0.50 $p = 0.002$	4.54 m
Resultant ball launch velocity	SJ height (28.67)	ML CM position at KFO (-0.083)	7.15	0.57 $p < 0.001$	0.14 $p = 0.024$	1.840	0.524	0.426	0.56 $p = 0.001$	1.83 m/s
Resultant kicking foot velocity	SJ height (18.727)	-	12.418	0.55 $p = 0.001$	-	1.573	0.256	0.192	0.46 $p = 0.003$	0.98 m/s
Lateral direction of kicking foot	ML CM position at KFO (-0.199)	AP CM position at BC (0.237)	8.513	0.56 $p = 0.001$	0.15 $p = 0.016$	1.723	0.524	0.426	0.59 $p < 0.001$	3°

Abbreviations: ML, medio-lateral; AP, antero-posterior; CM, centre of mass; BC, ball contact; KFO, kicking foot take-off; SJ, squat jump; SEM, standard error of measurement.

Discussion

We explored the association between the kickers' approach to the ball, their physical characteristics and rugby place kicking performance. Using PCA we identified four components which explained 95% of the variance in the *maximum distance* place kickers can achieve. These four components categorised 1) width of approach, 2), anterior-posterior body position 3) height of the CM and 4) lower limb strength, highlighting the importance of considering the three-dimensional motion of the kickers' approach to the ball and their physical capabilities. The variables which best represented each component were 1) medio-lateral CM position at the final kicking foot take-off prior to ball contact, 2) antero-posterior CM position at ball contact, 3) vertical CM velocity at the final kicking foot take-off prior to ball contact and 4) squat jump height. Each of these variables were retained in either the regression model that predicted overall performance (*maximum distance*) or one of the models that predicted the other associated performance criteria (resultant ball velocity magnitude, kicking foot velocity magnitude or lateral direction of the kicking foot). In order to develop the understanding of successful overall performance, we will first consider how favourable kicking foot velocity (both magnitude and direction) at ball contact is achieved, then ball launch velocity, and finally *maximum distance*.

The kicking foot is the distal end of the linked segment system which contacts the ball, determines its flight post-contact and ultimately kick distance. The resultant kicking foot velocity magnitude demonstrated a strong relationship with *maximum distance* ($r = 0.81$, $p < 0.001$), as previously reported in Australian Rules punt kicking for distance (Ball, 2008). Lower-limb strength was the sole significant predictor of the variance in resultant kicking foot velocity magnitude (explaining 55% of the total variance). Given the weak-moderate correlations between *maximum distance* and the recorded GRFs and change in horizontal CM velocity during support foot contact, increased strength does not appear to influence a kicker's ability to brake their forward momentum. Instead, greater lower limb strength could facilitate positive lower limb joint work during the downswing and subsequently the velocity of the kicking foot. Thus, greater lower limb concentric strength as evidenced through increased SJ height, is likely reflective of increased capacity of the knee extensors (Luhtanen & Komi, 1979) which can then be utilised to achieve faster kicking foot velocities (Atack et al., 2019b). Although previous research has presented contradictory findings as to the relationship between lower-limb strength and kicking performance in other football codes (e.g. Cabri et al., 1988; Cometti et al., 2001), the use of isokinetic dynamometry or squat tests are a likely reason as they do not adequately reflect the knee extension velocities observed during the downswing of a place kick (>1000°/s). Those studies which did employ explosive tests, such as maximal jumps, tended to identify stronger correlations but may also have been impacted by the varied experience of the participants and the lack of familiarisation provided.

In addition to kicking foot velocity magnitude, it is also important to consider the direction of the foot velocity vector given the importance of an appropriate ball trajectory in rugby place kicking (Atack et al., 2019a). We found the lateral direction of the kicking foot velocity vector in the horizontal plane at BC was strongly correlated with *maximum distance* ($r = 0.69$, $p = 0.002$). Whilst lower limb strength is important in determining the magnitude of the kicking foot velocity, it is the position of the body that determines its direction - width of approach and antero-posterior body position combined to explain 71% of its variance. Although experimental manipulations to approach angle have produced equivocal findings in terms of ball velocity magnitude (Kellis et al., 2004; Isokawa & Lees, 1988; Scurr & Hall, 2009), the effect on the direction of the kicking foot or ball velocity is previously unexplored as these studies have not considered kick accuracy. Analysis of the variables loaded to these two components highlights the importance of adopting a wider approach earlier in the kicking phase (i.e. at kicking foot-take off to support foot contact) but a more anterior position later in the phase (from support foot contact to ball contact). Therefore, the inclusion of these components in this model suggests that the two factors combine to influence the kicking foot swing plane during the downswing and ultimately the foot velocity direction at BC. Although previous research (Bezodis et al., 2019) has identified differences in both the inclination and direction of the kicking foot swing planes of accurate and inaccurate place kickers, such an analysis has not been conducted across solely those who are limited by their range. An observed difference in this swing plane may explain how different foot-ball collisions are achieved and the subsequent effect this can have on ball flight. Thus, in order to understand the effect of these two factors (a wider approach and a more forward body position) on the range achieved by accurate rugby union place kickers, further analysis of kicking foot swing planes alongside the foot-ball interaction is warranted.

As expected, resultant ball velocity magnitude demonstrated a strong relationship with *maximum distance* ($r = 0.81$, $p < 0.001$). The regression model for resultant ball velocity included two of the components identified in the models describing kicking foot motion. Lower limb strength combined with the width of the approach to explain 71% of the total variance. Given lower limb strength was the sole significant predictor of resultant kicking foot velocity and the strong relationship observed between resultant foot and ball velocities in a range of football codes ($r = 0.68$ - 0.83; Ball, 2008; De Witt & Hinrichs, 2012; Nunome et al., 2006), the importance of lower limb strength in achieving a fast ball velocity is clear. The inclusion of a wider approach in the model is of interest given the previously identified relationship it has with the direction of the kicking foot velocity vector at BC and the equivocal findings in the literature when approach angle was experimentally manipulated (Kellis et al., 2004; Isokawa & Lees, 1988; Scurr & Hall, 2009). Participants in the present study approached from a mean angle of 49° (range 36-66°), which is comparable to the 45° previously found to elicit the fastest mean ball velocities in soccer instep kicking. Isokawa and Lees (1988) suggested a more angled approach may enable a greater effective mass of the foot due to the player adopting a more rigid ankle joint, thereby increasing coefficient of restitution during impact. This is supported by research investigating impact efficiency using a mechanical kicking leg which found that increased simulated ankle rigidity enabled a more efficient collision and subsequently faster ball velocities (Peacock & Ball, 2018). A more proximal impact location on the kicking foot has also been found to reduce the amount of plantarflexion at a mechanical ankle joint resulting in a greater coefficient of restitution and ball velocity compared with a more distal impact location (Peacock & Ball, 2019). Therefore, we propose that it is not an angled approach that enables a faster ball velocity to be achieved *per se*, but that the greater lateral distance of the kicker from the ball at the initiation of kicking leg retraction allows them more space for the downswing, altering the direction of the foot velocity vector and enabling a more efficient foot-ball collision. High-speed analyses of the impact phase of rugby place kicks are required to directly investigate this, and these findings must also currently be applied with caution as it is possible that approaching from too great an angle or achieving too great a lateral distance from the ball could negatively affect other key technical features and thus an optimum may exist. Furthermore, the relative importance of different variables and the existence or location of optima are likely to differ between individuals. Any interventions to address these aspects should therefore be applied on an individual-specific basis and with an awareness of other potential consequences, whilst kickers with ‘extreme’ technique features should be considered with caution as they may fall outside the ranges studied in the current cohort.

Although the magnitude and direction of the kicking foot velocity and the magnitude of ball velocity are associated with rugby place kick performance, these alone do not determine overall place kick success (Atack et al., 2019a). Therefore, to complete our understanding it is vital to consider the factors that contribute to true place kick performance outcome, namely *maximum distance*. The antero-posterior body position and CM height explained 64% of the variance in *maximum distance*. First to note, is that whilst lower limb strength was a significant predictor of both foot and ball velocity magnitudes, its omission from this final regression suggests that although lower limb strength is important in achieving fast kicking foot and ball speeds, the position and motion of the CM ultimately differentiates the overall true performance outcome. Secondly, the antero-posterior body position of the kicker was earlier identified as important in determining the direction of the kicking foot velocity vector, potentially through alterations to the kicking foot swing plane. Further to this, by positioning their body further forward, and closer to the ball, the kicking foot will likely be in a lower position on its downward path and therefore can contact the ball towards the more proximal end of the foot resulting in a more efficient foot-ball collision, thereby influencing ball flight. Finally, this is the first model that has included CM height as a significant predictor. Augustus et al. (2017) previously suggested that raising the support leg hip enabled greater transfer of momentum to the kicking foot and subsequently a faster ball velocity in soccer kicking. However, as vertical CM motion was not included in the previous regression model for ball velocity magnitude, it is suggested that raising the CM earlier in the approach likely contributes to place kicking performance in another way. If we consider the variable used to represent CM height in this regression, vertical CM velocity at kicking foot take-off, kickers who have a faster velocity (and subsequently greater height into the final step), will also have greater downward velocity at support foot contact. If they are then able to absorb this downward momentum and use it to rebound through the kicking action, they may be able to achieve a more favourable ball flight. The ability to rebound would likely be reflected by an increased EUR or a greater change in vertical velocity following support foot contact. Both these variables were identified as strongly correlated to *maximum distance* but were removed from the PCA after the first iteration due to cross-loading over multiple components. Given neither the antero-posterior body position or CM height were included in the model that explained the variance in ball velocity magnitude, it may be that they instead affect another aspect of ball flight post-contact such as the vertical launch direction. The variance in vertical launch direction was not investigated as an associated performance measure, as only a moderate linear relationship was identified with *maximum distance*. Previous research identified a non-linear (cubic) relationship between vertical launch direction and kick distance for an individual place kicker (Linthorne & Stokes, 2014), and although such a relationship was not apparent in the present study, future research should consider the factors that may contribute to this aspect of ball flight.

In conclusion, several aspects describing both the kicker’s approach to the ball and their physical capabilities that are meaningful to coaches were found to influence place kick performance. Lower limb strength appears important for a kicker to achieve a fast kicking foot velocity, whilst taking a wider approach and adopting a more anterior body position (closer to the ball) affect the direction of the kicking foot’s motion at BC. A combination of these factors (greater lower limb strength and a wide approach) is subsequently required to achieve a fast ball velocity. However, CM height and the anterior-posterior body position of the kicker ultimately determines the maximum range of accurate place kickers. Replication of the present study with a different sample population is suggested to assess the robustness of these findings. Additionally, the specific mechanisms by which increased kicking range is achieved requires further investigation, particularly in terms of the detail of the foot-ball impact which is currently unexplored in place kicking but appears vital in determining overall performance.

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Disclosure of interest

The authors report no conflict of interest.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supplementary Table 1. Anatomical marker locations (adapted from the Vicon Plug-in-Gait marker setup, Vicon, Oxford, UK; detailed in Vicon, 2012).

Marker	Anatomical Position	Segment(s) Defined
Right / Left Front Head	Temple	Head
Right / Left Back Head	On a horizontal plane to the temple markers	Head
C7	Spinous process of 7th cervical vertebra	Upper Trunk
Clavicle	Jugular notch	Upper Trunk
† Right / Left Acromion	Acromion process	Upper Trunk/Arm
† Right / Left Anterior Glenohumeral	Anterior aspect of the glenohumeral joint	Upper Trunk/Arm
† Right / Left Posterior Glenohumeral	Posterior aspect of the glenohumeral joint	Upper Trunk/Arm
Sternum	Xiphoid process of sternum	Upper/Lower Trunk
T10	Spinous process of 10th thoracic vertebra	Upper/Lower Trunk
† Right / Left Iliac Crest	Iliac crest	Lower Trunk/Pelvis
Right / Left ASIS	Anterior superior iliac spine	Pelvis
Right / Left PSIS	Posterior superior iliac spine	Pelvis
† Right / Left Medial Elbow	Medial epicondyle of the elbow	Upper/Lower Arm
Right / Left Lateral Elbow	Lateral epicondyle of the elbow	Upper/Lower Arm
Right / Left Medial Wrist	Styloid process of the ulna	Lower Arm
Right / Left Lateral Wrist	Styloid process of the radius	Lower Arm
† Right / Left Greater Trochanter	Greater trochanter	Pelvis/Upper Leg
† Right / Left Medial Knee	Medial epicondyle of the knee	Upper/Lower Leg
Right / Left Lateral Knee	Lateral epicondyle of the knee	Upper/Lower Leg
† Right / Left Medial Ankle	Medial malleolus	Lower Leg/Foot
Right / Left Lateral Ankle	Lateral malleolus	Lower Leg/Foot
Right / Left Heel	Calcaneus, on a horizontal plane with the ankle joint centre	Foot
† Right / Left Midfoot	Lateral aspect of foot, non-collinear to lateral ankle and 5MTP markers	Foot
† Right / Left 5MTP	Head of 5th metatarsal phalangeal joint	Foot
† Right / Left 1MTP	Head of 1st metatarsal phalangeal joint	Foot

† Additional markers used for the identification of body segments (adapted from the models presented by Chin, Elliot, Alderson, Lloyd & Foster (2009); Lloyd, Alderson & Elliott (2010).

Supplementary Table 2. The definition of the 14-segment full-body model.

Segment	Proximal Joint Definition	Distal Joint Definition	Additional Information
Head	A landmark midway between the two front head markers was identified as the joint centre, and 50% distance between this landmark and the right front head marker was the joint radius.	A landmark midway between the two back head markers was identified as the joint centre, and the distance between this landmark and the right back head marker as the joint radius.	A landmark midway between the right front and back head markers was an additional lateral landmark to determine segment orientation. All markers were used to track the segment.
Upper Trunk	A landmark midway between the clavicle and C7 markers was identified as the joint centre, and 50% distance between the right and left shoulder joint centres was the joint radius.	A landmark midway between the sternum and T10 markers was identified as the joint centre, and 50% distance between the right and left iliac crest markers was the joint radius.	The C7, sternum and clavicle markers were used to track the segment.
Lower Trunk	A landmark midway between the sternum and T10 markers was identified as the joint centre, and 50% distance between the right and left iliac crest markers was the joint radius.	The right and left iliac crest markers were identified as the lateral and medial joint markers respectively.	The T10 and right and left iliac crest markers were used to track the segment.
Pelvis	The right and left iliac crest markers were identified as the lateral and medial joint markers respectively.	The right and left greater trochanter markers were identified as the lateral and medial joint markers respectively.	The right and left ASIS and PSIS markers were used to track the segment.
Upper Arm	A landmark defined as the point where the line between the anterior and posterior glenohumeral markers intersects with the perpendicular line from the acromion marker, was identified as the joint centre and 50% distance between the anterior and posterior glenohumeral markers* was the joint radius.	The lateral and medial elbow markers determined the joint.	A three-marker cluster was used to track the segment.
Forearm	A landmark defined as the point midway between the medial and lateral elbow markers was identified as the joint centre and the distance between this landmark and the medial elbow marker* was the joint radius.	The lateral and medial wrist markers determined the joint.	A three-marker cluster was used to track the segment.
Upper Leg	The greater trochanter marker* was used as the lateral definition of the joint and 25% distance between the right and left greater trochanter markers* was the joint radius.	The lateral and medial knee markers determined the joint.	A four-marker cluster was used to track the segment.
Lower Leg	The lateral and medial knee markers determined the joint.	The lateral and medial ankle markers determined the joint.	A four-marker cluster was used to track the segment.
Foot	The lateral and medial ankle markers determined the joint.	The 5MTP and the 1MTP markers were identified as the lateral and medial joint markers respectively.	The heel, lateral ankle, midfoot and 5MTP markers were used to track the segment.

* Marker position adjusted by 50% of marker diameter