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**Assessing rugby place kick performance from initial ball flight kinematics:
development, validation and application of a new measure**

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1 *Abstract*

2 The appropriate determination of performance outcome is critical when appraising a
3 performer's technique. Previous studies of rugby place kicking technique have
4 typically assessed performance based on ball velocity, but this is not the sole
5 requirement. Therefore, a mathematical model of rugby place kick ball flight was
6 developed to yield a single measure more representative of true performance. The
7 model, which requires only initial ball flight kinematics, was calibrated and validated
8 using empirical place kick data, and found to predict ball position with a mean error
9 of 4.0% after 22 m of ball flight. The model was then applied to the performances of
10 33 place kickers. The predicted maximum distance, a single performance measure
11 which accounted for initial ball velocity magnitude and direction, and spin, was
12 determined using the model and was compared against ball velocity magnitude. A
13 moderate association in the rank-order of the kicks between these two measures (ρ
14 = 0.52) revealed that the relative success of the kicks would be assessed differently
15 with each measure. The developed model provides a representative measure of
16 place kick performance that is understandable for coaches, and can be used to
17 predict changes in performance outcome under different ball launch or
18 environmental conditions.

19 **Keywords**

20 aerodynamics, biomechanics, kicking, model, simulation

21 **Word count:** 4869

22 **Introduction**

23 Place kicks contributed 45% of the points scored in a large sample of international
24 Rugby Union matches from 2002-2011 (Quarrie & Hopkins, 2015) and this
25 contribution may increase in games between more closely-matched teams or games
26 of high importance (e.g. 70% of total points in Rugby World Cup finals from 1987-
27 2015 came from place kicks). The average place kicking success percentage in the
28 582 matches analysed by Quarrie and Hopkins (2015) was 72% (4874/6769 kicks),
29 and if the success percentage of the competing teams' kicks had been reversed in
30 these matches, 14% of the results would have reversed (Quarrie & Hopkins, 2015).
31 Although other factors must be considered, place kick performance is clearly
32 important in determining match outcome and therefore improving place kicking
33 performance provides an important means for enhancing team success.

34 Given the crucial role of place kicking, it is important for sport biomechanists to
35 understand how successful kicks are achieved. Previous biomechanical studies have
36 analysed kicking leg kinematics during the downswing (Sinclair et al., 2014; Sinclair
37 et al., 2017; Zhang, Liu & Xie, 2012), variability in kicking foot movement at ball
38 contact (Ford & Sayers, 2015), approach to the ball and support foot placement
39 (Baktash, Hy, Muir, Walton & Zhang, 2009; Ball, Talbert & Taylor, 2013; Green, Kerr,
40 Olivier, Dafkin & McKinon, 2016; Cockcroft & van den Heever, 2015), whole-body
41 orientation at ball contact (Ball et al., 2013; Green, Kerr, Olivier, Dafkin & McKinon,
42 2016) or motion of the non-kicking-side arm (Bezodis, Trewartha, Wilson & Irwin,
43 2007), and have often attempted to relate these aspects of technique to performance
44 outcome. The majority of these studies were laboratory-based, meaning the full flight
45 path of the ball could not be tracked. Instead, performance was quantified as the
46 initial ball velocity magnitude. However, a sufficiently high ball velocity magnitude is

47 not the complete performance requirement as the ball must pass between two posts
48 (5.6 m apart) and above a crossbar (3.0 m above the ground). Whilst the lateral
49 position of the ball relative to the target line has also been used as an additional
50 performance measure (Bezodis et al., 2007; Green et al., 2016), a single value
51 incorporating the distance and accuracy requirements in to a representative measure
52 of how far any given kick could be taken from and be successful is needed if place
53 kicking performance is to be appropriately assessed in laboratory studies.
54 Importantly, this could lead to a different interpretation of place kick performance
55 outcomes, and thus of the techniques associated with high levels of performance,
56 compared with when the more traditional measure of ball velocity magnitude is used.

57 Predicting the flight path of the ball from the initial flight kinematics would enable a
58 more complete and meaningful measure to be determined for use in applied
59 research (e.g. how far from the posts any given kick would be successful). The flight
60 path is directly determined by the magnitude and direction of the ball's linear and
61 angular velocities at the instant it leaves the kicker's boot, and the gravitational and
62 aerodynamic forces which act on the ball during flight. Although the aerodynamic
63 forces cannot be directly measured in flight, wind-tunnel experiments have been
64 conducted to determine the drag, lift, and side forces in simulated rugby ball flight
65 (e.g. Seo, Kobayashi & Murakami, 2006; Seo, Kobayashi & Murakami, 2007). These
66 experiments were conducted with the ball rotating about different principal axes and
67 yielded aerodynamic force coefficients as functions of wind-speed and ball
68 orientation. Whilst these published coefficients can be applied to simulate ball flight,
69 there has been no experimental validation of their accuracy. Furthermore, as there
70 are different functions available, a systematic assessment is required to determine
71 the most appropriate combination of coefficients which best predict the outcome of a

72 kick, and to quantify the accuracy of this prediction. The model can then be applied
73 with confidence to assess performance outcome and also used to provide valuable
74 insight regarding place kick performance, as kicks can be unsuccessful for different
75 reasons. For example, an investigation into how the magnitude and direction of the
76 linear and angular ball velocities differ between sub-groups of kicks which result in
77 different outcomes (e.g. long 'successful' kicks versus those which are less
78 successful because they miss short, left, or right) will provide an understanding of
79 the aspects of ball launch which future technical investigations should endeavour to
80 address.

81 Our primary aim was therefore to develop and validate a model of ball flight to
82 assess rugby place kick performance using a single measure. This measure should
83 be fully representative of field-based performance and easily understandable for
84 coaches and players. In order to demonstrate the applicability of this measure, we
85 secondly aimed to categorise the performance outcomes of a group of kicks and
86 investigate differences in initial ball flight kinematics between sub-groups. We
87 hypothesised that (1) assessing performance using a single measure based on the
88 modelled flight path would provide a different interpretation of performance levels
89 compared with initial linear ball velocity magnitude, and that (2) both linear and
90 angular (i.e. spin) initial ball flight kinematics would differ between sub-groups of
91 place kicks which result in different outcomes.

92 **Methods**

93 *Overview of methodological approach*

94 A mathematical model that simulated the entire flight path of a rugby ball from initial
95 flight kinematics was developed. The combination of aerodynamic force and moment

96 coefficients included in the equations of motion were then selected based on
97 comparison against empirical data from four kickers. The accuracy of the model
98 output was validated against additional empirical data from these kickers. Finally, the
99 validated model was applied to the place kicks of 33 experienced kickers to
100 demonstrate its application and to address our hypotheses. All procedures were
101 approved by the St Mary's University Ethics Committee, and all kickers were free
102 from injury, volunteered, and provided written informed consent.

103 *Model development*

104 A six degree-of-freedom ball flight model was developed in Matlab (v.7.12.0, The
105 MathWorks Ltd., USA). The global coordinate system was aligned such that the y-
106 axis represented the horizontal direction from the kicking tee to the centre of the
107 target, the z-axis was vertical, and the x-axis was the cross-product of the two. The
108 required model inputs were empirically measured initial three-dimensional linear
109 velocity of the ball centre of mass (CM), pitch angle, yaw angle, and the pitch, yaw,
110 and roll velocities of the ball at the onset of flight. The initial roll angle was excluded
111 as it has a negligible effect on the forces subsequently acting (Seo et al., 2004). The
112 ball CM position at the onset of flight relative to its original position on the tee was
113 also input. In order to ultimately determine ball position in all subsequent time
114 iterations (i, 0.0001 s), the side (F_x), drag (F_y) and lift (F_z) forces were first calculated
115 using the following equations (Seo et al., 2006, 2007):

$$F_{x(i)} = C_{x(i)} \cdot \rho \cdot V^{2/3} \cdot 0.5 \cdot \vec{v}_{(i-1)}^2 \quad (1)$$

$$F_{y(i)} = C_{y(i)} \cdot \rho \cdot V^{2/3} \cdot 0.5 \cdot \vec{v}_{(i-1)}^2 \quad (2)$$

$$F_{z(i)} = C_{z(i)} \cdot \rho \cdot V^{2/3} \cdot 0.5 \cdot \vec{v}_{(i-1)}^2 \quad (3)$$

116 where $V =$ ball volume (0.0048 m^3 ; Seo et al., 2006), $\rho =$ air density (1.225 kg/m^3
117 based on the assumption of standard atmospheric conditions at the testing location:
118 15°C , and 9 m above sea level), and $\vec{v} =$ resultant ball velocity. The three
119 aerodynamic force coefficients (C_x , C_y , C_z) were functions of instantaneous pitch
120 angle (θ_x), yaw angle (θ_y), roll velocity (ω_z) and a spin coefficient (see *Model*
121 *calibration and validation* section). For some model implementations, the pitch (M_x)
122 and yaw (M_y) moments were required, and were calculated using the following
123 equations (Seo et al., 2006, 2007):

$$M_{x(i)} = C_{m_{x(i)}} \cdot \rho \cdot V \cdot 0.5 \cdot \vec{v}_{(i-1)}^2 \quad (4)$$

$$M_{y(i)} = C_{m_{y(i)}} \cdot \rho \cdot V \cdot 0.5 \cdot \vec{v}_{(i-1)}^2 \quad (5)$$

124 The pitch and yaw moment coefficients (C_{m_x} and C_{m_y} , respectively) were
125 represented as functions of instantaneous pitch angle, yaw angle and a spin
126 coefficient. The force and moment coefficients were obtained from previous wind-
127 tunnel experiments (Seo et al., 2006, 2007), and the optimum combination of these
128 coefficients was determined (see *Model calibration and validation* section).

129 The ball CM linear accelerations (a_x , a_y , a_z) were determined based on the ball's
130 mass (m ; 0.435 kg) and gravity (g ; 9.81 m/s^2). In versions of the model where
131 moments were included, the angular accelerations (α_x , α_y) were also determined at
132 each time interval accounting for the ball's moment of inertia about the transverse
133 axis ($0.0033 \text{ kg}\cdot\text{m}^2$; Seo et al., 2006). All accelerations were numerically integrated
134 (trapezium rule) to update the linear (v_x , v_y , v_z) and angular (ω_x , ω_y) velocities of the
135 ball, which in turn were numerically integrated to update its position (d_x , d_y , d_z) and
136 orientation (θ_x , θ_y). The model was terminated when one of the following conditions
137 was met:

138 a) d_x reached ± 2.65 m (the maximum medio-lateral displacement of the ball before it
139 would hit one of the goalposts, assuming it was kicked from directly in front of the
140 posts, accounting for ball size (i.e. 0.30 m long axis) in a horizontal orientation)

141 b) d_z dropped back below 3.15 m (the height of the crossbar accounting for ball size
142 in a vertical orientation)

143 The primary output of the model was d_y in the penultimate simulation frame.
144 Assuming that the kick was taken from directly in front of the posts, this value
145 quantified the maximum anterior displacement immediately before the ball would
146 have struck either post or the crossbar. This *predicted maximum distance* measure
147 provided a single objective performance measure of kick length that fully accounted
148 for the initial 3D linear and angular velocities imparted on the ball and the forces
149 experienced during flight. Importantly, this measure is meaningful for coaches and
150 players who commonly refer to kick distances and are fully cognisant of their
151 maximum range. The reason for kick failure (i.e. missing left, missing right or
152 dropping short) was also identified from the model output.

153 *Model calibration and validation*

154 Thirty-eight place kicks were performed by four proficient rugby place kickers
155 (mean \pm SD age: 28 ± 4 years, mass: 79.3 ± 6.5 kg, height: 1.81 ± 0.09 m) in an
156 indoor sports hall. All kicks were from a tee positioned 22.00 m from a vertical wall
157 on which a 9.06×4.61 m calibrated area was measured. Two synchronised high-
158 speed cameras (Phantom V5.2, Vision Research Inc., USA; 240 Hz, shutter =
159 $1/1000$ s) recorded the initial 2.5 m of ball flight. The raw video files were imported
160 into Vicon Motus (v.9, Vicon Motion Systems, UK) and the top and bottom of the ball,
161 the centre of the visible panels (marked on the ball) or the middle of a seam

162 connecting the panels (also marked) were manually digitised at full resolution
163 (1280 × 800 pixels) from 10 frames before initial ball contact until four frames after
164 the ball had visibly left the boot. Due to the potential effects of error in the initial ball
165 flight kinematics on the predicted final ball location, each video clip was digitised 17
166 times to provide stable values within a bandwidth of ± 0.25 standard deviations either
167 side of the mean, which were considered to be an accurate representation of the true
168 value (Taylor, Lee, Landeo, O'Meara & Millett, 2015).

169 The 3D trajectories were reconstructed using direct linear transformation (DLT;
170 Abdel-Aziz & Karara, 1971) and exported to Visual3D (v.5, C-Motion, Ltd., USA) to
171 reconstruct the 3D kinematics of the ball. Initial ball flight was identified as the first
172 frame where the raw antero-posterior ball CM velocity first decreased after ball
173 contact (Shinkai et al., 2009). The initial linear ball CM velocity was calculated from
174 polynomial functions fitted to the first four frames of the raw displacement data
175 following initial ball flight (first order for both horizontal directions, second order for
176 vertical). Three-dimensional ball orientations relative to the global coordinate system
177 were calculated using an XYZ Cardan rotation sequence. The initial ball angular
178 velocities were calculated based on the change in ball orientation between the first
179 and fourth frames of flight.

180 The true ball position after 22.00 m of anterior displacement was measured using
181 two additional synchronised high-speed cameras (Sony FX1000, UK; 200 Hz, shutter
182 = 1/1000 s). One camera was placed close to the target wall to identify the frame in
183 which the ball contacted the wall. The corresponding frame from the other camera
184 (12.00 m in front of the centre of the target wall) was identified and the vertical and
185 medio-lateral positions of the ball were determined from this image using 2D DLT
186 with lens correction.

187 For this model calibration and validation, the model terminated automatically after
188 22.00 m of anterior displacement. Using the experimentally-measured initial ball
189 flight kinematics as model inputs, the model output (i.e. position where the ball first
190 made contact with the wall) was compared with the experimentally-measured ball
191 positions for each kick and the root mean square difference was calculated. Half of
192 the trials (i.e. 19) were randomly selected for use in the calibration process to identify
193 the optimal combination of aerodynamic force and moment coefficients from
194 previous wind tunnel experiments of a ball spinning about either the longitudinal (Seo
195 et al., 2006) or transverse axis (Seo et al., 2007). Although the ball primarily spins
196 about the transverse axis during a place kick, when longitudinal spin is imparted to
197 the ball, a lateral deviation in the flight path is observed due to the greater side force
198 (Seo et al., 2006). As no data is available for a ball spinning about multiple axes, the
199 calibration process assessed the accuracy of the model predictions using each of
200 eight different sets of coefficients (Table 1), obtained from both Seo et al. (2006) and
201 Seo et al. (2007). The remaining 19 trials were then used for an independent
202 validation of the model accuracy using the identified optimal coefficient set.

203

204 ****Table 1 near here****

205

206 *Model application*

207 In a separate empirical data collection, ball flight data were obtained from 33
208 competitive rugby kickers (ranging from amateur to senior international, mean \pm SD
209 age: 22 ± 4 years, mass: 86.2 ± 8.8 kg, height: 1.82 ± 0.06 m). Each kicker wore

210 moulded boots and performed rugby place kicks in an indoor laboratory with rubber
211 flooring. A 1.2 m wide by 2.3 m high net (The Net Return LLC, USA) was centred
212 2.00 m in front of the kicking tee. A 0.05 m wide by 1.20 m high target was hung from
213 the top centre of the net to represent the line of the centre of the posts. Six circles of
214 reflective tape (25 mm in diameter) were attached to a size 5 Gilbert Virtuo
215 Matchball, one in the centre of each of the panels of the ball and two at known
216 locations at the top of opposing panels to enable 3D tracking. All trials were recorded
217 at 240 Hz using a 10-camera motion capture system (MX-3, Vicon, UK) with the
218 global coordinate system defined as stated previously. Following a self-directed
219 warm-up and familiarisation kicks the kickers were asked to kick towards the target,
220 as if from their maximum range, for a minimum of seven kicks.

221 Marker trajectories were reconstructed and labelled using Vicon Nexus (v. 1.8.3).
222 Five kicks for each kicker were selected based on marker visibility and the subjective
223 rating of kick quality (provided by the kicker immediately after the kick on a scale of
224 1-10, with 10 perceived to be perfect), and exported to Visual 3D. The initial linear
225 and angular ball kinematics were calculated as outlined previously, and were input to
226 the validated ball flight model. The *predicted maximum distance* for each of the five
227 place kicks taken by each kicker was output, and the kick with the greatest *predicted*
228 *maximum distance* for each kicker was used for all subsequent analysis.

229 To address the first hypothesis, a Spearman's rank-order correlation coefficient (ρ)
230 was calculated between the *predicted maximum distance* and the magnitude of the
231 resultant initial ball velocity (the measure typically used in previous studies) for the
232 33 kicks. To address the second hypothesis, the kicks were grouped based on their
233 performance outcome. Initially, those kicks with a *predicted maximum distance*
234 greater than 32 m (the average place kick distance in international matches; Quarrie

235 & Hopkins, 2015) were identified and termed 'long' kicks. The remaining less
236 successful kicks were sub-divided based on the reason for failure: kicks which
237 dropped below crossbar height (short kicks), kicks which hit the left-hand goalpost
238 (wide-left kicks) or which hit the right-hand goalpost (wide-right kicks). Means and
239 standard deviations were calculated for each sub-group's initial ball flight kinematics.
240 The initial directions of ball flight (in the x-y plane and y-z plane, termed 'lateral
241 direction' and 'launch angle', respectively) were determined from the initial ball
242 velocities. Effect sizes were calculated (Cohen, 1988) to assess the magnitude of the
243 difference between the subgroups for each variable. The effect sizes were
244 interpreted as: <0.2, trivial; 0.2 to 0.6, small; 0.6 to 1.2, large and >2.0, very large
245 (Hopkins, Marshall, Batterham & Hanin, 2009). Following this, 90% confidence
246 intervals were calculated and magnitude-based inferences were derived (Hopkins,
247 2007). A threshold of 0.2 was considered to be a practically important effect
248 (Hopkins et al., 2009; Winter, Abt & Nevill, 2014). The likelihood of the true value
249 falling within each classification of positive, trivial and negative was calculated.

250 **Results**

251 *Model calibration and validation*

252 The model containing coefficient set 8 (Table 1) provided the closest match with
253 experimental data (Table 2). This combination of coefficients included drag and lift
254 coefficients for a ball spinning predominantly about the transverse axis (Seo et al.,
255 2007) and a side force coefficient for a ball spinning about the longitudinal axis at a
256 velocity greater than 360°/s (Seo et al., 2006) but no moment coefficients. When the
257 model contained coefficient set 8, its outputs matched the experimental data with a
258 mean resultant difference of displacement in the plane of the posts of 0.87 ± 0.42 m
259 (Table 2). When validated against a further 19 independent kicks, the mean resultant
260 difference was 0.88 ± 0.40 m – this error in displacement in the plane of the posts
261 equated to 4.0% of the total anterior displacement (i.e. 22.0 m) during flight.

262

263 ****Table 2 near here****

264

265 *Model application*

266 Using the model containing coefficient set 8, a moderate, positive relationship was
267 observed between the rank orders of the 33 place kicks based on the *predicted*
268 *maximum distance* and the magnitude of the resultant initial ball velocity ($\rho = 0.52$,
269 90% CI = 0.27 to 0.71; Figure 1). The 33 kicks were then categorised into distinct
270 groups based on their outcomes. As two of the kicks were within 4.0% (the accuracy
271 of the model as determined during the validation) of the 32 m *predicted maximum*
272 *distance* threshold, they could not be confidently categorised and were excluded

273 from all further analysis. Eighteen kicks achieved a *predicted maximum distance* >
274 32 m and were classified in the long group. Thirteen kicks achieved a *predicted*
275 *maximum distance* < 32 m. These kicks were then sub-divided based on their reason
276 for failure, with four classified in the short group, eight in the wide-left group and one
277 in the wide-right group. As only one kick was classified in the wide-right group, this
278 group was removed. Thirty kicks, classified into three distinct groups, were therefore
279 included in all subsequent analyses.

280

281 ****Figure 1 near here****

282

283 The *predicted maximum distance* of the long kicks was substantially longer than that
284 of both the wide-left (Figure 2a) and short kicks (Figure 2b) but there was no clear
285 difference between the two less successful groups (Figure 2c). Both the long and
286 wide-left kicks had a substantially faster resultant ball velocity compared with the
287 short kicks (Figure 2b and 2c) but there was no clear difference in ball velocity
288 magnitude between the long and wide-left kicks (Figure 2a). The lateral direction of
289 the ball velocity vector was substantially different between all three groups (Figure
290 2a-c) with the long and short kicks initially directed towards the right-hand-side and
291 the wide-left kicks towards the left-hand-side. The launch angle of the ball velocity
292 vector was substantially greater for the long kicks than the wide-left kicks (Figure
293 2a), whilst the short kicks had a substantially greater launch angle than both of the
294 other two groups (Figure 2b and 2c). There was no clear difference in pitch velocity
295 between the three groups (Figure 2a-c) but the long and short kicks possessed

296 substantially less roll velocity (longitudinal spin) than the wide-left kicks (Figure 2a
297 and 2c). The mean \pm SD values for these variables are in Table S1 (Appendix 1).

298

299 ****Figure 2 near here****

300

301 **Discussion and Implications**

302 We developed and validated a model of rugby ball flight which can be applied to
303 assess place kick performance outcome using a single, representative measure. We
304 also demonstrated the applicability of this model by addressing two specific
305 hypotheses using the model-determined place kick performance measures. The
306 model validation revealed it could accurately predict ball location when in the plane
307 of the posts to within 4.0% of the anterior displacement covered during flight. The
308 model was then applied to obtain a measure of *predicted maximum distance* that
309 quantified the maximum distance from which any given kick could be taken (from
310 directly in front of the posts) and remain successful. Comparison of the performance-
311 based ranking of 33 kicks using this *predicted maximum distance* measure against
312 the traditionally adopted linear velocity magnitude measure (Figure 1) supported our
313 first hypothesis as the rank orders of the 33 kicks were only moderately related ($\rho =$
314 0.52). When the kicks were then categorised in to sub-groups based on their
315 performance outcomes, our second hypothesis was also supported as clear
316 differences in both linear and angular initial ball flight kinematics were evident
317 between the sub-groups (Figure 2).

318 When developing any movement simulation, Hicks et al. (2015) proposed that the
319 model should be calibrated to identify appropriate constants that produce an output
320 closest to empirical data. Previous wind-tunnel experiments (Seo et al., 2006; 2007)
321 have rotated a rugby ball about different axes and in different wind speeds to
322 determine the aerodynamic force and moment coefficients, but no published
323 scientific studies have singularly represented the complete characteristics observed
324 during rugby place kick ball flight. The current model calibration therefore enabled
325 the determination of the set of these coefficients which yielded the most accurate
326 prediction of place kick performance – coefficient set 8 (Table 1) yielded an error in
327 predicted ball displacement in the plane of the posts of 0.87 ± 0.42 m after 22 m of
328 anterior flight (Table 2). The inclusion of moment coefficients increased the ball
329 angular velocities to unrealistic values when visually compared with the empirical
330 trials and observation of place kicking in match scenarios (coefficient set 6; Tables 1
331 and 2), whilst including side force coefficients for ball flights with low roll velocities
332 resulted in excessive lateral ball displacement (coefficient set 7; Tables 1 and 2).

333 Having identified set 8 as comprising the coefficients which yielded the most
334 accurate prediction of place kick performance, the model incorporating this
335 coefficient set was then validated against additional independent data. The error
336 (0.88 ± 0.40 m) was consistent with that observed during the calibration process –
337 the model was therefore capable of predicting place kick performance with a mean
338 error of 4.0%. This mean error is considerably smaller than that recorded by Tanino
339 and Suito (2009) who simulated rugby kicks (out of hand) with a mean error of 25.8%
340 of the measured anterior displacement of the ball. The greater accuracy in the
341 current study may be due to Tanino and Suito (2009) only considering the spin of the
342 ball about one axis for each kick type (the longitudinal axis for a screw kick, the

343 transverse axis for a high punt kick). As is evident from the current results, and from
344 the sequence of still images presented by Tanino and Suito (2009), the ball typically
345 rotates about multiple axes; inclusion of these degrees of freedom in the initial flight
346 parameters is therefore necessary. The model estimates demonstrated comparable
347 errors in both the lateral and vertical displacements of the ball (mean absolute errors
348 of 0.59 ± 0.47 m and 0.51 ± 0.35 m, respectively; Table 2). This suggests that there
349 was not a specific model input or parameter that was causing greater error in a
350 particular direction. The 4.0% error in the current model is most likely due to the
351 aerodynamic force values being estimates of the true forces experienced in flight,
352 given the accuracy of the input data obtained through repeated digitisations and the
353 ball location when it hit the wall. Whilst the low magnitude of error in the current
354 model supports the overall accuracy of the utilised values from wind-tunnel
355 experiments (Seo et al., 2006; 2007), future experiments could look to apply
356 constrained optimised functions to fit the aerodynamic forces, using information from
357 empirical ball flights, such as those in the current study.

358 The calibrated and validated model was then applied to predict the maximum
359 distance that the kicks of 33 rugby place kicks could successfully be taken from.
360 Previous research has typically determined the success of a place kick based solely
361 on the ball velocity magnitude (e.g. Baktash et al., 2009; Sinclair et al., 2014; Zhang
362 et al., 2012). Ball velocity magnitude does not account for the accuracy of a kick, and
363 our results demonstrate that the rank order of kicks based on their velocity is only
364 moderately associated with the rank order based on the *predicted maximum*
365 *distance* ($\rho = 0.52$; Figure 1) - the different performance measures give a different
366 interpretation of the relative success of a kick. This is an important consideration for
367 researchers and practitioners as it highlights the importance associated with the

368 choice of measure used to assess performance levels, similar to previous findings in
369 other sporting actions such as the sprint start (Bezodis, Trewartha & Salo, 2010).
370 Whilst a high ball velocity can result in a greater *predicted maximum distance*, the
371 ball velocity magnitude only explains 27% of the variance between the two rank
372 orders, supporting our first hypothesis. Other factors such as the direction of the ball
373 velocity vector and the ball spin must account for the remaining variance. This is
374 further illustrated when performance differences between the sub-groups of kicks are
375 considered. Despite no clear difference in ball velocity magnitude between the long
376 and wide-left kicks, the *predicted maximum distance* of the long kicks was
377 substantially greater; this critical real-world difference in performance outcome would
378 be overlooked if solely assessing performance based on ball velocity magnitude.
379 Additionally, there was no clear difference in *predicted maximum distance* between
380 the short and wide-left kicks, but if performance had been determined simply based
381 on ball velocity magnitude, the wide-left kicks would have been considered to be
382 more successful. These findings provide clear examples supporting the need to use
383 a performance measure that represents overall place kick performance, such as the
384 *predicted maximum distance* value developed in this study. The current findings also
385 illustrate the role of factors in addition to the initial ball velocity magnitude; the initial
386 linear velocity direction and the spin imparted on the ball are also important
387 performance-related factors to consider.

388 Our second hypothesis was also supported as although there was no clear
389 difference in resultant ball velocity magnitude between the long and wide-left kicks,
390 there were differences in other linear and angular initial ball kinematics (Figure 2).
391 The wide-left kicks demonstrated substantially greater roll velocity which, combined
392 with an initial ball velocity vector directed towards the left-hand-side, caused the ball

393 to pass outside the left-hand goalpost from a distance of less than 32 m. These
394 results provide some support to the assertion from coaching literature that a curved
395 ball trajectory may not be desirable (Bezodis & Winter, 2014; Greenwood, 2003;
396 Wilkinson, 2005) and highlights potential limitations of studies that have not
397 considered this ball flight characteristic. In addition to their previously described
398 lower resultant ball velocity, the short kicks also possessed a substantially higher ball
399 launch angle compared with the long kicks. The short kicks' launch angle is higher
400 than the optimum launch angle identified for place kicks (32.3°) by Linthorne and
401 Stokes (2014), suggesting that changes in ball launch angle could be a simple
402 performance factor for coaches to first manipulate with kickers who lack distance.
403 The current model could be used to inform this – for example, if the maximum initial
404 ball velocity of a kicker is known, the model inputs could be systematically adjusted
405 to identify the optimum launch angle for a given kicker. Furthermore, the model could
406 also be used to inform coaches of the effect of specific environments that may be
407 experienced during matches. For example, the model indicates that a kick which was
408 just successful from 22 m at -5°C at sea level, would be successful from 2.96 m
409 further away if the same kick was taken at 20°C at 1810 m (the altitude of Ellis Park
410 in Johannesburg) based on alterations to the air density constant.

411 **Conclusion**

412 A ball flight model was developed which was capable of predicting the maximum
413 distance any given place kick could be successful from given its initial flight
414 kinematics. The model was able to locate position in the plane of the posts to within
415 4.0% of the anterior displacement during flight. Differences were found in the rank
416 orders of kicks based on their resultant ball velocity magnitude or the newly
417 proposed *predicted maximum distance* measure, because the ball velocity measure
418 does not account for the accuracy requirement of the task which are clearly an
419 important consideration. When the full flight path of the ball cannot be assessed (e.g.
420 in an indoor/laboratory environment), using the current model to predict the
421 maximum distance provides an ecologically valid assessment of true place kick
422 performance, and one which is readily understandable for players and coaches. The
423 model can also be used by players and applied practitioners to predict the effect of
424 changes to the initial ball flight kinematics on performance outcome, as well as to
425 understand how their performance levels vary in the different environmental
426 conditions that they may encounter.

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Table S1. Initial ball flight kinematics of the three groups (mean \pm SD).

	Long Kicks	Wide-left Kicks	Short Kicks
Predicted maximum distance (m)	39.30 \pm 4.92	25.88 \pm 3.24	27.25 \pm 3.80
Resultant velocity (m/s)	27.6 \pm 1.7	26.9 \pm 1.6	20.8 \pm 2.2
Lateral direction ($^{\circ}$)	1 \pm 3	-1 \pm 2*	2 \pm 3
Launch angle ($^{\circ}$) [†]	31 \pm 3	28 \pm 7	35 \pm 3
Pitch velocity ($^{\circ}$ /s)	2263 \pm 877	2307 \pm 663	2070 \pm 1377
Roll velocity ($^{\circ}$ /s)	288 \pm 206	746 \pm 466	473 \pm 394

* A negative lateral direction indicates that the ball was initially travelling towards the left-hand-side of the goalposts, with a positive value directed towards the right-hand-side. [†] The launch angle represents the direction of the ball flight in the y-z plane.

Table 1. The sets of aerodynamic coefficients included within the model for the calibration process.

Coefficient set	Side force coefficient (Seo et al., 2007)*	Side force coefficient (Seo et al., 2006)*	Drag force coefficient	Lift force coefficient	Pitching moment coefficient	Yaw moment coefficient
1	-	-	-	-	-	-
2	-	-	✓	✓	-	-
3	✓	-	✓	✓	-	-
4	✓	-	✓	✓	-	✓
5	✓	✓	✓	✓	-	✓
6	✓	✓	✓	✓	✓	✓
7	✓	✓	✓	✓	-	-
8	-	✓	✓	✓	-	-

* When both side force coefficients were included in a model version, the coefficient presented by Seo et al. (2007) was applied to those trials where the roll velocity of the ball was less than or equal to 360°/s, whilst the coefficient presented by Seo et al. (2006) was applied to those trials where the roll velocity of the ball was greater than 360°/s.

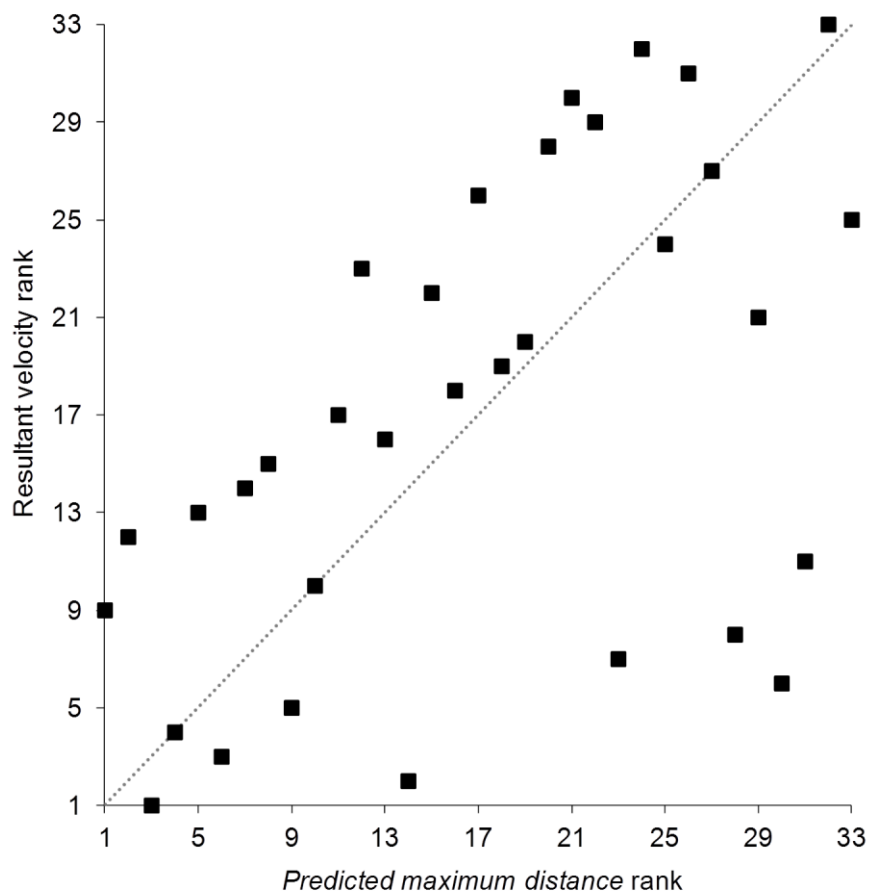
Table 2. Absolute differences between the predicted and true ball positions for each coefficient set included in the ball flight model calibration (all data presented as mean \pm SD).

Coefficient set	Difference in resultant displacement in the plane of the posts (m)	Difference in lateral position in the plane of the posts (m)	Difference in vertical position in the plane of the posts (m)
1	1.59 \pm 0.54	0.95 \pm 0.84	1.06 \pm 0.35
2	1.18 \pm 0.68	0.93 \pm 0.75	0.53 \pm 0.36
3	1.72 \pm 1.06	1.56 \pm 1.08	0.58 \pm 0.40
4	1.39 \pm 0.69	1.15 \pm 0.71	0.60 \pm 0.40
5	1.06 \pm 0.60	0.84 \pm 0.58	0.60 \pm 0.40
6	0.99 \pm 0.50	0.76 \pm 0.54	0.53 \pm 0.37
7	1.47 \pm 1.07	1.29 \pm 1.10	0.59 \pm 0.39
8*	0.87 \pm 0.42	0.59 \pm 0.47	0.51 \pm 0.35

* Model version 8 was identified as providing the most accurate representation of ball flight and therefore, used for all subsequent analyses.

514 **Figure captions**

515 **Figure 1.** The performance rankings of the best kicks of 33 kickers based on their
516 *predicted maximum distance* and the magnitude of their resultant initial ball velocity.
517 A ranking of 1 represents the best performance and 33 the worst. The grey dotted
518 line represents a perfect rank order correlation; those kicks below the line were
519 ranked higher based on their resultant velocity and those above the line were ranked
520 higher on their *predicted maximum distance*.



521

522

523 **Figure 2.** Effect sizes (\pm 90% CI) between initial ball flight kinematics of a) the long
 524 and wide-left kicks, b) the long and short kicks and c) the wide-left and short kicks.
 525 The dashed vertical lines represent a trivial effect (0.0 ± 0.2). Percentages for each
 526 comparison represent the likelihood that the effect is negative | trivial | positive. *A
 527 negative effect represents a lateral ball velocity vector directed more towards the left-
 528 hand-side of the goal whilst a positive effect was more towards the right-hand-side of
 529 the goal.

