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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.

Introduction

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

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

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

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

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

116 where V = ball volume (0.0048 m^3; Seo et al., 2006), ρ = 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):

$$M_{x_{(i)}} = Cm_{x_{(i)}} \cdot \rho \cdot V \cdot 0.5 \cdot \vec{v}^2_{(i-1)} \tag{4}$$

$$M_{y_{(i)}} = Cm_{y_{(i)}} \cdot \rho \cdot V \cdot 0.5 \cdot \vec{v}^2_{(i-1)} \tag{5}$$

124 The pitch and yaw moment coefficients (Cm_x and Cm_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 kg.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 ± 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 ± 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.

Results

Model calibration and validation

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

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

Model application

Using the model containing coefficient set 8, a moderate, positive relationship was observed between the rank orders of the 33 place kicks based on the *predicted maximum distance* and the magnitude of the resultant initial ball velocity ($\rho = 0.52$, 90% CI = 0.27 to 0.71; Figure 1). The 33 kicks were then categorised into distinct groups based on their outcomes. As two of the kicks were within 4.0% (the accuracy of the model as determined during the validation) of the 32 m *predicted maximum 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 ± 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).

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

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

Conclusion

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

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511 **Appendix 1**

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

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

List of tables

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 ± 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 ± 0.54	0.95 ± 0.84	1.06 ± 0.35
2	1.18 ± 0.68	0.93 ± 0.75	0.53 ± 0.36
3	1.72 ± 1.06	1.56 ± 1.08	0.58 ± 0.40
4	1.39 ± 0.69	1.15 ± 0.71	0.60 ± 0.40
5	1.06 ± 0.60	0.84 ± 0.58	0.60 ± 0.40
6	0.99 ± 0.50	0.76 ± 0.54	0.53 ± 0.37
7	1.47 ± 1.07	1.29 ± 1.10	0.59 ± 0.39
8*	0.87 ± 0.42	0.59 ± 0.47	0.51 ± 0.35

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

Figure captions

Figure 1. The performance rankings of the best kicks of 33 kickers based on their

predicted maximum distance and the magnitude of their resultant initial ball velocity.

A ranking of 1 represents the best performance and 33 the worst. The grey dotted

line represents a perfect rank order correlation; those kicks below the line were

ranked higher based on their resultant velocity and those above the line were ranked

higher on their *predicted maximum distance*.
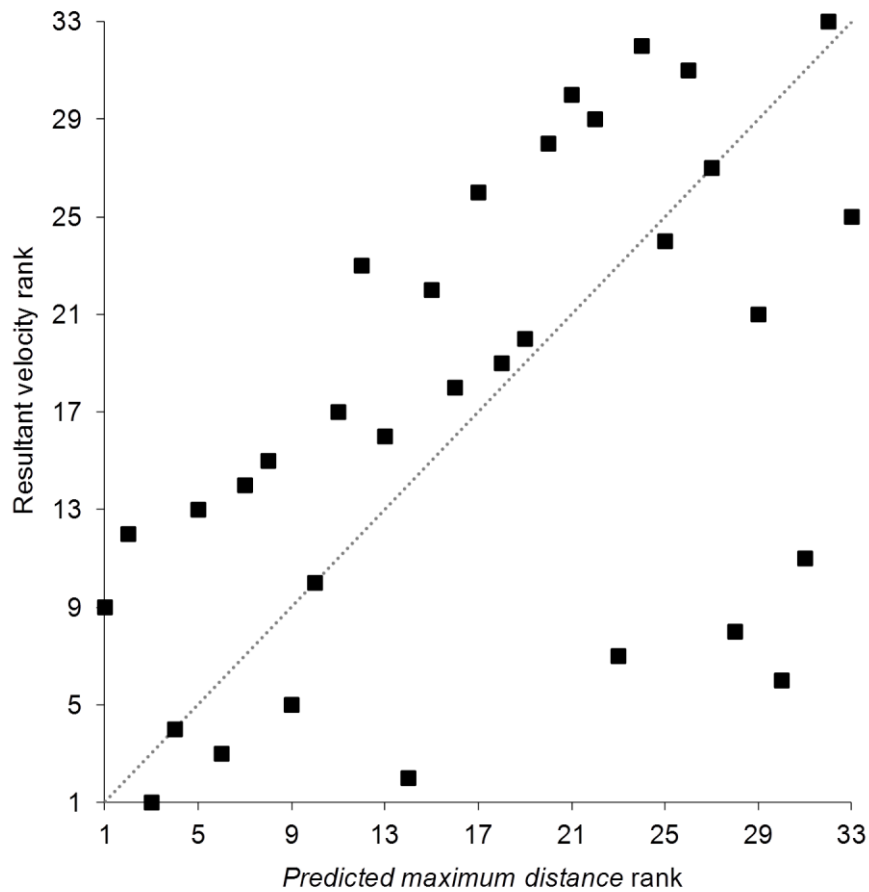
523 **Figure 2.** Effect sizes (± 90% CI) between initial ball flight kinematics of a) the long

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.

530