1   Kicking foot swing planes and support leg kinematics in rugby place kicking: differences

2   between accurate and inaccurate kickers

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5

7   *Abstract*

8   Place kicking is a complex whole-body movement that contributes 45% of the points scored

9   in international Rugby Union. This study compared the kicking foot swing plane

10   characteristics of accurate and inaccurate kickers, underpinned by differences in their

11   support leg and pelvis kinematics at support foot contact, to identify key technique

12   characteristics. Motion capture data (240 Hz) were collected from 33 experienced kickers,

13   and distinct groups of accurate (n = 18) and inaccurate (n = 8) kickers were identified based

14   on their performance characteristics. All accurate kickers were capable of kicking

15   successfully from at least 33.3 m, whereas all inaccurate kickers would have missed left

16   from distances greater than 30.7 m. The accurate group exhibited a moderately shallower

17   swing plane inclination (50.6 ± 4.8° vs. 54.3 ± 2.1°) and directed the plane moderately

18   further to the right of the target (20.2 ± 5.4° vs. 16.7 ± 4.1°). At support foot contact, the

19   accurate group placed their support foot moderately less far behind the ball (0.08 ± 0.08 m

20   vs. 0.12 ± 0.04 m) and positioned their centre of mass moderately further to the support leg

21   side (0.77 ± 0.07 m vs. 0.72 ± 0.01 m) due to a moderately greater stance leg lean (29.3 ±

22   4.1° vs. 26.8 ± 3.2°). The kicking foot swing plane is highly planar in rugby place kicking but

23   its orientation differs between accurate and inaccurate kickers. These plane characteristics

24   may be controlled by support foot placement and support leg and pelvis kinematics at

25   support foot contact.

26

27   *Keywords*

28   3D analysis, biomechanics, coaching, performance, team sport

2

Introduction

30 Place kicking provides a valuable opportunity to score points in Rugby Union (hereafter,

31 rugby) by kicking a stationary ball between two vertical posts which are 5.6 m apart and over

32 a horizontal crossbar which is 3.0 m above the ground. Place kicks accounted for 45% of the

33 total points scored in international rugby matches between 2002 and 2011 (Quarrie &

34 Hopkins, 2015). These kicks must often travel over considerable distances, and maintain a

35 sufficiently accurate trajectory towards the target, in order for the outcome to be successful.

36 The mean (± *SD*) distance and absolute angle (relative to a horizontal line projected from the

37 centre of the upright posts) of the 6,428 place kicks analysed in detail by Quarrie and

38 Hopkins (2015) were 32 m (± 12 m) and 29° (± 17°), respectively. As the average success

39 rate of these kicks (Quarrie & Hopkins, 2015) was 73%, there is clear scope for

40 improvements in place kicking performance, even at the highest level of the game.

41

42 The success of a place kick is directly determined by the three-dimensional linear and

43 angular velocities of the ball at the instant it leaves the kicker's foot (Atack, Trewartha, &

44 Bezodis, 2018). This motion of the ball at its launch is determined by specific aspects of the

45 contact from the kicker's boot (Bull Andersen, Dorge, & Thomsen, 1999), and thus coaches

46 and kickers spend considerable time focussing on various aspects of place kicking technique

47 to improve the outcome of the foot-ball contact. Previous research has therefore investigated

48 rugby place kick ball launch characteristics using a combination of empirical and theoretical

49 methods (Atack et al., 2018; Holmes, Jones, Harland, & Petzing, 2006; Linthorne & Stokes,

50 2014; Seo, Kobayashi, & Murakami, 2006), and with mechanical simulators (Minnaar & van

51 den Heever, 2015). Other studies have focussed on specific aspects of kickers' techniques

52 which might influence the ball launch characteristics, such as the approach towards the ball

53 and support foot positioning (Baktash, Hy, Muir, Walton, & Zhang, 2009; Cockcroft & van

54 den Heever, 2016; Padulo, Granatelli, Ruscello, & D'Ottavio, 2013), kicking leg joint

55 kinematics (Ball, Talbert, & Taylor, 2013; Sinclair et al., 2014; 2017; Zhang, Liu, & Xie, 2012)

56 and trunk and arm motions (Ball et al., 2013; Bezodis, Trewartha, Wilson, & Irwin, 2007;

57   Green, Kerr, Olivier, Dafkin, & McKinon, 2016). In some instances, the above variables were

58   compared between kicks with a primary focus on either distance or accuracy (Bezodis et al.,

59   2007; Sinclair et al., 2017), or distance and accuracy were treated as separate dependent

60   variables against which specific aspects of technique were related (Green et al., 2016).

61   Furthermore, whilst some of the aforementioned studies have reported the magnitude of the

62   kicking foot velocity at initial ball contact, and many of the variables they have described will

63   partly contribute to the kicking foot trajectory, none have directly investigated the path of the

64   kicking foot - the distal endpoint of a linked-segment system - prior to ball contact.

65

66   In other ballistic striking actions such as a golf swing, the motion of the distal endpoint (i.e.

67   the clubhead) has been shown to be planar from the mid-downswing onwards (Kwon, Como,

68   Singhal, Lee, & Han, 2012; Morrison, McGrath, & Wallace, 2014; 2018). Specific properties

69   of this plane have been investigated such as its orientation with respect to the global axes

70   which are aligned with the intended target (e.g. Kwon et al., 2012; Morrison et al., 2014;

71   2018; Takagi, Yokozawa, Inaba, Matsuda, & Shiraki, 2017; Williams & Sih, 2002). These

72   plane orientations have been found to differ between golfers of different skill-levels (Morrison

73   et al., 2018) as well as to be related to certain clubhead kinematic parameters at impact,

74   such as clubhead angles and velocities (Williams & Sih, 2002; Takagi et al., 2017), that

75   ultimately affect the performance outcome of the shot.

76

77   Other ballistic sporting movements have also been demonstrated to exhibit planar endpoint

78   motion, such as the stick face during the final 83% of the downswing during a field hockey hit

79   (Willmott & Dapena, 2012) and the kicking foot during the final 1.25 m of the downswing

80   prior to ball contact during a rugby place kick (Bezodis, Willmott, Atack, & Trewartha, 2014).

81   However, these studies have not considered how the properties of these swing planes might

82   relate to performance outcome factors. In a study of soccer kicking, Alcock, Gilleard, Hunter,

83   Baker and Brown (2012) found that the orientations of swing planes fitted to the kicking hip,

84   knee and ankle joint centre coordinates from support foot contact to ball contact differed

85   between curve and instep kicks. However, Alcock et al. (2012) did not quantify the planarity

86   of this motion and it has been shown in golf that, unlike just the distal endpoint, multiple

87   points within a linked-segment system (e.g. shoulder girdle, arm, club shaft, clubhead) do

88   not move in a consistent, single plane (Coleman & Rankin, 2005).

89

90   Based on the importance of the swing plane in golf and potentially in other striking actions,

91   the properties of the kicking foot swing plane have been proposed as an important

92   consideration for accurate rugby place kicking (Ball et al., 2013; Bezodis, Winter, & Atack,

93   2018). However, despite these suggestions, the potential role of the kicking foot swing plane

94   in accurate rugby place kicking has not been empirically investigated. It is also important to

95   consider the role that support leg kinematics at support foot contact may play in helping to

96   determine the orientation of the kicking foot swing plane. The kicking foot path is affected by

97   support foot placement given the linked-segment nature of the human body, and kicking foot

98   kinematics at ball contact have been shown to be strongly related to support leg kinematics

99   at the instant of support foot contact in punt kicking (Ball, 2013). The primary aim of this

100   study was therefore to investigate how the properties of the kicking foot swing plane differ

101   between accurate and inaccurate kickers. A second aim was to investigate differences in the

102   support leg and pelvis kinematics at support foot contact between the groups to identify

103   potential strategies for how the swing plane, and ultimately place kick accuracy, can be

104   controlled.

105

106

107   *Methods*

108   Thirty-three male place kickers (mean ± *SD*: age = 22 ± 4 years; mass = 86.2 ± 8.8 kg;

109   height = 1.82 ± 0.06 m) who were free from injury and playing at levels ranging from amateur

110   to senior international provided written informed consent to participate. All procedures were

111   approved by the local research ethics committee prior to any testing. Data collection took

112   place in an indoor laboratory with kickers wearing their own moulded-rubber boots and using

113 their personal kicking tee and a Gilbert Virtuo matchball. Seventy-four 25 mm spherical

114 markers were used to define a 14-segment rigid-body model of each kicker using a CAST

115 approach (Cappozzo, Catani, Della Croce, & Leardini, 1995), with 54 markers retained to

116 track full body motion during the kicking trials (see Bezodis et al. 2018 for illustration of

117 marker locations). Following their typical self-directed kicking warm-up, each kicker

118 completed a series of familiarisation kicks until they were comfortable with the environment.

119 They then performed a minimum of seven place kicks, as if from their maximum range,

120 aiming towards a vertical target which represented the centre of the posts and was

121 suspended 2 m from the kicking tee in front of a net.

122

123 During all kicking trials, a 10- or 11-camera motion capture system (MX, Vicon, UK) was

124 used to track the markers at 240 Hz. Flat markers were also attached to the ball in the centre

125 of each panel (n = 4) and towards one end of the ball (n = 2) to enable its geometric centre

126 to be determined and its three-dimensional translation and rotation to be tracked (Atack et

127 al., 2018). Ground reaction forces (GRFs) were recorded at 960 Hz from under the support

128 foot using a force platform (9287BA, Kistler, Switzerland) which was covered so as to be

129 flush with the surrounding floor. The motion capture and force platform data were

130 synchronously collected (Nexus v.1.8., Vicon, UK) and their co-ordinate systems were

131 aligned such that the y-axis was horizontal and in the direction of the target from the kicking

132 tee, the z-axis was vertical, and the x-axis was the cross-product of the y- and z-axes.

133 Marker trajectories were labelled and the raw marker and GRF data were exported as .c3d

134 files for analysis in Visual3D (v.5.1., C-Motion, USA) and Matlab (v.7.12., MathWorks, USA).

135

136 Initial ball contact and the first frame of ball flight were identified using the procedures of

137 Shinkai, Nunome, Isokawa and Ikegami (2009). The initial ball flight kinematics were

138 determined and input in to a model of rugby ball flight to predict the maximum successful

139 distance that each kick could be taken from, assuming it was kicked from directly in front of

140 the posts (Atack et al., 2018). Each kicker's best kick (i.e. greatest predicted maximum

6

141 successful distance) was identified, and groups were determined based on the predicted

142 maximum successful distance and eventual reason for failure (i.e. miss left, miss right, fall

143 short) of each kick (Figure 1). A threshold of 32 m (the average kick distance in international

144 rugby; Quarrie & Hopkins, 2015) ± 1.3 m (the reported ball flight model error; Atack et al.,

145 2018) was initially used to divide the kicks, with those below the lower threshold sub-divided

146 based on their eventual reason for failure (Figure 1). The accurate group comprised 18

147 kicks, all of which had a predicted maximum successful distance greater than 33.3 m. The

148 inaccurate group comprised eight kicks, all of which had a predicted maximum successful

149 distance less than 30.7 m because the kick would have missed to the left of the posts from

150 any greater distance (but importantly these kicks did not lack 'range', i.e. they were still

151 above the height of the crossbar at this point).

152

153 ****Figure 1 near here****

154

155 To analyse each kicker's kinematics, all marker co-ordinates from the corresponding trial

156 were firstly expressed relative to the position of the ball centre when resting on the tee, and

157 global x-axis co-ordinates for left-footed kickers were inverted. The kicking foot centre of

158 mass (CM) location was determined (Winter, 2005) and its raw trajectory was resampled at

159 equal (0.01 m) spatial intervals (Willmott & Dapena, 2012) using an interpolating cubic

160 spline, ending at initial ball contact. This resampling was necessary due to the increasing

161 velocity of the foot CM during the downswing, meaning that using equal temporal intervals

162 would have biased the fit more towards the earlier part of the downswing. The start point of

163 the trajectory was identified at a total path distance prior to ball contact equal to 125% of leg

164 length, because the kicking foot swing plane is planar for up to 1.25 m pre-contact in rugby

165 place kicking (Bezodis et al., 2014) and the mean ± *SD* leg length of the 26 retained kickers

166 was 0.96 ± 0.04 m. A least-squares plane was then fitted to this trajectory using orthogonal

167 distance regression (Willmott & Dapena, 2012). The *direction* of each kicker's swing plane

168 was determined as the angle between the global y-axis (aligned with the horizontal direction

169   of the centre of the target from the centre of the kicking tee) and the line of intersection of the

170   swing plane with the global x-y (horizontal) plane (Figure 3b). Swing plane *inclination* was

171   determined as the angle between the global x-axis and the line of intersection of the swing

172   plane with the global x-z plane (Figure 3a). The root mean square (RMS) residual between

173   the raw kicking foot CM path and the fitted swing plane was determined to quantify the

174   *planarity* as the goodness of fit of the plane to the actual kicking foot trajectory (Figure 3c).

175

176   All marker co-ordinates were then low-pass filtered at 18 Hz (Butterworth 4th-order) based on

177   a residual analysis (Winter, 2005) and segmental kinematics were reconstructed using an

178   evenly-weighted inverse kinematics procedure (Lu & O'Connor, 1999). Whole-body CM

179   location was calculated (de Leva, 1996) and the orientations of stance leg and pelvis

180   segments about each global axis were determined using XYZ Cardan rotations (Lees,

181   Barton, & Robinson, 2010). Support foot contact was identified when the vertical GRF first

182   exceeded 10 N and kinematic variables of interest (Figure 4) were extracted at this instant to

183   address the second stated aim of this study.

184

185   Each group's mean ± *SD* values were calculated for all dependent variables, and effect sizes

186   (Cohen, 1988) were then calculated to assess the magnitude of the difference between the

187   groups. 90% confidence intervals for these effect sizes were calculated and magnitude-

188   based inferences were derived based on a threshold of 0.2 as a practically important effect

189   (Hopkins, Marshall, Batterham, & Hanin, 2009; Winter, Abt, & Nevill, 2014), enabling

190   calculation of the percentage likelihood of any difference being positive, trivial or negative. In

191   all subsequent descriptions, only variables where the confidence intervals did not span

192   across effect sizes of both -0.2 and +0.2 are considered different between the two groups

193   (all other comparisons were considered to be unclear effects). The magnitudes of the

194   differences are described based on the thresholds proposed by Hopkins et al. (2009) of 0.2,

195   0.6, 1.2 and 2.0 for small, moderate, large and very large mean effect sizes, respectively.

196

197

Results

199 The groups were defined based on their predicted maximum successful kick distance; the

200 difference in this critical performance outcome between the two groups was large (mean

201 difference = 13.4 m, d = 1.6; Figure 2). The inaccurate group would have missed to the left

202 of the posts because moderately more longitudinal spin (anticlockwise from above) (mean

203 difference = 8.0 rad·s^{-1}, d = -1.1; Figure 2) was imparted on the ball and the launch direction

204 was already to the left of the target (mean difference = 2°, d = 0.5; Figure 2). There was no

205 clear difference in resultant ball velocity magnitude or end-over-end spin between the groups

206 (Figure 2). The mean ± *SD* mass of the kickers in the accurate and inaccurate groups were

207 87.0 ± 6.8 kg and 88.9 ± 12.7 kg, respectively, whilst their respective heights were 1.82 ±

208 0.05 m and 1.82 ± 0.09 m. There were no clear differences in either mass or height between

209 the groups (mass: d = 0.19 ± 0.64, height: d = 0.03 ± 0.61).

210

211 ****Figure 2 near here****

212

213 There were moderate differences in the swing plane inclination and direction between the

214 groups (Figure 3). The accurate group exhibited a shallower swing plane inclination (by 3.7°,

215 d = -0.8) than the inaccurate group (Figure 3a), and directed their plane further to the right of

216 the target (by 3.5°, d = 0.6; Figure 3b). There was no clear difference in the planarity of the

217 kicking foot trajectory, based on the RMS residuals, between the two groups (Figure 3c).

218

219 ****Figure 3 near here****

220

221 There was no clear difference between the groups in the resultant distance between the

222 support foot CM and the ball centre in the horizontal plane at support foot contact. However,

223 the accurate group placed their support foot moderately less far behind the ball (mean

224 difference = 0.04 m, d = -0.6) in the antero-posterior direction (Figure 4). There was also no

225 clear difference in the resultant distance between the whole-body CM and the ball centre in

226 the horizontal plane at support foot contact between the groups, but the accurate group

227 positioned their CM moderately further to the left of the ball (viewed from behind; mean =

228 0.05 m, d = 0.9) in the medio-lateral direction (Figure 4). There was no clear difference in

229 medio-lateral foot placement so this more lateral CM positioning was due to a greater

230 support leg lateral lean, evident in the moderate difference (mean = 2.5°, d = 0.6) in the

231 support leg shank angle about the global y-axis between the two groups (Figure 4). With

232 regards to the pelvis, the accurate group exhibited moderately less anterior tilt (mean

233 difference = 3.3°, d = 0.9) and a lateral tilt that was moderately lower on the support-leg side

234 compared with the inaccurate group (mean difference = 4.5°, d = 0.8; Figure 4).

235

236 ****Figure 4 near here****

237

238

239 *Discussion*

240 We aimed to investigate differences in the kicking foot swing plane characteristics between

241 accurate and inaccurate groups of rugby place kickers, and to identify how different support

242 leg and pelvis kinematics might help to explain these differences in kicking foot trajectories

243 and ultimately in place kick performance outcome. Both groups achieved higher mean ball

244 velocities than kickers in previous studies of maximal effort place kicking with an inherent

245 accuracy requirement at university (Bezodis et al., 2007; Sinclair et al., 2014; Zhang et al.,

246 2012), semi-professional (Linthorne & Stokes, 2014), and professional (Holmes et al., 2006;

247 Padulo et al., 2013) levels. However, the inaccurate group would have missed to the left of

248 the target from substantially shorter kick distances due to a combination of the medio-lateral

249 direction of the initial velocity vector and the longitudinal spin imparted on the ball (Figure 2).

250 To contextualise this, at the mean distance of 25.9 m when the inaccurate group would have

251 missed to the left of the target (assuming kicks were taken from directly in front of the posts),

252 the ball would still have been at a mean height of 10.8 m, considerably higher than the

253 crossbar (3.0 m). It was therefore the accuracy of these kicks, rather than their range, which

254 limited performance.

255

256 The kicking foot trajectories of both groups were highly planar in nature. The RMS residuals

257 between the plane and the raw kicking foot trajectories were approximately 2 mm for both

258 groups (Figure 3c). Although comparable residual data are not available from other kicking

259 tasks, these residuals are similar to those observed between the stick face and swing plane

260 over similar trajectory lengths during a field hockey hit (Willmott & Dapena, 2012). The

261 planarity of the kicking foot trajectories (i.e. RMS difference <0.2% of the analysed kicking

262 foot trajectory length) suggests that late adjustments are not made to the foot path, and

263 justifies the quantification of the kicking foot trajectories using a swing plane approach in the

264 current study. Swing plane inclinations and directions relative to the global axes (which were

265 aligned with the kicking target) can therefore be investigated with confidence to identify

266 gross differences in kicking foot trajectories between the accurate and inaccurate groups.

267

268 The inaccurate group exhibited swing planes which were inclined more vertically (i.e.

269 steeper) and less far to the right of the target than those of the accurate group (Figure 3).

270 One possible explanation for the difference in plane inclination is evident in the results of the

271 only other published study which has investigated swing planes in kicking. Alcock et al.

272 (2012) observed the kicking leg swing plane to be nearly 9° steeper in curve kicks compared

273 with instep kicks in soccer, and ball spin was almost twice as great in the curve kicks than in

274 the instep kicks. As the kickers studied by Alcock et al. (2012) were intentionally trying to

275 impart spin on the ball in order to achieve the desired outcome of the curve kicks, the

276 adoption of a steeper plane may have been a technique adjustment which facilitated their

277 ability to impart spin on the ball. Combining these findings (Alcock et al., 2012) with the fact

278 that the inaccurate group in the current study imparted over 2.5 times more longitudinal spin

279 on the ball than the accurate group (Figure 2), future applied investigations should seek to

280   determine whether adoption of a shallower swing plane could lead to a reduction in the spin

281   imparted on the ball by kickers who have a tendency to miss the target to the left.

282

283   The fact that the accurate group directed their swing plane further to the right of the target

284   than the inaccurate group was likely a compensation for their less inclined plane (Figure 3).

285   The kicking foot is moving upwards during the ball contact phase of a place kick (average

286   vertical velocity from first to final frame of ball contact = 3.87 ± 1.43 $m \cdot s^{-1}$ and 3.73 ± 0.64

287    $m \cdot s^{-1}$ for the accurate and inaccurate groups, respectively), and thus the kicking foot will be

288   travelling to the left of the swing plane direction in the horizontal plane. The actual foot path

289   direction during ball contact is therefore less far to the right of the target than the direction of

290   the swing plane; both groups exhibited an average foot direction of 10 ± 4° during ball

291   contact and ended with their foot travelling in a direction slightly to the left of the target line in

292   the final frame of ball contact prior to ball flight (-2 ± 5° and -1 ± 5° for the accurate

293   inaccurate groups, respectively). This suggests that both groups exhibit comparable lateral

294   foot motion during ball contact, but that they progress their foot towards ball contact in a

295   different way. Given their less inclined plane, the accurate group have to direct their swing

296   plane further to the right to achieve this comparable foot direction during ball contact. Whilst

297   this may simply be a function of the aforementioned desire to adopt a less inclined plane to

298   limit longitudinal spin, it may also enable the accurate group to achieve different kicking foot

299   kinematics through the ball contact.

300

301   The inclination and direction of the kicking foot swing plane are partly controlled by the

302   support leg kinematics, as the support foot placement locates the kicker in the global space

303   relative to the ball. Furthermore, support leg kinematics at support foot contact have been

304   shown to be related to kicking foot kinematics in punt kicking (Ball, 2013). As the medio-

305   lateral foot placement did not differ between the groups, the difference in swing plane

306   inclination between the two groups appears to be controlled by the lean of the support leg

307   shank about the global y-axis and an associated lateral tilt of the pelvis so that it is typically

12

308   lower on the support leg side for the accurate kickers (Figure 4). Both of these motions

309   assisted in positioning the accurate group's whole body CM further to the left of the ball at

310   support foot contact compared with the inaccurate group (Figure 4), meaning that their

311   kicking foot had to travel in a shallower plane towards the ball. The accurate group's

312   placement of the support foot less far behind the ball (Figure 4) may also assist with their

313   kicking foot swing plane being directed further to the right of the target without them having

314   to reach too far in front of the support leg to strike the ball. Despite this placement of the

315   support foot closer to the ball in the antero-posterior direction by the accurate group, there

316   was no clear difference in the antero-posterior position of the whole body CM relative to the

317   ball at support foot contact between the groups. The accurate group controlled their antero-

318   posterior CM position by leaning their support shank slightly posteriorly about the global x-

319   axis and by exhibiting less anterior pelvic tilt than the inaccurate group (Figure 4).

320

321   Based on the current findings, coaches working with kickers who have a tendency to miss to

322   the left of the target, rather than being restricted by range, may wish to encourage their

323   kickers to adopt shallower kicking foot swing planes. In an attempt to achieve this, practice

324   environments which encourage greater sideways lean away from the ball in the support leg

325   should be explored, potentially through the use of physical constraints on the right-hand-side

326   of the (right-footed) kicker which prevent them from maintaining too upright a body position

327   during the kicking action. Coaches should also ensure that these kickers direct their swing

328   plane sufficiently far to the right of the target. This could potentially be achieved by

329   encouraging kickers to land with their support foot closer to the ball (anteriorly), but coaches

330   must be cognisant of the need to ensure that the stance leg and pelvis compensate

331   accordingly and that the kicker maintains the antero-posterior distance between their CM

332   and the ball at support foot contact. One strategy to encourage such a manipulation could be

333   through exploring ways to increase the length of the final approach step, as there was a

334   large difference in final step length between the accurate (1.69 ± 0.13 m) and inaccurate

335   (1.51 ± 0.11 m, d = 1.4) groups, and a longer final step length has also been shown to be

13

336   moderately (r = 0.41) associated with greater kick distance in accurate punt kicking (Ball,

337   2008).

338

339   Our study analysed a comparatively large cohort of experienced place kickers and was

340   therefore able to identify two adequately-sized groups with performance outcomes that were

341   distinctly different between-group, but homogeneous within-group. We believe that our

342   analysis has inherently considered the kickers by skill level, rather than grouping them by

343   playing level. The outcome of a place kick is a direct measure of place kicking skill, and

344   players who play at a higher level are not necessarily better kickers than those at lower

345   playing levels given the importance of numerous other technical aspects of the game (e.g. a

346   player at a lower level may be an excellent place kicker but have very poor tackling and

347   passing abilities and thus would not be successful playing at a higher level, in spite of being

348   an excellent kicker). Importantly, both groups were capable of achieving high ball velocities,

349   but only the accurate group were also able to kick straight over long distances. This

350   ecologically valid consideration of performance outcome enabled us to analyse three-

351   dimensional kinematic aspects of technique with high internal validity in a laboratory setting.

352   Our laboratory environment also meant that all kicks were taken as if from each kicker's

353   maximum range, whereas in reality kicks are taken from a variety of pitch locations during a

354   match. Whilst we are confident that our data are representative of their true techniques as

355   kickers are typically coached to execute kicks in a consistent manner irrespective of pitch

356   location, it is known that task constraints (e.g. distance and angle to posts) and contextual

357   factors (e.g. scoreline, time remaining) can influence place kicking success rates (Pocock,

358   Bezodis, Davids, & North, 2018; Quarrie & Hopkins, 2015) and future research could

359   investigate the effects of these factors on swing plane properties and other features of

360   technique. By fitting planes to their kicking foot trajectories and analysing how these were

361   controlled by support leg kinematics, we were able to identify certain technique strategies

362   which appeared to distinguish the accurate group from the inaccurate group. Future

363   experimental studies should use acute applied interventions designed to manipulate the

364 technical features discussed in the current study, and to determine their effect on swing

365 plane characteristics, ball launch kinematics, and ultimately performance outcome.

366

367 The kicking foot swing plane is highly planar in rugby place kicking but its orientation differs

368 between accurate and inaccurate groups of kickers, both of whom were capable of achieving

369 comparably high ball velocity magnitudes. The accurate group exhibited a shallower swing

370 plane which was directed further to the right of the target than the inaccurate group. These

371 plane characteristics may be controlled by support foot placement and support leg and pelvis

372 kinematics at support foot contact.

373

377

378 *Disclosure Statement*

379 None of the authors have any financial interest in, or benefit arising from, the direct

380 application of this research.

381

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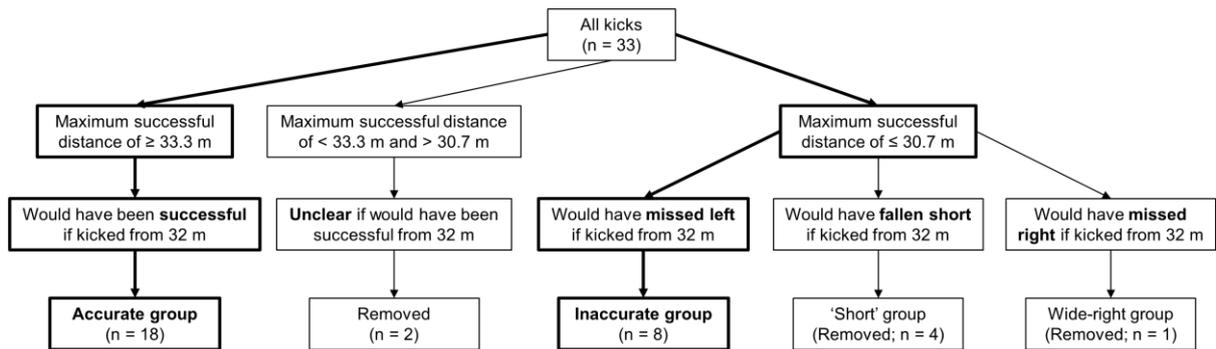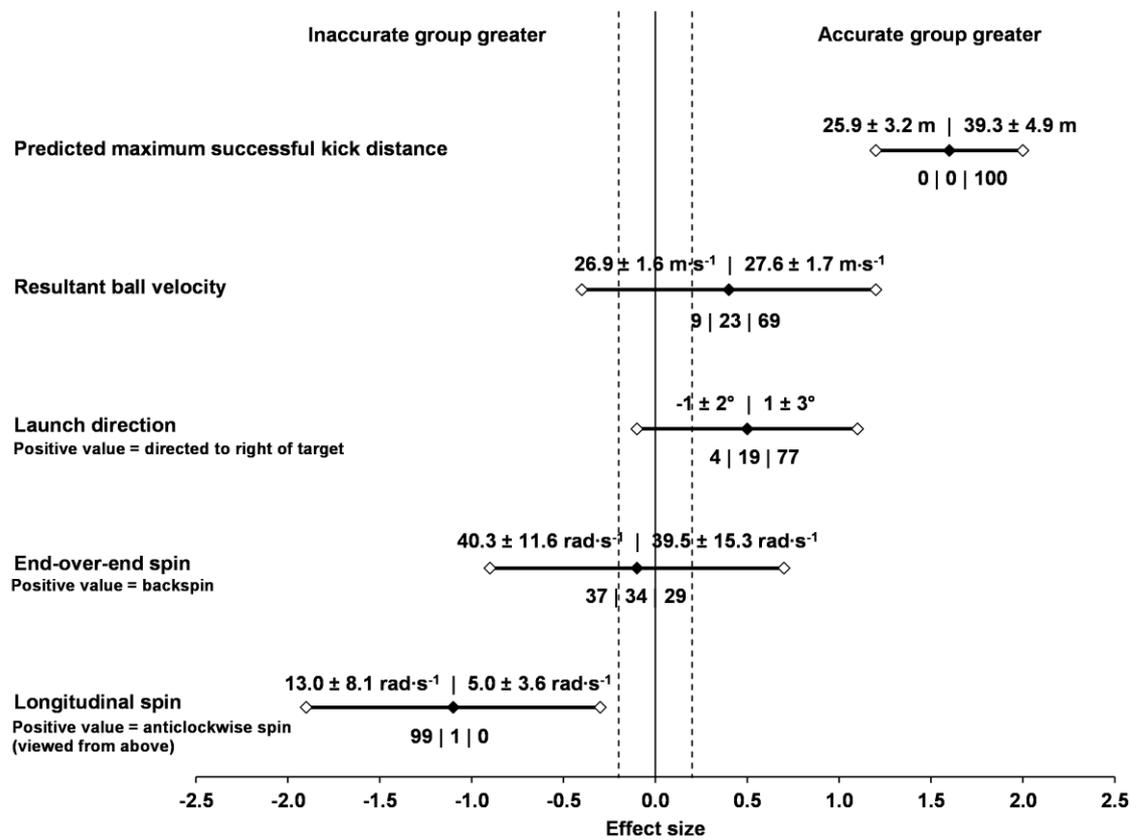
Figures

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518

519   Figure 1. Illustration of the categorisation of kicks based on their predicted maximum

520   successful distance and their eventual reason for failure. A distance of 32 m (the average

521   kick distance in international rugby (Quarrie and Hopkins, 2015) ± 4.0% (1.3 m; the reported

522   model error; Atack et al., 2018) yielded the threshold limits of 33.3 m and 30.7 m. The

523   accurate group contains only kicks with a predicted maximum successful distance ≥ 33.3 m.

524   The inaccurate group contains only kicks with a predicted maximum successful distance ≤

525   30.7 m because they would have missed to the left of the posts from any greater distance.

526   Of the remaining kicks, two were removed because they lay within the threshold limits (i.e. a

527   predicted maximum successful distance between 30.7 m and 33.3 m), four were removed

528   because they would have fallen short from a range of 30.7 m (i.e. they were not limited by

529   inaccuracy), and one kick was removed as it had a predicted maximum successful distance

530   ≤ 30.7 m but missed to the right of the posts and was thus not comparable to the other

531   inaccurate kicks (nor sufficient in number to include as a second inaccurate group).
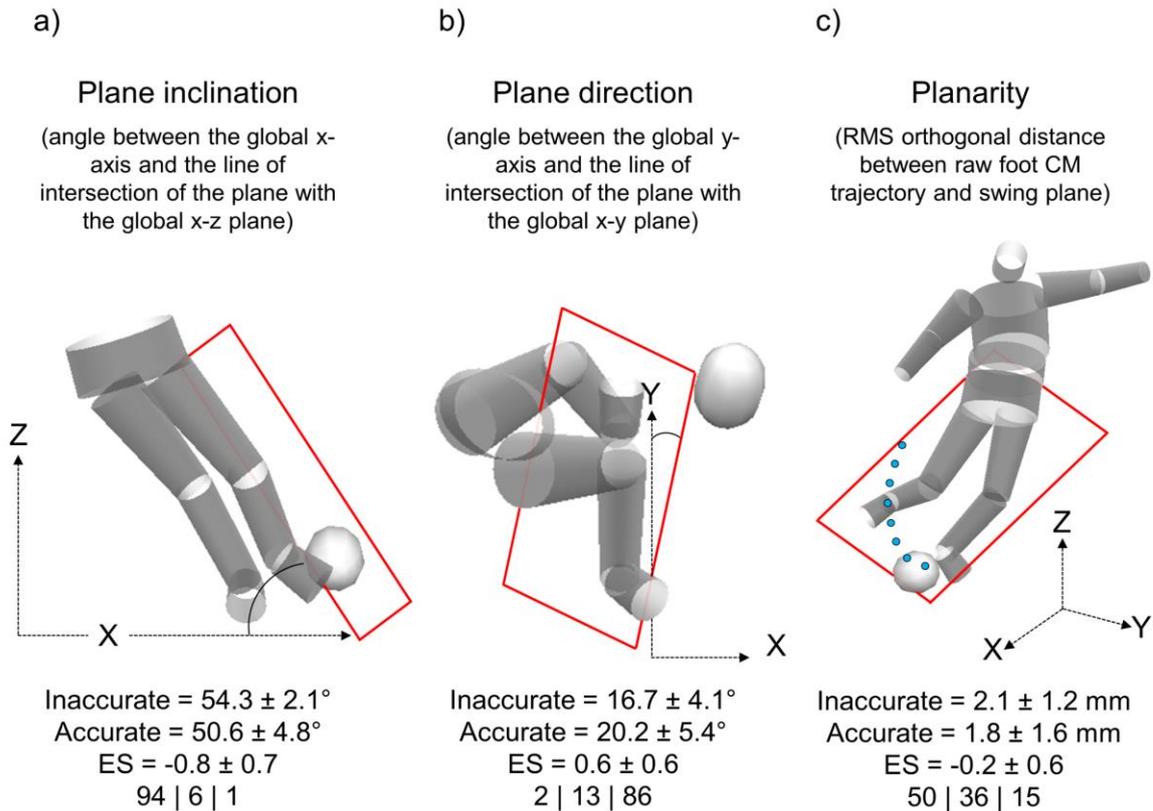
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Figure 2. Comparison of performance and ball flight characteristics between the inaccurate and accurate groups. Black diamonds represent the effect size (Cohen's *d*; inaccurate group as the reference category) with error bars (capped by white diamonds) indicating the 90% confidence limits. The mean ± *SD* group values for the inaccurate | accurate groups are presented above each bar and the percentage likelihood of the inaccurate group being greater | trivial difference | accurate group being greater (based on a smallest worthwhile effect of 0.2; dashed vertical lines) are presented below each bar.

a) **Plane inclination**
(angle between the global x-axis and the line of intersection of the plane with the global x-z plane)

b) **Plane direction**
(angle between the global y-axis and the line of intersection of the plane with the global x-y plane)

c) **Planarity**
(RMS orthogonal distance between raw foot CM trajectory and swing plane)

Inaccurate = 54.3 ± 2.1°
Accurate = 50.6 ± 4.8°
ES = -0.8 ± 0.7
94 | 6 | 1

Inaccurate = 16.7 ± 4.1°
Accurate = 20.2 ± 5.4°
ES = 0.6 ± 0.6
2 | 13 | 86

Inaccurate = 2.1 ± 1.2 mm
Accurate = 1.8 ± 1.6 mm
ES = -0.2 ± 0.6
50 | 36 | 15

543

544

545 Figure 3. The mean ± *SD* swing plane (illustrated in red) a) inclination, b) direction and c)

546 planarity, i.e. root mean square (RMS) residual between the plane and the raw kicking foot

547 CM trajectory, for the inaccurate and accurate groups. The values on the bottom row

548 quantify the percentage likelihood of the inaccurate group being greater | trivial difference |

549 accurate group being greater (based on a smallest worthwhile effect of 0.2). ES = effect size

550 (Cohen's *d*). For visual purposes, only the lower body is presented in figures a and b.

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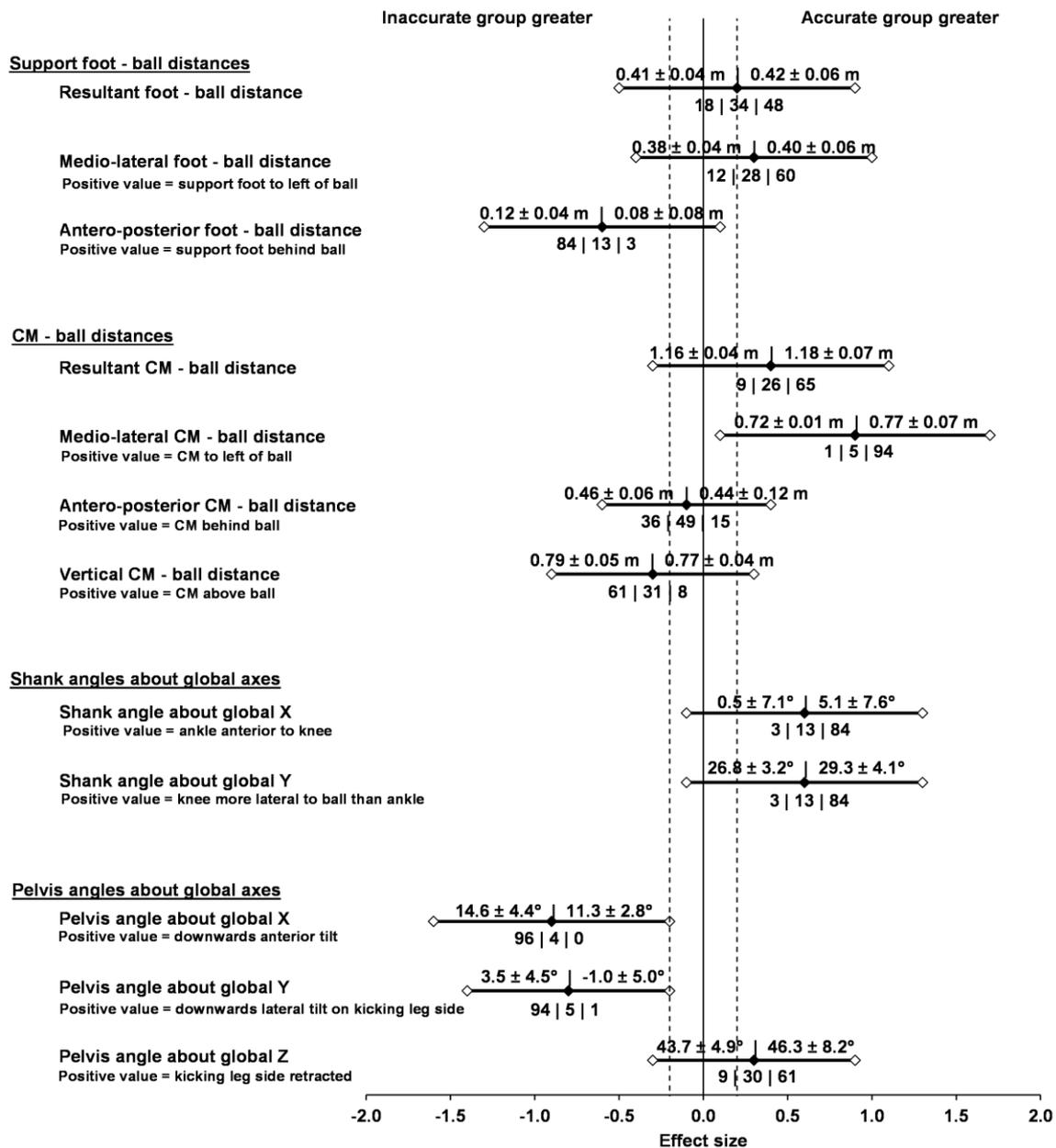
Figure 4. Comparison of support leg and pelvis kinematics between the inaccurate and accurate groups. Black diamonds represent the effect size (Cohen's *d*; inaccurate group as the reference category) with error bars (capped by white diamonds) indicating the 90% confidence limits. The mean ± *SD* group values for the inaccurate | accurate groups are presented above each bar and the percentage likelihood of the inaccurate group being greater | trivial difference | accurate group being greater (based on a smallest worthwhile effect of 0.2; dashed vertical lines) are presented below each bar. CM = centre of mass.