

- 1 Kicking foot swing planes and support leg kinematics in rugby place kicking: differences
- 2 between accurate and inaccurate kickers
- 3
- 4 Neil E. Bezodis, Alexandra Atack, Alexander P. Willmott, Jon E. B. Callard, Grant Trewartha
- 5
- 6 European Journal of Sport Science (accepted 22/08/2018)

This is an Accepted Manuscript of an article published by Taylor & Francis Group in European Journal of Sport Science on 15/09/2018, available online: <https://www.tandfonline.com/doi/full/10.1080/17461391.2018.1519039>

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 ($50.6 \pm 4.8^\circ$ vs. $54.3 \pm 2.1^\circ$) and directed the plane moderately
18 further to the right of the target ($20.2 \pm 5.4^\circ$ vs. $16.7 \pm 4.1^\circ$). 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 ($29.3 \pm$
22 4.1° vs. $26.8 \pm 3.2^\circ$). 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

29 *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 (\pm *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 (\pm 12 m) and 29° (\pm 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, & McKinnon, 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 \pm SD: age = 22 \pm 4 years; mass = 86.2 \pm 8.8 kg;
109 height = 1.82 \pm 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

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) \pm 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 \pm 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 \pm *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

198 *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 = $8.0 \text{ rad}\cdot\text{s}^{-1}$, $d = -1.1$; 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 \pm SD mass of the kickers in the accurate and inaccurate groups were
207 $87.0 \pm 6.8 \text{ kg}$ and $88.9 \pm 12.7 \text{ kg}$, respectively, whilst their respective heights were $1.82 \pm$
208 0.05 m and $1.82 \pm 0.09 \text{ m}$. There were no clear differences in either mass or height between
209 the groups (mass: $d = 0.19 \pm 0.64$, height: $d = 0.03 \pm 0.61$).

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 = $3.87 \pm 1.43 \text{ m}\cdot\text{s}^{-1}$ and 3.73 ± 0.64
287 $\text{m}\cdot\text{s}^{-1}$ 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 $10 \pm 4^\circ$ 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 ($-2 \pm 5^\circ$ and $-1 \pm 5^\circ$ 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

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

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

374 *Acknowledgements*

375 The authors are grateful to Mr Jack Lineham for his technical assistance throughout all data
376 collections.

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

382 *References*

383

384 Alcock, A. M., Gilleard, W., Hunter, A. B., Baker, J., & Brown, N. (2012). Curve and instep
385 kick kinematics in elite female footballers. *Journal of Sports Sciences*, 30(4), 387-394.

386

387 Atack, A., Trewartha, G., & Bezodis, N.E. (2018). Assessing rugby place kick performance
388 from initial ball flight kinematics: development, validation and application of a new measure.
389 *Sports Biomechanics*, ahead of print. doi: 10.1080/14763141.2018.1433714

390

391 Baktash, S., Hy, A., Muir, S., Walton, T., & Zhang, Y. (2009). The effects of different instep
392 foot positions on ball velocity in place kicking. *International Journal of Sports Sciences and*
393 *Engineering*, 3, 85-92.

394

395 Ball, K. A. (2013). Loading and performance of the support leg in kicking. *Journal of Science*
396 *and Medicine in Sport*, 16, 455-459.

397

398 Ball, K. A. (2008). Biomechanical considerations of distance kicking in Australian Rules
399 football. *Sports Biomechanics*, 7, 10-23.

400

401 Ball, K. A., Talbert, D., & Taylor, S. (2013). Biomechanics of goal-kicking in rugby league. In
402 H. Nunome, B. Drust & B. Dawson (Eds.), *Science and Football VII* (pp. 47-53), Abingdon,
403 UK: Routledge.

404

405 Bezodis, N. E., Trewartha, G., Wilson, C., & Irwin, G. (2007). Contributions of the non-
406 kicking-side arm to rugby place-kicking technique. *Sports Biomechanics*, 6, 171-186.

407

408 Bezodis, N. E., Willmott, A. P., Atack, A., & Trewartha, G. (2014). The kicking foot swing
409 plane in rugby place kicking. *International Society of Biomechanics in Sports Conference*

410 *Proceedings*, 32, 304-307. Retrieved from <https://ojs.ub.uni->
411 [konstanz.de/cpa/article/view/5999/5480](https://ojs.ub.uni-konstanz.de/cpa/article/view/5999/5480).
412
413 Bezodis, N., Winter, S., & Attack, A. (2018). The biomechanics of place kicking in rugby
414 union. In H. Nunome, E. Hennig & N. Smith (Eds.), *Football Biomechanics* (pp. 24-36),
415 Abingdon, UK: Routledge.
416
417 Bull Andersen, T., Dorge, H. C., & Thomsen, F. I. (1999). Collisions in soccer kicking. *Sports*
418 *Engineering*, 2, 121-125.
419
420 Cappozzo, A., Catani, F., Della Croce, U., & Leardini, A. (1995). Position and orientation in
421 space of bones during movement: anatomical frame definition and determination. *Clinical*
422 *Biomechanics*, 10, 171-178.
423
424 Cockcroft, J., & van den Heever, D. (2016). A descriptive study of step alignment and foot
425 positioning relative to the tee by professional rugby union goal-kickers. *Journal of Sports*
426 *Sciences*, 34, 321-329.
427
428 Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale,
429 NJ: Lawrence Earlbaum Associates.
430
431 Coleman, S. G. S., & Rankin, A. J. (2005). A three-dimensional examination of the planar
432 nature of the golf swing. *Journal of Sports Sciences*, 23, 227-234.
433
434 de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters.
435 *Journal of Biomechanics*, 29(9), 1223-1230.
436

437 Green, A., Kerr, S., Olivier, B., Dafkin, C., & McKinnon, W. (2016). The trade-off between
438 distance and accuracy in the rugby union place kick: a cross-sectional, descriptive study.
439 *Kinesiology, 48*, 251-257.

440

441 Holmes, C., Jones, R., Harland, A., & Petzing, J. (2006). Ball launch characteristics for elite
442 rugby union players. *The Engineering of Sport, 6*, 211-216.

443

444 Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics
445 for studies in sports medicine and exercise science. *Medicine & Science in Sports &*
446 *Exercise, 41*(1), 3-12.

447

448 Kwon, Y.-H., Como, C. S., Singhal, K., Lee, S. S. M., & Han, K. H. (2012). Assessment of
449 planarity of the golf swing based on the functional swing plane of the clubhead and motion
450 planes of the body points. *Sports Biomechanics, 11*(2), 127-148.

451

452 Lees, A., Barton, G., & Robinson, M. (2010). The influence of Cardan rotation sequence on
453 angular orientation data for the lower limb in the soccer kick. *Journal of Sports Sciences, 28*,
454 445-450.

455

456 Linthorne, N. P., & Stokes, T. G. (2014). Optimum projection angle for attaining maximum
457 distance in a rugby place kick. *Journal of Sports Science and Medicine, 13*, 211-216.

458

459 Lu, T. W., & O'Connor, J. J. (1999). Bone position estimation from skin marker co-ordinates
460 using global optimisation with joint constraints. *Journal of Biomechanics, 32*, 129-134.

461

462 Minnaar, N., & van den Heever, D. J. (2015). A kicking simulator to investigate the foot-ball
463 interaction during a rugby place kick. *IEEE Transactions on Biomedical Engineering, 62*,
464 6724-6727.

465

466 Morrison, A., McGrath, D., & Wallace, E. (2014). Changes in club head trajectory and
467 planarity throughout the golf swing. *Procedia Engineering*, 72, 144-149.

468

469 Morrison, A., McGrath, D., & Wallace, E. S. (2018). The relationship between the golf swing
470 plane and ball impact characteristics using trajectory ellipse fitting. *Journal of Sports*
471 *Sciences*, 36, 144-149.

472

473 Padulo, J., Granatelli, G., Ruscello, B., & D'Ottavio, S. (2013). The place kick in rugby.
474 *Journal of Sports Medicine and Physical Fitness*, 53, 224-231.

475

476 Pocock, C., Bezodis, N. E., Davids, K., & North, J. S. (2018). Hot hands, cold feet?
477 Investigating effects of interacting constraints on place kicking performance at the 2015
478 Rugby Union World Cup. *European Journal of Sport Science*, ahead of print. doi:
479 10.1080/17461391.2018.1486459

480

481 Quarrie K. L., & Hopkins, W. G. (2015). Evaluation of goal kicking performance in
482 international rugby union matches. *Journal of Science and Medicine in Sport*, 18, 195-198.

483

484 Seo, K., Kobayashi, K., & Murakami, M. (2006). Multi-optimisation of the screw kick in rugby
485 by using a genetic algorithm. *Sports Engineering*, 9, 87-96.

486

487 Shinkai, H., Nunome, H., Isokawa, M., & Ikegami, Y. (2009). Ball impact dynamics of instep
488 soccer kicking. *Medicine and Science in Sports and Exercise*, 41, 889-897.

489

490 Sinclair, J., Taylor, P. J., Atkins, S., Bullen, J., Smith, A., & Hobbs, S. J. (2014). The
491 influence of lower extremity kinematics on ball release velocity during in-step place kicking in
492 rugby union. *International Journal of Performance Analysis in Sport*, 14, 64-72.

493

494 Sinclair, J., Taylor, P. J., Smith, A., Bullen, J., Bentley, I., & Hobbs, S. J. (2017). Three-
495 dimensional kinematic differences between accurate and high velocity kicks in rugby union
496 place kicking. *International Journal of Sports Science & Coaching*, 12, 371-380.

497

498 Takagi, T., Yokozawa, T., Inaba, Y., Matsuda, Y., & Shiraki, H. (2017). Relationships
499 between clubshaft motions and clubface orientation during the golf swing. *Sports*
500 *Biomechanics*, 16, 387-398.

501

502 Williams, K. R., & Sih, B. L. (2002). Changes in golf clubface orientation following impact
503 with the ball. *Sports Engineering*, 5, 65-80.

504

505 Willmott, A. P., & Dapena, J. (2012). The planarity of the stickface motion in the field hockey
506 hit. *Journal of Sports Sciences*, 30(4), 369-377.

507

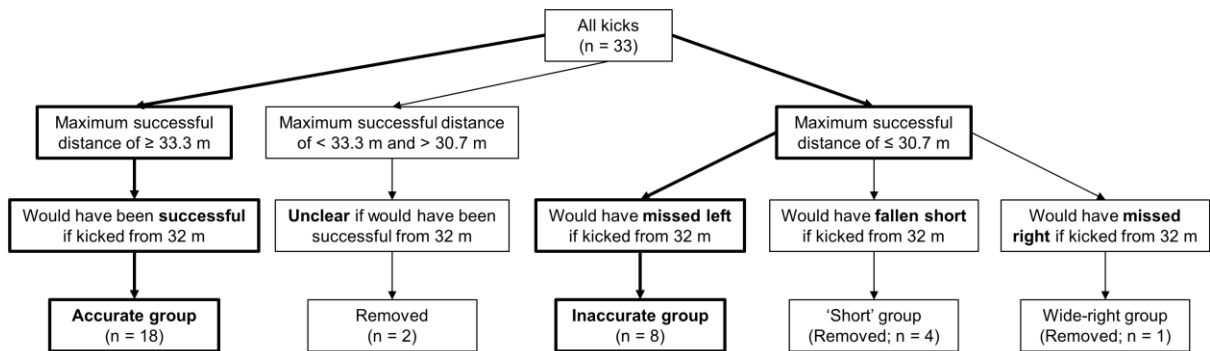
508 Winter, D. A. (2005) *Biomechanics and motor control of human movement* (3rd ed.). New
509 York, NY: Wiley.

510

511 Winter, E. M., Abt, G. A., & Nevill, A. M. (2014). Metrics of meaningfulness as opposed to
512 sleights of significance. *Journal of Sports Sciences*, 32, 901-902.

513

514 Zhang, Y., Liu, G., & Xie, S. (2012). Movement sequences during instep rugby kick: a 3D
515 biomechanical analysis. *International Journal of Sports Science and Engineering*, 6, 89-95.

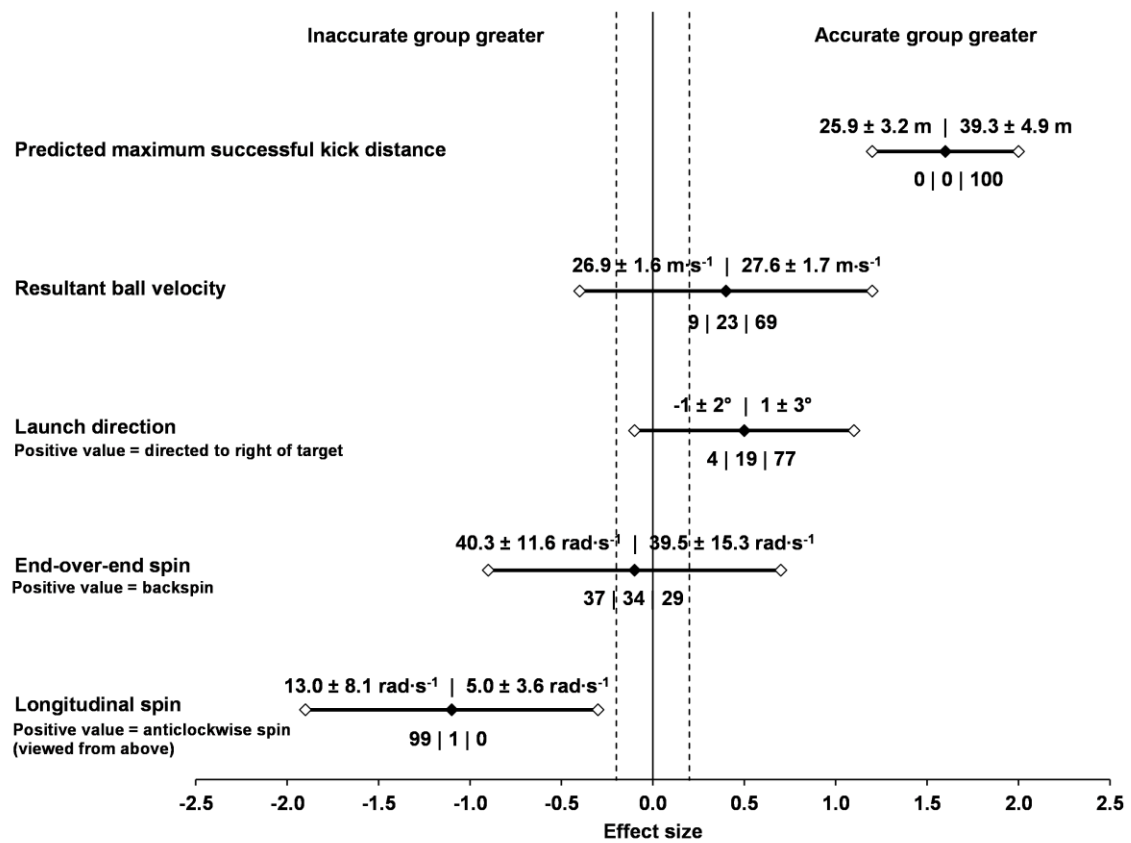


517

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) \pm 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 \geq 33.3 m.
 524 The inaccurate group contains only kicks with a predicted maximum successful distance \leq
 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 \leq 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).

532

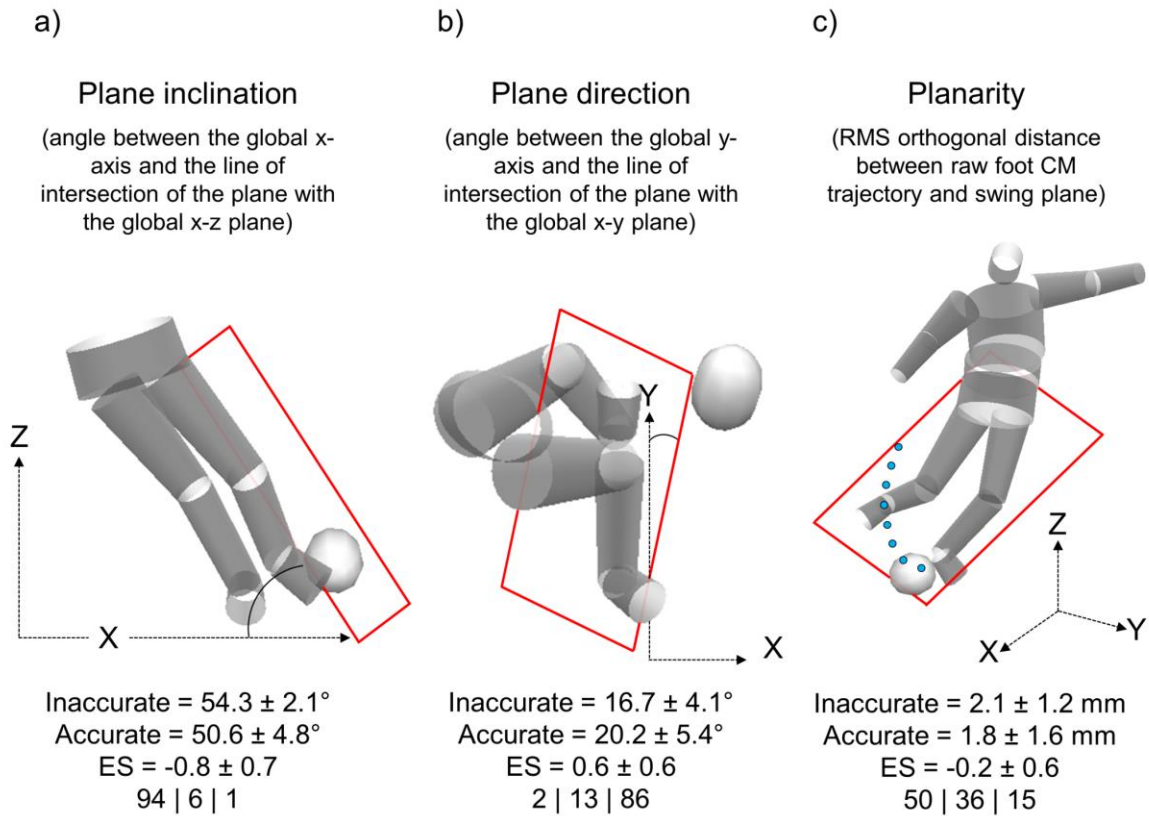


533

534

535 Figure 2. Comparison of performance and ball flight characteristics between the inaccurate
 536 and accurate groups. Black diamonds represent the effect size (Cohen's *d*; inaccurate group
 537 as the reference category) with error bars (capped by white diamonds) indicating the 90%
 538 confidence limits. The mean ± *SD* group values for the inaccurate | accurate groups are
 539 presented above each bar and the percentage likelihood of the inaccurate group being
 540 greater | trivial difference | accurate group being greater (based on a smallest worthwhile
 541 effect of 0.2; dashed vertical lines) are presented below each bar.

542

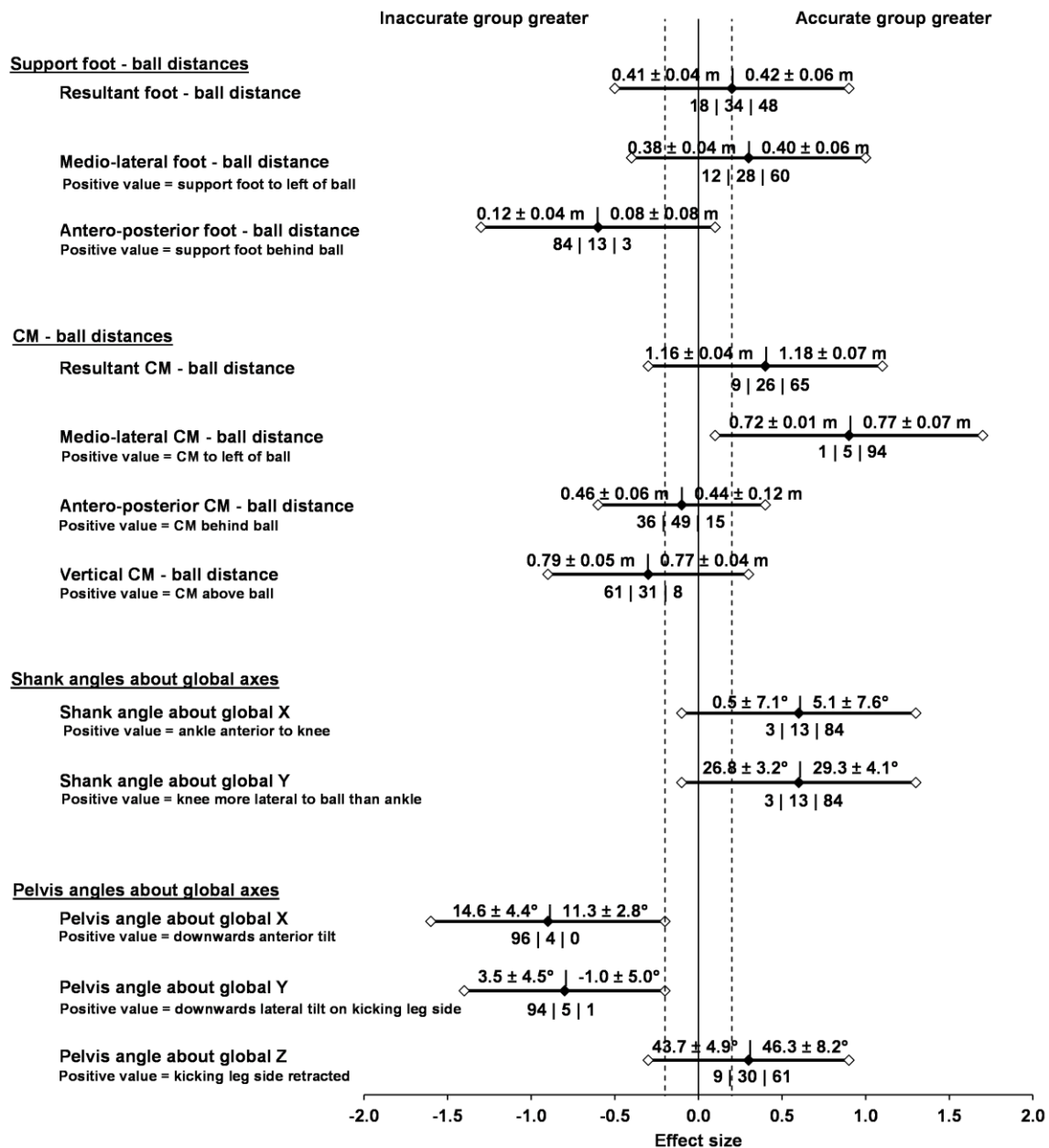


543

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.

551



552

553

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