Cronfa - Swansea University Open Access Repository

This is an author produced version of a paper published in:
European Journal of Sport Science

Cronfa URL for this paper:
http://cronfa.swan.ac.uk/Record/cronfa43538

Paper:

Bezodis, N., Atack, A., Willmott, A., Callard, J. & Trewartha, G. (2018). Kicking foot swing planes and support leg kinematics in rugby place kicking: Differences between accurate and inaccurate kickers. *European Journal of Sport Science*, 1-10.

http://dx.doi.org/10.1080/17461391.2018.1519039

Kicking foot swing planes and support leg kinematics in rugby place kicking: differences between accurate and inaccurate kickers

Neil E. Bezodis, Alexandra Atack, Alexander P. Willmott, Jon E. B. Callard, Grant Trewartha

European Journal of Sport Science (accepted 22/08/2018)

Abstract

Place kicking is a complex whole-body movement that contributes 45% of the points scored in international Rugby Union. This study compared the kicking foot swing plane characteristics of accurate and inaccurate kickers, underpinned by differences in their support leg and pelvis kinematics at support foot contact, to identify key technique characteristics. Motion capture data (240 Hz) were collected from 33 experienced kickers, and distinct groups of accurate (n = 18) and inaccurate (n = 8) kickers were identified based on their performance characteristics. All accurate kickers were capable of kicking successfully from at least 33.3 m, whereas all inaccurate kickers would have missed left from distances greater than 30.7 m. The accurate group exhibited a moderately shallower swing plane inclination (50.6 ± 4.8° vs. 54.3 ± 2.1°) and directed the plane moderately further to the right of the target (20.2 ± 5.4° vs. 16.7 ± 4.1°). At support foot contact, the accurate group placed their support foot moderately less far behind the ball (0.08 ± 0.08 m vs. 0.12 ± 0.04 m) and positioned their centre of mass moderately further to the support leg side (0.77 ± 0.07 m vs. 0.72 ± 0.01 m) due to a moderately greater stance leg lean (29.3 ± 4.1° vs. 26.8 ± 3.2°). The kicking foot swing plane is highly planar in rugby place kicking but its orientation differs between accurate and inaccurate kickers. These plane characteristics may be controlled by support foot placement and support leg and pelvis kinematics at support foot contact.

Keywords

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

Introduction

Place kicking provides a valuable opportunity to score points in Rugby Union (hereafter, rugby) by kicking a stationary ball between two vertical posts which are 5.6 m apart and over a horizontal crossbar which is 3.0 m above the ground. Place kicks accounted for 45% of the total points scored in international rugby matches between 2002 and 2011 (Quarrie & Hopkins, 2015). These kicks must often travel over considerable distances, and maintain a sufficiently accurate trajectory towards the target, in order for the outcome to be successful. The mean (± *SD*) distance and absolute angle (relative to a horizontal line projected from the centre of the upright posts) of the 6,428 place kicks analysed in detail by Quarrie and Hopkins (2015) were 32 m (± 12 m) and 29° (± 17°), respectively. As the average success rate of these kicks (Quarrie & Hopkins, 2015) was 73%, there is clear scope for improvements in place kicking performance, even at the highest level of the game.

The success of a place kick is directly determined by the three-dimensional linear and angular velocities of the ball at the instant it leaves the kicker's foot (Atack, Trewartha, & Bezodis, 2018). This motion of the ball at its launch is determined by specific aspects of the contact from the kicker's boot (Bull Andersen, Dorge, & Thomsen, 1999), and thus coaches and kickers spend considerable time focussing on various aspects of place kicking technique to improve the outcome of the foot-ball contact. Previous research has therefore investigated rugby place kick ball launch characteristics using a combination of empirical and theoretical methods (Atack et al., 2018; Holmes, Jones, Harland, & Petzing, 2006; Linthorne & Stokes, 2014; Seo, Kobayashi, & Murakami, 2006), and with mechanical simulators (Minnaar & van den Heever, 2015). Other studies have focussed on specific aspects of kickers' techniques which might influence the ball launch characteristics, such as the approach towards the ball and support foot positioning (Baktash, Hy, Muir, Walton, & Zhang, 2009; Cockcroft & van den Heever, 2016; Padulo, Granatelli, Ruscello, & D'Ottavio, 2013), kicking leg joint kinematics (Ball, Talbert, & Taylor, 2013; Sinclair et al., 2014; 2017; Zhang, Liu, & Xie, 2012) and trunk and arm motions (Ball et al., 2013; Bezodis, Trewartha, Wilson, & Irwin, 2007;

Green, Kerr, Olivier, Dafkin, & McKinon, 2016). In some instances, the above variables were compared between kicks with a primary focus on either distance or accuracy (Bezodis et al., 2007; Sinclair et al., 2017), or distance and accuracy were treated as separate dependent variables against which specific aspects of technique were related (Green et al., 2016). Furthermore, whilst some of the aforementioned studies have reported the magnitude of the kicking foot velocity at initial ball contact, and many of the variables they have described will partly contribute to the kicking foot trajectory, none have directly investigated the path of the kicking foot - the distal endpoint of a linked-segment system - prior to ball contact.

In other ballistic striking actions such as a golf swing, the motion of the distal endpoint (i.e. the clubhead) has been shown to be planar from the mid-downswing onwards (Kwon, Como, Singhal, Lee, & Han, 2012; Morrison, McGrath, & Wallace, 2014; 2018). Specific properties of this plane have been investigated such as its orientation with respect to the global axes which are aligned with the intended target (e.g. Kwon et al., 2012; Morrison et al., 2014; 2018; Takagi, Yokozawa, Inaba, Matsuda, & Shiraki, 2017; Williams & Sih, 2002). These plane orientations have been found to differ between golfers of different skill-levels (Morrison et al., 2018) as well as to be related to certain clubhead kinematic parameters at impact, such as clubhead angles and velocities (Williams & Sih, 2002; Takagi et al., 2017), that ultimately affect the performance outcome of the shot.

Other ballistic sporting movements have also been demonstrated to exhibit planar endpoint motion, such as the stick face during the final 83% of the downswing during a field hockey hit (Willmott & Dapena, 2012) and the kicking foot during the final 1.25 m of the downswing prior to ball contact during a rugby place kick (Bezodis, Willmott, Atack, & Trewartha, 2014). However, these studies have not considered how the properties of these swing planes might relate to performance outcome factors. In a study of soccer kicking, Alcock, Gilleard, Hunter, Baker and Brown (2012) found that the orientations of swing planes fitted to the kicking hip, knee and ankle joint centre coordinates from support foot contact to ball contact differed between curve and instep kicks. However, Alcock et al. (2012) did not quantify the planarity of this motion and it has been shown in golf that, unlike just the distal endpoint, multiple points within a linked-segment system (e.g. shoulder girdle, arm, club shaft, clubhead) do not move in a consistent, single plane (Coleman & Rankin, 2005).

Based on the importance of the swing plane in golf and potentially in other striking actions, the properties of the kicking foot swing plane have been proposed as an important consideration for accurate rugby place kicking (Ball et al., 2013; Bezodis, Winter, & Atack, 2018). However, despite these suggestions, the potential role of the kicking foot swing plane in accurate rugby place kicking has not been empirically investigated. It is also important to consider the role that support leg kinematics at support foot contact may play in helping to determine the orientation of the kicking foot swing plane. The kicking foot path is affected by support foot placement given the linked-segment nature of the human body, and kicking foot kinematics at ball contact have been shown to be strongly related to support leg kinematics at the instant of support foot contact in punt kicking (Ball, 2013). The primary aim of this study was therefore to investigate how the properties of the kicking foot swing plane differ between accurate and inaccurate kickers. A second aim was to investigate differences in the support leg and pelvis kinematics at support foot contact between the groups to identify potential strategies for how the swing plane, and ultimately place kick accuracy, can be controlled.

Methods

Thirty-three male place kickers (mean ± *SD*: age = 22 ± 4 years; mass = 86.2 ± 8.8 kg; height = 1.82 ± 0.06 m) who were free from injury and playing at levels ranging from amateur to senior international provided written informed consent to participate. All procedures were approved by the local research ethics committee prior to any testing. Data collection took place in an indoor laboratory with kickers wearing their own moulded-rubber boots and using their personal kicking tee and a Gilbert Virtuo matchball. Seventy-four 25 mm spherical markers were used to define a 14-segment rigid-body model of each kicker using a CAST approach (Cappozzo, Catani, Della Croce, & Leardini, 1995), with 54 markers retained to track full body motion during the kicking trials (see Bezodis et al. 2018 for illustration of marker locations). Following their typical self-directed kicking warm-up, each kicker completed a series of familiarisation kicks until they were comfortable with the environment. They then performed a minimum of seven place kicks, as if from their maximum range, aiming towards a vertical target which represented the centre of the posts and was suspended 2 m from the kicking tee in front of a net.

During all kicking trials, a 10- or 11-camera motion capture system (MX, Vicon, UK) was used to track the markers at 240 Hz. Flat markers were also attached to the ball in the centre of each panel (n = 4) and towards one end of the ball (n = 2) to enable its geometric centre to be determined and its three-dimensional translation and rotation to be tracked (Atack et al., 2018). Ground reaction forces (GRFs) were recorded at 960 Hz from under the support foot using a force platform (9287BA, Kistler, Switzerland) which was covered so as to be flush with the surrounding floor. The motion capture and force platform data were synchronously collected (Nexus v.1.8., Vicon, UK) and their co-ordinate systems were aligned such that the y-axis was horizontal and in the direction of the target from the kicking tee, the z-axis was vertical, and the x-axis was the cross-product of the y- and z-axes. Marker trajectories were labelled and the raw marker and GRF data were exported as .c3d files for analysis in Visual3D (v.5.1., C-Motion, USA) and Matlab (v.7.12., MathWorks, USA).

Initial ball contact and the first frame of ball flight were identified using the procedures of Shinkai, Nunome, Isokawa and Ikegami (2009). The initial ball flight kinematics were determined and input in to a model of rugby ball flight to predict the maximum successful distance that each kick could be taken from, assuming it was kicked from directly in front of the posts (Atack et al., 2018). Each kicker’s best kick (i.e. greatest predicted maximum successful distance) was identified, and groups were determined based on the predicted maximum successful distance and eventual reason for failure (i.e. miss left, miss right, fall short) of each kick (Figure 1). A threshold of 32 m (the average kick distance in international rugby; Quarrie & Hopkins, 2015) ± 1.3 m (the reported ball flight model error; Atack et al., 2018) was initially used to divide the kicks, with those below the lower threshold sub-divided based on their eventual reason for failure (Figure 1). The accurate group comprised 18 kicks, all of which had a predicted maximum successful distance greater than 33.3 m. The inaccurate group comprised eight kicks, all of which had a predicted maximum successful distance less than 30.7 m because the kick would have missed to the left of the posts from any greater distance (but importantly these kicks did not lack 'range', i.e. they were still above the height of the crossbar at this point).

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

To analyse each kicker's kinematics, all marker co-ordinates from the corresponding trial were firstly expressed relative to the position of the ball centre when resting on the tee, and global x-axis co-ordinates for left-footed kickers were inverted. The kicking foot centre of mass (CM) location was determined (Winter, 2005) and its raw trajectory was resampled at equal (0.01 m) spatial intervals (Willmott & Dapena, 2012) using an interpolating cubic spline, ending at initial ball contact. This resampling was necessary due to the increasing velocity of the foot CM during the downswing, meaning that using equal temporal intervals would have biased the fit more towards the earlier part of the downswing. The start point of the trajectory was identified at a total path distance prior to ball contact equal to 125% of leg length, because the kicking foot swing plane is planar for up to 1.25 m pre-contact in rugby place kicking (Bezodis et al., 2014) and the mean ± *SD* leg length of the 26 retained kickers was 0.96 ± 0.04 m. A least-squares plane was then fitted to this trajectory using orthogonal distance regression (Willmott & Dapena, 2012). The *direction* of each kicker's swing plane was determined as the angle between the global y-axis (aligned with the horizontal direction of the centre of the target from the centre of the kicking tee) and the line of intersection of the swing plane with the global x-y (horizontal) plane (Figure 3b). Swing plane *inclination* was determined as the angle between the global x-axis and the line of intersection of the swing plane with the global x-z plane (Figure 3a). The root mean square (RMS) residual between the raw kicking foot CM path and the fitted swing plane was determined to quantify the *planarity* as the goodness of fit of the plane to the actual kicking foot trajectory (Figure 3c).

All marker co-ordinates were then low-pass filtered at 18 Hz (Butterworth 4^{th}-order) based on a residual analysis (Winter, 2005) and segmental kinematics were reconstructed using an evenly-weighted inverse kinematics procedure (Lu & O'Connor, 1999). Whole-body CM location was calculated (de Leva, 1996) and the orientations of stance leg and pelvis segments about each global axis were determined using XYZ Cardan rotations (Lees, Barton, & Robinson, 2010). Support foot contact was identified when the vertical GRF first exceeded 10 N and kinematic variables of interest (Figure 4) were extracted at this instant to address the second stated aim of this study.

Each group's mean ± *SD* values were calculated for all dependent variables, and effect sizes (Cohen, 1988) were then calculated to assess the magnitude of the difference between the groups. 90% confidence intervals for these effect sizes were calculated and magnitude-based inferences were derived based on a threshold of 0.2 as a practically important effect (Hopkins, Marshall, Batterham, & Hanin, 2009; Winter, Abt, & Nevill, 2014), enabling calculation of the percentage likelihood of any difference being positive, trivial or negative. In all subsequent descriptions, only variables where the confidence intervals did not span across effect sizes of both -0.2 and +0.2 are considered different between the two groups (all other comparisons were considered to be unclear effects). The magnitudes of the differences are described based on the thresholds proposed by Hopkins et al. (2009) of 0.2, 0.6, 1.2 and 2.0 for small, moderate, large and very large mean effect sizes, respectively.

Results

The groups were defined based on their predicted maximum successful kick distance; the difference in this critical performance outcome between the two groups was large (mean difference = 13.4 m, *d* = 1.6; Figure 2). The inaccurate group would have missed to the left of the posts because moderately more longitudinal spin (anticlockwise from above) (mean difference = 8.0 $rad \cdot s^{-1}$, *d* = -1.1; Figure 2) was imparted on the ball and the launch direction was already to the left of the target (mean difference = 2°, *d* = 0.5; Figure 2). There was no clear difference in resultant ball velocity magnitude or end-over-end spin between the groups (Figure 2). The mean ± *SD* mass of the kickers in the accurate and inaccurate groups were 87.0 ± 6.8 kg and 88.9 ± 12.7 kg, respectively, whilst their respective heights were 1.82 ± 0.05 m and 1.82 ± 0.09 m. There were no clear differences in either mass or height between the groups (mass: *d* = 0.19 ± 0.64, height: *d* = 0.03 ± 0.61).

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

There were moderate differences in the swing plane inclination and direction between the groups (Figure 3). The accurate group exhibited a shallower swing plane inclination (by 3.7°, *d* = -0.8) than the inaccurate group (Figure 3a), and directed their plane further to the right of the target (by 3.5°, *d* = 0.6; Figure 3b). There was no clear difference in the planarity of the kicking foot trajectory, based on the RMS residuals, between the two groups (Figure 3c).

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

There was no clear difference between the groups in the resultant distance between the support foot CM and the ball centre in the horizontal plane at support foot contact. However, the accurate group placed their support foot moderately less far behind the ball (mean difference = 0.04 m, *d* = -0.6) in the antero-posterior direction (Figure 4). There was also no clear difference in the resultant distance between the whole-body CM and the ball centre in the horizontal plane at support foot contact between the groups, but the accurate group positioned their CM moderately further to the left of the ball (viewed from behind; mean = 0.05 m, d = 0.9) in the medio-lateral direction (Figure 4). There was no clear difference in medio-lateral foot placement so this more lateral CM positioning was due to a greater support leg lateral lean, evident in the moderate difference (mean = 2.5°, d = 0.6) in the support leg shank angle about the global y-axis between the two groups (Figure 4). With regards to the pelvis, the accurate group exhibited moderately less anterior tilt (mean difference = 3.3°, d = 0.9) and a lateral tilt that was moderately lower on the support-leg side compared with the inaccurate group (mean difference = 4.5°, d = 0.8; Figure 4).

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

Discussion

We aimed to investigate differences in the kicking foot swing plane characteristics between accurate and inaccurate groups of rugby place kickers, and to identify how different support leg and pelvis kinematics might help to explain these differences in kicking foot trajectories and ultimately in place kick performance outcome. Both groups achieved higher mean ball velocities than kickers in previous studies of maximal effort place kicking with an inherent accuracy requirement at university (Bezodis et al., 2007; Sinclair et al., 2014; Zhang et al., 2012), semi-professional (Linthorne & Stokes, 2014), and professional (Holmes et al., 2006; Padulo et al., 2013) levels. However, the inaccurate group would have missed to the left of the target from substantially shorter kick distances due to a combination of the medio-lateral direction of the initial velocity vector and the longitudinal spin imparted on the ball (Figure 2). To contextualise this, at the mean distance of 25.9 m when the inaccurate group would have missed to the left of the target (assuming kicks were taken from directly in front of the posts), the ball would still have been at a mean height of 10.8 m, considerably higher than the crossbar (3.0 m). It was therefore the accuracy of these kicks, rather than their range, which limited performance.

The kicking foot trajectories of both groups were highly planar in nature. The RMS residuals between the plane and the raw kicking foot trajectories were approximately 2 mm for both groups (Figure 3c). Although comparable residual data are not available from other kicking tasks, these residuals are similar to those observed between the stick face and swing plane over similar trajectory lengths during a field hockey hit (Willmott & Dapena, 2012). The planarity of the kicking foot trajectories (i.e. RMS difference <0.2% of the analysed kicking foot trajectory length) suggests that late adjustments are not made to the foot path, and justifies the quantification of the kicking foot trajectories using a swing plane approach in the current study. Swing plane inclinations and directions relative to the global axes (which were aligned with the kicking target) can therefore be investigated with confidence to identify gross differences in kicking foot trajectories between the accurate and inaccurate groups.

The inaccurate group exhibited swing planes which were inclined more vertically (i.e. steeper) and less far to the right of the target than those of the accurate group (Figure 3). One possible explanation for the difference in plane inclination is evident in the results of the only other published study which has investigated swing planes in kicking. Alcock et al. (2012) observed the kicking leg swing plane to be nearly 9° steeper in curve kicks compared with instep kicks in soccer, and ball spin was almost twice as great in the curve kicks than in the instep kicks. As the kickers studied by Alcock et al. (2012) were intentionally trying to impart spin on the ball in order to achieve the desired outcome of the curve kicks, the adoption of a steeper plane may have been a technique adjustment which facilitated their ability to impart spin on the ball. Combining these findings (Alcock et al., 2012) with the fact that the inaccurate group in the current study imparted over 2.5 times more longitudinal spin on the ball than the accurate group (Figure 2), future applied investigations should seek to determine whether adoption of a shallower swing plane could lead to a reduction in the spin imparted on the ball by kickers who have a tendency to miss the target to the left.

The fact that the accurate group directed their swing plane further to the right of the target than the inaccurate group was likely a compensation for their less inclined plane (Figure 3). The kicking foot is moving upwards during the ball contact phase of a place kick (average vertical velocity from first to final frame of ball contact = 3.87 ± 1.43 $m \cdot s^{-1}$ and 3.73 ± 0.64 $m \cdot s^{-1}$ for the accurate and inaccurate groups, respectively), and thus the kicking foot will be travelling to the left of the swing plane direction in the horizontal plane. The actual foot path direction during ball contact is therefore less far to the right of the target than the direction of the swing plane; both groups exhibited an average foot direction of 10 ± 4° during ball contact and ended with their foot travelling in a direction slightly to the left of the target line in the final frame of ball contact prior to ball flight (-2 ± 5° and -1 ± 5° for the accurate inaccurate groups, respectively). This suggests that both groups exhibit comparable lateral foot motion during ball contact, but that they progress their foot towards ball contact in a different way. Given their less inclined plane, the accurate group have to direct their swing plane further to the right to achieve this comparable foot direction during ball contact. Whilst this may simply be a function of the aforementioned desire to adopt a less inclined plane to limit longitudinal spin, it may also enable the accurate group to achieve different kicking foot kinematics through the ball contact.

The inclination and direction of the kicking foot swing plane are partly controlled by the support leg kinematics, as the support foot placement locates the kicker in the global space relative to the ball. Furthermore, support leg kinematics at support foot contact have been shown to be related to kicking foot kinematics in punt kicking (Ball, 2013). As the medio-lateral foot placement did not differ between the groups, the difference in swing plane inclination between the two groups appears to be controlled by the lean of the support leg shank about the global y-axis and an associated lateral tilt of the pelvis so that it is typically lower on the support leg side for the accurate kickers (Figure 4). Both of these motions assisted in positioning the accurate group's whole body CM further to the left of the ball at support foot contact compared with the inaccurate group (Figure 4), meaning that their kicking foot had to travel in a shallower plane towards the ball. The accurate group's placement of the support foot less far behind the ball (Figure 4) may also assist with their kicking foot swing plane being directed further to the right of the target without them having to reach too far in front of the support leg to strike the ball. Despite this placement of the support foot closer to the ball in the antero-posterior direction by the accurate group, there was no clear difference in the antero-posterior position of the whole body CM relative to the ball at support foot contact between the groups. The accurate group controlled their antero-posterior CM position by leaning their support shank slightly posteriorly about the global x-axis and by exhibiting less anterior pelvic tilt than the inaccurate group (Figure 4).

Based on the current findings, coaches working with kickers who have a tendency to miss to the left of the target, rather than being restricted by range, may wish to encourage their kickers to adopt shallower kicking foot swing planes. In an attempt to achieve this, practice environments which encourage greater sideways lean away from the ball in the support leg should be explored, potentially through the use of physical constraints on the right-hand-side of the (right-footed) kicker which prevent them from maintaining too upright a body position during the kicking action. Coaches should also ensure that these kickers direct their swing plane sufficiently far to the right of the target. This could potentially be achieved by encouraging kickers to land with their support foot closer to the ball (anteriorly), but coaches must be cognisant of the need to ensure that the stance leg and pelvis compensate accordingly and that the kicker maintains the antero-posterior distance between their CM and the ball at support foot contact. One strategy to encourage such a manipulation could be through exploring ways to increase the length of the final approach step, as there was a large difference in final step length between the accurate (1.69 ± 0.13 m) and inaccurate (1.51 ± 0.11 m, d = 1.4) groups, and a longer final step length has also been shown to be moderately (r = 0.41) associated with greater kick distance in accurate punt kicking (Ball, 2008).

Our study analysed a comparatively large cohort of experienced place kickers and was therefore able to identify two adequately-sized groups with performance outcomes that were distinctly different between-group, but homogeneous within-group. We believe that our analysis has inherently considered the kickers by skill level, rather than grouping them by playing level. The outcome of a place kick is a direct measure of place kicking skill, and players who play at a higher level are not necessarily better kickers than those at lower playing levels given the importance of numerous other technical aspects of the game (e.g. a player at a lower level may be an excellent place kicker but have very poor tackling and passing abilities and thus would not be successful playing at a higher level, in spite of being an excellent kicker). Importantly, both groups were capable of achieving high ball velocities, but only the accurate group were also able to kick straight over long distances. This ecologically valid consideration of performance outcome enabled us to analyse three-dimensional kinematic aspects of technique with high internal validity in a laboratory setting. Our laboratory environment also meant that all kicks were taken as if from each kicker's maximum range, whereas in reality kicks are taken from a variety of pitch locations during a match. Whilst we are confident that our data are representative of their true techniques as kickers are typically coached to execute kicks in a consistent manner irrespective of pitch location, it is known that task constraints (e.g. distance and angle to posts) and contextual factors (e.g. scoreline, time remaining) can influence place kicking success rates (Pocock, Bezodis, Davids, & North, 2018; Quarrie & Hopkins, 2015) and future research could investigate the effects of these factors on swing plane properties and other features of technique. By fitting planes to their kicking foot trajectories and analysing how these were controlled by support leg kinematics, we were able to identify certain technique strategies which appeared to distinguish the accurate group from the inaccurate group. Future experimental studies should use acute applied interventions designed to manipulate the technical features discussed in the current study, and to determine their effect on swing plane characteristics, ball launch kinematics, and ultimately performance outcome.

The kicking foot swing plane is highly planar in rugby place kicking but its orientation differs between accurate and inaccurate groups of kickers, both of whom were capable of achieving comparably high ball velocity magnitudes. The accurate group exhibited a shallower swing plane which was directed further to the right of the target than the inaccurate group. These plane characteristics may be controlled by support foot placement and support leg and pelvis kinematics at support foot contact.

Acknowledgements

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

Disclosure Statement

None of the authors have any financial interest in, or benefit arising from, the direct application of this research.

References

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

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

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

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

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

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

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

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

Proceedings, 32, 304-307. Retrieved from https://ojs.ub.uni-konstanz.de/cpa/article/view/5999/5480.

Bezodis, N., Winter, S., & Atack, A. (2018). The biomechanics of place kicking in rugby union. In H. Nunome, E. Hennig & N. Smith (Eds.), *Football Biomechanics* (pp. 24-36), Abingdon, UK: Routledge.

Bull Andersen, T., Dorge, H. C., & Thomsen, F. I. (1999). Collisions in soccer kicking. *Sports Engineering, 2*, 121-125.

Cappozzo, A., Catani, F., Della Croce, U., & Leardini, A. (1995). Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clinical Biomechanics*, *10*, 171-178.

Cockcroft, J., & van den Heever, D. (2016). A descriptive study of step alignment and foot positioning relative to the tee by professional rugby union goal-kickers. *Journal of Sports Sciences, 34,* 321-329.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Earlbaum Associates.

Coleman, S. G. S., & Rankin, A. J. (2005). A three-dimensional examination of the planar nature of the golf swing. *Journal of Sports Sciences*, *23*, 227-234.

de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics, 29*(9), 1223-1230.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Figures

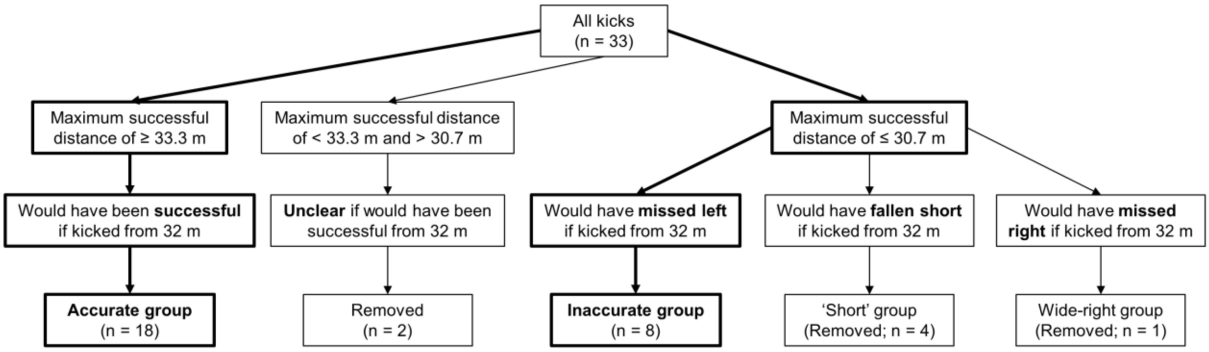

Figure 1. Illustration of the categorisation of kicks based on their predicted maximum successful distance and their eventual reason for failure. A distance of 32 m (the average kick distance in international rugby (Quarrie and Hopkins, 2015) ± 4.0% (1.3 m; the reported model error; Atack et al., 2018) yielded the threshold limits of 33.3 m and 30.7 m. The accurate group contains only kicks with a predicted maximum successful distance ≥ 33.3 m. The inaccurate group contains only kicks with a predicted maximum successful distance ≤ 30.7 m because they would have missed to the left of the posts from any greater distance. Of the remaining kicks, two were removed because they lay within the threshold limits (i.e. a predicted maximum successful distance between 30.7 m and 33.3 m), four were removed because they would have fallen short from a range of 30.7 m (i.e. they were not limited by inaccuracy), and one kick was removed as it had a predicted maximum successful distance ≤ 30.7 m but missed to the right of the posts and was thus not comparable to the other inaccurate kicks (nor sufficient in number to include as a second inaccurate group).

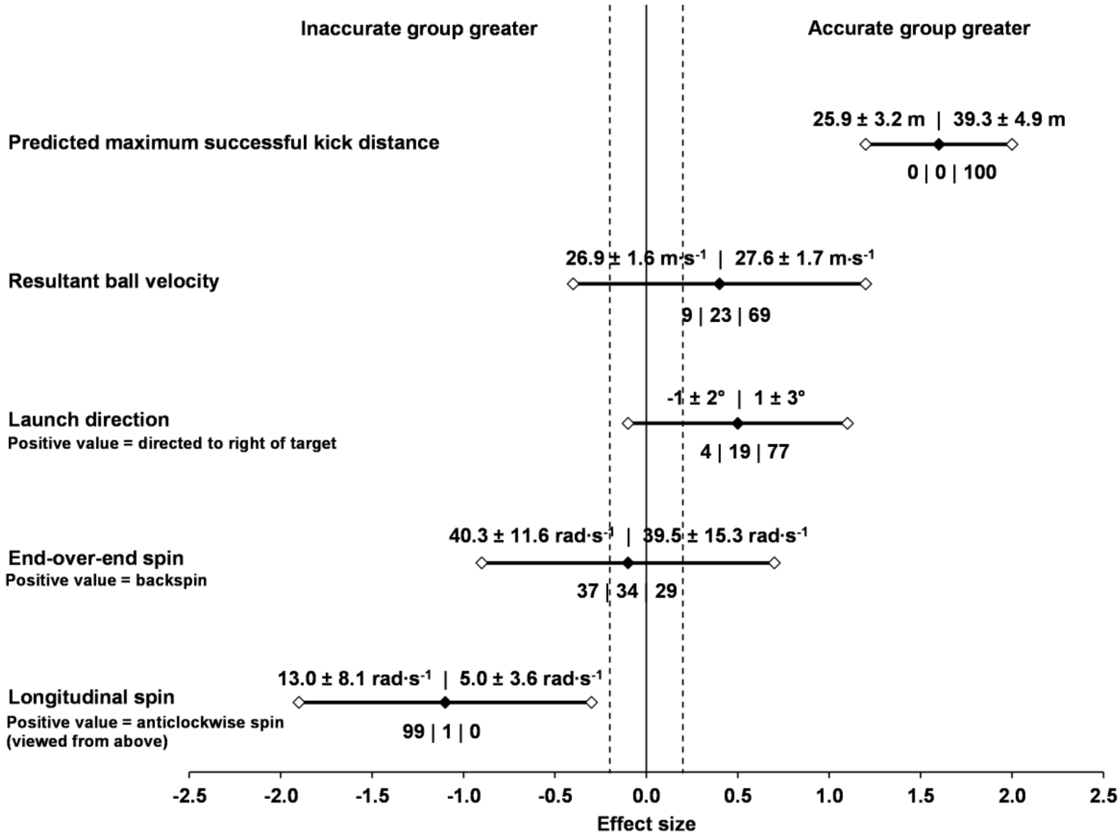

Figure 2. Comparison of performance and ball flight characteristics between the inaccurate and accurate groups. Black diamonds represent the effect size (Cohen's *d*; inaccurate group as the reference category) with error bars (capped by white diamonds) indicating the 90% confidence limits. The mean ± *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.

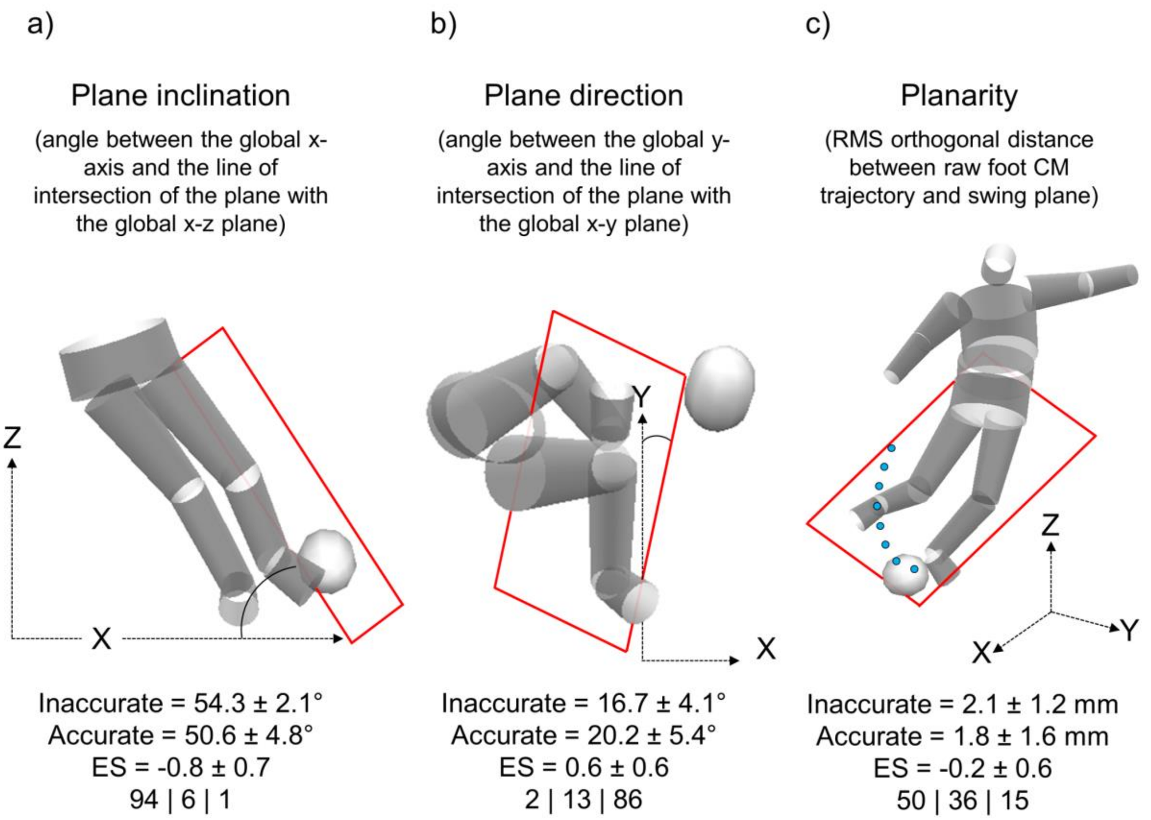

Figure 3. The mean ± *SD* swing plane (illustrated in red) a) inclination, b) direction and c) planarity, i.e. root mean square (RMS) residual between the plane and the raw kicking foot CM trajectory, for the inaccurate and accurate groups. The values on the bottom row quantify the percentage likelihood of the inaccurate group being greater | trivial difference | accurate group being greater (based on a smallest worthwhile effect of 0.2). ES = effect size (Cohen's *d*). For visual purposes, only the lower body is presented in figures a and b.

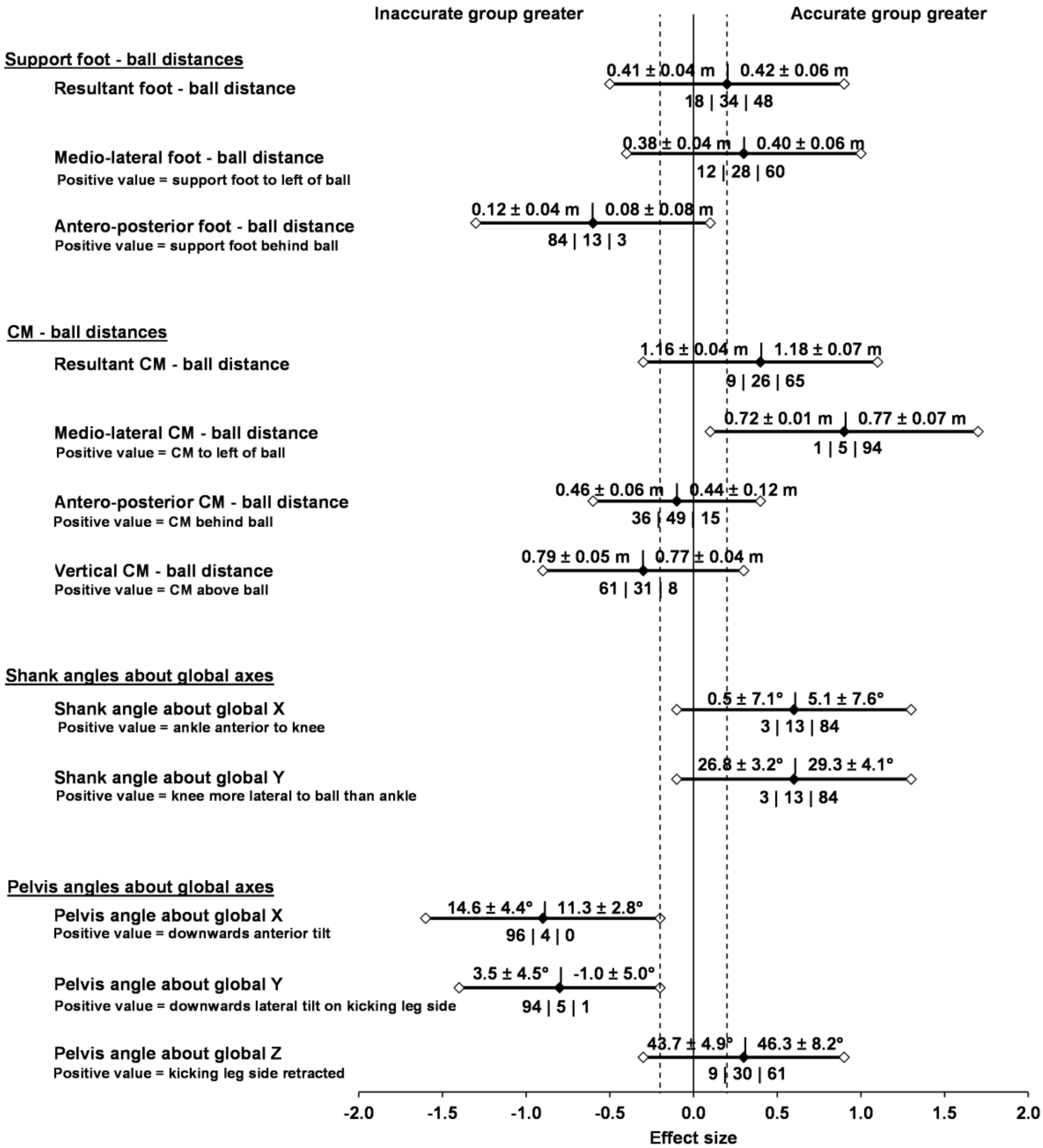

Figure 4. Comparison of support leg and pelvis kinematics between the inaccurate and accurate groups. Black diamonds represent the effect size (Cohen's *d*; inaccurate group as the reference category) with error bars (capped by white diamonds) indicating the 90% confidence limits. The mean ± *SD* group 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.