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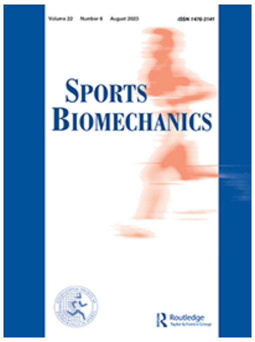

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Understanding the effects of ball orientation in Rugby Union place kicking: the preferences of international kickers and the kinematics of the foot-ball impact

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ABSTRACT

Rugby Union place kicking is influential to match outcome. Previous research has analysed kicker motion prior to ball contact in detail, but ball orientation and the impact phase are typically ignored. This study aims to firstly identify the ball orientations used by international place kickers, and secondly to experimentally analyse the foot-ball interaction in trained kickers using different ball orientations. Overall, 25.5% of the international kickers used an upright ball orientation, 27.5% used a diagonal orientation and 47.1% used a horizontal orientation. However, ball orientation preference was not significant in predicting kick outcome in a binomial logistic regression model. To address the second aim, ball orientation was experimentally manipulated and lower limb and ball kinematics were captured using high-speed (4000 Hz) video. Whilst the impact location on the ball differed significantly between most ball orientation conditions, the impact location relative to the global vertical was largely consistent across all conditions. This was likely due to kickers adopting very consistent lower limb kinematics, although the shank and ankle angles at impact were affected by ball orientation conditions for some kickers. Impact durations also differed between some conditions, although this did not appear to affect the impact efficiency.

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Contact; efficiency; football; performance; technique

Introduction

The importance of Rugby Union (hereafter ‘rugby’) place kicking on match outcome is well established (Quarrie & Hopkins, 2015), and the biomechanics during the approach and kicking action clearly differ between kickers (Bezodis et al., 2019; Cockcroft & van den Heever, 2016; Ford & Sayers, 2015; Sinclair et al., 2014, 2017). However, differences are also evident before kickers commence their approach as kickers orientate the ball to their individual preference on the kicking tee. In the only study to have quantified the preferential ball orientations of rugby place kickers, 14 highly trained kickers used

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orientations ranging from 2° (long axis of the ball nearly vertical) to 56° (top of the ball leaning towards the target) (Bezodis et al., 2018). Given the prolate spheroid shape of the ball, different ball orientations could interact with a kicker's technique to affect the impact and subsequent ball flight characteristics, and ultimately, the outcome of the kick. However, ball orientation preferences have not been quantified in the field for elite kickers. Therefore, investigation of preferences within a greater sample of elite kickers and a competition environment would be valuable. Potential interactions between ball orientation, technique, and performance also remain unknown.

Rugby place kicking technique before foot-ball impact has been extensively explored (Atack et al., 2019; Bezodis et al., 2007, 2018, 2019; Ford & Sayers, 2015; Sinclair et al., 2014, 2017). When using their preferred ball orientation, between-kicker differences in kicking foot swing planes (Bezodis et al., 2019), kicking leg movement variability (Ford & Sayers, 2015), and kicking leg angular displacements (Sinclair et al., 2014, 2017) during the downswing have been reported. Accurate kickers have displayed a shallower swing plane inclination (50.6 ± 4.8° vs. 54.3 ± 2.1°) and directed the swing plane further to the right (20.2 ± 5.4° vs. 16.7 ± 4.1°) than inaccurate kickers (Bezodis et al., 2019). The important end-product of motion earlier in the kicking movement is the kinematics of the kicking foot relative to the ball at initial foot-ball contact, and individual kickers are relatively consistent at controlling kicking foot position and orientation at initial ball contact when using their preferred ball orientation (Ford & Sayers, 2015). However, it is during the impact phase that the kicker applies impulse to the ball and, whilst this ultimately determines the kick outcome, the impact phase has been largely ignored to date in rugby place kicking studies.

The impact phase using a prolate spheroid ball has been investigated in detail in Australian Foot-ball (Ball, 2010; Peacock & Ball, 2017, 2018a, 2018b, 2019a, 2019b; Peacock et al., 2017), with values of coefficient of restitution (~0.55–0.65) (Peacock & Ball, 2019a) and foot-ball velocity ratio (1.25–1.28) (Peacock et al., 2017) often reported. However, these have focused on drop punt kicking where the ball is not stationary before impact, and the composition of rugby and Australian Foot-ball balls are also different. Foot-ball impact has recently been examined using a rugby ball, but this involved a mechanical kicking leg and so the human element was overlooked (Ball & Peacock, 2020). Understanding the ball orientation preferences and impact characteristics of human place kickers will provide valuable information to enhance the current understanding of how the well-described techniques used by place kickers contribute to the motion of the ball and ultimately to kick success. Therefore, this study aimed to, firstly, identify the ball orientations used by international place kickers and the potential association of these orientations with kick outcome and, secondly, to provide the first high-speed analysis of the foot-ball interaction in human rugby place kicking, including a preliminary investigation of how manipulations to ball orientation interact with kick technique and affect impact characteristics. It was hypothesised that 1) different ball orientation preferences would exist among international kickers but that 2) performance outcome would not differ between different ball orientation preference categories and that experimental manipulations to ball orientation would 3) affect the prior technique of a kicker, and 4) influence the foot-ball interaction.

Materials and methods

To sufficiently investigate the four hypotheses, two non-sequential parts of the study were designed. Part 1 aims to investigate the first two hypotheses using publicly available data from the Rugby World Cup, and Part 2 aims to investigate the second two hypotheses using a direct experimental approach. Consequently, the methods, results, and discussion are each separated into the associated two parts.

Part 1: notational analysis of the ball orientation preferences of international Rugby Union kickers

Data collection and analysis

To address the first two hypotheses, all place kicks (n = 416) from the 2019 Rugby World Cup were analysed. Fifty-one kickers (mean ± *SD*: age = 27 ± 4 years; mass = 88.8 ± 6.6 kg; height = 1.83 ± 0.05 m; www.rugbyworldcup.com/2019) attempted at least one place kick during the tournament. Televised footage of the 45 matches was used to obtain the following variables for each kick (Pocock et al., 2018): time in game (categorised into 10-min intervals), current score (categorised into winning by 8+, 4–7, 1–3; scores tied; or losing by 13, 4–7, 8+ points. These ranges were consistent with those of Pocock et al. (Pocock et al., 2018) and were chosen to indicate whether a team was winning or losing by more than one converted try, within one converted try, or within one successful penalty kick), kick type (conversion or penalty), outcome (success or miss) and outcome of the kicker's previous kick (success, miss or first kick). Additionally, the orientation of the ball when placed on the kicking tee was observed for each kicker, at each kick. This was categorised as either *upright*, *diagonal*, or *horizontal* depending on whether the long axis visually appeared to be closest to 15°, 45° or 75° (Figure 1) in front of the vertical, respectively. All kicks were viewed twice by the same investigator, and each kick was categorised into the same category on both occasions. Distance and angle to the goal posts of each kick were obtained from www.goalkickers.co.za; kick angle was defined as 0° if the kick was straight in front of the posts and increased as the kick position moved towards either the left or right touchline.

Statistical analysis

Mean distance and angle were calculated for the kicks taken in each ball orientation category, and the overall success percentage for each category was determined. To consider the known effects of contextual factors (Pocock et al., 2018), a binomial logistic regression was performed to estimate the probability of kick success (SPSS Statistics v26, IBM, USA). Categorised time of kick and score margin, kick distance, kick angle, and success of previous kick were all used in the regression model as independent variables (Pocock et al., 2018), with ball orientation category being an additional independent variable to address the current aim. Predicted percentages of success were then calculated at each independently increasing metre and degree for each ball orientation category.

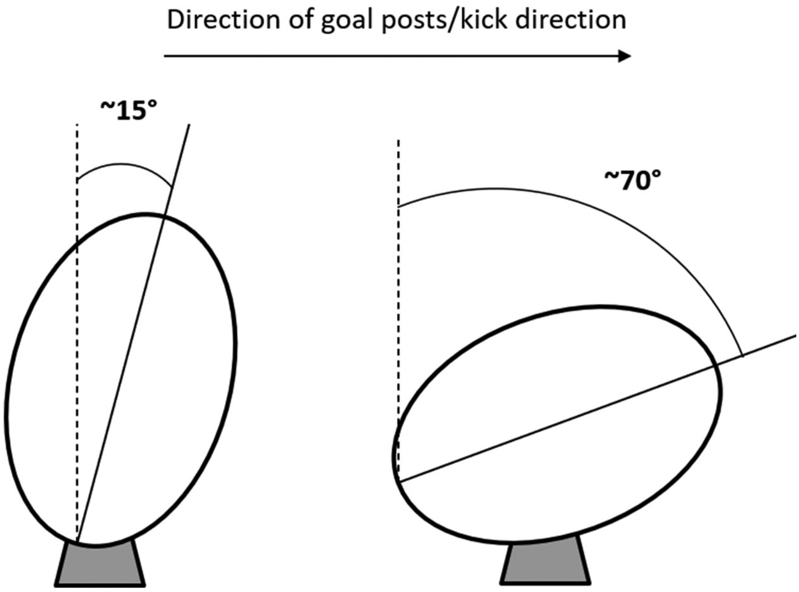

Figure 1. Examples of the ball orientation convention used throughout this study. Zero degrees represents the long axis of the ball being orientated vertically and a positive value indicates the top of the ball leaning towards the goal posts.

Part 2: empirical analysis of the foot-ball impact and effect of experimental manipulations to ball orientation

Participants

To address the third and fourth hypotheses, eight male kickers (mean ± *SD*: age = 23 ± 4 years; mass = 73.0 ± 2.9 kg; height = 1.75 ± 0.04 m), consisting of four trained rugby players and four trained soccer players, volunteered to participate. Soccer kickers were included since they did not have a preferred ball orientation but were highly experienced with a general kicking technique, unlike novice participants. All procedures were approved by the local institutional ethics committee.

Data collection

Data were collected outdoors on a rubber infill 3 G pitch using three cameras (Photron Fastcam MiniAX50) at 4000 Hz. The global coordinate system was set such that the y-axis was horizontal in the direction of the target, the z-axis was vertical, and the x-axis was the cross product of the two. One camera was placed 4 m from the ball setup and perpendicular to the y-z plane. The other two cameras were placed approximately 30° either side of the first camera (each approximately 4.6 m away from the ball setup). A volume of 0.80 m × 1.30 m × 0.60 m was calibrated inside a capture volume of approximately 1.20 m × 1.50 m × 0.75 m. Six hemispherical markers were placed on each kicker's kicking leg (lateral epicondyle; lateral malleolus; lateral aspect of calcaneus; head of fifth metatarsal) and three points on the ball's surface were clearly marked. Each kicker performed nine maximal effort place kicks as far and straight as possible along a ~50 m line marked out along the y-axis. For the rugby kickers, these comprised three kicks where the ball (size 5, Gilbert Virtuo) was placed leaning forwards slightly (*upright* orientation = 14.4 ± 0.6°), three with the long axis of the ball orientated closer to the horizontal (*horizontal* orientation = 69.6 ± 1.5°), and three taken with the kicker's personal preference of ball orientation (*preferred* orientation = 4.6 ± 4.2°). The soccer kickers took three using the *upright* orientation (15.8 ± 0.6°), three with the *horizontal* orientation (69.0 ± 0.3°) and three where the ball was placed leaning backwards (*backward* orientation = 15.8 ± 0.4°) (Figure 1). The soccer kickers were prescribed a backward orientation based on pilot testing with a separate group of soccer kickers where this orientation was the preference for some. No familiarisation periods were allowed between conditions and the order of conditions was randomised between each kicker. One investigator placed the ball on the tee for all kicks, except those taken with the rugby kicker's preferred orientation. All mean ± SD orientations stated above were determined post-testing (Quintic Biomechanics v31, Quintic Consultancy Ltd, UK).

Data analysis

All videos were manually digitised (Frame Dias V, DKH/Q'sfix, Japan) from ≥88 frames before the start of impact to ≥24 frames after the end of impact. The three-dimensional marker coordinates were reconstructed using 3D-DLT (Abdel-Aziz & Karara, 1971). Impact start and end frames were identified when the foot and ball first visually made contact and when they first visually separated, respectively. All subsequent processing was performed using custom-written scripts in MATLAB R2018b (v9.5, MathWorks, USA).

The kicking foot swing plane was determined by estimating the kicking foot centre of mass (CM) location (de Leva, 1996) and resampling its trajectory at 0.01 m intervals over a total path distance equal to 24% of the kicker's height prior to the start of impact (Bezodis et al., 2019; Willmott & Dapena, 2012) (24% was the greatest relative distance that could be analysed for all kickers). Swing plane direction was defined as the angle between the global y-axis and the line of intersection between the swing plane and the global x-y plane, whilst swing plane inclination was the angle between the global x-axis and the line of intersection between the swing plane and the global x-z plane (Bezodis et al., 2019).

The raw kicking leg marker displacement data were then filtered using an adapted fractional Fourier filter (FrFF) which has previously been validated in high-speed analysis of the impact phase during soccer kicking and uses an adapted fourth-order Butterworth filter to adjust the cut-off frequency during the impact phase to reduce errors when filtering through impact (Augustus et al., 2020). During the phases before and after impact, a cut-off frequency of 80 Hz was used. From the start of the impact phase, the cut-off frequency linearly increased to a peak value at the temporal midpoint of impact, before linearly decreasing back down to the end of impact. Kicker-specific peak cut-off frequencies (range: 100–265 Hz) were identified for each marker based on visual assessment of the raw and filtered displacement and velocity data for each trial with the aim of removing noisy data during impact whilst retaining the true sudden accelerations from the start to the end of impact.

Shank and foot segments were reconstructed from the filtered marker data as three-dimensional vectors from the ankle (lateral malleolus) to knee (lateral epicondyle) and heel (lateral aspect of calcaneus) to fifth metatarsal markers, respectively. The azimuth angle for each segment was defined as the angle between a vector in the positive x direction (originating from the segment's origin) and the segment vector projected in the x-y plane. The elevation angle for each segment was defined as the elevation of the three-dimensional segment vector from the x-y plane (Figure 2). Plantar flexion of the ankle was defined as the angle between the shank and foot segments, calculated using the vector product. An angle of 0° was defined as, when the segment vectors were perpendicular, with a positive value indicating plantar flexion. The change in plantar flexion angle between the start and end of impact was defined as the plantar flexion range of motion during impact.

The impact location on the ball (visually determined as the location on the ball shell of the first contact made by the kicking foot) was obtained from the camera perpendicular

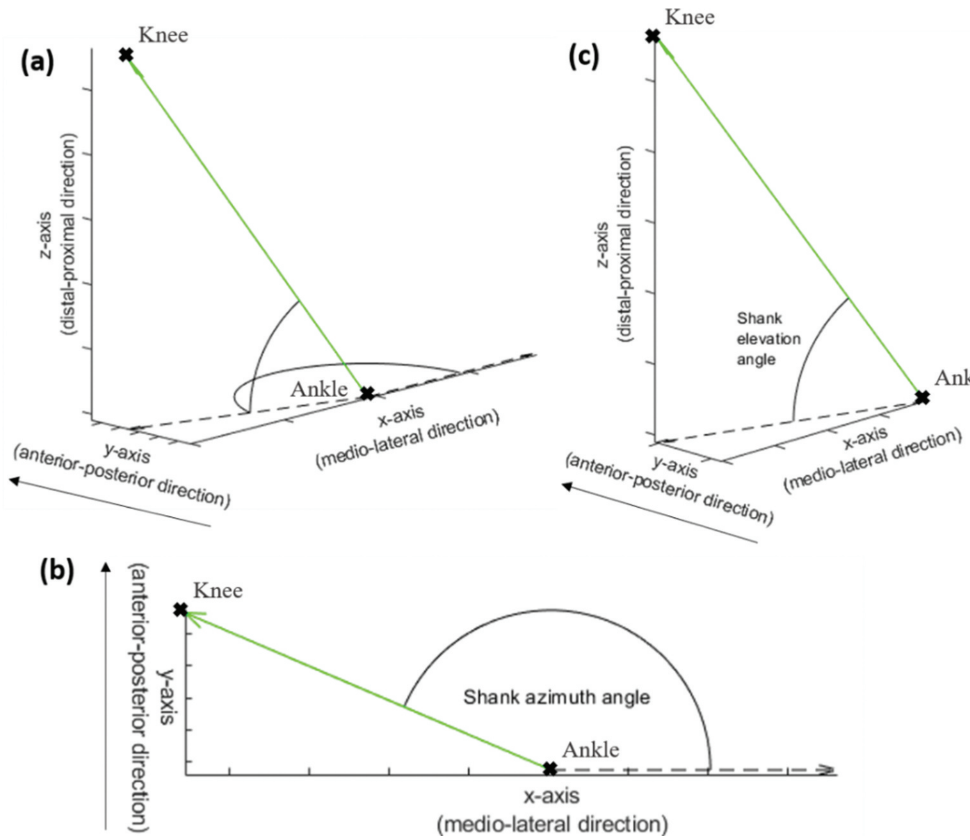

Figure 2. Segment angle conventions for the shank (green arrow), with the origin of the arrow representing the ankle (lateral malleolus) and the arrowhead representing the knee (lateral epicondyle). The solid black arrow indicates the direction of kick (positive y direction). (a) Both the shank segment azimuth and elevation angles. (b) Shank segment azimuth angle (angle between a vector in the positive x direction, originating from the ankle, to the segment vector projected in the x-y plane), viewed from above. (c) Shank segment elevation angle (angle between the 3D segment vector and the x-y plane).

to the y-z plane. The top and bottom of the ball and the impact location were digitised for each kick (Quintic Biomechanics v31, Quintic Consultancy Ltd, UK). Impact location was described relative to the top of the ball (Figure 4), and the global impact location relative to the vertical was also determined.

Three–dimensional resultant ball velocity was determined by reconstructing the geometric centre of the ball (Visual3D v2020.08.3, C–Motion, Inc., USA) and by fitting polynomial equations to the first 10 frames of raw ball flight displacement data immediately after it had visually left the foot (first order for both horizontal directions and second order for the vertical direction). Ball launch elevation (angle between the resultant ball flight velocity vector and the x–y plane) and azimuth (angle between the resultant ball flight velocity vector and the y–zplane) angles were also measured. Resultant foot CM velocity at impact start and end were each determined by averaging eight frames (i.e., 2 ms) of velocity data (calculated using the first central difference method) either side of the impact, respectively. Impact efficiency was quantified using the coefficient of restitution (CoR) and foot-ball velocity ratio (F:B) (Peacock & Ball, 2018b):

$$\text{Coefficient of restitution} = \frac{v_b - v_f}{u_f}$$

$$\text{Foot} - \text{ball velocity ratio} = v_b : u_f$$

Where: v_b = resultant velocity of the ball geometric centre at the end of impact; v_f = resultant velocity of the foot CM at impact end; u_f = resultant velocity of the foot CM at the impact start.

Statistical analysis

Paired-samples t-tests were performed to assess the significance of the observed effects between ball orientation conditions. The alpha level (0.05) was adjusted using the Benjamini–Hochberg procedure (Benjamini & Hochberg, 1995) to account for 112 comparisons being made across the analysed combinations of groups for all variables. When comparing the upright and horizontal ball orientation conditions, three sets of comparisons were made using data from all kickers ($n = 8$), data from only the rugby kickers ($n = 4$), and data from only the soccer kickers ($n = 4$). For any comparisons that involved either the preferred or backward ball orientation conditions, only data from the rugby kickers ($n = 4$) or the soccer kickers ($n = 4$) were used, respectively. Effect sizes (Cohen's d) and 95% confidence intervals were calculated (Cohen, 1988) and interpreted as follows: < 0.20, trivial; 0.20–0.59, small; 0.60–1.19, medium; 1.20–1.99, large; and ≥ 2.00, very large (Hopkins, 2000).

Results

Part 1: notational analysis of the ball orientation preferences of international Rugby Union kickers

Each kicker used a consistent ball orientation for all of their kicks throughout the tournament, and 314 out of 416 (75.5%) kicks were successful (Table 1). Thirteen (25.5%) kickers used an upright ball orientation, 14 (27.5%) used a diagonal orientation,

Table 1. Success percentages and mean distances and angles for all kicks taken in each category (mean ± *SD [range]*).

Ball orientation category	Success (%)	Distance (m)	Angle (°)
Upright	73.3	28.0 ± 12.1 *[6 - 50]*	31 ± 15 *[0 - 56]*
Diagonal	78.9	29.8 ± 11.4 *[8 - 47]*	31 ± 16 *[0 - 54]*
Horizontal	73.6	31.0 ± 11.3 *[8 - 57]*	29 ± 16 *[0 - 56]*
All	75.5	29.7 ± 11.6 *[6 - 57]*	30 ± 16 *[0 - 56]*

and 24 (47.1%) used a horizontal orientation. 116 (27.9%), 152 (36.5%) and 148 (35.6%) kicks were taken from each respective orientation.

In comparison to a model with no independent variables, the binary logistic regression was statistically significant in predicting the outcome of kicks at goal ($\chi^2 = 93.1$, $df = 19$, $p < 0.001$). The model correctly predicted 79.1% of cases; 92.7% of successful kicks and 37.3% of misses were classified correctly. From the tournament mean distance (29.7 m) and an angle of 0°, the model indicated that a place kick had an expected success of 84.4%, 90.0%, or 86.8% when taken using an upright ball orientation, diagonal orientation, or horizontal orientation, respectively (Figure 3). However, ball orientation categories were not significant independent variables in the model; only kick angle and kick distance were (Table S1).

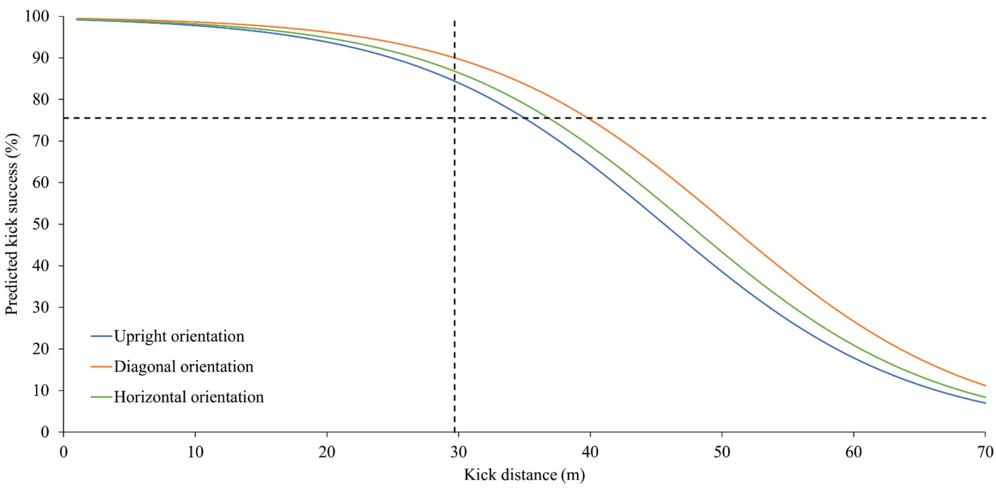

Figure 3. Predicted percentages of kick success at each independent metre when angle is kept constant at 0°, presented for each ball orientation category. Mean tournament success percentage is illustrated by the horizontal dashed line and the mean tournament kick distance is illustrated by the vertical dashed line.

Part 2: empirical analysis of the foot-ball impact and effect of experimental manipulations to ball orientation

The mean impact location on the ball ranged from 181.2 ± 3.8° to 253.5 ± 4.4°, and all conditions were significantly different ($d = 0.25$ to 17.68; Table S2) except for the upright and preferred conditions within the rugby kickers (Figure 4). In the horizontal condition, the mean impact location was close to the bottom end of the ball's long axis, and mean impact location moved clockwise around the ball for the other conditions, with impact occurring closest to the middle of the ball's belly for the backward condition. However, when measured relative to the vertical, the only significant difference in mean global impact location was between the upright and horizontal conditions when compared across all kickers (Figure 4).

Mean duration of the impact phase ranged from 9.0 ± 0.8 ms to 11.8 ± 1.5 ms (Table 2). The horizontal ball orientation had a significantly longer mean impact duration than the upright condition when compared across all kickers, and there were small to very large differences in impact duration across all comparisons ($d = 0.35$ to 2.13; Table S3). The greatest mean CoR (0.62 ± 0.04) and mean foot-ball velocity ratio (F:B; 1.25 ± 0.05) were achieved by the soccer kickers during the backward condition, and

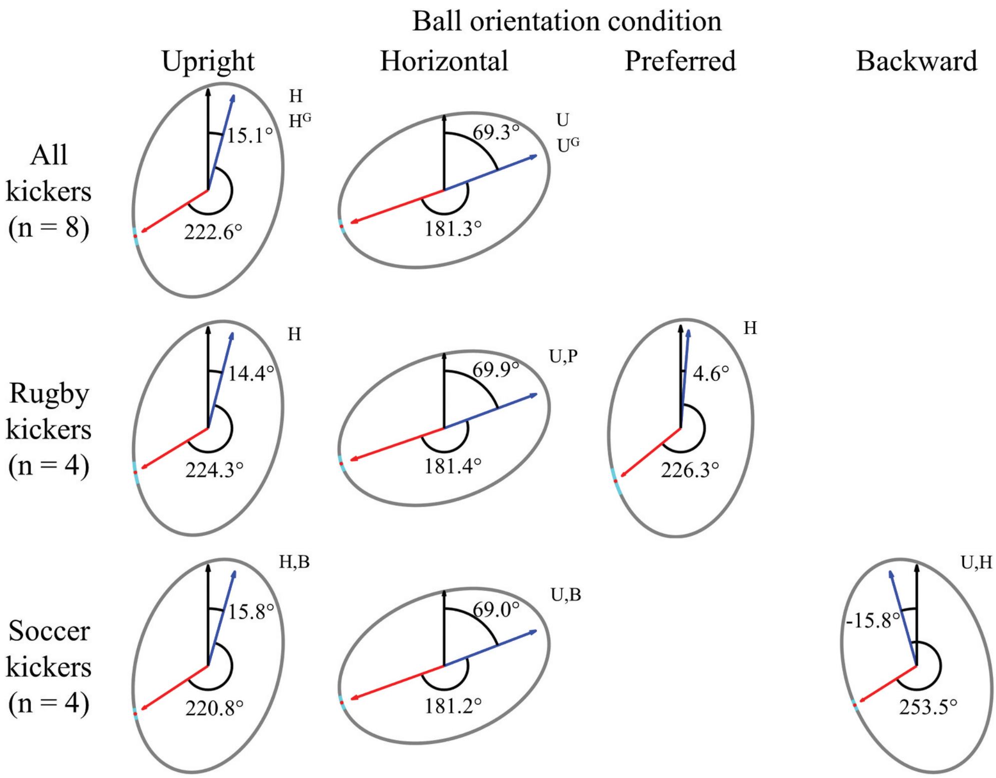

Figure 4. Ball orientation and impact location on the ball for kicks taken using different ball orientations. The black arrow is a vertical vector from the ball centre. The blue arrow is along the ball's long axis from the ball centre towards the top of the ball. The red arrow is pointed towards the mean impact location (red dot on the ball's shell) from the ball centre. Standard deviation of the impact location is represented by the cyan on the ball's shell.
Pairwise comparisons between ball orientation conditions are indicated with letters: U = significantly ($p < 0.05$) different to kicks taken with an upright ball orientation; H = significantly ($p < 0.05$) different to kicks taken with a horizontal ball orientation; P = significantly ($p < 0.05$) different to kicks taken with a preferred ball orientation; B = significantly ($p < 0.05$) different to kicks taken with a backward ball orientation. Superscript G indicates significant differences when the global impact location was compared between conditions.

Table 2. Impact, lower limb kinematic and performance variables for kicks taken using different ball orientation conditions (mean ± SD).

		Ball orientation condition			
		Upright	Horizontal	Preferred	Backward
All kickers (n = 8)	Impact duration (ms)	9.6 ± 1.0 ^{H}	11.1 ± 1.3 ^{U}		
	Coefficient of restitution	0.55 ± 0.10	0.54 ± 0.05		
	Foot-ball velocity ratio	1.20 ± 0.06	1.20 ± 0.04		
	Foot azimuth angle at foot-ball impact (°)	24.8 ± 7.1	27.2 ± 5.2		
	Foot elevation angle at foot-ball impact (°)	−15.0 ± 8.0	−15.5 ± 7.9		
	Shank azimuth angle at foot-ball impact (°)	153.2 ± 5.6	156.8 ± 4.5		
	Shank elevation angle at foot-ball impact (°)	57.0 ± 6.8	57.0 ± 6.4		
	Plantar flexion angle at foot-ball impact (°)	31.8 ± 8.0	33.0 ± 8.2		
	Plantar flexion range of motion (°)	10.2 ± 2.2	8.1 ± 2.4		
	Swing plane inclination (°)	49.6 ± 4.9	49.3 ± 3.7		
	Swing plane direction (°)	13.5 ± 7.1	12.0 ± 4.9		
	Resultant ball flight velocity (m/s)	26.6 ± 1.7	27.0 ± 2.4		
	Ball launch elevation angle (°)	25.6 ± 6.0	27.7 ± 4.1		
	Ball launch azimuth angle (°)	−1.5 ± 5.9	0.5 ± 5.6		
Rugby kickers (n = 4)	Impact duration (ms)	10.1 ± 1.1	11.8 ± 1.5	10.7 ± 1.2	
	Coefficient of restitution	0.61 ± 0.05	0.55 ± 0.07	0.57 ± 0.05	
	Foot-ball velocity ratio	1.24 ± 0.02	1.20 ± 0.04	1.21 ± 0.04	
	Foot azimuth angle at foot-ball impact (°)	22.6 ± 7.5	26.5 ± 6.1	24.4 ± 7.9	
	Foot elevation angle at foot-ball impact (°)	−11.2 ± 8.6	−10.9 ± 7.4	−10.6 ± 7.9	
	Shank azimuth angle at foot-ball impact (°)	152.7 ± 5.4	156.6 ± 1.6	158.6 ± 2.4	
	Shank elevation angle at foot-ball impact (°)	58.3 ± 9.7	57.7 ± 8.7	57.3 ± 8.0	
	Plantar flexion angle at foot-ball impact (°)	28.0 ± 8.6	28.6 ± 8.0	30.2 ± 8.4	
	Plantar flexion range of motion (°)	8.6 ± 2.0	8.4 ± 3.2	10.0 ± 1.6	
	Swing plane inclination (°)	50.3 ± 7.3	49.1 ± 4.4	48.3 ± 5.0	
	Swing plane direction (°)	16.4 ± 5.6	14.2 ± 3.2	19.1 ± 4.7	
	Resultant ball flight velocity (m/s)	26.0 ± 1.5	25.4 ± 0.7	25.6 ± 0.6	
	Ball launch elevation angle (°)	27.8 ± 8.4	28.0 ± 1.5	32.9 ± 4.4	
	Ball launch azimuth angle (°)	−4.4 ± 6.5	−0.5 ± 6.5	3.2 ± 3.5	
Soccer kickers (n = 4)	Impact duration (ms)	9.2 ± 0.7	10.4 ± 0.5		9.0 ± 0.8
	Coefficient of restitution	0.49 ± 0.10	0.52 ± 0.03 ^{B}		0.62 ± 0.04 ^{H}
	Foot-ball velocity ratio	1.16 ± 0.07	1.19 ± 0.05 ^{B}		1.25 ± 0.05 ^{H}
	Foot azimuth angle at foot-ball impact (°)	27.0 ± 7.0	27.9 ± 4.9		27.4 ± 5.0
	Foot elevation angle at foot-ball impact (°)	−18.8 ± 6.0	−20.2 ± 5.9		−17.5 ± 8.7
	Shank azimuth angle at foot-ball impact (°)	153.7 ± 6.5 ^{B}	157.1 ± 6.6		160.3 ± 6.0 ^{U}
	Shank elevation angle at foot-ball impact (°)	55.8 ± 3.0	56.3 ± 4.1		55.6 ± 2.6
	Plantar flexion angle at foot-ball impact (°)	35.5 ± 6.2 ^{H}	37.5 ± 6.2 ^{U}		37.7 ± 7.6
	Plantar flexion range of motion (°)	11.8 ± 0.9	7.8 ± 1.7		6.3 ± 2.7
	Swing plane inclination (°)	48.9 ± 1.3	49.4 ± 3.6		48.4 ± 3.5
	Swing plane direction (°)	10.7 ± 8.0	9.8 ± 5.8		11.3 ± 7.1
	Resultant ball flight velocity (m/s)	27.2 ± 1.9	28.6 ± 2.6		29.6 ± 2.7
	Ball launch elevation angle (°)	23.3 ± 0.3	27.3 ± 6.0		24.5 ± 4.3
	Ball launch azimuth angle (°)	1.4 ± 4.0	1.6 ± 5.3		1.7 ± 6.2

Pairwise comparisons between ball orientation conditions are indicated with superscript letters: U = significantly (p < 0.05) different to kicks taken with an upright ball orientation; H = significantly (p < 0.05) different to kicks taken with a horizontal ball orientation; P = significantly (p < 0.05) different to kicks taken with a preferred ball orientation; B = significantly (p < 0.05) different to kicks taken with a backward ball orientation.

these were significantly different from their horizontal condition (Table 2). All other CoR and F:B comparisons were not significantly different between conditions ($d = 0.16$ to 2.52 and 0.10 to 1.39, respectively; Table S4).

There were no significant differences in foot, shank, or swing plane kinematics between conditions when compared across all kickers (Table 2; $d = 0.01$ to 0.91, Tables S5 and S6). Likewise, there were also no significant differences in these variables between conditions when looking at the rugby kickers ($d = 0.03$ to 1.42). For the soccer kickers, shank azimuth angle at impact was significantly greater in the backward condition than the upright condition ($d = 1.06$), and the kicking foot was significantly more plantar flexed in the horizontal condition than the upright condition ($d = 0.32$). There were no significant effects of condition on swing plane properties, plantar flexion range of motion, resultant ball velocity, or ball launch angles in any comparison (Table 2; $d =$ 0.02 to 2.95, Tables S5, S6, and S7).

Discussion and implications

We aimed to identify the ball orientations used by international place kickers and whether these were associated with kick outcome, and to provide the first high-speed analysis of the foot-ball interaction in human rugby place kicking, including a preliminary investigation of how ball orientation manipulations interact with the foot-ball impact and kick technique. Our first two hypotheses were accepted as different ball orientation preferences were evident in international kickers but there was no significant effect of ball orientation choice on performance outcome when all kicks at the 2019 Rugby World Cup were analysed and situational factors were considered. Our third hypothesis was largely rejected as acute manipulations to ball orientation did not affect the techniques used by rugby kickers and only affected lower limb kinematics in soccer kickers in some instances. Our fourth hypothesis was also largely rejected because, although the different ball orientations led to different impact locations on the ball, there were no effects on the impact efficiency measures or the resulting ball flight characteristics, aside from when the soccer kickers used the backward condition.

Part 1: notational analysis of the ball orientation preferences of international Rugby Union kickers

All 51 kickers analysed used a consistent ball orientation. Whilst the horizontal orientation was most prevalent (47.1%), over a quarter of all kickers used each of the upright and diagonal orientations. Therefore, there is not an overwhelming single ball orientation preference even amongst the world's best kickers. The raw success percentage of kicks taken from a diagonal orientation was greater than from the other two orientations (Table 1), and when several situational variables were controlled for (Pocock et al., 2018), kicks taken with a diagonal ball orientation had greater predicted success (90.0% for a straight kick taken from 29.7 m) than the upright (84.4%) and horizontal (86.8%) orientations (Figure 3). However, although there may be a small effect of ball orientation on kick success, it was not a significant factor in the model, and it must also be considered that the model only correctly classified the outcome of 79.1% of kicks. This may be due to other confounding variables, which were not included in the model. Whilst some of these may be environmental (e.g., weather or pitch conditions), others are likely directly related to individual kickers and include variables associated with their technique. Given the clear existence of different ball orientation preferences, subsequent empirical analyses of foot-ball interaction and kicker technique were undertaken to help further the understanding of different ball orientation preferences.

Part 2: empirical analysis of the foot-ball impact and effect of experimental manipulations to ball orientation

Ball orientation clearly influenced the impact location on the ball, with significant differences observed across all comparisons with the exception of the rugby kickers' preferred and upright conditions (Figure 4). Ball impact locations were also consistent between the rugby and soccer kickers when using each of the upright and horizontal ball orientations. However, when considered relative to the global vertical axis, impact locations were not significantly different across all comparisons aside from the upright versus horizontal across all kickers (Figure 4). These combined findings suggest that although the ball may be orientated differently on the tee, kickers still appear to strike the ball in a very consistent location relative to the vertical.

This consistent impact location is likely achieved by a consistent delivery of the lower leg and foot across all conditions. The differences in kicking leg kinematics at the start of the impact phase between ball orientation conditions were non-significant, except for two variables within the soccer kickers. These relatively consistent foot and shank kinematics at ball contact suggest that the different ball impact locations between orientation conditions are likely a function of the altered ball orientation and that the kickers do not appear to position their legs differently at the start of impact. This consistency in technique is further confirmed by the lack of any significant differences in the swing plane properties. These properties were all broadly similar to those previously reported for rugby kickers from their preferred ball orientations (Bezodis et al., 2019), and they suggest that kickers also swing their foot towards the ball in a consistent plane irrespective of ball orientation on the tee.

It should be noted that there were significant differences in shank kinematics and plantar flexion angles at foot-ball impact between some conditions for the soccer kickers (Table 2). The soccer kickers produced a significantly greater plantar flexion angle at foot-ball impact in the horizontal condition than in the upright condition. A greater plantar flexion angle at foot-ball impact has previously been linked to a reduced plantar flexion range of motion during impact, and a subsequently improved impact efficiency in Australian foot-ball (Ball, 2010; Peacock et al., 2017) and mechanical simulations (Peacock & Ball, 2018b, 2019b). The soccer kickers also displayed this trend between the horizontal and upright conditions in the current study, although the differences were non-significant. Future research could further explore the implications of plantar flexion angle at foot-ball impact and confirm the direction of effects in rugby place kicking. Soccer kickers were included in the current study because they had a well-established kicking action (range = 12–25 years of experience playing competitive soccer) but no prior rugby ball orientation preference. The observed significant differences therefore suggest that acute changes to ball orientation could influence some lower leg kinematics in kickers with no experience of rugby kicking. However, in rugby kickers who already have a preference (range = 4–11 years of kicking in competitive rugby matches), acute changes to ball orientation would likely not lead to acute changes in their kicking leg kinematics. Longer-term interventions are required to understand how experienced rugby kickers might adapt to different ball orientations. Future studies could also compare the techniques of rugby kickers who habitually prefer different ball orientations, but the causality of any differences would be difficult to ascertain, hence why the current exploratory experimental approach was preferred. One alternative could be to investigate the impact characteristics associated with different rugby ball orientations using a mechanical simulator (e.g., 12,13,15) alongside systematic adjustments to the mechanical leg kinematics in order to understand potential interactions between kicking leg kinematics and ball orientation preferences.

This is the first study to report impact durations in human Rugby Union place kicking. Mean impact duration ranged from 9.0 to 11.8 ms; comparable to when using a mechanical kicking leg (10.9 ms to 11.8 ms) (Ball & Peacock, 2020) and to maximum distance Australian foot-ball kicking in humans (12.1 ± 1.3 ms) (Peacock et al., 2017), although slightly longer than in human Rugby League place kicks (7.4 ± 0.3 ms) (Ball, 2010). It may be that the impact durations of Rugby Union place kicks in this study were slightly longer than in Rugby League place kicks (Ball, 2010) due to slight differences in the shape and mass of the balls. When compared between conditions, impact duration was significantly shorter in the upright than the horizontal condition across all kickers (Table 2). Given the aforementioned lack of significant differences in kicking leg kinematics between these conditions, this is most likely an effect of the different ball impact locations. Horizontal ball orientations led to an impact very near the point of the ball and the longest mean impact durations. An increased impact duration when impacting the point of the ball (11.8 ms) has also been seen in mechanical kicking simulations when compared with impacting between the point and the belly (like the current upright and preferred conditions) of the ball (10.9 ms) when all other factors were held constant (Ball & Peacock, 2020). However, despite this difference in impact location and duration between the upright and horizontal ball orientation conditions, CoR and F:B ratio were not significantly different between the two. This suggests that despite different impact locations on the ball affecting the duration of impact, the overall efficiency of the impact is not affected, and the same outcome can be achieved for a given incoming foot velocity.

An important observation is that when impact was located closest to the belly of the ball (backward condition for the soccer kickers; 253.5°), the highest impact efficiencies of any condition were observed (CoR = 0.62 ± 0.04, F:B = 1.25 ± 0.05). Further investigation of each individual rugby kicker's impact efficiency results also revealed that mean CoR was greatest when their impact location was closest to the belly. Although a backwards orientation was not used by any of the international rugby kickers studied in Part 1, the soccer kickers were prescribed it based on pilot testing with a separate group of soccer kickers where some chose a backward orientation. This may be perceived by the soccer kickers as most similar to kicking a spherical soccer ball, but the fact that the impact efficiency values were highest in this across all analysed conditions suggests that further research is warranted to better understand the potential merits of a backward orientation which appears to encourage an impact nearest to the belly of the ball. This is generally consistent with previous research (Holmes, 2008; Michelini et al., 2019) which has found the greatest impact efficiency with an impact location near the belly of the ball. However, a decrease in CoR has been observed when impacting the ball between the point and belly (like the upright and preferred conditions in this study) compared with impacting the ball on its point (like the horizontal condition in this study) (Ball & Peacock, 2020; Michelini et al., 2019). The use of mechanical simulations and human kickers may partly influence this disparity between studies because simplification of elements such as the lack of soft tissue would likely influence energy transfer between the foot and ball (Peacock & Ball, 2018b).

The current study adopted a broad exploratory approach, comprising two parts, to investigate ball orientation in rugby place kicking. Whilst the two parts of this study have combined to provide valuable initial information to develop the understanding of place kicking, both parts contained limitations. A large sample of international players were studied in Part 1, but the within-competition analysis meant that ball orientation preferences could only be broadly categorised. Also, some kickers in Part 1 attempted only one place kick, whereas others attempted up to 34 across the tournament. This will likely have acted as a random factor and potentially resulted in the model being biased towards those kickers who attempted a greater number of kicks. The detailed high-speed analysis of the foot-ball impact was then undertaken on a smaller sample. The Benjamini–Hochberg procedure (Benjamini & Hochberg, 1995) was used to control the probability of making a Type I error, yet this increases the likelihood of a Type II error and further investigation of some observed effects with larger sample sizes is warranted. Although kickers were instructed to kick as straight as possible along a straight line on the ground and ball launch elevation and azimuth angles were measured to provide a component of ball flight direction, goal posts were not used as a target and kick accuracy was not of direct focus during the study. The primary interests were in the technique adaptations and changes in impact characteristics because of the different ball orientation conditions. Finally, our entire sample of rugby kickers preferred an orientation close to upright. This may have affected our results as none were experienced with the horizontal condition. We included soccer kickers to eliminate preference and previous rugby kicking experience from one sub-group of kickers, and we intentionally did not allow any kickers to familiarise themselves with the different orientations so that true acute effects were obtained. Future studies may wish to consider longer-term interventions where kickers (both rugby and soccer) can practise with different orientations.

Given that each kicker's choice of ball orientation currently appears to be a matter of personal preference (Bezodis et al., 2018), kickers and coaches should be encouraged to explore various ball orientations where possible. Whilst being cognisant of the limitations of the current study as discussed above, our results suggest that exploring orientations that result in an impact location closer to the belly of the ball, such as a backward orientation for the non-experienced (soccer) kickers in the current study, may prove beneficial for impact efficiency. Importantly, this exploration can likely be done without the need for, or causing, large alterations in the kicker's technique given the few clear effects of different ball orientation conditions on place kick technique.

Differences in ball orientation preference clearly existed between kickers at the Rugby World Cup 2019, although this was not a significant factor in predicting the success of any given kick. Experimental investigations then revealed that although there are different impact locations on the ball between different ball orientations, the impact location relative to the global was highly consistent and kickers appeared to adopt relatively consistent techniques irrespective of acute changes in ball orientation.

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