

Contributions of the non-kicking-side arm to rugby place-kicking technique

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Abstract

To investigate non-kicking-side arm motion during rugby place kicking, five experienced male kickers performed trials under two conditions, both with an accuracy requirement but one with an additional maximal distance demand. Joint centre coordinates were obtained at 120 Hz during kicking trials and a three-dimensional model was created to enable the determination of segmental contributions to whole-body angular momentum. All kickers possessed minimal non-kicking-side arm angular momentum about the global medio-lateral axis. The more accurate kickers exhibited greater non-kicking-side arm angular momentum about the global antero-posterior axis. This augmented the whole-body antero-posterior angular momentum, and altered the whole-body lateral lean at ball contact. The accurate kickers also exhibited greater non-kicking-side arm angular momentum about the global longitudinal axis, which opposed the kicking leg longitudinal angular momentum and attenuated the whole-body longitudinal angular momentum. All participants increased the longitudinal angular momentum of the non-kicking-side arm in the additional distance demand condition, except for one participant whose accuracy decreased, suggesting that the longitudinal angular momentum of the non-kicking-side arm assists maintenance of accuracy in maximum distance kicking. Goal kickers should be encouraged to produce non-kicking-side arm rotations about both the antero-posterior and longitudinal axes, as these appear important for both the initial achievement of accuracy, and for maintaining accuracy during distance kicking.

Keywords: *Angular momentum, arm, biomechanics, kicking, rugby, three-dimensional*

Introduction

Rugby union place-kicking technique remains largely unexplored by sports biomechanists, except for a two-dimensional analysis (Aitchison and Lees, 1983). Many two-dimensional sagittal-plane studies of soccer kicking have been undertaken, but differences have been found in linear (up to 10%) and angular (up to 84%) speeds of the kicking leg joints between two- and three-dimensional analyses (Rodano and Tavana, 1993). This indicates that movement occurs in at least one of the non-sagittal planes, reinforcing the notion that accurate descriptions of kicking technique require a three-dimensional analysis (Lees and Nolan, 1998).

Segment rotations in both the transverse and frontal planes have been observed in soccer kicking analyses performed in three dimensions (Browder, Tant, and Wilkerson, 1991; Lees, Kershaw, and Moura, 2004; Lees and Nolan, 2002; Tant, Browder, and Wilkerson, 1991). When an accuracy demand is placed upon a kicker, ball speed has been found to fall by between 20 and 25% from maximal values (Asami, Togarie, and Kikuchi, 1976; Lees and Nolan, 2002), and it has been postulated that ball speed is influenced by trunk segment rotations about the longitudinal axis (Browder et al., 1991; Lees and Nolan, 2002). This has led to suggestions of the need for further upper extremity analyses during kicking (Lees and Nolan, 2002; Tant et al., 1991). A full-body kinematic model was recently applied to the study of instep soccer kicks (Shan and Westerhoff, 2005), and upper-body movements were found to vary between participants of differing abilities. Flexion and adduction of the non-kicking-side arm were found to be widely used by skilled kickers before ball contact, but were scarcely noticeable in their novice counterparts. These movements were suggested as one cause of the increased ball speeds exhibited by skilled kickers (Shan and Westerhoff, 2005), but they may also relate to their accuracy.

Angular momentum is a variable that provides a measure of the quantity of rotational motion. The angular momentum of any rotating body is a product of its moment of inertia and its angular velocity. Whole-body angular momentum can be considered to be the sum of the angular momentum possessed by all the segments comprising that body. The angular momentum possessed by a given body segment consists of a local term, owing to rotations about the segment centre of mass, and a remote term, owing to rotations of the segment about the whole-body centre of mass. Despite regular inferences about the importance of various segment rotations in kicking technique, no studies have investigated the segmental contributions to the generation of angular momentum during kicking. Owing to the rapid knee extensions (1520–1960 degrees/s) previously observed in rugby kicking (Aitcheson and Lees, 1983), it is likely that the largest peak values of kicking leg angular momentum will occur about the medio-lateral axis. However, movements of the upper body may also be used to either reduce or augment the total angular momentum generated about each axis. The arms will likely experience rapid changes in position during the kicking action, particularly in skilled kickers (Shan and Westerhoff, 2005). Therefore, it is likely that these skilled kickers will exhibit a greater potential to alter their total angular momentum profiles about each axis, which may be beneficial for performance in terms of accuracy or ball speed. Using three-dimensional analysis techniques, the aim of the present study was to investigate how the non-kicking-side arm contributes to the generation and control of whole-body angular momentum during rugby place kicking.

Methods

Participants

Five university first-team male kickers (mean age 20.6 years, $s = 2.7$; stature 1.81 m, $s = 0.09$; body mass 80.2 kg, $s = 7.7$), each with at least 5 years' kicking experience, participated in the study. All were free from injury and provided informed consent in accordance with the procedures of the university research ethics committee.

Procedures

After a self-directed warm-up, 39 spherical markers of 12.5 mm diameter were attached to specific anatomical landmarks on the participant for use with the Plug-In-Gait model

(Vicon™, Oxford Metrics Ltd., Oxford, UK). A marker was also placed on the surface of a standard weight and pressure size-five rugby ball, at one end of the longitudinal axis. Ball contact was subsequently identified from initial displacement of this marker, but the marker was not used to calculate ball velocity, as its path is unlikely to be representative of the centre of mass of the ball owing to rotations.

All participants completed seven accuracy trials in which the emphasis was placed on accuracy relative to a vertical target; no distance requirement was included. Each participant also completed seven distance trials in which, in addition to ensuring accuracy, the participants also had to attempt to kick the ball as far as they could. The order of conditions was randomized between participants. The accuracy condition was intended to replicate, for example, kicks at the posts from the 22-m line, while the distance condition was intended to replicate kicks at the posts from the limit of the kicker's range, where accuracy remains vital but maximal kick distance is also required for a kick to be successful. No instructions about speed of movement or ball velocity were given to the participants.

Data collection

Kinematic data from each participant were recorded in a large indoor sports hall using an eight-camera Vicon™ 612 motion analysis system (Oxford Metrics Ltd., Oxford, UK), sampling at 120 Hz and calibrated to the manufacturer's instructions (mean residual calibration error = 1.89 mm, $s = 0.53$). A digital video camera (Sony, DCR TRV-900E) operating at 50 Hz, and positioned above and behind the kicker, captured video data to record the horizontal deviation of the ball from a 10×0.08 m target. This target was suspended vertically on an expanse of netting about 10 m in front of the kicker, and represented the centre of the goal posts. Two further 50 Hz digital video cameras (Sony, DCR TRV-900E) were placed in front of the kicker at angles of about 45° to the intended direction of ball travel so that their optical axes intersected at an angle approximating 90° . The two cameras were synchronized to within 1 ms by illuminating an array of 20 light-emitting diodes, sequentially at 1-ms intervals, in each camera view, and were used to reconstruct ball velocity. Synchronized ground reaction force data from the support leg were recorded (600 Hz) in three orthogonal directions (vertical, antero-posterior, medio-lateral) through a force platform (Kistler, 9287BA, Amherst, NY). The ball, placed upon a kicking tee of the participant's choice, was positioned such that the kicker could adopt his preferred angled approach towards the ball, and that the support foot would land on the force platform.

Data reduction

For each trial, three-dimensional coordinates for each of the 40 reflective markers were reconstructed using Workstation software (version 4.5, Oxford Metrics Ltd., Oxford, UK). The marker trajectories were smoothed using a generalized cross-validatory spline (Woltring, 1986), and all subsequent data were processed using custom Matlab code (Matlab 7.0, Mathworks Inc., USA). A 10-segment kinematic model was then created from the calculated joint centre coordinates produced from the Plug-In-Gait model, consisting of head, trunk, upper-arm, forearm, thigh, and shank segments. Owing to incomplete kinematic data for the hands and feet throughout many of the trials, the foot and hand segments were incorporated into the shank and forearm segments, respectively. Segment inertia parameters (mass, centre of mass location, and radius of gyration) were obtained from de Leva (1996), and

adjustments were made to create combined shank–foot and forearm–hand segments based upon the anthropometric measurements of the five participants.

Segment centre of mass time-histories were then calculated and whole-body centre of mass was subsequently determined from these values. All of the displacement trajectories of the centre of mass were fitted with interpolating quintic spline functions (Wood and Jennings, 1979) and their velocities derived. Three-dimensional vectors were constructed from each segment centre of mass to the whole-body centre of mass, and the instantaneous velocity of each segment centre of mass relative to the whole-body centre of mass was computed. This enabled the computation of the remote term of angular momentum for each segment, using the modified methods of Dapena (1978), as detailed by Bahamonde (2000). Vectors in the direction of the longitudinal axis of each segment, originating from the proximal end-points, were then computed. The unit vector components of these were fitted with interpolating quintic spline functions (Wood and Jennings, 1979) and their velocities subsequently derived. The velocities of the segment vector components were used to compute the local angular momentum terms for each segment, again using the procedures outlined by Bahamonde (2000). The local and remote terms were then summed to yield total angular momentum values for each segment, which were subsequently grouped into five new segments: kicking leg, support leg, kicking-side arm, non-kicking-side arm, and trunk. Angular momentum values were then calculated about three fixed orthogonal axes passing through the centre of mass of the kicker (views of rotations about each axis are illustrated in Figure 1). The X-axis was perpendicular to the intended direction of ball travel, with the positive direction to the right. The positive Y-axis pointed in the intended direction of ball travel, while the Z-axis pointed vertically, with the upwards direction being positive. Values of angular momentum are subsequently reported as anti-clockwise (positive) or clockwise (negative) and these are reported when viewing the kicker from the right (X-axis), from in front (Y-axis), and from above (Z-axis), as depicted in Figure 1. Absolute values of angular momentum were normalized by dividing by individual ($\text{mass} \times \text{height}^2$) anthropometric characteristics and multiplying by the group mean ($\text{mass} \times \text{height}^2$) anthropometric characteristics. For the left-footed kickers, angular momentum values about the Y- and Z-axes were inverted so that all kickers conformed to the same convention.

Resultant ball velocity was calculated by digitizing (Peak Motus, version 8.1, Englewood, CO) the centre of the ball from recordings obtained by the two synchronized video cameras and subsequent three-dimensional direct linear transformation reconstruction (Abdel-Aziz and Karara, 1971). Final resultant velocity was reported as the average of the five fields after ball contact. To determine kick accuracy, video images from the rear camera were digitized.

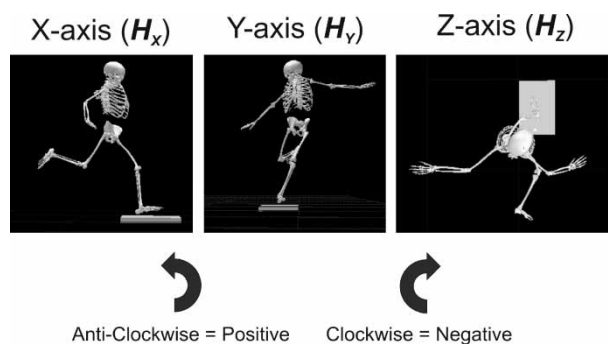


Figure 1. Pictorial representation of the reference system used for defining angular momentum about the three orthogonal axes.

By identifying the field in which the ball made contact with the net, and calculating the scaled horizontal displacement of the ball centre from the target, an accuracy score was produced, with a score of zero indicating perfect accuracy. Support leg contact was identified as the first field of kinematic data after the vertical ground reaction force exceeded 10 N. The kinematic field of data at which the maximum vertical displacement of the ankle joint of the kicking leg occurred was also identified and defined as the end of the follow-through.

Statistical analyses

All data were confirmed for normality and are presented as means \pm standard deviations unless stated otherwise. Where necessary, two-tailed *t*-tests were used to compare variables between participants or conditions, with statistical significance set at $P < 0.05$. Owing to incomplete data, only five trials under each condition were available for the analysis of participant 3.

Results

Indicators of kick performance

Noticeable differences in inter-participant accuracy existed in horizontal ball displacements from the target, with participants 2 and 5 exhibiting the most accurate kicking (Table I). Participant 4 exhibited a significant ($P < 0.01$) decrease in accuracy in the distance condition, despite accuracy still being a fundamental requirement of these trials, while the rest of the kickers retained their accuracy in the distance trials. All five participants kicked the ball with significantly ($P < 0.05$) greater speed in the distance trials (Table I).

Whole-body angular momentum

The X-component of angular momentum typically reached larger average peak values than the Y- and Z-components (Table II). A large anti-clockwise increase in total X-component angular momentum occurred near support leg contact, peak values typically occurred just before ball contact, and remained anti-clockwise throughout the follow-through (e.g. Figure 2). The Y-component of angular momentum was initially clockwise but began to decrease in magnitude soon after support leg contact for all kickers (e.g. Figure 3). The Y-component of angular momentum typically became anti-clockwise before ball contact (Table II), and remained in this direction throughout the follow-through (e.g. Figure 3). The Z-component of angular momentum was anti-clockwise throughout and reached peak

Table I. Average kick accuracy (m) and ball speed (m/s) (mean \pm s).

	Participant 1	Participant 2	Participant 3	Participant 4	Participant 5
All trials, accuracy	0.38 \pm 0.22	0.27 \pm 0.19	0.57 \pm 0.40	0.57 \pm 0.53	0.22 \pm 0.25
A trials, accuracy	0.34 \pm 0.20	0.28 \pm 0.18	0.53 \pm 0.40	0.31 \pm 0.34	0.27 \pm 0.31
D trials, accuracy	0.43 \pm 0.23	0.26 \pm 0.20	0.60 \pm 0.45	0.84 \pm 0.58**	0.17 \pm 0.19
All trials, ball speed	22.7 \pm 1.8	24.2 \pm 1.6	23.5 \pm 2.2	23.5 \pm 2.3	21.7 \pm 1.5
A trials, ball speed	21.3 \pm 1.3	23.1 \pm 1.7	21.9 \pm 1.4	21.7 \pm 1.7	20.4 \pm 0.7
D trials, ball speed	24.0 \pm 0.9***	25.3 \pm 0.5*	25.1 \pm 1.5*	25.3 \pm 1.2***	23.0 \pm 0.8***

Abbreviations: A = accuracy, D = distance. Significantly different from accuracy trials: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

Table II. Normalized average peak angular momentum ($\text{kg}\cdot\text{m}^2/\text{s}$) about each of the three global axes (mean \pm s).

	Participant 1	Participant 2	Participant 3	Participant 4	Participant 5
Max H_X	24.7 ± 1.4	28.7 ± 2.3	29.6 ± 2.2	22.2 ± 1.8	19.5 ± 1.1
Max H_{YAC}	10.1 ± 3.6	14.8 ± 2.8	8.6 ± 2.0	6.9 ± 2.6	15.3 ± 3.2
Max H_{YC}	-25.3 ± 0.8	-16.4 ± 2.3	-20.0 ± 1.4	-14.3 ± 2.8	-14.3 ± 2.3
Max H_Z	17.2 ± 1.6	12.3 ± 1.6	15.5 ± 0.6	10.6 ± 1.9	11.6 ± 1.1
H_Y at ball contact	0.0 ± 2.7	13.1 ± 2.8	1.9 ± 4.1	3.8 ± 3.4	11.9 ± 3.8

Abbreviations: H_X = X-component of angular momentum, H_Y = Y-component of angular momentum, H_{YAC} = Y-component of angular momentum in anti-clockwise direction, H_{YC} = Y-component of angular momentum in clockwise direction, H_Z = Z-component of angular momentum.

values near ball contact (e.g. Figure 4); peak total values were lower in magnitude than peak total X- and Y-component angular momentum values for all participants (Table II).

Participant 1 exhibited slightly different trends compared with the rest of the cohort about the Y-axis, with larger peak clockwise angular momentum values (Table II), which remained clockwise throughout ball contact (Table II). Participants 2 and 5 exhibited significantly ($P < 0.001$) greater magnitudes of both maximum anti-clockwise Y-component angular momentum and Y-component angular momentum at ball contact, compared with the other four kickers (Table II).

Non-kicking-side arm contributions to angular momentum

The non-kicking-side arm possessed minimal X-component angular momentum throughout each trial for all participants (e.g. Figure 2), and average peak values did not exceed

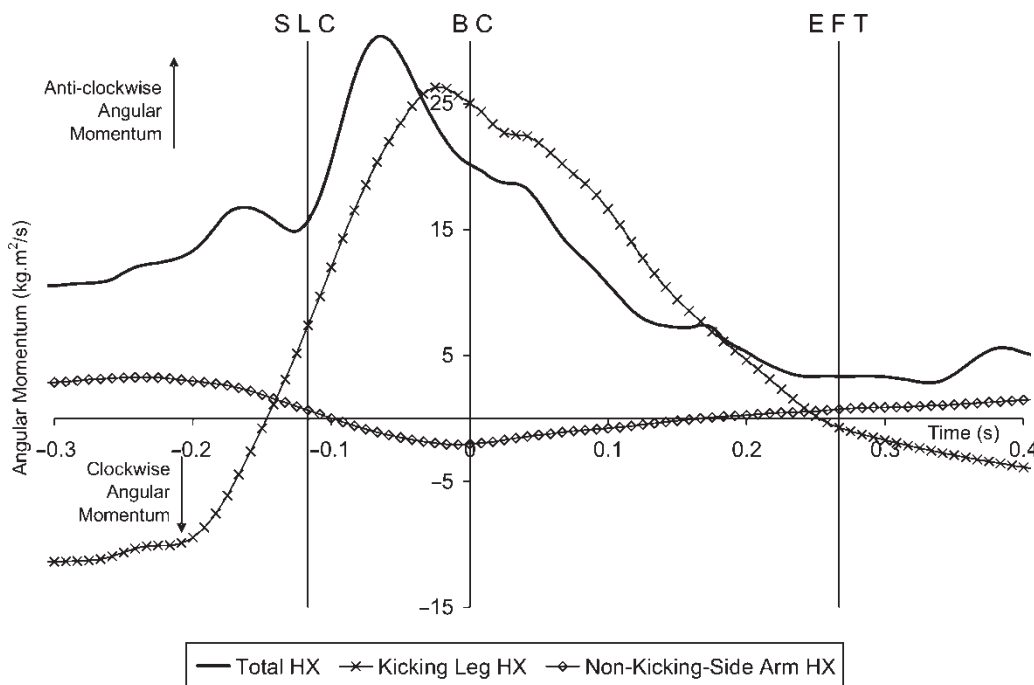


Figure 2. Segmental contributions to total angular momentum about the X-axis (HX) for a trial of participant 2 under accuracy conditions. SLC = support leg contact, BC = ball contact, EFT = end of follow-through.

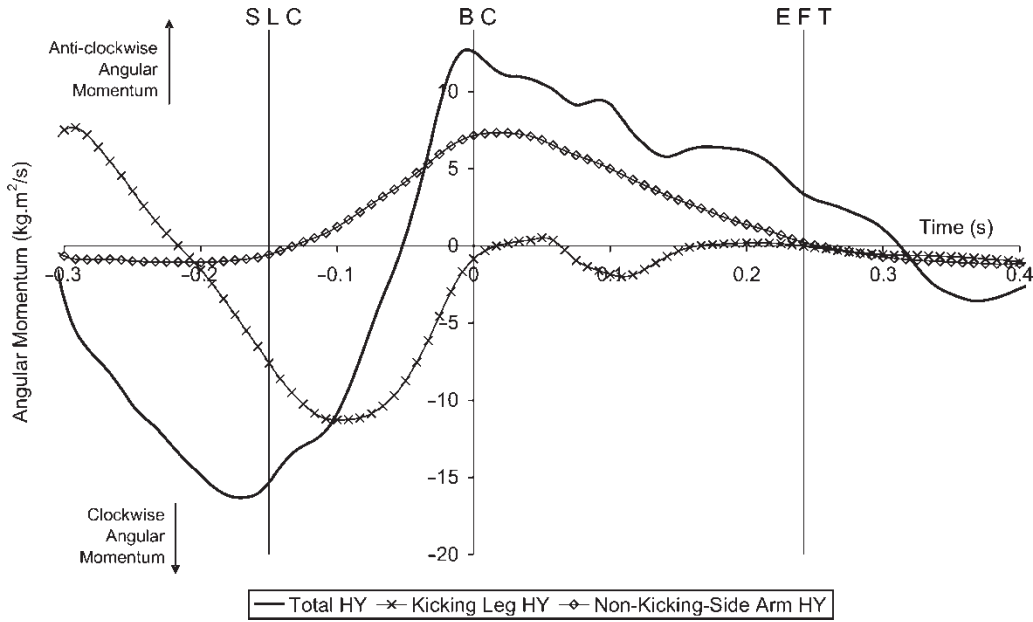


Figure 3. Segmental contributions to total angular momentum about the Y-axis (HY) for a trial of participant 5 under accuracy conditions. SLC = support leg contact, BC = ball contact, EFT = end of follow-through.

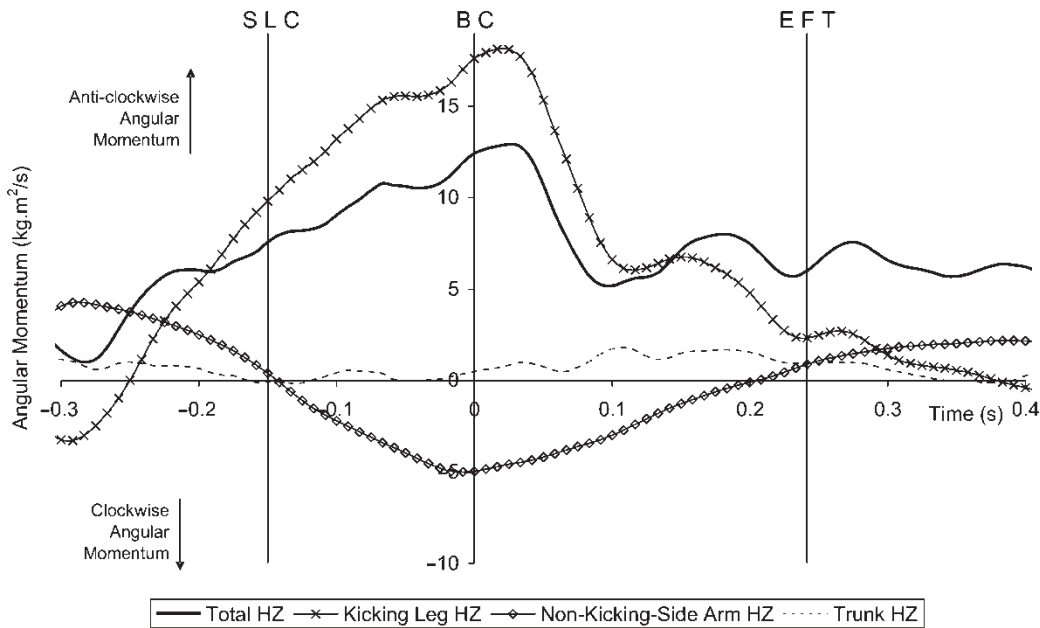


Figure 4. Segmental contributions to total angular momentum about the Z-axis (HZ) for a trial of participant 5 under accuracy conditions. SLC = support leg contact, BC = ball contact, EFT = end of follow-through.

2.03 kg·m²/s for any of the kickers. The Y-component angular momentum for the non-kicking-side arm was predominantly anti-clockwise between support leg contact and the end of the follow-through (e.g. Figure 3), while its Z-component angular momentum was mainly clockwise during this period (e.g. Figure 4). Peak magnitudes of both the Y- and Z-component angular momentums for the non-kicking-side arm occurred near ball contact (e.g. Figures 3 and 4). Clockwise Z-component angular momentum in the non-kicking-side arm was a consistent trend among the kickers, which opposed the large anti-clockwise Z-component angular momentum in the kicking leg (e.g. Figure 4).

Participants 2 and 5 exhibited significantly ($P < 0.001$) greater peak anti-clockwise Y-component angular momentum for the non-kicking-side arm than the remainder of the cohort (Figure 5). As previously stated, these peak magnitudes occurred near ball contact and, at this time, participants 2 and 5 also positioned their non-kicking-side arm centre of mass closer to the vertical projection of their base of support (stance ankle) through shoulder adduction and horizontal flexion (Figure 6). Magnitudes of Z-component angular momentum for the non-kicking-side arm at ball contact for participants 2 and 5 were also significantly ($P < 0.001$) greater than the corresponding values of their less accurate counterparts (Figure 7). With the exception of participant 4 ($P = 0.67$), all participants increased significantly ($P < 0.01$) their Z-component angular momentum for the non-kicking-side arm at ball contact in the distance trials (Figure 7).

Kicking leg contributions to angular momentum

After support leg contact, X-component angular momentum for the kicking leg was consistently anti-clockwise for all participants (Figure 2). Peak magnitudes occurred just before ball contact and values remained anti-clockwise throughout the follow-through (e.g. Figure 2). For all kickers, the kicking leg had the largest segmental X-component angular momentum in both conditions. The time history for the Y-component angular momentum of the kicking leg followed a general pattern similar to that of total Y-component angular momentum (e.g. Figure 3), being predominantly clockwise before ball contact and

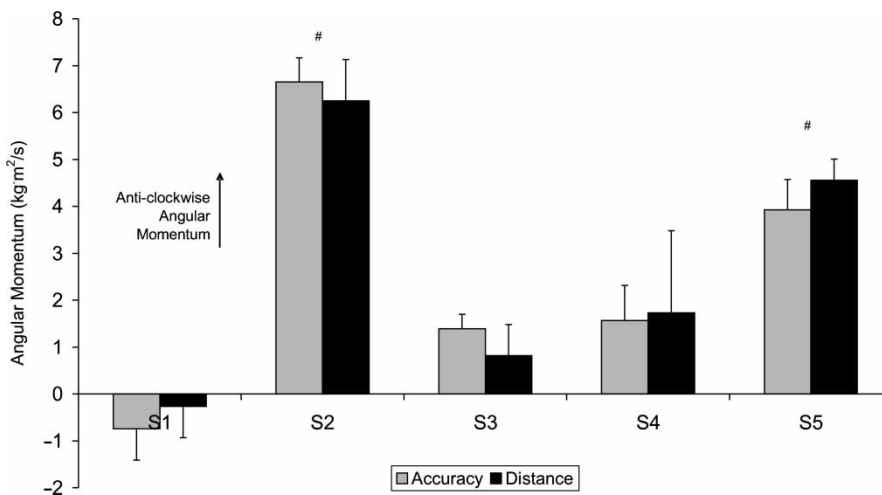


Figure 5. Contribution of the non-kicking-side arm to total angular momentum about the Y-axis at ball contact (mean \pm s). #Significantly different from participants 1, 3, and 4 (S1, S3, S4).

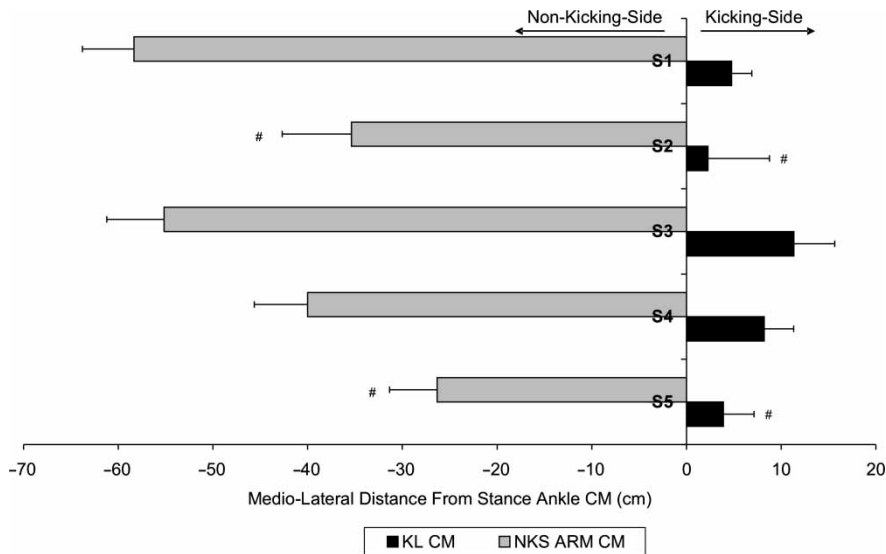


Figure 6. Positioning of the kicking leg and non-kicking-side arm relative to the base of support at ball contact (mean \pm s). CM = centre of mass, KL = kicking leg, NKS = non-kicking side. #Significantly different from participants 1, 3, and 4 (S1, S3, S4).

anti-clockwise afterwards. Anti-clockwise Z-component angular momentum for the kicking leg was large (e.g. Figure 4), and consistently exhibited the largest Z-component angular momentum of any segment. This caused the total Z-component angular momentum to mirror closely the kicking leg data, especially as the non-kicking leg and trunk (e.g. Figure 4) possessed minimal Z-component angular momentum throughout the kicking action. Peak

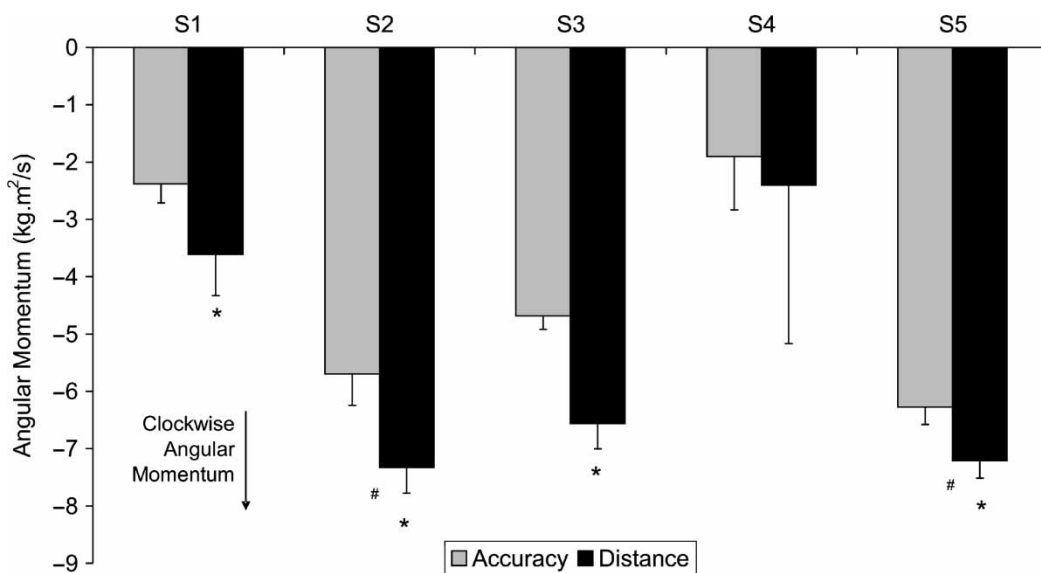


Figure 7. Contribution of the non-kicking-side arm to total angular momentum about the Z-axis at ball contact (mean \pm s). *Significantly different from accuracy trials ($P < 0.01$). #Significantly different from participants 1, 3, and 4 (S1, S3, S4).

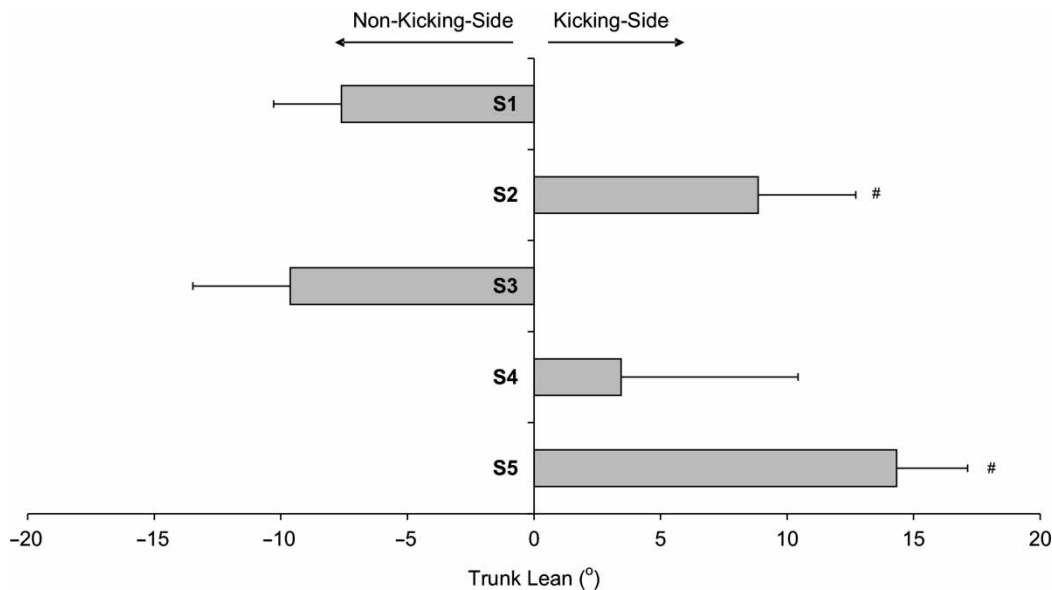


Figure 8. Lateral trunk lean at ball contact (mean \pm s). #Significantly different from participants 1, 3, and 4 (S1, S3, S4).

anti-clockwise total Z-component angular momentum was lower than the peak anti-clockwise kicking-leg component in all trials (e.g. Figure 4), with an average decrease of $4.4 \pm 1.9 \text{ kg}\cdot\text{m}^2/\text{s}$, due mainly to the opposing rotations of the non-kicking-side arm.

At ball contact, participants 2 and 5 positioned the centre of mass of their kicking leg closer to their stance ankle in the medio-lateral direction (Figure 6), and also exhibited a marked medio-lateral trunk lean towards the kicking-side at ball contact (Figure 8). In contrast, participants 1 and 3 exhibited trunk lean towards the non-kicking-side, and participant 4 leant only slightly towards the kicking-side (Figure 8).

Discussion and implications

Indicators of kick performance

Between-participant accuracy differences (Table I) indicate that inter-individual variations in skill existed, and that participants 2 and 5 were the more accurate, skilled kickers. The accuracy differences between participants would likely have practical importance. For instance, the average ball speed during distance trials for all participants was 25 m/s, at 35° above the horizontal. From standard projectile motion equations, ignoring air resistance and spin effects, we can calculate that the average kick of the cohort would successfully pass over the horizontal bar from a distance of 55.3 m. The two vertical posts are 5.6 m apart, and thus the ball cannot be more than 2.8 m from the centre line for a kick to be successful. In the context of the current research, when kicking from 10 m in front of the target, the ball can be no more than 0.51 m ($2.80/5.53$ m) away from the target horizontally. From Table I, it can be seen that participants 2 and 5 lie comfortably within these limits, exhibiting values of 0.26 and 0.17 m, respectively. The average kick of participant 1 lies only just within these limits (0.43 m), while participants 3 and 4 are considerably less accurate; they exhibited average accuracy scores of 0.60 and 0.8 m, respectively (Table I), markedly greater than the 0.51 m limit.

The larger mean accuracy scores and greater standard deviations exhibited by participants 3 and 4 indicate that they exhibited less consistent kick accuracy (Table I). Participant 4 also often exhibited large standard deviations for many of the analysed angular momentum values (Figures 5 and 7), which is indicative of less consistent movement patterns – a trait associated with less skilled kickers (Phillips, 1985). The lower skill of participant 4 was also highlighted by the fact that he was the only kicker to exhibit a significant ($P < 0.01$) decrease in accuracy under distance conditions (Table I).

Ball speed was significantly ($P < 0.05$) greater in the distance trials for all participants (Table I). Thus, when accuracy was the sole aim of a kick, and despite no specific instructions being given to the kickers about ball speed, ball speed did decrease, which confirms the findings of Asami et al. (1976) and Lees and Nolan (2002).

Whole-body angular momentum

The time-histories of the three components of whole-body angular momentum (Figures 2, 3, and 4) show that rotations occur about all three of the principal axes during a typical kicking action. This reinforces previous findings and suggestions that kicking is a three-dimensional movement (Browder et al., 1991; Lees and Nolan, 2002; Lees et al., 2004; Rodano and Taviana, 1993; Tant et al., 1991), and should be analysed as such. Total X-component angular momentum was expected to be large owing to the considerable lower body sagittal plane motion that occurs during rugby place kicking (Aitcheson and Lees, 1983). Large values of total Y- and Z-component angular momentum are likely reflective of both the non-planar movements that occur during kicking (Browder et al., 1991; Lees and Nolan, 2002; Lees et al., 2004; Shan and Westerhoff, 2005; Tant et al., 1991) and the angled approach towards the ball that is typically adopted by kickers (Lees and Nolan, 1998). However, the focus of this discussion primarily relates to the segmental contributions to kicking performance, particularly the non-kicking-side arm and how it interacts with the kicking leg.

The non-kicking-side arm

The non-kicking-side arm possessed minimal X-component angular momentum throughout the duration of the kicking action (e.g. Figure 2), for both the accuracy and the distance condition. Movements of this arm would therefore not be particularly evident in side-on (sagittal plane) two-dimensional studies, which comprise most existing kicking research. This may partly explain the scarcity of studies focusing on non-kicking-side arm movements during kicking.

Peak Y-component angular momentum of the non-kicking-side arm typically occurred near ball contact (e.g. Figure 3). The larger ($P < 0.001$) average Y-component angular momentum of the non-kicking-side arm exhibited by participants 2 and 5 at ball contact (Figure 5) contributed to their greater total anti-clockwise Y-component angular momentum at ball contact compared with the other three kickers (Table II). As participants 2 and 5 were the more accurate kickers (Table I), possession of anti-clockwise Y-component angular momentum at ball contact appears to be associated with superior accuracy. None of the participants exhibited a between-condition difference ($P > 0.05$) in Y-component angular momentum of the non-kicking-side arm at ball contact (Figure 5), suggesting that greater Y-component angular momentum for the non-kicking-side arm and total Y-component angular momentum are associated with the greater accuracy of participants 2 and 5, and do not relate to any intra-participant differences between conditions. Movements of

the non-kicking-side arm have been found to be adopted by skilled kickers to a greater extent than their novice counterparts (Shan and Westerhoff, 2005); as accuracy is a key feature of skilled rugby union kicking, the present findings appear consistent with those results. A possible explanation for how greater Y-component angular momentum for the non-kicking-side arm, and thus total Y-component angular momentum, augmented the accuracy of participants 2 and 5 becomes apparent when the medio-lateral posture of the kickers at ball contact is viewed (Figures 6 and 8).

An increased ($P < 0.001$) anti-clockwise Y-component angular momentum for the non-kicking-side arm for participants 2 and 5 was associated with the positioning of this segment further towards the kicking-side at ball contact ($P < 0.001$; Figure 6). This was accompanied by a greater ($P < 0.001$) trunk lean towards the kicking-side at the same time (Figure 8). These upper-body movements occur concurrently with a smaller distance between the kicking leg and stance ankle joint centre (Figure 6). Although a causal relationship cannot be determined between the positioning of the kicking leg and the non-kicking-side arm, it is likely that these two segments interact to maintain a balanced position in the medio-lateral direction at ball contact. While all kickers may be balanced at ball contact, it appears that the more skilled kickers adopt a position that involves contact of the ball and positioning of the non-kicking-side arm closer to the base of support, and trunk lean towards the kicking-side. It is possible that one, or a combination of, these movements may have a direct effect upon accuracy, and that the synchronous movements are used to sustain balance at ball contact.

The non-kicking-side arm also had an influence on peak total Z-component angular momentum, consistently reaching peak clockwise values near ball contact for all participants (e.g. Figure 4), which opposed the large anti-clockwise Z-component angular momentum of the kicking leg, and reduced the total anti-clockwise Z-component angular momentum. It appears that non-kicking-side arm movement occurred in a combination of planes – primarily shoulder horizontal flexion and adduction – as participants 2 and 5 exhibited a significantly greater ($P < 0.001$) non-kicking-side arm angular momentum at ball contact about both the Y- and Z-axes (Figures 5 and 7), reinforcing the findings of Shan and Westerhoff (2005). Unlike the motions about the Y-axis where both segments rotated in the same direction, the non-kicking-side arm movement about the Z-axis opposed the anti-clockwise motions of the kicking leg. This may be related to an action–reaction principle, which can affect technique and thus performance. As average trunk Z-component angular momentum at ball contact did not exceed $1.3 \text{ kg}\cdot\text{m}^2/\text{s}$ for any of the kickers (e.g. Figure 4), this suggests that non-kicking-side arm rotations helped to control whole-body rotations about the Z-axis by interacting with, and opposing, the anti-clockwise rotations of the kicking leg. Total Z-component angular momentum was thus reduced, which potentially stopped the whole body from over-rotating about the Z-axis. This is essentially the same principle as that which occurs during gait, where, as one leg moves forwards and creates Z-axis angular momentum about the centre of mass in one direction, the contralateral arm also moves forwards and creates Z-axis angular momentum in an opposing direction (Roberts, 1995). The similar timing of peak clockwise Z-component angular momentum in the non-kicking-side arm and peak anti-clockwise values in the kicking leg near ball contact (e.g. Figure 4) may, therefore, relate to the prevention of over-rotation about the longitudinal axis, which the considerable anti-clockwise Z-component angular momentum induced by kicking leg movements could produce. The presence of Z-component angular momentum in the non-kicking-side arm can, therefore, be considered a performance-enhancing action, as it allows the kickers to generate greater Z-component angular momentum in the kicking leg without obtaining excessive total Z-component angular momentum.

When comparing individual participants between conditions, Z-component angular momentum for the non-kicking-side arm also appears to have a role as a performance-maintaining strategy. The magnitude of Z-component angular momentum in the non-kicking-side arm increased under distance conditions (Figure 7), with the difference being significant ($P < 0.01$) for four of the five kickers, but not for participant 4, who was also the only participant to be significantly ($P < 0.01$) less accurate in the distance trials (Table I). To maintain accuracy during maximal distance kicking, an increased acquisition of clockwise Z-component angular momentum in the non-kicking-side arm appears necessary. As greater linear and angular joint speeds in the kicking leg, and greater end-point (i.e. kicking foot) speeds, are evident during maximal distance kicking (Lees and Nolan, 2002), there is a greater potential to over-rotate and perform movements that could negatively affect accuracy. However, increased clockwise Z-component angular momentum of the non-kicking-side arm appears to negate this problem for the kickers who maintain their accuracy. The increased use of the non-kicking-side arm in distance conditions reinforces previous suggestions that rotations about the Z-axis can influence ball velocity (Browder et al., 1991), and that these may occur in segments beyond the lower extremities (Lees and Nolan, 2002).

The kicking leg

It is clear that non-kicking-side arm movements exist in the kicking technique, and they appear to have an effect upon kick performance, particularly through interaction with the kicking leg. As the kicking leg plays the major role in the kicking technique, the following section provides a brief discussion about the three-dimensional movements and angular momentum possessed by this segment.

The time-history of the X-component angular momentum of the kicking leg (e.g. Figure 2) reflects the hip flexion and knee extension that occur between support leg contact and end of the follow-through during kicking (Browder et al., 1991). The timing of the peak value just before ball contact (e.g. Figure 2) is consistent with previously presented angular velocity time histories (Reilly, 1996). Large values of kicking-leg angular momentum were expected about the X-axis (e.g. Figure 2) owing to several previous reports of large kicking leg angular velocities in the sagittal plane (Aitchison and Lees, 1983; Putnam, 1983; Reilly, 1996). It is likely that the X-component angular momentum of the kicking leg was transferred in a proximal-to-distal manner from the thigh to the shank and, finally, the foot (Isokawa and Lees, 1988; Reilly, 1996). This would have augmented the linear speed of the foot, which contributes to ball speed at impact (Asami and Nolte, 1983; Togari, Asami, and Kikuchi, 1972).

Angular momentum of the kicking leg was also evident about the other two axes (e.g. Figures 3 and 4). For all kickers, kicking-leg angular momentum about the Y-axis was near zero at ball contact (e.g. Figure 3), but was large and anti-clockwise about the Z-axis (e.g. Figure 4). The minimal Y-component angular momentum of the kicking leg at ball contact (e.g. Figure 3) reflects relatively stationary medio-lateral movement of the kicking leg at this time. This may be an important principle for kicking performance, as the largely planar movements of the kicking leg at ball contact would likely assist the ability to make contact with the ball at the desired point of the foot's curved trajectory. The considerable clockwise Y-component angular momentum of the kicking leg before ball contact (e.g. Figure 3) was required to position this segment correctly at ball contact, as kickers characteristically adopt an angled approach to the ball (Lees and Nolan, 1998). The anti-clockwise kicking-leg rotations about the Z-axis (e.g. Figure 4) are reflective of pelvic rotations, which have been reported in some of the existing three-dimensional studies

(Browder et al., 1991; Lees and Nolan, 2002; Lees et al., 2004; Tant et al., 1991). These considerable magnitudes of angular momentum for the kicking leg about the Y- and Z-axes confirm suggestions that rotations in the two non-sagittal planes are important aspects of kicking technique, and that three-dimensional analyses are needed to achieve a full understanding of the technique (Browder et al., 1991; Lees and Nolan, 2002; Lees et al., 2004; Tant et al., 1991).

In future work, a full analysis of segment interactions, both internally and externally with the environment, would provide a suitable framework in which the current findings could be extended. In addition to the interaction between the kicking leg and the non-kicking-side arm, it is likely that other segments interact with each other as well as with the external force vector, and that these movements all contribute towards the place-kicking technique. The timings of the segment movements may also be another aspect worthy of further investigation. For example, the onset of movement of both the non-kicking-side arm and kicking leg, and their peak speeds, appear to interact so that both are positioned favourably at ball contact, and performance is thus enhanced.

Implications and practical applications for practitioners

The following points highlight the key findings of this research, and how it can be applied to a practical setting:

- Rotations of the non-kicking-side arm – shoulder horizontal flexion and adduction during the downswing of the kicking leg – are used to a greater extent by more accurate kickers.
- These arm rotations affect the posture of the kicker at the point of ball contact, so that more accurate kickers position both their non-kicking-side arm and kicking leg closer to their base of support, as well as exhibiting trunk lean towards the kicking-side.
- If a coach is working with an inaccurate kicker who does not use the non-kicking-side arm to a great extent, corrections to the stance leg positioning relative to the ball could be tried so that the kicking leg, non-kicking-side arm, and trunk all interact and adjust to form a more optimal posture at ball contact; one that appears to be associated with more accurate kicking.
- About a vertical axis, rotations of the non-kicking-side arm oppose the rotations of the kicking leg. This may be the result of an action–reaction principle, whereby movement of this arm helps to prevent over-rotation of the whole body about this axis.
- Increased use of rotations of the non-kicking-side arm about a vertical axis during maximal-distance kicking appears to assist the maintenance of accuracy.
- Coaches should be encouraged to emphasize the importance of these exaggerated non-kicking-side arm rotations about a vertical axis when kickers are striving for greater distance. They may enable a kicker who is accurate in short distance kicks, and who can kick the ball a great distance, to combine these two assets and become a skilled, accurate kicker over long distances.

Conclusion

The three-dimensional nature of kicking was reinforced in this study, as there was significant angular momentum about each of the three global axes. Two-dimensional sagittal-plane analyses may, therefore, omit key aspects of the rugby place-kicking technique, particularly motions of the non-kicking-side arm, which only occur to a minimal extent in this plane.

The non-kicking-side arm had considerable angular momentum about both the Y- and Z-axes. Anti-clockwise movements of the non-kicking-side arm about the Y-axis increased the generation of whole-body angular momentum about this axis. This was a strategy adopted by the more accurate kickers under both accuracy and distance conditions and potentially improved their posture at ball contact. Angular momentum of the non-kicking-side arm about the Z-axis opposed the motion of the kicking leg and increased during maximal distance kicks for the participants who maintained their accuracy under these conditions. Increased use of the non-kicking-side arm by the more accurate and skilled kickers confirmed recent findings (Shan and Westerhoff, 2005), and highlighted the importance of integrating upper-body movement analysis into subsequent kicking studies. Goal kickers should be encouraged to produce upper-body motions throughout the place-kicking movement in an attempt to improve performance. Movements of the non-kicking-side arm are important for accuracy, and their contribution to angular momentum about the Z-axis appears especially important for the maintenance of accuracy during maximum speed kicking.

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