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Title: Contributions of the Non-Kicking-Side Arm to Rugby Place Kicking Technique

Running Title: Arm Contributions to Rugby Place Kicking

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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 co-ordinates were obtained (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 ($\boldsymbol{H}_X$). The more accurate kickers exhibited greater non-kicking-side arm angular momentum about the global antero-posterior axis ($\boldsymbol{H}_Y$). This augmented whole body $\boldsymbol{H}_Y$, 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 ($\boldsymbol{H}_Z$), which opposed kicking leg $\boldsymbol{H}_Z$ and attenuated whole body $\boldsymbol{H}_Z$. All subjects increased non-kicking-side arm $\boldsymbol{H}_Z$ in the additional distance demand condition, aside from the one subject whose accuracy decreased, suggesting that non-kicking-side arm $\boldsymbol{H}_Z$ 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.

INTRODUCTION

Rugby union place kicking technique remains largely unexplored by sports biomechanists, aside from a two-dimensional (2D) analysis (Aitcheson and Lees, 1983). Numerous 2D sagittal-plane soccer kicking studies have been undertaken, but differences have been found in linear (up to 10%) and angular (up to 84%) velocities of the kicking leg joints between two- and three-dimensional analyses (Rodano and Tavana, 1993). This indicates that movement in at least one of the non-sagittal planes occurs, reinforcing the notion that accurate descriptions of kicking technique require a three-dimensional (3D) analysis (Lees and Nolan, 1998).

Segment rotations in both the transverse and frontal planes have been observed in the soccer kicking analyses performed in 3D (Browder *et al*., 1991; Tant *et al*., 1991; Lees and Nolan, 2002; Lees *et al*., 2004). When an accuracy demand is placed upon a kicker, ball velocity has been found to reduce by between 20 and 25% from maximal values (Asami *et al*., 1976; Lees and Nolan, 2002), and it has been postulated that ball velocity 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 (Tant *et al*., 1991; Lees and Nolan, 2002). 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 subjects of differing skill levels. Flexion and adduction of the non-kicking-side arm were found to be widely used by skilled kickers prior to ball contact (BC), but were scarcely noticeable in their novice counterparts. These movements were suggested as one cause of the increased ball velocity values exhibited by skilled kickers (Shan and Westerhoff, 2005), but they may also relate to their accuracy.

Angular momentum is a kinetic variable which 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 (due to rotations about the segment centre of mass) and a remote (due to rotations of the segment about the whole body centre of mass) term. Despite regular inferences regarding the importance of various segment rotations in kicking technique, no studies have investigated the segmental contributions to generation of angular momentum during kicking. Due to the rapid knee extensions (1520 – 1960 º/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 employed 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 velocity. Using 3D analysis techniques, the aim of the present study was therefore to further understand 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 1st team-level male kickers (mean ± *s*: age = 20.6 ± 2.7 years, height = 1.81 ± 0.09 m, mass = 80.2 ± 7.7 kg), each with at least five years kicking experience participated in the study. All were free from injury and provided informed consent in accordance with the University Research Ethics Committee procedures.

Procedures

After a self-directed warm-up, 39 spherical markers of 12.5 mm diameter were attached to specific anatomical landmarks on the subject 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 (BC) 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 due to rotations.

All subjects completed seven accuracy (A) trials where the emphasis was placed on accuracy relative to a vertical target, but no distance requirement was included. Each subject also completed seven distance (D) trials where in addition to ensuring accuracy, the subjects also had to attempt to kick the ball *"as far as they could"*. The order of conditions was randomised between subjects. The A condition was intended to replicate a situation such as a kick at the posts from the 22-metre line, whilst the D 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 in order for a kick to be successful. No instructions relating to speed of movement or ball velocity were given to the subjects.

Data Collection

Kinematic data from each subject 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 ± 0.53 mm). 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 x 0.08 m target. This target was suspended vertically on an expanse of netting approximately 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 approximately 45° to the intended direction of ball travel so that their optical axes intersected at an angle approximating 90°. The two cameras were synchronised to within 1 ms by illuminating an array of 20 LEDs (sequentially at 1 ms intervals) in each camera view, and were used to reconstruct ball velocity. Synchronised ground reaction force (GRF) 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 subject's choice, was positioned such that the kicker could adopt their preferred angled approach towards the ball, and that the support foot would land on the force platform.

Data Reduction

For each trial, 3D co-ordinates 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 co-ordinates produced from the Plug-In-Gait model, consisting of head, trunk, upper-arm, forearm, thigh and shank segments. Due 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 subjects.

Segment centre of mass (CM) time-histories were then calculated and whole body CM was subsequently determined from these values. All of the CM displacement trajectories were fitted with interpolating quintic spline functions (Wood and Jennings, 1979) and their velocities derived. Three-dimensional vectors were constructed from each segment CM to the whole body CM and the instantaneous velocity of each segment CM relative to the whole body CM was computed. This enabled the computation of the remote term of angular momentum for each segment, using the modified methods of Dapena (1978), detailed by Bahamonde (2000). Vectors in the direction of the longitudinal axis of each segment, originating from the proximal endpoints 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 summated to yield total angular momentum values for each segment, which were subsequently grouped into five new segments; kicking leg (leg_K), support leg (leg_{NK}), kicking-side arm (arm_{KS}), non-kicking-side arm (arm_{NKS}), and trunk. Angular momentum values were then calculated about three fixed orthogonal axes passing through the CM 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, and 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 normalised by dividing by individual (mass x height^2)

anthropometric characteristics and multiplying by the group mean (mass x 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 digitising (Peak Motus, version 8.1., Englewood, CO, USA) the centre of the ball from recordings obtained by the two synchronised video cameras and subsequent 3D DLT reconstruction (Abdel-Aziz and Karara, 1971). Final resultant velocity was reported as the average of the five fields following BC. To determine kick accuracy, video images from the rear camera were digitised. 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 (SLC) was identified as the first field of kinematic data after the vertical GRF 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 (EFT).

Statistical Analyses

All data were confirmed for normality and are presented as mean ± *s* unless stated otherwise. Where necessary, two-tailed t-tests were used to statistically compare variables between either subjects or conditions, with statistical significance accepted below a probability level (p) of 0.05. Due to incomplete data, only five trials under each condition were available for the analysis of subject 3.

RESULTS

Indicators of Kick Performance

Noticeable differences in inter-subject accuracy (in terms of horizontal ball displacements from the target) existed, with subjects 2 and 5 exhibiting the most accurate kicking compared with the remainder of the cohort (Table 1). Subject 4 exhibited a significant ($p < 0.01$) decrease in accuracy in the D condition, despite accuracy still being a fundamental requirement of these trials, whilst the rest of the kickers retained their accuracy in D trials. All five subjects kicked the ball with significantly ($p < 0.05$) greater velocity in the D trials (Table 1).

Whole Body Angular Momentum

The X-component of angular momentum ($\boldsymbol{H}_X$) typically reached larger average peak values than the Y ($\boldsymbol{H}_Y$) and Z ($\boldsymbol{H}_Z$) components (Table 2). A large anti-clockwise increase in total $\boldsymbol{H}_X$ occurred near support leg contact (SLC), peak values typically occurred just prior to BC, and $\boldsymbol{H}_X$ remained anti-clockwise throughout the follow through (e.g. Figure 2). The Y-component of angular momentum ($\boldsymbol{H}_Y$) was initially clockwise but began to decrease in magnitude soon after SLC for all kickers (e.g. Figure 3). The Y-component of angular momentum typically became anti-clockwise prior to BC (Table 2), and remained in this direction throughout the follow through (e.g. Figure 3). The Z-component of angular momentum ($\boldsymbol{H}_Z$) was anti-clockwise throughout and reached peak values near BC (e.g. Figure 4). Peak total $\boldsymbol{H}_Z$ values were lower in magnitude than peak total $\boldsymbol{H}_X$ and $\boldsymbol{H}_Y$ values for all subjects (Table 2).

Subject 1 exhibited slightly different trends compared with the rest of the cohort about the Y-axis, with larger peak clockwise $\boldsymbol{H}_Y$ values (Table 2), which remained clockwise throughout BC (Table 2). Subjects 2 and 5 exhibited significantly ($p < 0.001$) greater magnitudes of both total anti-clockwise $\boldsymbol{H}_Y$, and $\boldsymbol{H}_Y$ at BC, compared to the other four kickers (Table 2).

Non-Kicking-Side Arm Contributions to Angular Momentum

The arm_{NKS} possessed minimal $\boldsymbol{H}_X$ throughout each trial for all subjects (e.g. Figure 1), and average peak values did not exceed 2.03 $(kg{\cdot}m^2)/s$ for any of the kickers. Possession of arm_{NKS} $\boldsymbol{H}_Y$ was predominantly anti-clockwise between SLC and EFT (e.g. Figure 3), whilst arm_{NKS} $\boldsymbol{H}_Z$ was mainly clockwise during this period (e.g. Figure 4). Peak magnitudes of both arm_{NKS} $\boldsymbol{H}_Y$ and $\boldsymbol{H}_Z$ occurred near BC (e.g. Figures 3 and 4). Clockwise $\boldsymbol{H}_Z$ in the arm_{NKS} was a consistent trend amongst the group, which opposed the large anti-clockwise leg_K $\boldsymbol{H}_Z$ (e.g. Figure 4).

Subjects 2 and 5 exhibited significantly ($p < 0.001$) greater peak anti-clockwise arm_{NKS} $\boldsymbol{H}_Y$ than the remainder of the cohort (Figure 5). As previously stated, these peak arm_{NKS} $\boldsymbol{H}_Y$ magnitudes occurred near BC, and at this point in time, subjects 2 and 5 also positioned their arm_{NKS} CM closer to the vertical projection of their base of support (stance ankle) through shoulder adduction and horizontal flexion (Figure 6). Magnitudes of arm_{NKS} $\boldsymbol{H}_Z$ at BC for subjects 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 subject 4 (p = 0.67), all subjects significantly ($p < 0.01$) increased arm_{NKS} $\boldsymbol{H_Z}$ at BC in D trials (Figure 7).

Kicking Leg Contributions to Angular Momentum

After SLC, leg_K $\boldsymbol{H_X}$ was consistently anti-clockwise for all subjects (e.g. Figure 2). Peak magnitudes occurred just prior to BC and values remained anti-clockwise throughout the follow through (e.g. Figure 2). For all kickers, the leg_K constituted the largest segmental $\boldsymbol{H_X}$ values in both conditions. The leg_K $\boldsymbol{H_Y}$ time-history followed a general pattern similar to that of total $\boldsymbol{H_Y}$ (e.g. Figure 3), being predominantly clockwise prior to BC, and anti-clockwise afterwards. Anti-clockwise leg_K $\boldsymbol{H_Z}$ was large in magnitude (e.g. Figure 4), and consistently exhibited the largest $\boldsymbol{H_Z}$ magnitudes of any segment. This caused total $\boldsymbol{H_Z}$ to closely mirror the leg_K $\boldsymbol{H_Z}$ data, especially as the leg_{NK} and trunk (e.g. Figure 4) possessed minimal $\boldsymbol{H_Z}$ throughout the entire kicking action. Peak anti-clockwise total $\boldsymbol{H_Z}$ was lower than peak anti-clockwise leg_K $\boldsymbol{H_Z}$ in all trials (e.g. Figure 4), with an average decrease of 4.4 ± 1.9 (kg·m^2)/s, due mainly to the opposing rotations of the arm_{NKS}.

At BC, subjects 2 and 5 positioned their leg_K CM 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 BC (Figure 8). In contrast, subjects 1 and 3 exhibited trunk lean towards the non-kicking-side, and subject 4 leant only slightly towards the kicking-side (Figure 8).

DISCUSSION

Indicators of Kick Performance

Between-subject accuracy differences (Table 1) indicate that inter-individual variations in skill level existed, and that subjects 2 and 5 were the more accurate, skilled kickers. The accuracy differences between subjects would likely have practical importance. For instance, the average ball velocity during D trials for all subjects was 25 m/s, at 35° above the horizontal. From standard projectile motion equations (ignoring air resistance and spin effects), it can be calculated 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 in order 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 2.80/5.53 m, or 0.51 m away from the target horizontally. From table 1, it can be seen that subjects 2 and 5 lie comfortably within these limits, exhibiting values of 0.26 and 0.17 m, respectively. The average kick of subject 1 lies only just within these limits (0.43 m), whilst subjects 3 and 4 are considerably less accurate; they exhibit average accuracy scores of 0.60 and 0.8 m, respectively (Table 1); markedly greater than the 0.51 m limit.

The larger mean accuracy scores and greater standard deviation values exhibited by subjects 3 and 4 indicate that they exhibited less consistent kick accuracy (Table 1). Subject 4 also often exhibited large standard deviation values for many of the analysed angular momentum values (e.g. Figures 5 and 7), which is indicative of less consistent movement patterns – a trait associated with less skilled kickers (Phillips, 1985). The lower skill levels of subject 4 were also highlighted by the fact that he was the only kicker to exhibit a significant ($p < 0.01$) decrease in accuracy under D conditions (Table 1).

Ball velocity was significantly ($p < 0.05$) greater in the D trials for all subjects (Table 1). Thus when accuracy was the sole aim of a kick, and despite no specific instructions being given to the kickers regarding ball velocity, ball velocity did actually decrease, which confirms the findings of Asami *et al*. (1976) and Lees and Nolan (2002).

Whole Body Angular Momentum

The total $\boldsymbol{H}_X$, $\boldsymbol{H}_Y$ and $\boldsymbol{H}_Z$ time-histories (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 3D movement (Browder *et al*., 1991; Tant *et al*., 1991; Rodano and Tavana, 1993; Lees and Nolan, 2002; Lees *et al*., 2004), and should be analysed as such. Total $\boldsymbol{H}_X$ was expected to be large due to the considerable lower-body sagittal plane motion that occurs during rugby place kicking (Aitcheson and Lees, 1983). Large values of total $\boldsymbol{H}_Y$ and $\boldsymbol{H}_Z$ are likely reflective of both the non-planar movements that occur during kicking (Browder *et al*., 1991; Tant *et al*., 1991, Lees and Nolan, 2002; Lees *et al*., 2004; Shan and Westerhoff, 2005) 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 arm_{NKS} and how it interacts with the leg_K.

The Non-Kicking-Side Arm

The arm_{NKS} possessed minimal $\boldsymbol{H}_X$ throughout the duration of the kicking action (e.g. Figure 2), for both the A and the D condition. Movements of this arm would therefore not be particularly evident in *"side-on"* (sagittal plane) 2D studies, which comprise the majority of existing kicking research. This may partly explain the sparse existence of studies focusing on arm_{NKS} movements during kicking.

Peak arm_{NKS} $\boldsymbol{H}_Y$ typically occurred near BC (e.g. Figure 3). The larger ($p < 0.001$) average arm_{NKS} $\boldsymbol{H}_Y$ exhibited by subjects 2 and 5 at BC (Figure 5) contributed to their possession of greater total anti-clockwise $\boldsymbol{H}_Y$ at BC compared to the remainder of the cohort (Table 2). As subjects 2 and 5 were the more accurate kickers (Table 1), possession of anti-clockwise $\boldsymbol{H}_Y$ at BC appears to be a strategy associated with superior accuracy. None of the subjects exhibited a between-condition difference ($p > 0.05$) in arm_{NKS} $\boldsymbol{H}_Y$ at BC (Figure 5), suggesting that greater arm_{NKS} and total $\boldsymbol{H}_Y$ are traits associated with the greater accuracy of subjects 2 and 5 *per se*, and do not relate to any intra-subject between-condition differences. Movements of the arm_{NKS} have been found to be adopted by skilled kickers to a greater extent than their novice counterparts (Shan and Westerhoff, 2005), and as accuracy is a key feature of skilled rugby union kicking, the present findings appear consistent with the results of Shan and Westerhoff (2005). A possible explanation for how greater arm_{NKS} and thus total $\boldsymbol{H}_Y$ possession augmented the accuracy of subjects 2 and 5 becomes apparent when the medio-lateral posture of the kickers at BC is viewed (Figures 6 and 8).

An increased ($p < 0.001$) possession of anticlockwise arm_{NKS} $\boldsymbol{H}_Y$ by subjects 2 and 5 was associated with the positioning of this segment further towards the kicking-side at BC (*p* < 0.001; Figure 6). This was accompanied by a greater (*p* < 0.001) trunk lean towards the kicking-side at the same point in time (Figure 8). These upper body movements occur concurrently with a smaller distance between the leg_K and stance ankle joint centre (Figure 6). Although a causal relationship cannot be determined between leg_K and arm_{NKS} positioning, it is likely that these two segments interact in order to maintain a balanced position in the medio-lateral direction at BC. Whilst all kickers may be balanced at BC, it appears that the more skilled kickers adopt a position which involves contact of the ball and positioning of the arm_{NKS} closer to the base of support, and trunk lean towards the kicking-side. It is possible that either 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 BC.

The arm_{NKS} also had an influence on peak total $\boldsymbol{H}_Z$, consistently reaching peak clockwise values near BC for all subjects (e.g. Figure 4), which opposed the large anti-clockwise leg_K $\boldsymbol{H}_Z$, and reduced the anti-clockwise total $\boldsymbol{H}_Z$. It appears that arm_{NKS} movement occurred in a combination of planes (primarily shoulder lateral flexion and adduction) as subjects 2 and 5 exhibited a significantly greater (*p* < 0.001) arm_{NKS} angular momentum at BC 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 arm_{NKS} movement about the Z-axis opposed the anti-clockwise leg_K motions. This may be related to an *"action-reaction"* principle which can affect technique and thus performance. As average trunk $\boldsymbol{H}_Z$ at BC did not exceed 1.3 (kg·m^2)/s for any of the kickers (e.g. Figure 4), this suggests that arm_{NKS} rotations helped to control whole body rotations about the Z-axis by interacting with, and opposing, the anticlockwise leg_K rotations. Total $\boldsymbol{H_Z}$ 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 CM 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 arm_{NKS} $\boldsymbol{H_Z}$ and peak anti-clockwise leg_K $\boldsymbol{H_Z}$ near BC (e.g. Figure 4) may therefore relate to the prevention of over-rotation about the longitudinal axis, which the considerable anti-clockwise $\boldsymbol{H_Z}$ induced by leg_K movements could potentially produce. The presence of arm_{NKS} $\boldsymbol{H_Z}$ can therefore be considered a *"performance enhancing"* action, as it allows the kickers to generate greater leg_K $\boldsymbol{H_Z}$ without obtaining excessive amounts of total $\boldsymbol{H_Z}$.

When comparing individual subjects between conditions, arm_{NKS} $\boldsymbol{H_Z}$ also appears to have a role as a *"performance maintaining"* strategy. The magnitude of arm_{NKS} $\boldsymbol{H_Z}$ increased under D conditions (Figure 7), with the difference being significant ($p < 0.01$) for four of the five kickers, but not for subject 4, who was also the only subject to be significantly ($p < 0.01$) less accurate in D trials (Table 1). In order to maintain accuracy during maximal distance kicking, an increased acquisition of clockwise arm_{NKS} $\boldsymbol{H_Z}$ thus appears necessary. As greater linear and angular leg_K joint velocities, and greater end-point (i.e. kicking foot) velocities are evident during maximal distance kicking (Lees and Nolan, 2002), there is a greater potential to *"over-rotate"* and perform movements which may negatively affect accuracy.

However, increased clockwise $\boldsymbol{H}_Z$ of the arm_{NKS} appears to negate this problem for the kickers who maintain their accuracy. The increased use of the arm_{NKS} in D 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 arm_{NKS} movements exist in the kicking technique, and they appear to have an effect upon kick performance, particularly through interaction with the leg_K. As the leg_K plays the major role in the kicking technique, the following section provides a brief discussion relating to the 3D movements and angular momentum possessed by this segment.

The leg_K $\boldsymbol{H}_X$ time-history (Figure 2) reflects the hip flexion and knee extension which occur between SLC and EFT during kicking (Browder *et al*., 1991). The timing of the peak value just prior to BC (e.g. Figure 2) is consistent with previously presented angular velocity time-histories (Reilly, 1996). Large values of leg_K angular momentum were expected about the X-axis (e.g. Figure 2) due to several previous reports of large leg_K angular velocities in the sagittal plane (Aitcheson and Lees, 1983; Putnam, 1983; Reilly, 1996). It is likely that the $\boldsymbol{H}_X$ possessed by the leg_K was transferred in a proximal-to-distal fashion from the thigh to the shank and finally the foot (Isokawa and Lees, 1988; Reilly, 1996). This would have augmented the linear velocity of the foot, which contributes to ball velocity at impact (Togari *et al*., 1972; Asami and Nolte, 1983).

Angular momentum of the leg_K was also evident about the other two axes (Figures 3 and 4). For all kickers, leg_K angular momentum about the Y-axis was near zero at BC (e.g. Figure 3), but was large and anti-clockwise about the Z-axis (e.g. Figure 4). The minimal leg_K $\boldsymbol{H}_Y$ at BC (e.g. Figure 3) reflects relatively stationary medio-lateral movement of the leg_K at this point in time. This may be an important principle for kicking performance, as the largely planar movements of the leg_K at BC would likely assist the ability to make contact with the ball at the desired point of the foot's curved trajectory. The considerable possession of clockwise leg_K $\boldsymbol{H}_Y$ prior to BC (e.g. Figure 3) was required to position this segment correctly at BC, as kickers characteristically adopt an angled approach to the ball (Lees and Nolan, 1998). The anti-clockwise leg_K rotations about the Z-axis (e.g. Figure 4) are reflective of pelvic rotations, which have been reported in some of the existing 3D studies (Browder *et al*., 1991; Tant *et al*., 1991; Lees and Nolan, 2002; Lees *et al*., 2004). These considerable magnitudes of angular momentum possessed by the leg_K about the Y- and Z-axes confirm suggestions that rotations in the two non-sagittal planes are important aspects of kicking technique, and that 3D analyses are paramount in order to achieve a full understanding of the technique (Browder *et al*., 1991; Tant *et al*., 1991; Lees and Nolan, 2002; Lees *et al*., 2003).

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 leg_K and the arm_{NKS}, 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 area worthy of further investigation. For example, the onset of movement of both the arm_{NKS} and leg_K, and their peak velocities appear to interact so that both are positioned favourably at BC, and performance is thus enhanced.

CONCLUSION

The three-dimensional nature of kicking was reinforced in this study, as there was significant possession of 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 arm_{NKS} motions which only occur to a minimal extent in this plane.

The arm_{NKS} possessed considerable angular momentum about both the Y- and Z-axes. Anti-clockwise arm_{NKS} movements 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 arm_{NKS} about the Z-axis opposed the motion of the leg_K and increased in magnitude during maximal distance kicks for the subjects who maintained their level of accuracy under these conditions. Increased arm_{NKS} use by the more accurate and thus 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 arm_{NKS} are important for accuracy purposes, and their contribution to angular momentum about the Z-axis appears particularly important for the maintenance of accuracy during maximum velocity kicking.

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 lateral flexion and adduction during the downswing of the kicking leg) are used to a greater extent by the more accurate kickers.
- These arm rotations affect the posture of the kicker at the point of ball contact, so that the 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 attempted so that the kicking leg, non-kicking-side arm, and trunk all interact and adjust to form a more optimal posture at BC; 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 (trunk) about this axis.

- Increased use of non-kicking-side arm rotations about a vertical axis during maximal distance kicking appear to assist the maintenance of accuracy.
- Coaches should be encouraged to emphasise 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 large distances.

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Table 1 Average kick accuracy (m) and ball velocity (m/s) (mean ± SD).

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

Abbreviations: A = accuracy, D = distance. Significantly different from accuracy trials * ($p < 0.05$); ** ($p < 0.01$); *** ($p < 0.001$).

Table 2 Normalised average peak angular momentum ((kg·m^2)/s) about each of the three global axes (mean ± SD).

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5
Max $\boldsymbol{H}_X$	24.7 ± 1.4	28.7 ± 2.3	29.6 ± 2.2	22.2 ± 1.8	19.5 ± 1.1
Max $\boldsymbol{H}_{YAC}$	10.1 ± 3.6	14.8 ± 2.8	8.6 ± 2.0	6.9 ± 2.6	15.3 ± 3.2
Max $\boldsymbol{H}_{YC}$	-25.3 ± 0.8	-16.4 ± 2.3	-20.0 ± 1.4	-14.3 ± 2.8	-14.3 ± 2.3
Max $\boldsymbol{H}_Z$	17.2 ± 1.6	12.3 ± 1.6	15.5 ± 0.6	10.6 ± 1.9	11.6 ± 1.1
$\boldsymbol{H}_Y$ at BC	0.0 ± 2.7	13.1 ± 2.8	1.9 ± 4.1	3.8 ± 3.4	11.9 ± 3.8

Abbreviations: $\boldsymbol{H}_X$ = X-component of angular momentum, $\boldsymbol{H}_Y$ = Y-component of angular momentum, $\boldsymbol{H}_{YAC}$ = Y-component of angular momentum in anti-clockwise direction, $\boldsymbol{H}_{YC}$ = Y-component of angular momentum in clockwise direction, $\boldsymbol{H}_Z$ = Z-component of angular momentum, BC = ball contact.

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

Figure 2 Segmental contributions to total angular momentum about the X-axis for a trial of subject 2 under accuracy conditions.

Figure 3 Segmental contributions to total angular momentum about the Y-axis for a trial of subject 5 under accuracy conditions.

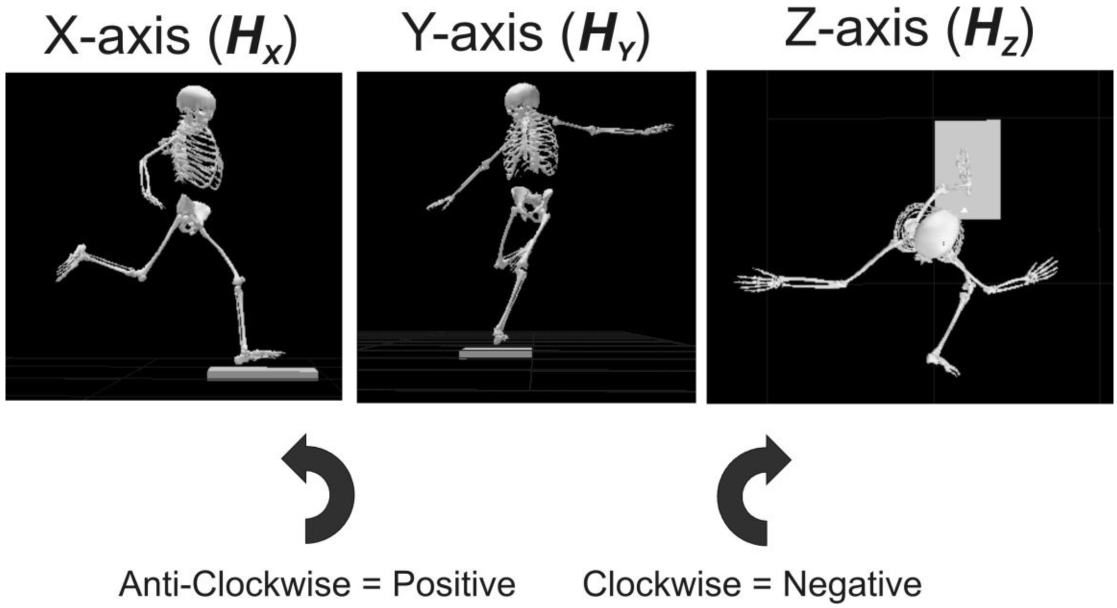
Figure 4 Segmental contributions to total angular momentum about the Z-axis for a trial of subject 5 under accuracy conditions.

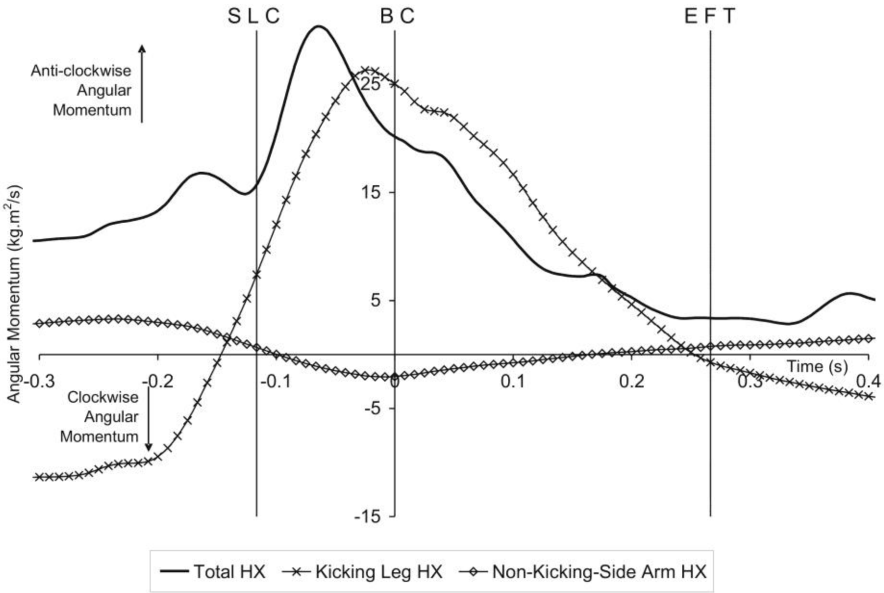
Figure 5 Contribution of the non-kicking-side arm to total angular momentum about the Y-axis at ball contact (mean ± *s*). $^{\#}$ = significantly different from subjects 1, 3 and 4.

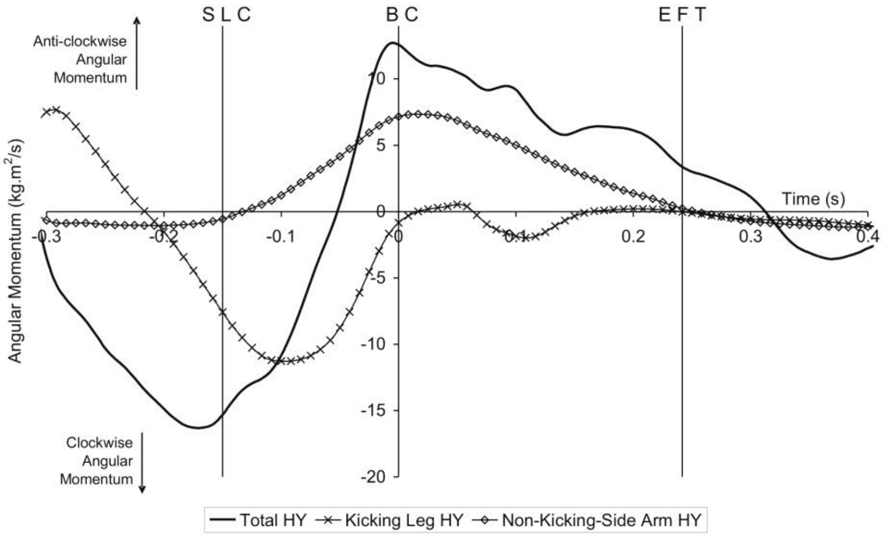
Figure 6 Positioning of the kicking leg and non-kicking-side arm relative to the base of support at ball contact (mean ± *s*). $^{\#}$ = significantly different from subjects 1, 3 and 4.

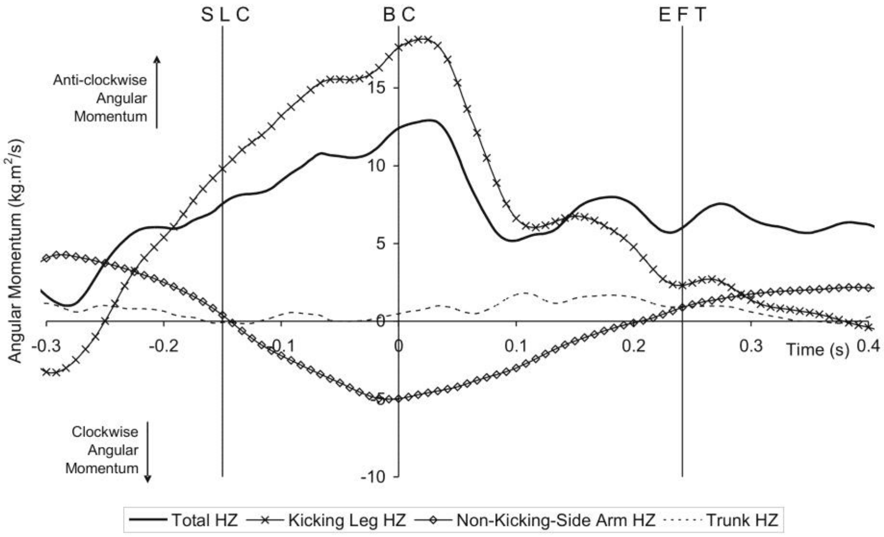
Figure 7 Contribution of the non-kicking-side arm to total angular momentum about the Z-axis at ball contact (mean ± *s*). * = significantly different from accuracy trials ($p < 0.01$). $^{\#}$ = significantly different from subjects 1, 3 and 4.

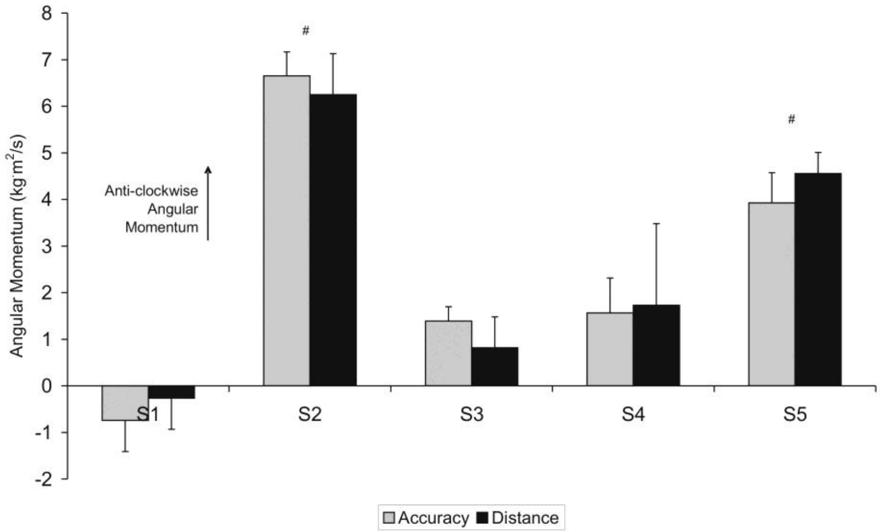
Figure 8 Lateral trunk lean at ball contact (mean ± *s*). # = significantly different from subjects 1, 3 and 4.

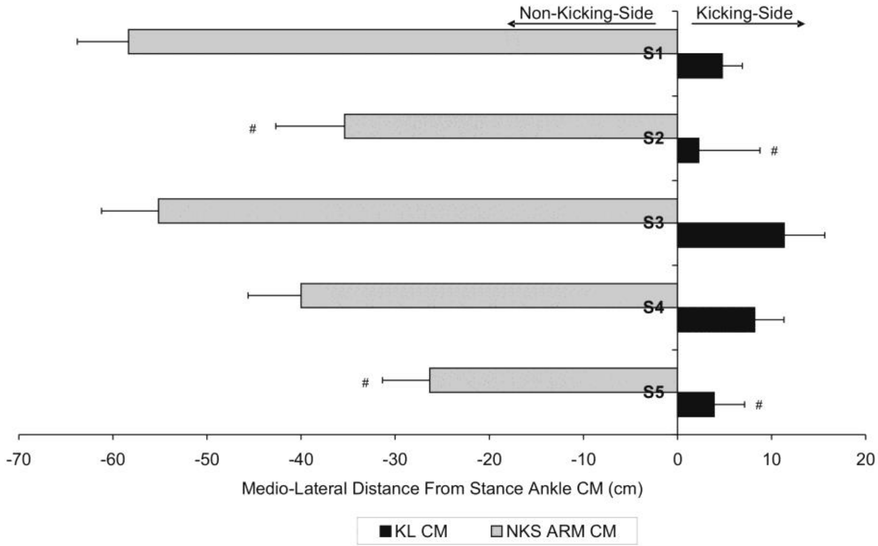

X-axis (Hx)
Y-axis (HY)
Z-axis (HZ)
Anti-Clockwise = Positive
Clockwise = Negative


SLC
BC
EFT
Anti-clockwise Angular Momentum
Clockwise Angular Momentum
Angular Momentum (kg.m2/s)
Time (s)
25
15
5
-5
-15
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
Total HX
Kicking Leg HX
Non-Kicking-Side Arm HX

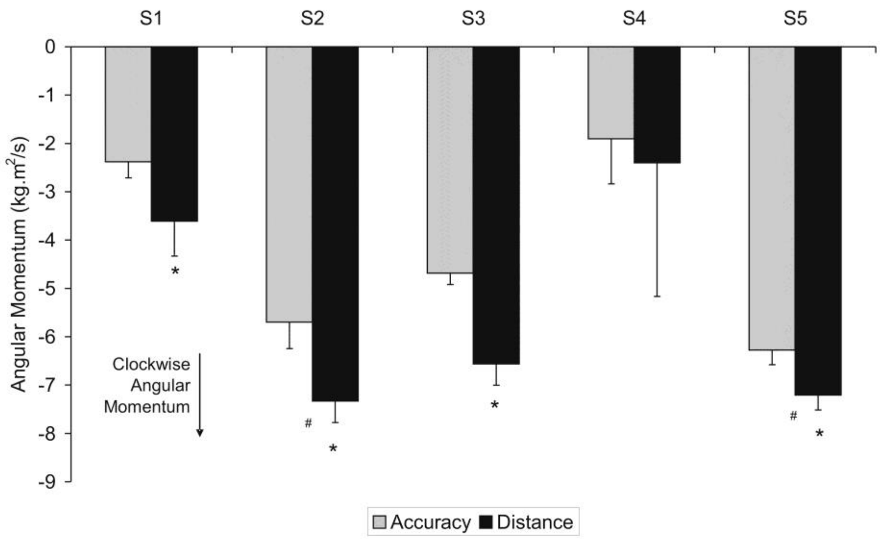

S L C
B C
E F T
Anti-clockwise Angular Momentum
Clockwise Angular Momentum
Angular Momentum (kg.m2/s)
Time (s)
10
5
0
-5
-10
-15
-20
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
Total HY
Kicking Leg HY
Non-Kicking-Side Arm HY

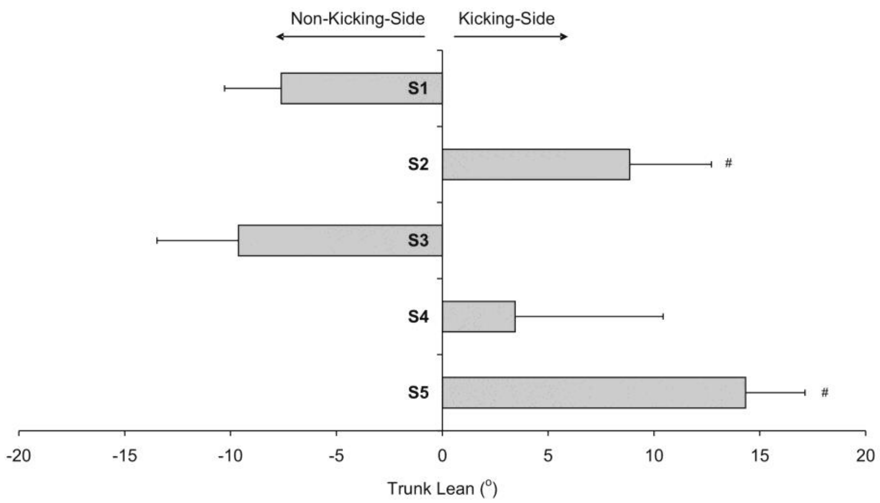

S L C
B C
E F T
Anti-clockwise Angular Momentum
Clockwise Angular Momentum
Angular Momentum (kg.m2/s)
Time (s)
15
10
5
0
-5
-10
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
Total HZ
Kicking Leg HZ
Non-Kicking-Side Arm HZ
Trunk HZ


Angular Momentum (kg·m²/s)
Anti-clockwise
Angular
Momentum
#
#
S1
S2
S3
S4
S5
8
7
6
5
4
3
2
1
0
-1
-2
Accuracy
Distance



Non-Kicking-Side
Kicking-Side
S1
S2
S3
S4
S5
#
#
#
#
-70
-60
-50
-40
-30
-20
-10
0
10
20
Medio-Lateral Distance From Stance Ankle CM (cm)
KL CM
NKS ARM CM


S1
S2
S3
S4
S5
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
Angular Momentum (kg.m²/s)
Clockwise
Angular
Momentum
*
#
Accuracy
Distance


Non-Kicking-Side
Kicking-Side
S1
S2
#
S3
S4
S5
#
-20
-15
-10
-5
0
5
10
15
20
Trunk Lean (°)