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Multiplanar lumbar, pelvis and kick leg sequencing during soccer instep kicking from different approach angles

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ABSTRACT

Multiplanar kinematic and kinetic sequencing from different approach angles can highlight how soccer players perform fast and accurate kicks. This study therefore aimed to a) determine multiplanar torso, pelvis and kick leg sequencing during instep kicks and b) highlight the effect of different approach angles on these sequencing patterns. Twenty male soccer players (mass 77.9 ± 6.5 kg, height 1.71 ± 0.09 m, age 23.2 ± 3.7 years) performed kicks from self-selected ($\sim 30-45°$), straight ($0°$) and wide ($67.5°$) approaches and multiplanar lumbo-pelvic, hip and knee angular velocities, moments and powers were derived from 3D motion analysis. The results suggest tension arc release between the upper and lower body functions as a two-stage mechanism. The first phase of arc release was characterised by increases in concentric hip flexion and transverse lumbo-pelvic velocities towards the ball. The second phase was characterised by increasing concentric lumbo-pelvic flexion and knee extension work to angularly accelerate the kicking knee towards foot-to-ball contact. Further, alterations in kinematic and kinetic sequencing helped maintain performance (ball and foot velocities at ball contact) and accuracy at approach angles other than self-selected. These findings can help coaches and practitioners design effective training practices.

1. Introduction

Instep kicking is important in soccer. It is commonly performed when shooting (Lees et al., 2010) and successful execution of the skill influences match outcomes. Maximising ball velocity and accuracy is advantageous as this gives goalkeepers less chance to react, and increases the chances of scoring (Dörge et al. 2002). Attempts to understand how skilled players achieve fast and accurate kicks have thus been undertaken. Descriptions of lower limb function are most prevalent (Kellis & Katis, 2007; Lees et al., 2010), but the pelvis and upper body also contributes to kicking performance. Larger and faster torso rotations (Fullenkamp et al., 2015), range of motion (Smith & Gilleard, 2015), and pelvic-torso separations (Lees & Nolan, 2002) are associated with faster ball velocities, and formation and release of a 'tension arc' between the upper and lower body indicative of skilled kicking (Shan & Westerhoff, 2005). Kicking hip extension, pelvic retraction and anterior tilt, and torso transverse rotation to the non-kick side help store energy in anterior torso, pelvis and hip muscles during arc formation, which is released via opposing rotations during arc release.

Effective torso, pelvis and kick leg sequencing thus facilitates energy transfers needed for fast foot velocities (Nunome et al., 2006; Putnam, 1991) and precise foot-to-ball impact (Lees & Nolan, 2002). Unfortunately, torso, pelvis and kick leg interactions remains poorly understood. Whilst the torso and pelvis become coupled with the kicking thigh to accelerate the lower leg during the downswing (Naito et al., 2010), multiplanar joint kinetics and their sequencing under different task constraints are rarely considered. Wider approaches to the ball exhibit larger lumbo-pelvic (L-P) and kicking hip frontal and transverse motions than straighter approaches (Andersen & Dörge, 2011; Kellis et al., 2004; Scurr & Hall, 2009), but these studies only investigated joint function independently. Since altering joint action will incur compensations at other joints comprising the chain, investigating sequencing from different approach angles can highlight performance maintenance strategies when approaches are perturbed. While these strategies are currently unknown, kinetic sources responsible for frontal and transverse rotations will likely contribute to maintain performance from wider approaches, whereas straighter approaches will rely on sources responsible for sagittal rotations to achieve similar performance

outcomes. This study therefore had two aims. First, to illustrate multi-planar torso, pelvis and kick leg sequencing during fast and accurate instep soccer kicks. Second, to highlight the effect of different approach angles on these sequencing patterns. It was hypothesised that: a) non-planar (i.e. transverse and frontal) L-P and kicking hip angular velocities, moments and powers would be more prominent from wider approaches, but b) compensations in sequencing would allow players to maintain performance across different approaches angles.

2. Materials and methods

2.1. Participants

Twenty male soccer players volunteered (mean ± SD; 77.9 ± 6.5 kg, 1.71 ± 0.09 m, 23.2 ± 3.7 years). All were aged 18–35, right footed, injury free, had > 10 years competitive playing experience, and affiliated to a semi-professional club at the time of testing. Nineteen participants was sufficient to achieve statistical power of 0.80 based on α = 0.05 and medium to large pairwise effect sizes between two dependent means (d = 0.7; Scurr & Hall, 2009; G*Power 3.1.9.7). Ethical approval was granted by the University's ethics committee, and written informed consent obtained prior to data collection.

2.2. Data collection & modelling

After warm up (~10 mins of jogging, dynamic stretches and kicks of increasing effort), participants kicked a size 5 soccer ball in a carpeted laboratory (800 Hpa; Mitre Monde, UK) 'fast and accurately' towards a circular target (0.5 m radius) 4 m away. Kicks from self-selected (SS), straight (0°) and wide (67.5°) approach angles were performed (Fig. 1). The SS kicks were performed first and were between 30° and 45° for all participants. The order of subsequent 0° and 67.5° kicks were counter-balanced between participants. Lines were drawn on the floor to ensure correct approach angles were performed, and these were verified using centre of mass displacements relative to the lab medio-lateral axis (Fig. 1). Approach distance was 3 m (allowing 3–5 steps; Lees et al., 2010) and participants self-selected approach velocities. Trials that missed the target were discounted and reperformed.

Kicking actions were captured via 10-camera, 3D motion analysis (Vicon T40S, Vicon Motion Systems, UK) and a piezoelectric force platform (9287C, Kistler, UK), (both 1000 Hz). Reflective markers defined the position and orientation of eight segments (bilateral feet, shanks and thighs, pelvis, and a lumbar segment) in a direct kinematic model. Segments were rigid geometrical volumes scaled to participant height and mass (Hanavan, 1964). Lower limb segment parameters were derived from de Leva (1996) and the mass of the shoe added to each foot (0.3–0.4 kg). Pelvis and lumbar segment parameters were derived from

Pearsall et al. (1996). Lower limb segment coordinate system origins and joint centres and were defined at the proximal end of each segment using calibration markers (Augustus et al; 2021). Additionally, two coordinate systems were adopted for the pelvis. A technical coordinate system was defined at a point 5% along a line between the L5-S1 marker and a mid-ASIS virtual landmark per Seay et al., (2008). This defined the L-P joint centre and served as the point of application for joint kinetics at the approximate location of the L5-S1 joint (Khoo et al., 1995). Next, an anatomical coordinate system was defined by the midpoints between iliac crest (IC) and greater trochanter markers to resolve L-P kinematic parameters into a more appropriate frame of reference (Seay et al., 2008). Full details of the marker set and how coordinate systems were defined can be found in the Supplemental material. Following static calibration, segments were tracked using either calibration markers (feet and pelvis) or marker clusters attached to shanks, thighs and lumbar segments. Six semi-hemispherical markers were attached to ball to define its geometric centre.

2.3. Data analysis

Marker trajectories and ground reaction forces (GRFs) were exported to Visual 3D (V6, C-Motion, USA), where kicking foot and shank markers were low-pass filtered using a time–frequency, fractional Fourier filter (cut-off frequency 18–300 Hz; Augustus et al., 2020). All other markers and GRFs were smoothed using a fourth-order, dual-pass Butterworth low-pass filter (cut-off frequency = 18 Hz, determined by residual analyses). Multiplanar (sagittal, frontal and transverse) L-P and kicking hip, and sagittal plane kicking knee joint angular velocities were defined as the distal relative to proximal segments. Kicking foot velocity at the instance of ball contact, post-strike ball velocity as per Inoue et al. (2014) and the number of kicks to produce five accurate trials were calculated as measures of kicking performance, as were ball to foot velocity ratios as an indicator of foot-to-ball contact efficiency (Peacock & Ball, 2018). Multiplanar joint moments and powers were estimated using Newton-Euler inverse dynamics and reflected for the final 10 ms before ball contact to remove ball impact artefacts. Joint powers were the scalar product of corresponding joint moments and angular velocities, where positive values indicated net power generation (concentric action) and negative values net power absorption (eccentric action). All joint kinetics were resolved to the joint co-ordinate system and normalised to body mass (Schache & Baker, 2007). For discrete variables, mean responses were determined for each participant in each condition, and for time-series variables, all trials were used to determine ensemble average curves per condition.
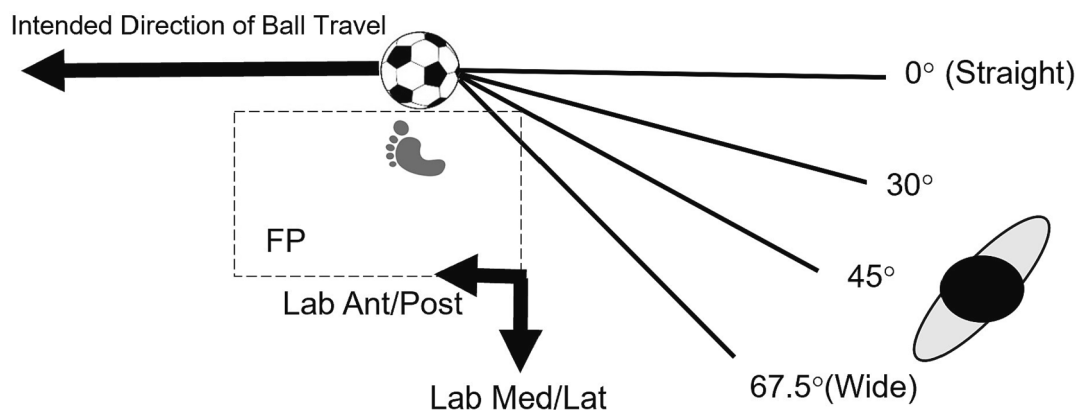

Fig. 1. Aerial view schematic of different approach angles showing starting position of each condition (3 m from ball), force plate (FP; dashed line) and ball locations, and angles relative to lab anterior/posterior and medio-lateral axes. Example shown for right-footed kicker.

2.4. Statistical analyses

Following normality checks (Shapiro-Wilks = P < 0.05), one-way repeated measures ANOVAs examined performance measures across approach angles (SPSS V23, IBM, New York, USA). Significance was α = 0.05 and if sphericity was violated, the Greenhouse-Geisser adjustment was used. Bonferroni adjusted, paired t-tests determined pairwise

differences (N = 3, α = 0.017) and effect sizes (trivial $d < 0.2$, small $d = 0.2$–0.5, medium $d = 0.5$–0.8, large $d > 0.8$; Cohen, 1988). Statistical parametric mapping (SPM1D 0.4.8; Pataky, 2012) evaluated differences in time-series data between kicking foot take off (KFTO; 0%) and ball contact start (BCS; 100%) in Matlab (2019b, Mathworks Inc, Natick, USA). Repeated measures ANOVA statistical curves (SPM{F}) were computed and significance set at α = 0.05. Post-hoc, Bonferroni
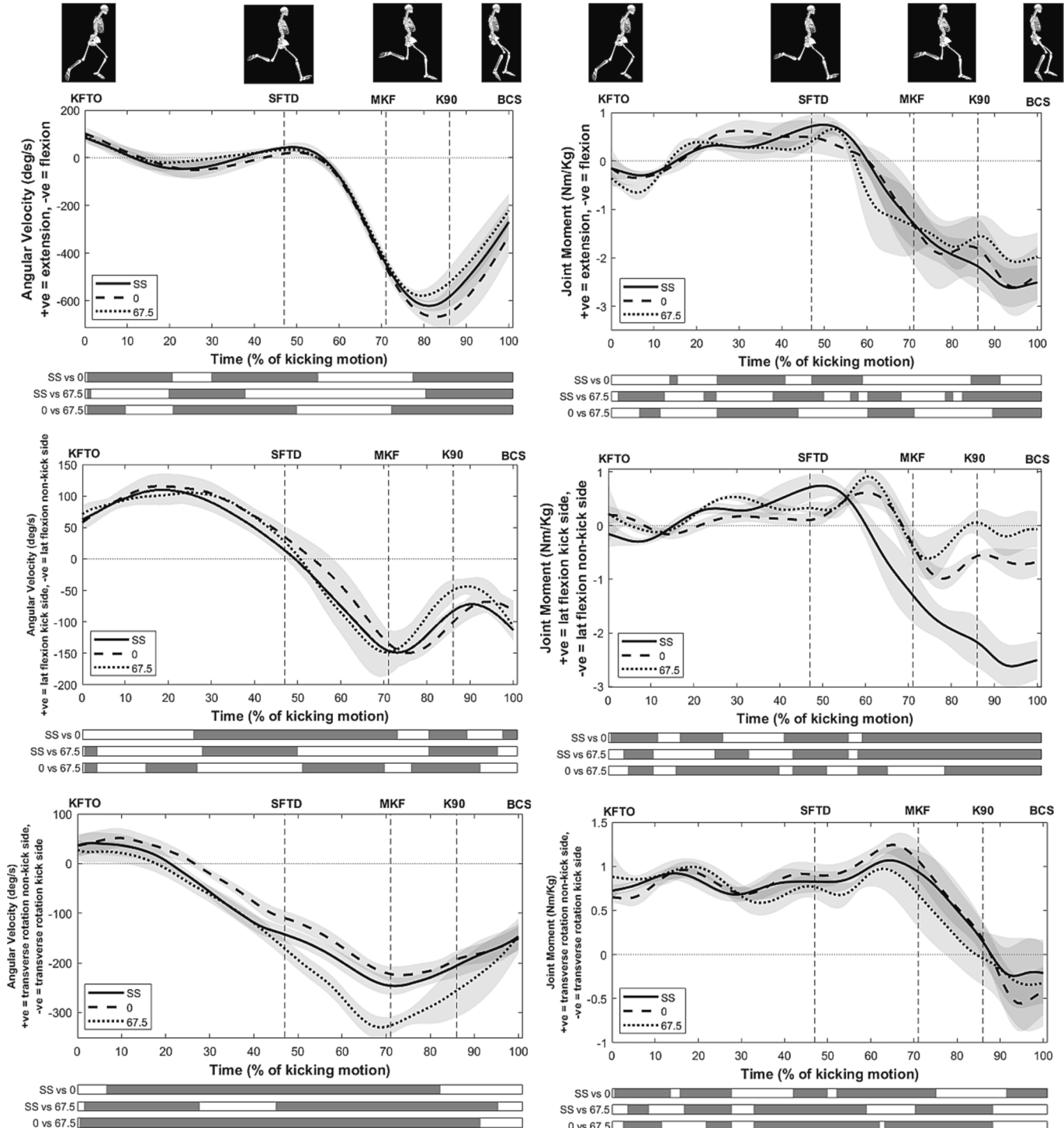

Fig. 2. Mean ± SD lumbo-pelvic joint angular velocities and moments in each sagittal (1st row), frontal (2nd row) and transverse (3rd row) planes for SS, Straight (0°) and Wide (67.5°) conditions between kicking foot take off (KFTO, 0%) and ball contact start (BCS, 100%). The average instances of support foot touch down (SFTD), maximal kicking knee flexion (MKF) and kicking knee angle at 90° (K90) are also shown. Grey bars under each plot indicate the corresponding locations of pairwise significant differences between curves (i.e. where SPM{t} exceeded critical threshold at which alpha % of curves would traverse, P < 0.017). Transverse rotation to the non-kick side = counter-clockwise rotation for a right footed kicker from aerial view.

adjusted, two-tailed SPM paired *t*-tests (SPM{*t*}) determined where pairwise differences occurred (N = 3, α = 0.017).

3. Results

3.1. Performance variables

All performance variables except the number of kicks taken to produce five accurate trials showed significant main effects (P < 0.05). Ball velocities from 67.5° (25.2 ± 1.5 m/s) were slower than both SS (26.1 ± 1.7 m/s, p = 0.001, d = 0.56) and 0° (25.9 ± 1.7 m/s, p = 0.011, d = 0.46). Foot velocities from 0° (18.6 ± 1.2 m/s) were slower than those from SS (19.0 ± 1.2 m/s, p = 0.014, d = 0.32) and 67.5° (19.2 ± 1.1, p = 0.005, d = 0.48). Ball to foot ratios obtained from 67.5° (1.31 ± 0.05) were smaller than those from SS (1.37 ± 0.06, p < 0.001, d = 1.09, P < 0.017) and 0° (1.39 ± 0.09, p < 0.001, d = 1.10). The number of kicks to produce 5 accurate trials were 0° = 5.7 ± 0.5, SS = 5.4 ± 0.6 and 67.5° = 5.5 ± 0.6.
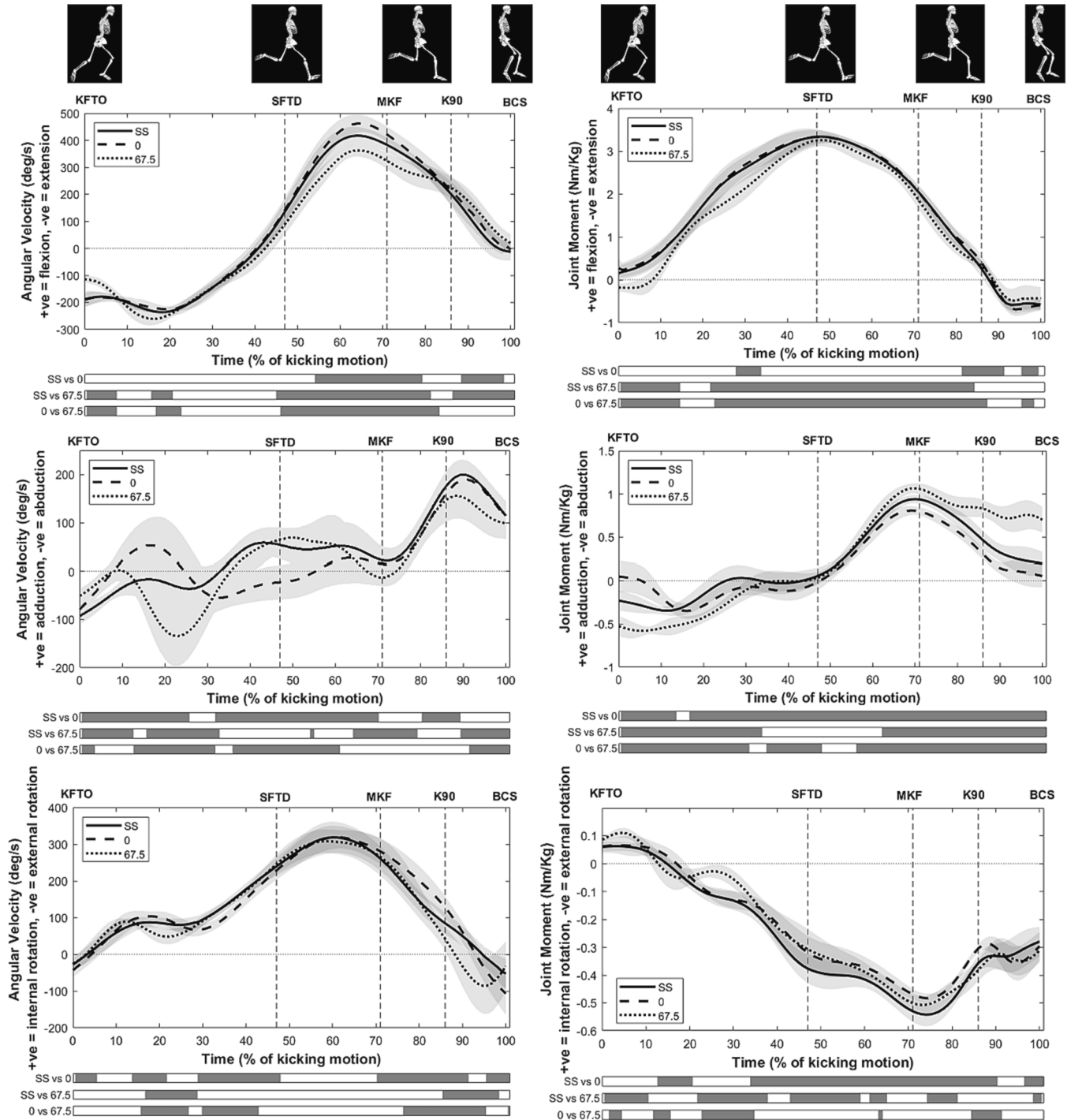

Fig. 3. Mean ± SD hip joint angular velocities and moments in each sagittal (1st row), frontal (2nd row) and transverse (3rd row) planes for SS, Straight (0°) and Wide (67.5°) conditions between kicking foot take off (KFTO, 0%) and ball contact start (BCS, 100%). The average instances of support foot touch down (SFTD), maximal kicking knee flexion (MKF) and kicking knee angle at 90° (K90) are also shown. Grey bars under each plot indicate the corresponding locations of pairwise significant differences between curves (i.e. where SPM{t} exceeded critical threshold at which alpha % of curves would traverse, P < 0.017).

3.2. Kinematic sequencing

The SPM{F} tests showed significant differences in angular velocities for each joint and plane (P < 0.05). Between KFTO and support foot touchdown (SFTD) corresponded to tension arc formation (0–48% of kick), and between SFTD and BCS as tension arc release (48–100% of kick). L-P flexion velocities increased to peaks at 80–90% of the kick and was faster from progressively straighter approaches in the final stages of tension arc release (~70–100%; Fig. 2). Transverse rotations were towards the non-kick side for the initial 20% of the kick, before reversing later in the kick. These were significantly faster in the 67.5° compared to SS and 0° kicks (Fig. 2). The kicking hip was extending during arc formation before peak hip flexion was reached at ~65% of the kick. Straighter approaches showed faster hip flexion during this phase (Fig. 3). During arc formation, SS and 67.5° displayed hip abduction, before reversing to adduction later in the kick. In contrast, 0° showed hip adduction during arc formation (7–25%) before abducting later in the kick (Fig. 3). The kicking hip was internally rotating for most of the kick, with peak rotation velocities (250–350°/s) occurring at ~60%. The hip then reversed to external rotation between 80 and 100% of kick. The kicking knee was flexing during tension arc formation and extending during arc release towards peak values at BCS (Fig. 4). Knee extension was faster during most of tension arc release from 67.5° and SS, compared to

0° (Fig. 4).

3.3. Kinetic sequencing

The SPM{F} tests showed significant differences for all joint moments and powers (P < 0.05). The L-P joint moments showed small extension moments (10–50%) that reversed to flexion during arc release. Small L-P lateral flexion moments to the kick side during arc formation reversed to lateral flexion to the non-kick side during arc release. These moments were larger from SS, compared to 67.5° and 0° (Fig. 2). Transverse rotation moments towards the non-kick side were observed throughout tension arc formation, but these reversed to act towards the kick side later in the kick (85–100%). The kicking hip showed a flexion moment for 0–90%, with peaks occurring near to SFTD. Hip flexion moments were larger in the straight 0° and SS kicks for most of the kick (Fig. 3). The kicking hip showed an abduction moment that reduced by SFTD, and reversed to adduction for the remainder of the kick. This adduction moment was more pronounced from 67.5° (Fig. 3). The kicking knee displayed an initial flexion moment before reversing to extension most of the kick (10–85%). These extension moments were more prominent for the straighter 0° and SS kicks (Fig. 4). This extension moment reversed to flexion as the knee extended past 90°.

The L-P and hip joints were absorbing power during arc formation (0–50%). As tension arc released (50–100%), power generation was evident. The SS and 0° kicks generated more power during the final stages of the kick (85–100%; Fig. 5). Peak hip power generation occurred at ~60% and was more pronounced in 0° and SS, compared to 67.5°. After a brief period of power generation, the kicking knee absorbed power during tension arc formation and early arc release (15–70%). Power was generated briefly between 70 and 90% before reverting to power absorption.

4. Discussion

4.1. Kicking performance

This study aimed to a) illustrate multiplanar torso, pelvis and kick leg sequencing during fast and accurate instep soccer kicks and b) highlight the effect of different approach angles on these sequencing patterns. The 67.5° approach produced slower ball velocities compared to SS, despite similar foot and faster knee extension velocities at BCS. Conversely, 0° approaches displayed slower foot and knee extension velocities at BCS, but ball velocities were not different to SS. Previous studies noted performance reductions at non-optimal approaches (>or <30-45°; Isokawa & Lees, 1988; Andersen and Dörge, 2011) or that performance can be maintained (Kellis et al., 2004; Scurr & Hall, 2009). Straighter approaches are indicative of a foot velocity trajectory that is congruent with the intended direction of ball travel (Ball, 2008). This maximises impact efficiency and resulting ball velocities, as indicated by the ball to foot velocity ratios. Wider approaches offset the trajectory of the foot relative to the ball's intended direction, and players may compensate by enhancing foot velocities to account for less efficient impact mechanics. In support of hypothesis a), this compensation was achieved via faster frontal and transverse plane L-P and kicking hip rotations, as wider approaches often elicit larger and faster non-sagittal rotations (Kellis et al., 2004; Scurr & Hall, 2009). Interestingly, accuracy was maintained across approach angles, indicating these compensations did not negatively influence speed-accuracy trade-offs. These findings partially support hypothesis b), and suggest different movement strategies can function to ensure successful instep kicking from different approach angles. The kinematic and kinetic sequencing strategies used to achieve these outcomes are discussed below.

4.2. Kinematic sequencing

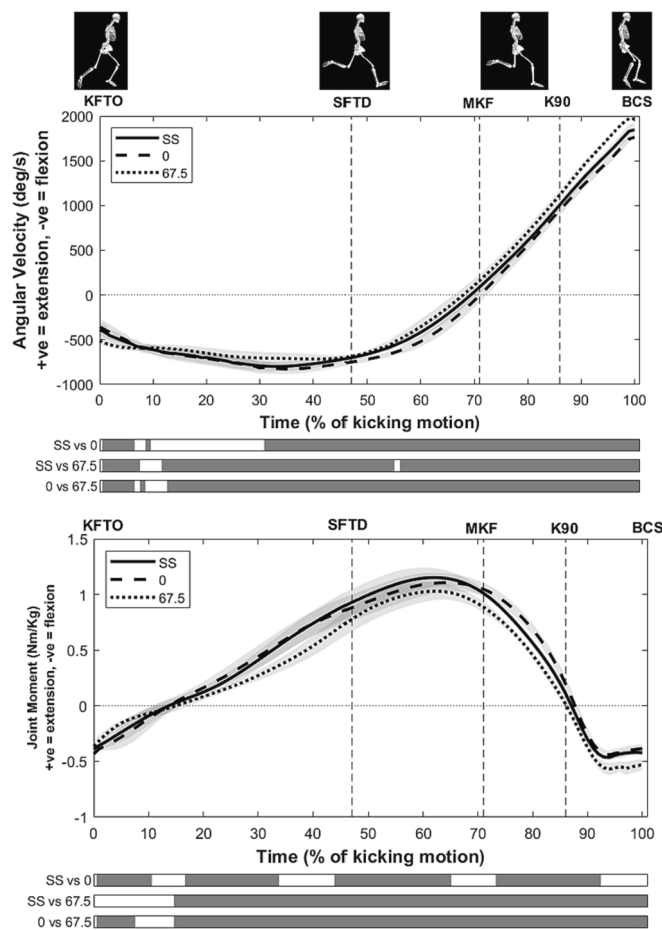L-P angular velocities before SFTD were indicative of tension arc

Fig. 4. Mean ± SD knee joint angular velocities and moments in the sagittal plane for SS, Straight (0°) and Wide (67.5°) conditions between kicking foot take off (KFTO, 0%) and ball contact start (BCS, 100%). The average instances of support foot touch down (SFTD), maximal kicking knee flexion (MKF) and kicking knee angle at 90° (K90) are also shown. Grey bars under each plot indicate the corresponding locations of pairwise significant differences between curves (i.e. where SPM{t} exceeded critical threshold at which alpha % of curves would traverse, P < 0.017).

Fig. 5. Mean ± SD lumbo-pelvic (L-P), hip and knee joint powers for SS, Straight (0°) and Wide (67.5°) conditions between the instances of kicking foot take off (KFTO, 0%) and ball contact start (BCS, 100%). The average instances of support foot touch down (SFTD), maximal kicking knee flexion (MKF) and kicking knee angle at 90° (K90) are also shown. Grey bars under each plot indicate the corresponding locations of pairwise significant differences between curves (i.e. where SPM{t} exceeded critical threshold at which alpha % of curves would traverse, P < 0.017).
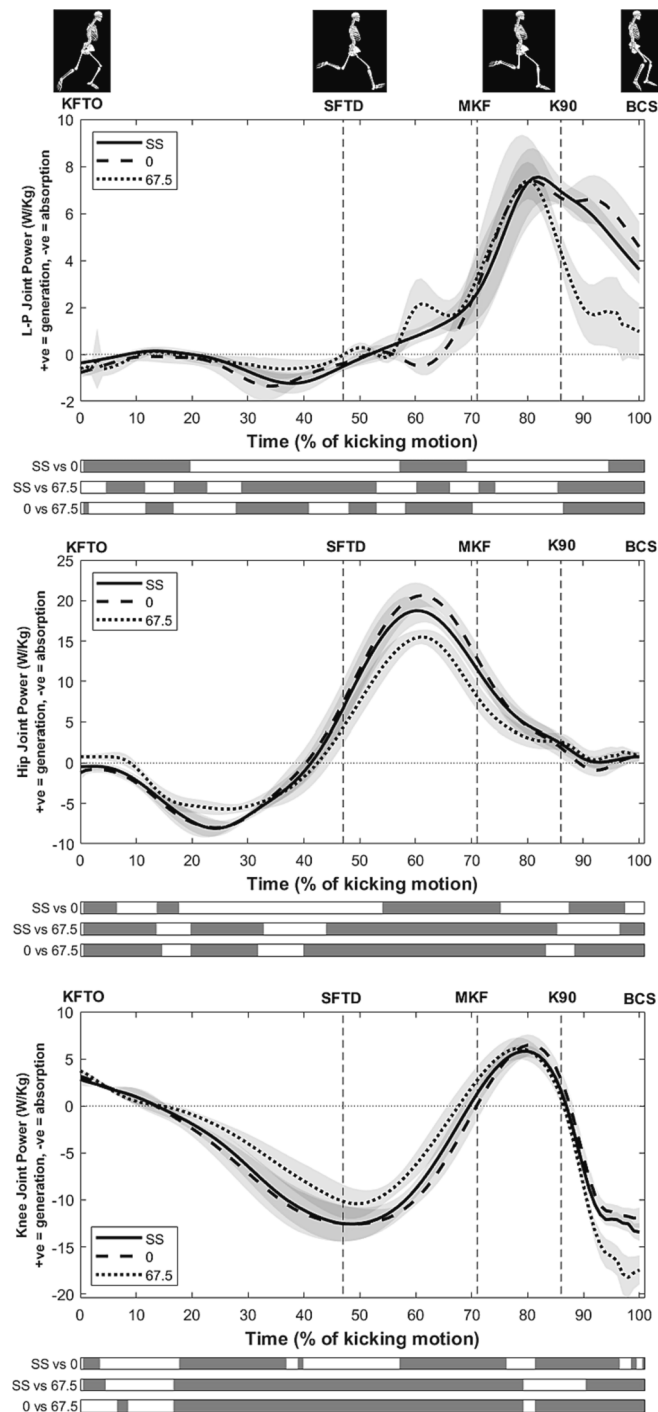
formation (Fullenkamp et al., 2015; Langhout et al., 2015; Shan & Westerhoff, 2005). The L-P joint was extending, laterally flexing to the kick side and transversely rotating to the non-kick side, while the kicking hip was extending and abducting (Figs. 2 and 3). These motions stretch the anterior torso and hip flexor muscles (Atack et al., 2019) and increase hip-shoulder separation angles (Lees & Nolan, 2002; Smith &

Gilleard, 2015) to enable coordinated tension arc release (Shan & Westerhoff, 2005). By considering the sequencing of these joints, this study showed skilled kickers release the tension arc in two distinct phases that complement kick leg proximal-to-distal action. The first phase corresponded to leg-cocking (i.e. SFTD to maximal kicking knee flexion) and was characterised by increases in hip flexion and transverse L-P velocities. Initiation of thigh forward rotation has been attributed to hip flexion and adduction (Nunome et al., 2006), but evidence suggests forward rotation of the thigh is coupled with L-P rotations as well (Langhout et al., 2015).

After hip flexion and L-P transverse rotation velocities slowed, the second phase of tension arc release was characterised by increasing L-P flexion velocity to a peak which coincided with angular extension of the knee past 90°. Concurrence of these rotations decelerates the thigh via pelvic backwards tilt (Langhout et al., 2015) and induce motion-dependent angular acceleration of the knee joint during the down-swing (Naito et al., 2010). However, although L-P flexion velocities were fastest at 0° for the final 25% of the kick, these kicks exhibited slower knee extension and foot velocities at BCS. The participants seemingly initiated tension arc release earlier in the kicking motion from SS and 67.5°. Peak hip flexion velocity and the onset of knee extension occurred earlier from these approaches and more time afforded to accelerate the knee and foot towards ball contact. Lees & Nolan (2002) noted a similar mechanism when using an elongated final stride. Greater pelvis retraction on the kick side allowed for larger pelvis, hip and knee rotations during the downswing and faster foot velocities at BCS. The faster peak L-P and hip flexion velocities observed during arc release at 0° may compensate for the lack of range of motion and time available to generate knee extension and foot velocities.

The players also adapted L-P strategy to optimise arc formation at straighter approaches. Greater L-P extension and transverse rotation velocities to the non-kick side were performed from 0°, suggesting attempts to maximise pelvis-torso separation and retract the kicking hip away from the ball (Lees & Nolan, 2002; Scurr & Hall, 2009). Slower L-P transverse rotations were observed in SS and 67.5°, suggesting optimal arc formation was achieved without the need for faster transverse rotations. During tension arc release, it was not surprising 0° induced greater L-P and hip flexion velocities, whereas 67.5° induced greater L-P transverse rotations (Scurr & Hall, 2009; Shan & Westerhoff, 2005). Further, trade-offs between transverse L-P and sagittal hip rotations was apparent. At straight approaches, L-P transverse rotations were constrained, so greater hip flexion and adduction velocities were required. At wider approaches, faster L-P transverse velocities were evident, with less input from hip flexion and adduction. Fullenkamp et al. (2015) noted a positive association between peak torso transverse rotation velocities and ball velocities (r = 0.57) and concluded faster torso rotations lead to performance enhancements. However, they used novice participants who may not have developed an adaptive movement strategy. Indeed, Anderson & Sidaway (1994) showed that novice kickers rely on a more rigid and less adaptive kinematic strategy than experienced counterparts.

4.3. Kinetic sequencing

Naito et al. (2010) previously showed the contributions of 3D torso and kick leg kinetic sources for generating kicking knee extension velocities during instep kicking. However, the timing of kinetic sequencing between the torso, pelvis and kick leg has not been determined. In general, each joint was absorbing power during arc formation, before generating power during arc release. This supports that eccentric pre-lengthening of the anterior torso, hip and knee muscles should precede subsequent concentric work to generate more powerful kicks. The L-P, hip and knee joint kinetics also support the idea of a two-phase tension arc release. During the first phase, large hip flexion and L-P transverse moments to the non-kick side were evident and peaked as the kicking knee became maximally flexed. Whilst thigh forward rotation is

primarily from concentric hip flexor action (Lees et al., 2009), this suggests a contribution, albeit smaller in magnitude, from the L-P transverse rotators. Moreover, contributions from L-P and hip work varied by approach. In opposition to hypothesis a), The 0° kicks exhibited greater L-P transverse rotation and hip flexion moments compared to SS and 67.5°, suggesting more reliance on muscular input to initiate tension arc release when performing kicks from straighter approaches. The joint moments and powers from 67.5° were generally smaller in magnitude compared to SS and 0° for most of the kick, yet this condition also exhibited faster or equivalent knee extension and foot velocities. Kicks from wider approaches may therefore be more mechanically efficient. However, while hip flexion moments were reduced at 67.5°, corresponding hip abduction/ adduction moments were larger, suggesting a greater contribution from the groin muscles during arc release. During the second phase, hip flexion and L-P transverse moments became inhibited. In their place, L-P flexion and knee extension moments became dominant, and concurrent peak power generation was evident at these joints as the knee extended towards BCS. This supports previous inferences that simultaneous concentric torso and knee work is a mechanism by which experienced players produce fast knee extension and foot velocities (Naito et al., 2010). Moreover, this study identified a L-P flexor moment (and thus the torso flexor muscles) that predominantly performs this work. From a practical perspective, it might be pertinent to extend recommendations for strengthening this muscle group for effective kicking actions as well.

5. Conclusions

Multiplanar torso, pelvis and kick leg sequencing during fast and accurate soccer instep kicking functions as a two-stage tension arc release. The first phase was characterised by increases in concentric hip flexion and transverse lumbo-pelvic velocities. The second phase was characterised by increasing concentric lumbo-pelvic flexion and knee extension work to angularly accelerate the kicking knee towards foot-to-ball contact. Further, there was evidence of altering multiplanar torso, pelvis and kick leg actions to maintain ball velocity and accuracy at approach angles other than SS. These findings can help coaches and practitioners design effective training practices. For the first phase of arc release, conditioning exercises that couple torso transverse rotations and hip flexion may be appropriate. In contrast, exercises that couple torso flexion and knee extension might prove effective in the second phase of arc release. Exposing soccer players to different approach scenarios may promote development of strategies that are robust to deviations from non-optimal approaches.

CRediT authorship contribution statement

Simon Augustus: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Penny E. Hudson:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Neal Smith:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2023.111920.

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