Hip and Knee Joint Angle Patterns and Kicking Velocity in Female and Male Professional Soccer Players: A Principal Component Analysis of Waveforms Approach

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Abstract
This study used principal component analysis (PCA) of waveforms to extract movement patterns from hip and knee angle time-series data; and determined if the extracted movement patterns were predictors of ball velocity during a soccer kick. Twenty-three female and nineteen male professional soccer players performed maximal effort instep kicks while motion capture and post-impact ball
velocities data were recorded. Three-dimensional hip and knee joint angle time-series data were calculated from the beginning of the kicking leg's backswing phase until the end of the follow-through phase and entered into separate PCAs for females and males. Three principal components (PC) (i.e., movement patterns) were extracted and PC scores were calculated. Pearson correlation coefficients were calculated to establish correlations between hip and knee PC scores and kicking velocity. Results showed better kicking performance in male players was associated with a greater difference between the hip extension at the end of the backswing/beginning of the leg cocking phases and hip flexion at the end of the follow-through phase ($r = -0.519, p = 0.023$) and a delayed internal rotation of the hip ($r = 0.475, p = 0.040$). No significant correlations between ball velocity and hip and knee kinematics were found for female players.

Keywords
Biomechanics; continuous analysis; kicking cues; football; movement pattern

Introduction
Kicking is perhaps the most important skill in soccer as it is the main technique used to score goals (Kubayi & Toriola, [20]). Although kicking is a full-body motion (Shan & Westerhoff, [39]), the movement has been defined as a coordinated open chain movement of the lower limb that follows a sequential proximal-to-distal pattern (Lees & Nolan, [23]). This pattern begins with the motion of the hip and is followed by sequential motions of the knee and ankle, such that each of these joints reaches its maximal velocity in the same proximal-to-distal order (Juarez et al., [15]). In particular, the role of the hip and knee joints are crucial in kicking as they form the proximal components of the chain and thus contribute significantly to the sequential increases in distal joint velocities, and ensuring efficient kinetic energy transmission, and thus contributing to ball velocity (Lees et al., [22]). Electromyographic data corroborates and highlights the role of the gluteus maximus and medius in the initial part of the kick and the role of the vastus medialis right before impact (Brophy et al., [7]).

Although researchers have analysed the kicking motion with three-dimensional and two-dimensional motion capture, most have investigated only sagittal plane movements where the greatest range of motion is observed (Kellis & Katis, [17]; Lees et al., [22]). Nevertheless, previous research showed that the movements of the hip joint in the frontal (Charnock et al., [8]) and transverse plane (Lees et al., [22]) are important to determine the success of the kick (Sinclair et al., [40]), particularly when accuracy is considered along with the ball speed (Lees & Nolan, [24]; Nunome et al., [30]).

While the kicking motion is characterized by highly dynamic and time-varying movement patterns, most studies have only analysed discrete kinematics variables, such as peak hip or knee sagittal plane angles (Barfield et al., [3]; Dorge et al., [10]; Katis et al., [16]; Lyle et al., [26]; Nunome et al., [30]; Nunome, Ikegami et al., [31]; Ruscello et al., [35]; Sakamoto et al., [37]; Sinclair et al., [40]), which provide information about the ranges of motion but are difficult to translate to direct coaching of athletes as they do not provide information about when those peaks are reached and what are the time intervals between the different peaks. These studies have attributed a greater kicking velocity to greater peak values of hip extension (Ruscello et al., [35]) and knee flexion (Lees et al., [22]; Nunome et al., [30]), or greater ranges of motion (Sinclair et al., [40]), mainly in the sagittal plane (Katis et al., [16]) until ball impact. Very few researchers have studied the follow through phase (i.e., from ball impact...
until peak hip flexion) or the complete time-series data from toe-off until the end of follow-through (i.e., until peak hip flexion) in relation to kicking performance (Navandar et al., [28]; Shan & Westerhoff, [39]). Moreover, most of the aforementioned studies have been carried out with a small sample of university-level or elite youth players, with a dearth of literature on the kicking skills of professional soccer players. Moreover, a majority of studies have looked at male players, with very few studies investigating kicking in female players (Barfield et al., [3]; Brophy et al., [6]; Katis et al., [16]; Navandar et al., [28]; Ruscello et al., [35]; Sakamoto & Asai, [36]; Sakamoto et al., [37]). Female players have lower kicking speeds, perhaps owing to females activating the biarticular rectus femoris to the iliopsoas during hip flexion (Brophy et al., [6]); but as Katis et al. ([16]) and previous studies have described the need to develop sex-specific training modules to improve kicking (Ruscello et al., [35]), and specific cues to develop them have not been found in literature.

Principal components analysis (PCA) of waveforms is a common analytical technique that is used to investigate spatiotemporal dynamics within time-series data (Brandon et al., [5]; Deluzio & Astephen, [9]; Warmenhoven et al., [43]). When applied to biomechanical time-series data, PCA can provide information about the spatial and temporal movement patterns that characterize the time-varying task dynamics of the biomechanical data. Importantly, variables derived from PCA can capture and distinguish kinematic and kinetic differences data between groups and conditions to a better extent than traditional analyses of discrete variables (e.g., peak angle or angle at foot contact). Another important aspect of PCA is that no a priori assumptions are made about which discrete variables are important, which has important implications with respect to testing superfluous or extraneous variables, or even worse p-hacking. Sports biomechanists have used PCA in experimental paradigms to examine group- or task-related differences in movement patterns with respect to movement and sports performance such as vertical jumping (Floría et al., [13]), weightlifting (Kipp & Harris, [18]), cross-country skiing (Gløersen et al., [14]) and rowing (Warmenhoven et al., [44]). Although Smith and Gilleard ([41]) did apply PCA to analyse the effect of peak kinematic variables on the kicking technique in amateur players, no previous studies, however, used PCA of waveforms to investigate spatiotemporal movement patterns during a soccer kick. Given the strengths of PCA, its application in the context of kicking biomechanics could provide important insight into the movement patterns that reflect the time-varying task dynamics of the kicking motion. Moreover, correlating PCA-derived movement patterns with kicking performance (i.e., ball velocity) would further provide important practical information as more specific information about the spatiotemporal patterns across the entire kicking cycle can be obtained, instead of just peak values and/or ranges of motion. Such information may have the potential to help coaches design better coaching programmes that aim to improve the kicking skill of male and female players. Therefore, the purpose of the current study was to use PCA to extract movement patterns from hip and knee joint angle time-series data and to determine if the extracted movement patterns were predictors of ball velocity during a soccer kick. Based on previous research, it was hypothesized that the sagittal plane movement patterns at the hip and the knee would have the highest correlation with the ball velocity. Considering that previous research showed differences in the kicking techniques of male and female players (Barfield et al., [3]; Katis et al., [16]; Sakamoto & Asai, [36]), the PCA and correlation analysis between movement patterns and ball velocity were performed separately for a group of male and female professional soccer players.
Methods

Twenty-three female (age = 22 ± 5 years, weight = 60.7 ± 9.5 kg) and nineteen male soccer players (age = 21 ± 2 years, weight = 71.5 ± 6.2 kg) were recruited to participate in the current study. All participants were professional players: the female participants played in the "Primera División Femenina" (Women's first division) of the Spanish Women's league, and the male participants played in the Segunda Division B of the LaLiga. All players provided written informed consent following the departmental and university ethical procedures, which followed the principles outlined in the Declaration of Helsinki. Approval for the study was obtained from the Universidad Politécnica de Madrid ethics committee. Before the data collection session, participants answered questions about their preferred kicking limb (thirty-three players were right-footed and nine were left-footed) and professional playing experience at their current level (4.5 ± 4.3 years in the first and second division).

The data collection was carried out under laboratory conditions on FIFA™ approved artificial turf. A six-camera motion capture system (VICON, Oxford Metrics Ltd, United Kingdom) recorded kinematic data at 250 Hz. Twenty-four reflective markers (diameter = 14 mm) were attached to the anatomical landmarks of each participant and four markers were attached to the ball (Navandar et al., [28]). The body markers were attached symmetrically on the left and right sides to the anterior superior iliac spines, posterior superior iliac spines, heads of the greater trochanter of the femur, lateral thighs, medial and lateral epicondyles of the femur, lateral shanks, medial and lateral malleoli, calcanei (directly on the boot), and the heads of the second and fifth metatarsals (directly on the boot). Players were asked to wear boots appropriate for the artificial turf. The soccer ball met FIFA™ criteria (diameter = 22.5 cm, pressure = 12 psi).

A static trial, in which the participants were positioned in the kicking area with both feet parallel and stood with upright posture and outstretched arms, was performed to determine the joint centres. After the static trial, the markers on the head of the greater trochanter, medial epicondyle of the femur, medial malleolus, and the head of the second metatarsal on both the right and left limb were removed. Each participant then performed a general ten-minute warm-up, which was approved by the strength and conditioning coaches of the respective teams, before they performed warm-up kicks until they felt comfortable with the markers and test setup.

For the collection of the dynamic kicking trials, each participant was required to kick the ball into a 1 × 1 m marked target that hung on a net 7 m away (Barbieri et al., [2]; Navandar et al., [28]). Players were instructed to kick the ball as hard as possible using the instep kicking technique with a four-step run-up, such that the support leg was placed on the kick area. This process was repeated until each participant had performed five kicks that struck the target.

Trajectories of the real and virtual markers during the dynamic kicking trials were reconstructed and labelled with VICON Nexus (v. 1.8.4., Vicon Workstation, Oxford Metrics Ltd, UK). For each trial, the lower body was modelled based on the joint centres and a rigid 4-link segment model that included the foot, shank, thigh, and pelvis. Joint angles were calculated with a joint coordinate system and the Y-X-Z rotation sequence (Lees et al., [22]), where Y represented the mediolateral axis, X-axis represented the anteroposterior axis, and Z represented the vertical axis.
Given that the impact of the foot with the ball can distort data and affect filtering and smoothing procedures (Nunome, Ikegami et al., [31]), marker data from one frame before to five frames after ball impact were deleted and interpolated with a cubic spline (Reid et al., [34]). The instant of ball impact was determined based on the first frame (4 ms) of movement of a virtual marker at the midpoint of the soccer ball (Navandar et al., [28]). Deletion and spline interpolation of data helps avoid errors associated with the deformation of the ball (Nunome, Lake et al., [32]). All subsequent data were smoothed with a cross-validated quintic spline (mean square error of 4 mm²; Woltring, [45]). Ball velocity was calculated using a five-point numerical differentiation method and the kick with the median ball velocity was chosen for further analysis (Navandar et al., [28]).

Data were then cropped from toe-off through the end of the follow-through (Lees, [21]; Navandar et al., [28]). The cropped hip (in the sagittal, transversal, and frontal planes) and knee joint (in the sagittal plane) angle data were then normalized to 101 data points to represent the kicking motion from 0 to 100% (Figures 1 & 2 – top rows). The time-normalized joint angle data were used as inputs to separate PCAs (i.e., hip and knee joint angle data from the females and males separately). In each case, the input data represented an \( m \times n \) matrix (\( m = \) number of participants, \( n = \) normalized time [101 time points]). Within the PCA, each individual joint angle curve was normalized with respect to the mean and standard deviation of the entire sample. Principal components (PC) were extracted via eigenvector decomposition. PCs were not rotated to preserve the structure in the variation of the original data. Each PCA was set to extract the first three PCs since these explain the most variance in the data, and capture relevant biomechanical features such as magnitudes, differences, and phase shifts (Brandon et al., [5]). The eigenvalue of each PC was used to calculate the variance accounted for (VAF) by each respective PC (Figure 1 & 2 – bottom rows; O’Connor & Bottum, [33]). PC scores for the hip and knee angles of the female and male participants were then calculated and used for all statistical analyses. All PCA were performed with custom-written MATLAB code (The MathWorks, Natick, MA, USA).

Figure 1. Ensemble average (thick black line with one standard deviation cloud) Hip flexion (positive direction)/extension (negative direction) angles (top row) for females (left column) and males (right column), and the variance accounted for (VAF – bottom row) by the three extracted principal components (PC1 – thin solid line, PC2 – thin dashed line, PC3 – thin dotted line). The vertical lines indicate the average occurrence of key events during the kick: the peak Hip extension, the peak knee flexion, and ball impact respectively so that the phases, namely, backswing, leg cocking, leg acceleration, and follow through, can be identified.
Figure 2. Hip angle principal components (PC) and the respective motion patterns for females (left column) and males (right column). Note: positive and negative values represent Hip flexion and extension angles; positive and negative symbols reflect the respective effects of positive and negative PC scores on the motion pattern. VAF – variance accounted for (by each PC). The vertical lines indicate the average occurrence of key events during the kick: the peak Hip extension, the peak knee flexion, and ball impact respectively so that the phases, namely, backswing, leg cocking, leg acceleration, and follow through, can be identified.

The kicking motion was divided into four phases based on the following events: backswing (from toe-off of the kicking leg until its peak hip extension), leg cocking (from the peak hip extension until peak knee flexion), the leg acceleration (from the peak knee flexion until ball impact), and follow through (from ball impact until peak hip flexion; Navandar et al., [28]). The absolute duration of these phases were calculated.

The correlations between ball velocity and PC scores for the hip and knee angle data from the female and male players were assessed with Pearson correlation coefficients ($r$). Bootstrap resampling ($n = 100$) was performed to create 95% confidence intervals (CI) for each correlation. Only correlation coefficients where the confidence intervals did not cross zero were interpreted as significant. In addition, the correlations between the absolute duration of these four kicking phases and ball velocities were also calculated. The level for statistical significance was set to an $\alpha$-value of 0.05. Data are presented as Mean ± SD. All statistical analyses were performed in SPSS 26.0 (IBM Corporation, Somers, NY, USA).

**Results**

The average ball velocities were 24.9 ± 2.5 m/s for females and 28.6 ± 1.5 m/s for males. PCA was used to extract three PCs from the hip and knee joint angle time series of the female and male groups (Figures 1–8). The cumulative variance accounted for (VAF) by the PCs of the hip joint angle time-series data exceeded 90% in the females and males, whereas the knee joint angle time-series data exceeded 85% in the females and 90% in the males.
Figure 3. Ensemble average (thick black line with one standard deviation cloud) Hip abduction (positive direction)/adduction (-) angles (top row) for females (left column) and males (right column), and the variance accounted for (VAF – bottom row) by the three extracted principal components (PC1 – thin solid line, PC2 – thin dashed line, PC3 – thin dotted line). The vertical lines indicate the average occurrence of key events during the kick: the peak Hip extension, the peak knee flexion, and ball impact respectively so that the phases, namely, backswing, leg cocking, leg acceleration, and follow through, can be identified.

Figure 4. Hip angle principal components (PC) and the respective motion patterns for females (left column) and males (right column). Note: positive and negative values represent Hip adduction and abduction angles; positive and negative symbols reflect the respective effects of positive and negative PC scores on the motion pattern. VAF – variance accounted for (by each PC). The vertical lines indicate the average occurrence of key events during the kick: the peak Hip extension, the peak knee flexion, and ball impact respectively so that the phases, namely, backswing, leg cocking, leg acceleration, and follow through, can be identified.
Figure 5. Ensemble average (thick black line with one standard deviation cloud) Hip internal (positive direction)/external (-) rotation angles (top row) for females (left column) and males (right column), and the variance accounted for (VAF – bottom row) by the three extracted principal components (PC1 – thin solid line, PC2 – thin dashed line, PC3 – thin dotted line). The vertical lines indicate the average occurrence of key events during the kick: the peak Hip extension, the peak knee flexion, and ball impact respectively so that the phases, namely, backswing, leg cocking, leg acceleration, and follow through, can be identified.

Figure 6. Hip rotation angle principal components (PC) and the respective motion patterns for females (left column) and males (right column). Note: positive and negative values represent Hip internal and external rotation angles; positive and negative symbols reflect the respective effects of positive and negative PC scores on the motion pattern. VAF – variance accounted for (by each PC). The vertical lines indicate the average occurrence of key events during the kick: the peak Hip extension, the peak knee flexion, and ball impact respectively so that the phases, namely, backswing, leg cocking, leg acceleration, and follow through, can be identified.
Figure 7. Ensemble average (thick black line with one standard deviation cloud) knee flexion (positive direction)/extension (negative direction) angles (top row) for females (left column) and males (right column), and the variance accounted for (VAF – bottom row) by the three extracted principal components (PC1 – thin solid line, PC2 – thin dashed line, PC3 – thin dotted line). The vertical lines indicate the average occurrence of key events during the kick: the peak Hip extension, the peak knee flexion, and ball impact respectively so that the phases, namely, backswing, leg cocking, leg acceleration, and follow through, can be identified.

Figure 8. Knee angle principal components (PC) and the respective motion patterns for females (left column) and males (right column). Note: positive and negative values represent flexion and extension angles; positive and negative symbols reflect the respective effects of positive and negative PC scores on the motion pattern. VAF – variance accounted for (by each PC). The vertical lines indicate the average occurrence of key events during the kick: the peak Hip extension, the peak knee flexion, and ball impact respectively so that the phases, namely, backswing, leg cocking, leg acceleration, and follow through, can be identified.

With respect to the hip flexion/extension joint angles (Figures 1 and 2), the first three extracted movement patterns for both males and females captured variations in the hip joint angle magnitudes during the leg acceleration and follow-through phases (PC1), variations in the range of motion (PC2), and variation in the hip joint angle magnitudes during the backswing phase (PC3). For hip
adduction/abduction joint angles in female players (Figures 3 and 4), the first three extracted movement patterns captured variations in hip adduction after 40% of the cycle (PC1), variations in ranges of motion (PC2), and variations in hip abduction right after toe-off (PC3). In the case of male players (Figures 3 and 4), the extracted PCs represented a phase shift in hip abduction/adduction after 40% of the cycle (PC1), variations in hip adduction angle in the follow-through phase (PC2), and variations in hip abduction in the backswing phase (PC3). In the case of the hip internal/external rotation joint angles (Figures 5 and 6), the extracted PC in both males and females highlighted variations in transverse plane movement patterns throughout the kicking motion (PC1), a phase shift with a greater tendency for hip external rotation right after 20% of the kicking cycle and a delayed internal rotation (PC2), and variations in peak internal rotation angle for females and a limited external rotation in the follow-through phase in males (around 80% of the cycle) (PC3).

With respect to the knee joint angles for both male and female players (Figures 7 and 8), the first extracted movement pattern (PC1) captured a general phase shift in the timing of peak knee flexion in both females and males. In females the second and third extracted patterns captured variations in knee joint flexion magnitude during the leg cocking phase (PC2) and variations in knee joint angle range of motion during the leg acceleration phase (PC3). In contrast, in males the second and third extracted patterns captured variations in knee joint flexion magnitude during the backswing phase (PC2) and variations in knee joint angle range of motion during the follow-through phase (PC3).

The correlation analysis between the extracted PC scores and ball kicking velocity identified two significant correlations in the male group (Table 1). Specifically, faster kicking velocities were correlated with smaller sagittal plane hip PC2 scores (i.e., a greater difference in hip joint angle between the end of the backswing phase and the end of the follow through) and with greater transverse plane hip PC2 scores (i.e., greater external rotation of the hip at the end of the backswing phase followed by a delayed internal rotation). In addition, the correlation analysis between the absolute phase duration of the backswing phase and ball kicking velocity showed a significant correlation in the male group (Table 2).

Table 1. Pearson correlation coefficients (r), 95% confidence intervals (95% CI), and significance values (p-values) between kicking velocity and Hip and knee principal component (PC) scores in female (n = 23) and male (n = 19) professional soccer players.

<table>
<thead>
<tr>
<th></th>
<th>Females</th>
<th>Males</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>r</td>
<td>95% CI</td>
</tr>
<tr>
<td>Hip – Flex/Ext</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC1</td>
<td>-0.111</td>
<td>-0.661, 0.427</td>
</tr>
<tr>
<td>PC2</td>
<td>-0.063</td>
<td>-0.459, 0.255</td>
</tr>
<tr>
<td>PC3</td>
<td>0.377</td>
<td>-0.043, 0.728</td>
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<tr>
<td>Hip – Abd/Add</td>
<td></td>
<td></td>
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<tr>
<td>PC1</td>
<td>0.008</td>
<td>-0.581, 0.472</td>
</tr>
<tr>
<td>PC2</td>
<td>-0.105</td>
<td>-0.471, 0.213</td>
</tr>
<tr>
<td>PC3</td>
<td>-0.083</td>
<td>-0.525, 0.180</td>
</tr>
<tr>
<td>Hip – Int/Ext</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC1</td>
<td>-0.192</td>
<td>-0.411, 0.123</td>
</tr>
<tr>
<td>PC2</td>
<td>0.073</td>
<td>-0.314, 0.602</td>
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</table>
### Table 2. Pearson correlation coefficients (r), 95% confidence intervals (95% CI), and significance values (p-values) between kicking velocity and the absolute duration of the different phases in female (n = 23) and male (n = 19) professional soccer players.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Females</th>
<th>Males</th>
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<tbody>
<tr>
<td></td>
<td>r</td>
<td>95% CI</td>
</tr>
<tr>
<td>Backswing</td>
<td>0.097</td>
<td>−0.217, 0.393</td>
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<tr>
<td>Leg Cocking</td>
<td>−0.093</td>
<td>−0.39, 0.221</td>
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<tr>
<td>Leg Acceleration</td>
<td>0.17</td>
<td>−0.146, 0.454</td>
</tr>
<tr>
<td>Follow-through</td>
<td>−0.046</td>
<td>−0.349, 0.265</td>
</tr>
</tbody>
</table>

2 Note: Significant (p < 0.05) r and p-values are highlighted in **bold**

### Discussion

The purpose of the current study was to use PCA to extract movement patterns from hip and knee joint angle time-series data and to determine if the extracted movement patterns were predictors of ball velocity during a soccer kick. The correlation results from the current study indicate that two principal components associated with specific hip joint angle movement patterns (i.e., hip flexion/extension and internal/external rotation) were associated with ball kicking performance, but only in male soccer players. Specifically, the patterns captured differences between 30% and 100% of the kicking motion in hip flexion/extension angles, where a greater range of motion was associated with faster kicks; and between 15% and 70% of the kicking motion in the hip internal/external rotation angles, where a delayed internal rotation resulted in faster kicks.

When considering sagittal plane movements in professional male soccer players, a majority of the variances (80% or above) were on the hip flexion phase (PC1) and the range of motion in this plane (PC2). Specifically, reconstructing the effects of a positive one standard deviation change in the PC scores of the pattern of PC2 (Figure 2), resulted in greater peak hip extension at 30% and peak hip flexion at 100%, whereas a negative one standard deviation change resulted in smaller peak hip extension at 30% and peak hip flexion at 100%. The interpretation of the PC scores of this specific pattern along with the direction (i.e., sign) of the correlation coefficient suggests that the results showed that a greater hip range of motion between the initiation of the leg cocking phase and the end of the follow-through phase were able to produce greater kicking velocities in male players. This follows the theoretical principle that links a greater range of motion to greater momentum (Smith & Gilleard, [41]) via greater transfer of energy or longer times of force application by the respective muscles (Knudson, [19]). Future research, focusing on angular velocity patterns of the hip and the knee during the kicking cycle, the kinetics and muscular activity of the hip flexors, and their relation to ball velocity can help confirm this hypothesis. Based on the results, male players may benefit from delaying the peak hip extension angle and reaching a higher hip flexion angle at the end of the follow-through
phase in order to kick the ball faster. From an applied perspective, this finding could easily be translated into the coaching literature on the kicking technique. Future studies can look at the effect of asking players to continue flexing the hip joint, rather than braking, during the follow-through which, as hypothesized, may increase ball velocity. In Australian rules football, such a pattern has been described as "kicking through the ball" (Ball, [1]; Duhig et al., [11]), and its impact in soccer, where high velocities are advantageous, can be investigated.

Although kicking literature describes an initial external rotation of the hip of the kicking leg right after toe-off (Levanon & Dapena, [25]), such a movement pattern was not found to be evident in this study. The results (Figures 5 and 6) show a large variability in the hip internal/external rotation, where female players appear to sustain the internally rotated position of the hip from the beginning of the backswing phase, whereas male players tend to exhibit externally rotated hips at toe-off. When comparing ball velocities (with male players kicking the ball faster than females) these findings contradict those of Smith and Gilleard ([41]) who mentioned a reduced hip external rotation initially being key to greater kicking velocities, however, these differences can be attributed to professional players participating in this present study. These differences present novel findings that could occur from delayed activation of the hip rotator muscles, but would need to be confirmed with EMG studies. Furthermore, in the case of male players, reconstructing and observing the effects of a negative one standard deviation change in the PC scores of the pattern of PC2 (Figure 6), resulted in a delayed peak internal rotation angle when compared to a positive one standard deviation change, and an external rotation between 15 and 30% of the kicking cycle (absent in the case of a positive one standard deviation change). The interpretation of the PC scores of this specific pattern along with the direction (i.e., sign) of the correlation coefficient suggests that an external rotation of the hip at the end of the backswing and the beginning of the leg cocking phase, and a delayed internal rotation produce greater kicking velocities in male players. This is in line with a previous study of experienced futsal players from Brazil who produced greater external rotation in faster kicks from their dominant limb kicks when compared to the slower kicks from the non-dominant (Barbieri et al., [2]).

Based on the above results, it appears that the backswing phase can play an important role in determining the ball velocity in male players. This is further confirmed when correlating the absolute times for the backswing phase with the ball velocities: the greater the duration of the backswing phase, the greater the resulting ball velocity. Previous research, which compared peak values in the sagittal plane, has associated a greater hip extension angle to be a precursor to greater ball velocities in male soccer players (Barfield et al., [3]; Katis et al., [16]; Ruscello et al., [35]). Compared to previous research, however, the time-series approach of the current study also shows the importance of a longer backswing phase and shows the importance of hip external rotation in the same phase. It is believed that the gluteus maximus, the main extensor of the hip, provides the power for hip external rotation (Neumann, [29]). The results could imply that greater activation of the gluteus maximus muscles could lead to a faster kick, although this ought to be corroborated by future research. From an applied point of view, if the action of the gluteus maximus is improved in male players, this would not only help increase ball velocity but also has the potential to improve kicking mechanics in case a player suffers an injury to the hamstring muscles (Navandar et al., [28]). Moreover, the results suggest that internal rotation of the hip should not reach a peak before ball impact but continue to follow-through in order to reach higher velocities, similar to how shoulder internal rotation continues until after ball
release in throwing sports (Escamilla & Andrews, [12]). Based on research in baseball pitching (Escamilla & Andrews, [12]), quantifying the hip rotation torque in the cocking and acceleration phases could help provide information for the development of more specific training programmes and coaching cues for soccer players.

It should be noted that the correlation between the ball velocity and hip joint angle movement pattern was only found to be significant for male players, but not for female players. Several reasons for this discrepancy may exist. Primarily, the VAF differs between male and female players, indicating that the kicking strategies adopted by male and female players are completely different (Boyne et al., [4]). Previous research has shown that there is a difference in the ranges of motion in female players, with them exhibiting smaller peak hip extension angles than male soccer players (Navandar et al., [27]), which in turn may lead to less variation in predictor variables and may impair the ability of regression models to explain variance in the outcome variable. This assertion is supported by the fact that the VAF in hip joint flexion/extension angle data captured by PC2 was much larger in males than in females (Figure 1). Furthermore, as discussed earlier, this initial lack of internal/external rotation should be considered while coaching female players. Future research should use longitudinal designs that incorporate drills that aim to increase hip extension/flexion range of motion and simultaneous hip external rotation (with the hip in extension) to see if this would increase ball velocity.

In addition to the lack of correlation between ball velocity and hip joint angle motion patterns in females, it is interesting to note that none of the knee joint angle motion patterns were associated with kicking performance in either group. The poor correlations between knee joint angle motion pattern and ball velocity may be the result of the different hip flexion strategies that were adopted by the females and males, which could lead to differences in timing and magnitude of knee flexion motions. Indeed, high amounts of inter-subject variability, due to different individual strategies, may also contribute to the lack of correlation between ball velocities and knee joint angle patterns while kicking a soccer ball. Theoretical models of maximal instep ball kicking (Kellis & Katis, [17]; Lees et al., [22]; Lees & Nolan, [23]) typically ascribe high importance to magnitudes of hip and knee ranges of motion and the timing of the respective peak values, the results of the current study therefore only partially align with these models in respect to biomechanical predictors of ball velocity during soccer kicks.

The PCA identified hip and knee joint angle movement patterns that captured between-subject variations in kicking biomechanics. Although based on the VAF, these patterns sometimes differed between females and males for the hip joint motions, the differences were small and may suggest that the structure in movement variability is comparable between groups. In the case of the knee flexion/extension, only males exhibited a decrease in total VAF and in the standard deviation of knee joint angle flexion approximately 45% into the kicking motion, which occurred around the instant of maximum knee flexion, and thus suggests that the between-subject variation in peak knee flexion in males is significantly lower than in females. The spatiotemporal differences in the second and third extracted patterns and the VAF suggest that females and males exhibit different between-subject variations in kicking biomechanics and it would be of interest to investigate if these differences and variations have any functional significance.
It is important to consider several limitations of the current study. First, players were asked to kick with an accuracy constraint, which may result in lower ball velocities (Van den Tillaar and Ulvik ([42])). Nevertheless, kicking with an accuracy constraint closer approximates real-world situations and the ball velocities of female and male soccer players in the current study were comparable to those reported in studies previous studies (Katis et al., [16]; Ruscello et al., [35]; Shan, [38]). Second, data from male and female soccer kicks were used as inputs to separate PCAs. Female and male soccer players exhibit some differences in kicking biomechanics (Katis et al., [16]). Analysing male and female data together may therefore produce different results, but such a group-PCA would likely be more suitable for studying sex-specific group differences in kicking biomechanics rather than correlations with kicking velocity, especially given that kicking velocity is significantly different between females and males. Further, given the differences in spatiotemporal dynamics captured by the second and third extracted knee flexion pattern, grouping females and males may conflate the differences in between-subject kicking biomechanics that appear to exist within each group. Third, the results and interpretations presented in the current study are based on a cross-sectional research design and correlational statistical methods. It, therefore, remains to be determined whether increasing hip joint range motion patterns and/or delaying internal rotation of the hip in a future interventional study would lead to an increase in kicking velocity in male professional soccer players.

Conclusion
Kicking velocity in male professional soccer players males is correlated with hip joint angle movement patterns. Specifically, better kicking performance in male soccer players was associated with 1) a greater difference between the hip extension angles at the end of the backswing/beginning of the leg cocking phases and the hip joint angle flexion at the end of the follow-through phase, and 2) a delayed internal rotation of the hip.

Disclosure statement
No potential conflict of interest was reported by the author(s).

References


