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How anterior pelvic tilt affects the lower extremity kinematics during the late swing phase in soccer players while running: A time series analysis

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ABSTRACT

Anterior pelvic tilt has been proposed to predispose the hamstring in soccer players to injury at the late swing phase during a sprint, however the mechanism on how the changes in the alignment would affect the kinematics are still unclear. Thirty-four male amateur soccer players were recruited for this study. Pelvic tilt was measured using the DIERS Formetric 4D. Lower extremity angles were recorded using an 8-camera Vicon motion capture system at 200 Hz while the athlete performed a high speed run on a motorised treadmill. Late swing phase was extracted from 5 running cycle which were later analysed using statistical parametric mapping (SPM). The results show that the increase of anterior pelvic tilt angle was significantly correlated with hip ($r = -0.421$ to -0.462, $p = 0.015$) and knee flexion ($r = -0.424$ to -0.472, $p = 0.026$) values. No other correlation was found between the anterior pelvic tilt and the angles at the coronal plane. By using time series analysis it was shown that the anterior pelvic tilt measured in a standing position would affect the adjacent segments' kinematics while running as suggested in the kinetic chain theory; which would potentially predispose the soccer athletes to hamstring injury by maintaining knee extension.

1. Introduction

Anterior pelvic tilt has been proposed as a potential risk factor for musculoskeletal injury in soccer players (Woods et al., 2004). Soccer players have a higher tendency towards having a higher anterior pelvic tilt angle in comparison to the non-athletes (Wodecki, Guigui, Hanotel, Cardinne, & Deburge, 2002), leading the research community to propose this phenomenon as a contributing factor which may increase injury risk (Opar, Williams, & Shield, 2012; Small, McNaughton, Greig, Lohkamp, & Lovell, 2009; Woods et al., 2004). An increase in the amount of anterior pelvic tilt would alter the properties and function of the muscles attaching to the pelvis, as is the case for the hamstrings. The necessity of a postural pelvic alignment to prevent hamstring strain was suggested previously (Panayi, 2010). By tilting the pelvis anteriorly, the hamstring is lengthened beyond its normal resting length. Since the hamstring controls the amount of knee extension during the late swing phase, excessive amount of anterior pelvic tilt angle would predispose the hamstring to higher tension loads, increasing the possibility of sustaining an injury while performing a sprint (Cabello et al., 2015). Due to the common muscles overcrossing the pelvis, hip and knee and according to the kinematic chain principle, a change in the pelvis' orientation is expected to affect the adjacent kinematics. It was reported that peak anterior pelvic tilt angle at the terminal swing while sprint running was synchronous with maximum biceps femoris length (Nagano, Higashihara, Takahashi, & Fukubayashi,

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2014), but was not mentioned that whether if the anterior pelvic tilt was also correlated with angular changes in adjacent joints. The hamstrings also work to extend and flex the knee during a running cycle (Koulouris & Connell, 2005) and the length of the hamstring limits the range of motion of the knee as well as the hip. The over striding which is a result of excessive knee extension during the late swing phase while the hip is flexed has been proposed as a the time where hamstring is susceptible to injury (Kopydlowski, Weber, & Sekiya, 2014). The kinetic chain implies that the human body constitutes of different segments which are linked together via various joints (Steindler, 1977). During both close and open chain movements a change in a segment's position modifies the adjacent segment position in response (Svoboda, Janura, Kutilek, & Janurova, 2016). Deviation in the kinematics of the lower extremity was shown to be associated with hamstring injury in soccer players while performing a sprint (Schuermans, Van Tiggelen, Palmans, Danneels, & Witvrouw, 2017).

The late swing phase has been recognised as the onset of hamstring strain during a high speed sprint (Chumanov, Schache, Heiderscheit, & Thelen, 2012; Thelen et al., 2005). Inverse dynamic models show that during this stage the hamstring i.e. the biceps femoris long head experiences the highest amount of elongation in reference to the normal muscle length while standing (Thelen et al., 2005). Since the anterior pelvic tilt has been suggested as a risk factor for hamstring injury, analysing the association between anterior pelvic tilt angle and the kinematic changes of the lower extremity would provide us with valuable knowledge on how changes in the anterior pelvic angle while standing would alternate the kinematics during the late swing phase of a high speed running.

Human motion i.e. motion during the late swing phase, is a continuous sequence of actions when investigated in biomechanical terms it results in curve production which represents angular progression in different planes. However common analysis use discrete information that are extracted from the kinematic data which depict crucial time points during the human motion i.e. maximum knee flexion, foot contact and etc. Although discrete data may hold practical information it is not entail a comprehensive representation of the entire movement or motion pattern, as it only focuses on one kinematic feature at a given time point instead of taking into account the motion pattern throughout the entire time frame in which the movement occurs. Recently scientific studies have taken an interest into using time series analysis which allows the scholar to conduct statistical analysis without omitting data. Using this method of analysis in a sample of male soccer players, we hypothesised that anterior pelvic tilt angle in static standing position is correlated with pelvis, hip and knee kinematics at the late swing phase of a running cycle.

2. Method

2.1. Participants

Thirty-four male amateur soccer players were recruited from Hamburg's first division league. Players which sustained any injury 6 months prior to the measurement were excluded. In order to be included players had to have at least 5 years of experience and participate in 3 sessions of soccer specific activity (training and/or match) on a weekly basis. The study was approved by the University of Hamburg local scientific committee (ID: 2017_85).

2.2. Procedure

The pelvic tilt angle was measured using a video raster stereography, DIERS Formetric 4D (Formetric®-System, Diers International, Schlangenbad, Germany). The validity of the DIERS for pelvic measurements was assessed using X-ray radiography. The results showed high validity for all pelvic measurements including pelvic tilt (Abdel Raoof, Battecha, Elsayed, & Soliman, 2016). The pelvis tilt was defined as the angle produced between the plumb line and the tangent of the lumbar lordosis dimples. At this stage, the players were asked to take off their shoes and clothes and to take place onto the platform of the DRIERS system. This platform consists of a particular grid, specifically illustrating the subjects were to place their feet for standardized measurements of the skeletal alignment. The subjects were instructed to maintain a face forward stance and keep on breathing normally while remaining completely still until the measurement was finished. It was emphasized that they should maintain a normal standing posture and not try to correct themselves. Before starting the scan, we asked the subjects to stand on the DIERS platform. Displayed on this platform was a grid which provided coordinates for recording the position of the feet. Fig. 1 illustrates how subjects stood on the platform to measure the height of the first horizontal line relative to the hairline. The height of the first horizontal line of the projection line was adjusted to be below the hairline. Each player performed 3 scans with a 1-minute rest between each measurement. It was ensured that the player's feet were placed at the similar position to the initial scan for reproducibility. No audio or visual feedback was given to the players during and between the scans to avoid compensation.

Vicon motion analysis system (Vicon Motion Systems, Oxford, England) was used for kinematic data acquisition. Eight cameras with the sampling frequency of 200 Hz were set for motion capture system. Forty spherical reflective markers (15 mm) were attached to specific anatomical landmarks and segments in order to track lower extremity motion during running: posterior superior iliac spine (PSIS), anterior superior iliac spine (ASIS), four thigh cluster markers, lateral and medial epicondyle, four lower leg cluster markers, lateral and medial malleolus, three calcaneus markers, first metatarsal head, fifth metatarsal head and hallux. The athletes completed 3 trails of running on a motorised treadmill (h/p/cosmos; quasar-FDM-THQ-M der Firma Zebris Medical GmbH) for 6 s at 6.9 ± 0.1 m/s with a 3-minute rest between each trial. The running speed was determined by a previous study where a participant suffered a hamstring strain at 4.47 m/s (Heiderscheit et al., 2005) in addition to the maximum speed the treadmill can reach. Prior to the main measurement the participants warmed up at 2.2 ± 0.1 m/s for five minutes.

Fig. 1. Horizontal lines projected on the participant's back using DIERS Formetric 4D.

2.3. Data analysis

Marker gaps were filled using the Vicon Nexus software 2.6.1. All trials were filtered using a zero-lag low pass 4th order Butterworth filter. The cut-off frequency was set to 13 Hz by calculating the optimum cut-off frequency (Formula (1)) (Yu, Gabriel, Noble, & An, 1999). It has been found that the optimum cut-off frequency for kinematic studies can be calculated directly from the sampling frequency. Where f_c is the cut-off frequency and f_s is the sampling frequency.

$$f_c = 0.071f_s - 0.00003f_s^2 \quad (1)$$

Late swing phase was defined as the time frame in between the point at which the maximal knee flexion occurred during swing and the one at which initial ground contact was made. The hip centre of rotation was determined using 4 pelvic cluster markers and the knee centre of rotation was determined using the lateral and medial markers at the knee (Della Croce, Leardini, Chiari, & Cappozzo, 2005). Time of foot contact was determined by the built-in force plate in the motorized treadmill. Sagittal and frontal angles were obtained using Matlab software R2016a. In particular, pelvic tilt, hip flexion, hip abduction and knee flexion were calculated. Pelvic tilt angle was defined as the rotation angle about the Y-axis of the global coordinate system (sagittal plane). The hip flexion angle was defined as the rotation angle about the Y-axis of the local coordinate system between the thigh and pelvis segments (Schache, Bennell, Blanch, & Wrigley, 1999). Hip abduction was defined as the rotation angle about the X-axis of the local coordinate system between the thigh and pelvis segments (coronal plane). The knee flexion angle was defined as the rotation angle about the Y-axis of the local coordinate system between the thigh and shank around (Higashihara, Nagano, Ono, & Fukubayashi, 2016). For each trail that the athletes completed a minimum of 10–12 strides were obtained. Although the kinematic recording started as the athletes reached the maximum speed the strides recorded at the beginning and the end of the recording were removed from the overall analysis. For consecutive statistical analysis the late swing was then time normalized and an average kinematic profile was made using 5 late swing phases in each subject.

2.4. Statistical analysis

Statistical parametric mapping (SPM) was used for statistical calculation. Originally SPM was developed for analysis of functional brain imaging by using voxels for statistical analysis (Friston et al., 1994). Pataky adapted the concept of the SPM analysis to biomechanical data by replacing the voxels to kinematic curves, which are acquired during testing (Pataky, 2010). SPM uses random field theory (Adler, 2007) to assess the statistical inference level by mathematical foundation. Random field theory is a recent body of mathematics defining theoretical results for smooth statistical maps. Random field theory solves this problem by using results that give the expected Euler characteristic (EC) for a smooth statistical map that has been thresholded. The expected EC leads directly to the expected number of clusters above a given threshold, which in turn gives the height of threshold to base our statistical inference. Usage of the random field theory requires two assumptions. The first is that the error fields are a reasonable lattice approximation to an underlying random field with a multivariate Gaussian distribution. The second is that these fields are continuous, with a twice-differentiable autocorrelation function (Brett, Penny, & Kiebel, 2004).

The scalar output statistic, SPM-t, was calculated separately at each individual time node and is referred to as a SPM. At this stage it is worth noting that SPM refers to the overall methodological approach, and SPM-t to the scalar trajectory variable. The calculation of SPM-t simply indicates the magnitude of the correlation, therefore with this variable alone we cannot accept or reject our null hypothesis. To test our null hypothesis, we next calculated the critical threshold at which only α % (5%) of smooth random curves would be expected to traverse. This threshold is based upon estimates of trajectory smoothness via temporal gradients and, based on that smoothness (Friston, 2007), random field theory expectations regarding the field-wide maximum (Adler & Taylor, 2009). Conceptually, a SPM correlation is similar to the calculation and interpretation of a scalar correlation test; if the SPM-t trajectory crosses the critical threshold at any time node, the null hypothesis is rejected. Typically, due to waveform smoothness and the interdependence of neighbouring points, multiple adjacent points of the SPM-t curve often exceed the critical threshold, we therefore call these "supra-threshold clusters". SPM then uses random field theory expectations regarding supra-threshold cluster size to calculate cluster specific p-values which indicate the probability with which supra-threshold clusters could have been produced by a random field process with the same temporal smoothness (Adler & Taylor, 2009).

Since the current version of the SPM limits the users to analyse the correlation between a single parameter, in our case the anterior pelvic tilt in the static standing position, with a continuous data in the form of a curve i.e. angular progression of the joint during the late swing phase for each participant, other forms of correlation such as between each joint while in a dynamic task e.g. running was unattainable.

These assumptions can be tested using a built-in function in the spm1d program developed by Pataky which can be downloaded at www.spm1d.org. The current version for our analysis is 0.4 using the Matlab R2018b software as the platform to run the calculations. A two-tailed correlation analysis was used to analyse the data ($\alpha = 0.05$).

3. Results

All kinematic data showed to have normal distribution using the Shapiro-Wilk test ($p > 0.05$). Fig. 2 depicts all descriptive outcomes from the measurements.

Fig. 2A shows the distribution of pelvic tilt angle for each soccer player. The amount of stationary anterior pelvic tilt angle ranged from 8 to 25 degrees with a mean value and standard deviation of 18.7 ± 2.4. During the fast running test, the pelvis oscillated at the late swing phase but remained anteriorly tilted. The minimum and maximum angles during the last swing phase for pelvis tilt were 17.7 ± 4.1 and 20.9 ± 4.7 respectively (Fig. 2B). Simultaneously, the hip had an increase in flexion but started an extending motion when approaching foot contact. The minimum and maximum angle for hip flexion during the late swing phase were 33.8 ± 6.1 and 61.8 ± 6.1 (Fig. 2C). At the beginning of the late swing phase stage the hip was in an abducted position and progressed towards an adduction state when approaching foot contact. The minimum and maximum angles for hip abduction-

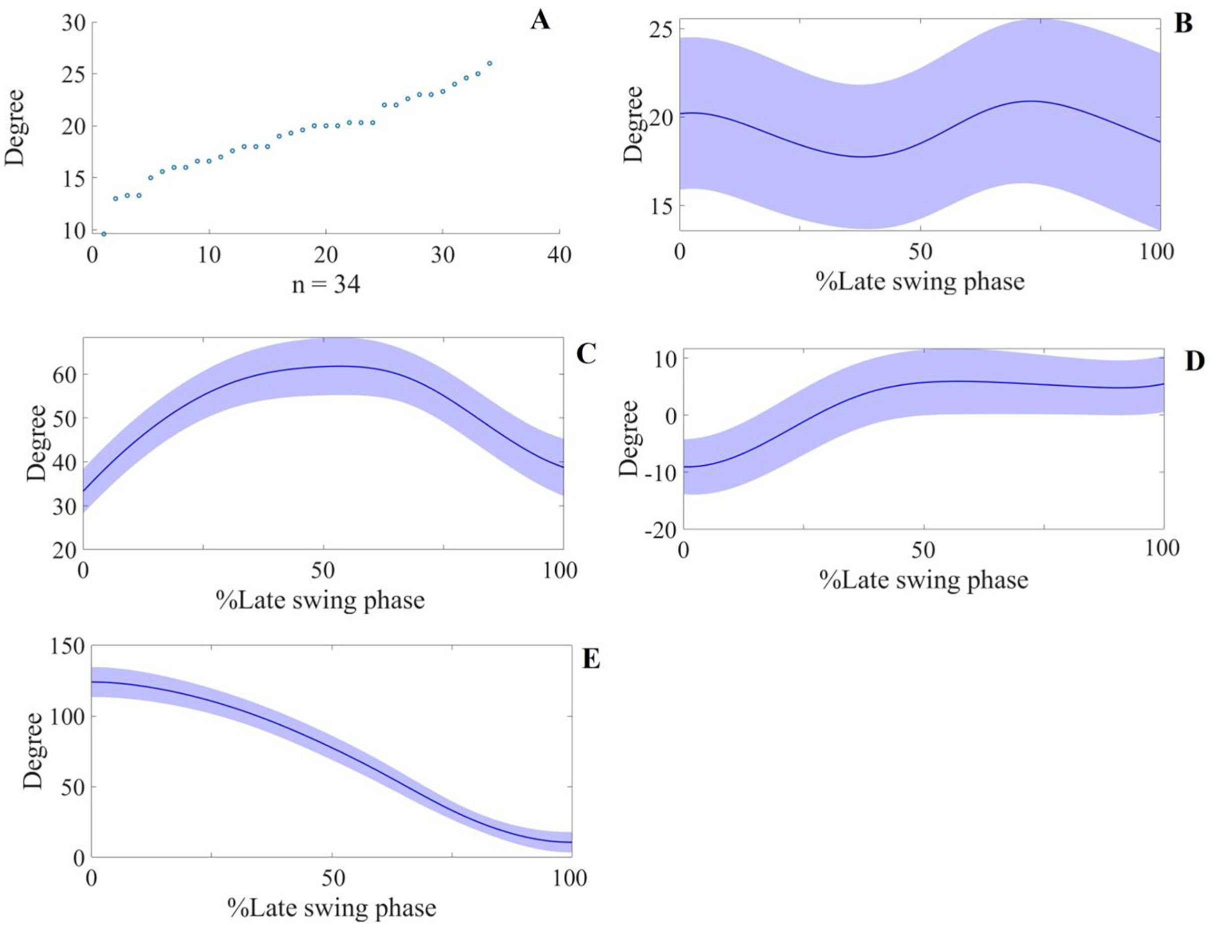

Fig. 2. Descriptive results of stationary pelvic tilt angle measurements and progression angles at the late swing phase. A: anterior pelvic tilt angles of 34 participants (n = 34). B: Pelvic tilt angle progression during the late swing phase of fast running. Positive values represent anterior pelvic tilt. C: Hip flexion angle progression during the late swing phase of fast running. Positive values represent hip flexion. D: Hip adduction-abduction angle progression during the late swing phase of fast running. Positive values represent hip adduction whereas negative values represent abduction. E: Knee flexion angle progression during the late swing phase of fast running. Positive values represent knee flexion. For all kinematic results, the blue line represents the mean angle of progression, whereas the shaded blue area represents one standard deviation from the mean angle of progression. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

adduction were -9.2 ± 4.7 and 5.9 ± 5.7 respectively (Fig. 2D). According to the definition of late swing phase the knee showed its peak flexion angle at the beginning of the phase and started and extending motion until foot contact. The minimum and maximum angles of knee flexion were 10.6 ± 7.3 and 123.9 ± 10.6 respectively (Fig. 2E).

Results showed a significant moderate negative correlation between the amount of anterior pelvic tilt, knee and hip angle during the late swing phase. A supra-threshold cluster exceeded the critical threshold calculated by SPM for each hip (Fig. 3A) and knee (Fig. 3C) flexion thus identifying a significant negative correlation. The anterior pelvic tilt angle measured at a stationary position was significantly correlated ($p = 0.015$) with hip flexion angle during the late swing phase (Fig. 3A). A greater anterior pelvic angle significantly decreased the hip flexion angle during the last 35% of the late swing phase. The anterior pelvic tilt accounted for 17% − 21% of the hip flexion variability during the last 35% of the late swing phase (Fig. 3B) (Table 1).

The anterior pelvic tilt angle measured at a stationary position was significantly negatively correlated ($p = 0.026$) with knee flexion angle during the late swing phase (Fig. 3C). A greater anterior pelvic angle significantly decreased the knee flexion angle from 53% to 83% of the late swing phase. The anterior pelvic tilt accounted for 17% − 22% of the knee flexion variability from 53% to 83% of the late swing phase (Fig. 3D).

No other significant correlation was found between anterior pelvic tilt angle while standing stationary and pelvic tilt and hip abduction at the late swing phase of running.

4. Discussion

Our results show that the amount of anterior pelvic tilt while standing was correlated with hip and knee angles during the late

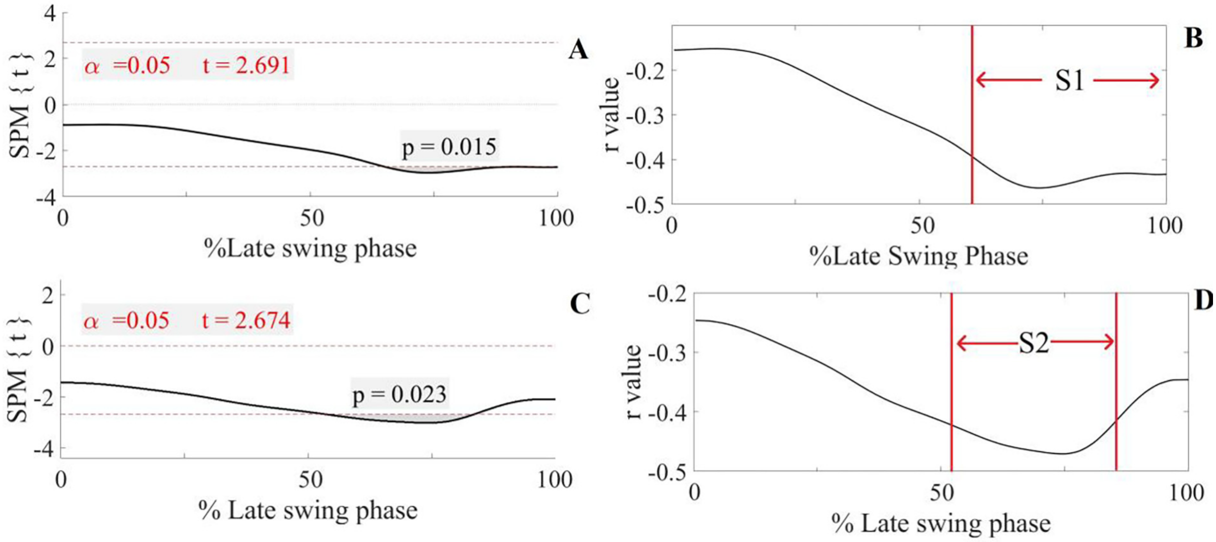

Fig. 3. A and C: SPM statistical correlation analysis of the stationary anterior pelvic tilt angle while standing with hip and knee flexion angles during the late swing phase respectively. SPM: t values calculated by the SPM which statistical inference (*p* value) was based. Red dashed lines: inference levels calculated for a two-tailed analysis. B and D: Correlation coefficients (r) for stationary anterior pelvic tilt angle and hip and knee flexion during the late swing phase respectively. S1 = significantly correlated section between stationary anterior pelvic tilt and hip flexion. S2 = significantly correlated section between stationary anterior pelvic tilt and knee flexion. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Correlation analysis between anterior pelvic tilt, hip and knee angle.

		Anterior Pelvic Tilt	*p*
Correlation	Hip flexion	−0.421 to −0.462	0.015
	Knee flexion	−0.424 to −0.472	0.026

swing phase of running. Using a time series analysis, SPM, it was found that anterior tilt angle of the male soccer players while standing in a stationary position, was moderately correlated with the amount of hip flexion and knee flexion angles during the late swing phase while running. In addition, our results did not indicate any correlation between the anterior pelvic tilt angle while standing statically and anterior pelvic tilt and hip abduction while performing a high speed run. Kinematic angles in this study are in agreement with angles reported from previous studies during a sprint (Higashihara, Nagano, Ono, & Fukubayashi, 2015; Nagano et al., 2014; Nicola & Jewison, 2012; Novacheck, 1998). This is the first study to incorporate time series analysis for statistical evaluation at the late swing phase with regards to pelvic changes in a standing position. By using time series analysis, we were able to determine the time frame where a negative correlation was determined. If common statistical analysis methods were used in the case of the pelvis and knee correlation, nothing significant would have been determined as was shown by previous studies (Alizadeh & Mattes, 2018).

The relationship between anterior pelvic tilt and hip range of motion has been previously verified (Franz, Paylo, Dicharry, Riley, & Kerrigan, 2009; Ross et al., 2014). It was reported that as the pelvic anterior tilt angle increases the amount of hip flexion decreases up to 10 degrees in the static position (Ross et al., 2014). Although the nature of the tasks is different, with one being static and ours being dynamic, it shows that changes in the pelvis' orientation is correlated with the amount of hip flexion. Similarly, in another study similarly a relationship between the anterior pelvic tilt and hip flexion was reported but during the stance phase while running, in which it was mentioned that the anterior pelvic tilt presented a negative correlation with hip motion but only during terminal stance phase (Schache et al., 1999; Schache, Blanch, & Murphy, 2000). Although the studied phases are different the findings confirm the relationship between the pelvic and hip motion. Schache and colleagues suggested that the restriction in the range of motion can cause the inverse relationship between the pelvis and hip angles. The mutual muscles and tendons overcrossing the pelvis and the hip region can be considered as a primary factor affecting the kinematics during a high speed running. As it was reported by Nagano and colleagues anterior pelvic tilt, while performing a sprint running, increases the length of hamstring i.e. biceps femoris long head (Nagano et al., 2014). The lengthening of the hamstring, as a result of anterior pelvic tilt, seems to induce the hamstring to reach its mechanical limitation in length thus reducing the amount the hip flexion due to this limitation.

Similarly the effects of the changes in the pelvic position on knee angle have been established previously (Herrington, 2013; Obeid et al., 2011). It was shown that an increase in the amount of anterior pelvic tilt angle corresponded with higher knee flexion in a static upright standing position (Obeid et al., 2011). It seems that as the anterior pelvic tilt increases, the amount of hip flexion reduces; and as a compensatory mechanism to retain step length the knee would maintain in an extended position while approaching ground contact eventually increasing the amount of hamstring elongation. Due to the smaller hip flexion moment arm for the semimembranosus compared to semitendinosus and biceps femoris (Arnold, Salinas, Asakawa, & Delp, 2000) and a larger knee flexion moment arm for semimembranosus and semitendinosus compared to biceps femoris long head, the net result of the merged effects would cause the semimembranosus to lengthen greater than biceps femoris long head and semitendinosus (Buford et al., 1997). Contrary to recent findings (Ekstrand et al., 2012), an increase in the amount of anterior pelvic tilt would predispose the semimembranosus to injury more than the biceps femoris. However, more study should be carried out to confirm this assumption.

The relationship between each segment in the lower extremity was previously studied and was confirmed that knee angles were associated with adjacent segment biomechanics at specific time points during the swing phase which constitutes as an open chain movement (Svoboda et al., 2016). This supports the concept of the kinetic chain theory which states that a movement in a joint would affect the adjacent joint along the chain. However, the premise and aim of this study was to see how a change in a static position would correspond to the changes in the adjacent segments during a high speed running with the use of time series analysis. By considering the functional anatomy of the hamstring, it could be noted that since the muscle originates from the pelvis and crosses over the thigh and knee joint, an increase in the pelvic tilt would limit the hip flexion as a result of muscle length. For the athlete to overcome this limitation, further extending the knee would be adopted as a compensatory mechanism. It is evident that if the conventional data extraction for statistical analysis were used in our study the results would have differed, thus excluding the duration which were found to be significantly related. Future studies should incorporate time series analysis in prospective design to verify how respective kinematic changes correlate with injuries while controlling other potential risk factors.

5. Conclusions

Changes in the anterior pelvic tilt angle are correlated with changes in the hip and knee kinematics during the late swing phase. By using time series analysis it is possible to detect the significant affects that conventional methods lack. Furthermore by applying time series analysis we were able to illustrate that the kinetic chain theory can also be applied to the open chain in addition to closed chain movements. The anterior pelvic tilt may predispose the hamstring to injury by compelling the athlete to maintain knee extension as a compensatory mechanism to the reduced hip flexion. Thus while screening the athletes it would be useful to take the anterior pelvic tilt angle and its implications on their movement pattern into account.

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Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.06.001.

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