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Title

Effects of running experience on coordination and its variability in runners

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Running title

Coordination variability in runners

Keywords

Continuous relative phase, training volume, joint couplings, dynamical systems, lower extremity

Abstract

The purpose of this study was to examine the differences in coordination variability in running gait between trained runners and non-runners using continuous relative phase analysis. Lower extremity kinematic data were collected for twenty-two participants during the stance phase. The participants were assigned to either a runner or non-runner group based on running volume training. Segment coordination and coordination variability were calculated for selected hip-knee and knee-ankle couplings. Independent t-tests and magnitude based inferences were used to compare the two groups. There were limited differences in the continuous relative phase and its variability among runners and non-runner groups. The runners group achieved moderately lower coordination compared with non-runners group in the phase angle for hip abduction/adduction and knee flexion/extension. The runners tended to show moderately lower coordination variability in the phase angle for knee flexion/extension and subtalar inversion/eversion in comparison to non-runners group. These results suggested that levels of experience as estimated from weekly training volume had little influence on coordination and its variability.

Introduction

Running is a fundamental skill that is acquired during childhood and can be improved with practise (Malina, Bouchard, & Bar-Or, 2004). There are various perspectives in the literature on the assessment of running biomechanics, including the analysis of intersegmental coordination (Hamill, Van Emmerik, Heiderscheit, & Li, 1999) which can facilitate the assessment of synchrony between segment movements. A lack of within-limb coordination across the stance phase could cause disturbances, which could in turn, increase injury risk or reduce movement efficiency (Boyer, Silvernail, & Hamill, 2014; DeLeo, Dierks, Ferber, & Davis, 2004; Hamill et al., 1999). It is also known that the level of coordination of a moving segment can be influenced by the level of practical skill (Bernstein, 1967).

In recreational runners, there are considerable variations in the level of practise, particularly training volume, with some runners demonstrating large training volumes (more than 50 km per week) and others, smaller volumes (approximately 25 km per week). Recent research has found differences in kinematic waveforms of the pelvis, hip, knee and foot during the running gait cycle between runners of differing training volumes (Boyer et al., 2014). However, there remains a lack of research examining the effect of practise volume on coordination in running. Consequently, more studies are needed to provide more understanding of the interrelation between inter-limb coordination and training volume and thereby deepen insights on running biomechanics.

A factor which may affect the coordination variability is the task-related skill level of the participants. The relationship between variability and skill level is complex because this depends on the type of movement analysed (Preatoni et al., 2013). Thus it should not be necessarily assumed that increased movement variability is attributed to higher levels for any task (Hiley, Zuevsky, & Yeadon, 2013). To date, few studies have examined the variability of running gait and coordination in relation to skill level. Nakayama et al. (2010) observed less variability in trained runners than non-runners suggesting that larger practice volumes in a task could produce stable and consistent motor patterns. These results however, could be limited to the type of variability analysed. Hamill, Palmer and Van Emmerik (2012) identified two types of variability: “End-point” variability (e.g. stride length, stride time, etc.) and coordinative variability (segmental relations). From this perspective, the “end-point” variability should decrease at higher skill levels (Nakayama et al., 2010), while high coordinative variability should permit a greater degree of flexibility in the movement pattern that may facilitate the goal-directed performance against any disturbance (Hiley et al., 2013).

The continuous relative phase (CRP) has been used as a method to provide a continuous measure of joint coupling during the stride cycle, using the relative phasing between two segments or joints (Hamill, Haddad, & McDermott, 2000). This measure provides a coordination variability profile which permits the calculation of the standard deviation on a point-by-point basis over the complete cycle or a portion of the running cycle (Hamill et al., 2012). Previous research (Dierks & Davis, 2007; Hamill et al., 2012, 1999; Hein et al., 2012; Miller, Meardon, Derrick, & Gillette, 2008) has focused on analysing whether CRP variability differentiates between healthy and injured runners however, the effects of other aspects such as the skill level, which could influence the coordination between segments remain unclear.

Thus, the objectives of this study were to examine the differences in coordinative variability in running gait between trained runners and non-runners. Continuous relative phase (CRP) analysis was used to assess coordination variability differences between trained runners and non-runners. It was hypothesised that there would be differences in coordination variability between runners of different skill levels.

Methods

Twenty-two participants were recruited and these were divided into two groups. A runner group, who had undergone running distance training of at least five days per week for the previous 12 months. A non-runners, who had not undergone running distance training nor practiced recreational running more than two days a week. The runners group consisted of 10 competitive females athletes (participating in regional and national championships) aged 23 ± 2 years, with a mass of 52 ± 5 kg and a height of 1.61 ± 0.06 m with training volume greater than 35 km per week. The non-runners group consisted of 12 females aged 24 ± 4 years (mean ± SD), with a mass of 55 ± 5 kg and a height of 1.64 ± 0.05 m with training volume not exceeding 20 km per week. There were no significant differences between the two groups with regard to their mean age, height, and weight ($t < 1.191$, $p > 0.247$). All participants had been free from any lower extremity musculoskeletal injury in the previous 12 months. The study had ethical approval from the University research ethics committee and all participants signed informed consent forms before participating in the study.

A 5-camera VICON motion capture system (Bonita-3, Vicon Motion Systems, Oxford, UK), and 9-mm retro-reflective markers, were used to collect 3-dimensional (3D) kinematic data at 200 Hz during treadmill running (Magna Pro, BH, Spain). Markers were placed in the same manner described by Pohl, Lloyd and Ferber (2010). In brief, 14 anatomical markers were attached bilaterally to the following landmarks: the greater trochanters, medial and lateral knee joint lines and medial and lateral malleoli. Technical marker clusters, glued to a rigid plastic shell, were placed on the pelvis (three markers), and bilateral thigh and shank (four markers each) with self-adhering straps. Three markers were taped to the heel counter of each of the standard running shoes (Nike, Air Pegasus). These twenty-five markers represented seven rigid segments.

Following placement of all the anatomical and segment markers, the participant was asked to stand for a static trial where standing position was controlled using a graphic template placed on the treadmill with feet positioned 0.3 m apart and pointing straight ahead. Once the feet were placed in the standardized position, the subject was asked to cross their arms over their chest and stand still while one-second of marker location data were recorded to identify joint centre locations and to calculate the segment coordinate systems. Upon completion of the static trial, the 14 markers on the anatomical landmarks were removed. All participants were permitted as much time as they required to select a comfortable treadmill speed and to accommodate to the treadmill. Running kinematic data were collected while participants ran at a self-selected, comfortable speed on a treadmill for 30 seconds during which, approximately 30-45 consecutive strides were collected for processing and analysis. After marker trajectories were filtered with a 10 Hz low-pass, 2nd order recursive Butterworth filter, 3D rigid body kinematics were calculated using 3D GAIT software (Running Injury Clinic Inc., Calgary, Alberta, Canada), then segmented for the stance phase based on a single value decomposition approach outlined by Söderkvist and Wedin (1993) and the joint coordinate system suggested by Cole, Nigg, Ronsky and Yeadon (1993).

For analysis, the stance phase was divided into four phases similar to previous studies (Hein et al., 2012; Perry & Burnfield, 2010). Loading stance was defined as the first 20% of stance phase, midstance phase ranged from 21% to 50% of stance phase, terminal stance phase ranged from 51% to 80% of stance phase, and the last 20% of the stance phase was defined as pre-swing.

CRP variability was calculated using a custom MATLAB routine (The Mathworks, Natick, MA). In brief, the CRP was calculated by generating a phase plane portrait of the time-normalised angular velocity curves, which were plotted against the time-normalised angular position curves for two segments of interest. Phase angles were calculated for all 101 points in the phase plane portrait and the CRP angle was calculated by subtracting the phase angle of the distal segment from the phase angle of the proximal segment. CRP values ranged between -180° to 180° with CRP values of 0° indicating complete in-phase coupling and 180° or -180° indicating complete out-of-phase coupling.

The angular displacement and angular velocity data sets of each stance phase were normalised to 101 points. Phase-plane plots were created with angular displacement in the x-axis and angular velocity in the y-axis for each joint movement. The phase-plane plots were normalised to a range of -1 to +1 for the angular displacement and angular velocity was normalised to absolute maximum value (Hamill et al., 1999; Hein et al., 2012; Miller et al., 2008). For each phase-plane plot, the phase angle was constructed using the following equation:

$$\emptyset(t) = tan^{-1}\frac{\omega(t)}{\theta(t)}$$

Where: Φ is the phase angle, ω is the normalised angular velocity, and θ is the normalised angular displacement at time t.

The phase angle was presented in the range 0º and 180º to avoid discontinuities which can appear at the transition from quadrant 2 (180º) to quadrant 3 (-180º) (Hamill et al., 1999; Hein et al., 2012). The CRP between two joints was calculated as the difference between the phase angles. For each coupling, the distal segment was subtracted from the proximal. CRPs were calculated from the phase angles for hip flexion/extension and knee flexion/extension ($HIP_{flex/ex}$-$KNEE_{flex/ex}$), hip abduction/adduction and knee flexion/extension ($HIP_{abd/ad}$-$KNEE_{flex/ex}$), knee flexion/extension and ankle flexion/extension ($KNEE_{flex/ex}$-$ANKLE_{flex/ex}$), knee flexion/extension subtalar inversion/eversion ($KNEE_{flex/ex}$-$ANKLE_{in/ev}$). These joint couplings were selected based on their importance for enhancing running performance (Schache, Dorn, Williams, Brown, & Pandy, 2014) and previous research on kinematic coupling in runners (Cunningham, Mullineaux, Noehren, Shapiro, & Uhl, 2014;

Dierks & Davis, 2007; Hafer, Freedman Silvernail, Hillstrom, & Boyer, 2015; Hein et al., 2012; Kurz, Stergiou, Buzzi, & Georgoulis, 2005; McClay & Manal, 1997; Wheat, Baltzopoulos, Milner, Bartlett, & Tsaopoulos, 2005).

Continuous methods were used to calculate the coordination variability and thus were based on the CRP from the stance phase of 10 consecutive strides on the same subject and the four previously identified sub-phases of the stance phase. From the CRP data, an ensemble average curve and standard deviation of each data point on the mean curve were calculated. The average of the standard deviations (SD_{avg}) for all strides were calculated using the following equations (James, 2004):

$$SD_{avg} = \sqrt{\left(\frac{\sum_{i=1}^{k} SD_i^2}{k}\right)}$$

For the equations, SD_{avg} is the average of individual point-by-point standard deviation values; i indicates the specific value for the i^{th} sample, SD_i is the standard deviation value for the i^{th} sample, and k is the number of samples.

All statistical analysis was conducted using PASW (SPSS, Inc., Chicago, IL). A Shapiro-Wilk test was executed to verify the normality of data. Independent samples Student's t-tests were conducted to determine group differences in CRP and its variability. The statistical significance level was set at $P < .05$. Statistical significance analysis was completed by the estimation of magnitude of differences between groups calculated and expressed as standardised differences (Cohen, 1977), which were calculated using pooled standard deviations. In determining group differences magnitude based inferences were given priority over t-tests. The criteria to interpret the standardised differences were: trivial = 0.00–0.19; small = 0.20–0.59; moderate = 0.60–1.19; large = 1.20-1.9; very large = 2.0-4.0 and; nearly perfect >4.0 (Hopkins, Marshall, Batterham, & Hanin, 2009). Confidence intervals (90%) and probabilities that the true effect was substantially positive and negative were estimated according to Hopkins et al. (2009). The scale for interpreting the probabilities for a mechanistic effect based on the 90% confidence limits were: <1%, almost certainly not; >1-5%, very unlikely; >5-25%, unlikely; >25-75%, possibly; >75-95%, likely; >95-99%, very likely; and >99%, almost certainly. When the positive and negative values were both >5%, the inference was classified as unclear (Batterham & Hopkins, 2006). All calculations were completed using a pre-designed spreadsheet (Hopkins, 2006).

Results

The runners group chose a higher speed at comfortable pace, $t = 3.809$, $p < 0.05$ (3.38 ± 0.44 *vs*. 2.75 ± 0.18 $m \cdot s^{-1}$) than the non-runners group. The CRP profiles for runners and non-runners groups during the stance phase are shown in Figure 1. $KNEE_{flex/ex}$-$ANKLE_{in/ev}$ ranging between ± 50º and remaining close to an in-phase relationship for much of the stance phase, while other coupling pairs ranged between ± 150º and demonstrating a more out-of-phase coordination pattern. For in-phase motions, CRP values approaching 0º indicated that the phase angles for the two joints moved in a similar fashion. A CRP approaching ± 180º indicated that the two joints were moving out-of-phase and both motions exhibited opposing movements (Dierks & Davis, 2007).

There were no statistically significant differences between the non-runners and runners groups in the CRP values for any of the coupling pairs analysed ($t < 1.598$, $p > 0.126$), however, the magnitude based inferences enabled more precise tracking of differences between groups and some of the differences were substantially clear (Figure 2). For example, the runners group achieved the highest similarity in the movements (moderately lower average CRP angles) of $HIP_{abd/ad}$-$KNEE_{flex/ex}$ across of entire stance phase (with chances of greater/similar/lower values of 4/9/87%) compared with non-runners group. When the stance phase was divided into four intervals the runners group achieved moderately lower CRP angles in the $HIP_{abd/ad}$-$KNEE_{flex/ex}$ during the midstance phase (4/17/79%), while the non-runners group achieved moderately lower CRP angles in $KNEE_{flex/ex}$-$ANKLE_{flex/ex}$ (80/16/4%) during pre-swing phase.

Figure 3 illustrates the CRP variability for the runners and non-runners groups during the stance phase in the four coupling relationships that were analysed. Average CRP variability in the stance phase across the four coupling pairs analysed ranged from 5.1º to 18.4º. Outcome coordination variability increased as more distal segments were involved in the

CRP variability calculation. The hip flexion-extension coupling pair showed the lowest values for average CRP variability ($HIP_{flex/ex}$-$KNEE_{flex/ex}$: non-runners group: 5.5, runners group: 5.1) and the ankle eversion-inversion coupling pair showed the highest values ($KNEE_{flex/ex}$-$ANKLE_{ev/in}$: non-runners group: 18.4, runners group: 12.7).

The results showed that the variability values were not similar throughout the entire stance phase and the higher scores of CRP variability were achieved at the start or end of the contact period. When the phase angles included only movements in the sagittal plane, the higher variability was achieved in the initial stance ($HIP_{flex/ex}$-$KNEE_{flex/ex}$ > 6.4º, $KNEE_{flex/ex}$-$ANKLE_{flex/ex}$ > 14.5º). Higher CRP variability values were observed in the pre swing phase when movements in the frontal plane were included in the coupling pair ($HIP_{abd/ad}$-$KNEE_{flex/ex}$ > 12.6º, $KNEE_{flex/ex}$- $ANKLE_{in/ev}$ > 17.6º).

There were no statistically significant differences between the non-runners and runners groups in the CRP variability any of the coupling pairs analysed ($t < 1.700$, $p > 0.106$). However the magnitude based inferences revealed differences in the CRP variability between groups in some of parameters studied; these differences tended to show lower variability in runners group compared with non-runners group. The average CRP variability for $KNEE_{flex/ex}$-$ANKLE_{in/ev}$ in runners group was moderately lower (with chances of greater/similar/lower values of 3/17/80%) in comparison to non-runners group. When considering the analysis of the intervals in which the stance phase was divided, moderately lower variability in runners group was found in $KNEE_{flex/ex}$-$ANKLE_{flex/ex}$ during midstance phase (2/14/75%), $HIP_{abd/ad}$-$KNEE_{flex/ex}$ during terminal phase (3/20/77%), $KNEE_{flex/ex}$-$ANKLE_{in/ev}$ during pre-swing phase (2/13/85%).

Discussion

The main finding in this study was that there were few differences in CRP and CRP variability between runners and non-runners groups. Only three CRP variables analysed showed moderate differences between groups. In addition, these were in opposite directions depending on the joint coupling analysed. The $HIP_{abd/ad}$-$KNEE_{flex/ex}$ profile (average and during midstance phase) in runners group was closer to in-phase coupling than in non-runners group, while the $KNEE_{abflex/ex}$-$ANKLE_{flex/ex}$ profile during preswing phase in non-runners group was closer to in-phase coupling than in runners group. This discrepancy in results was consistent with the literature for different skills. Depending on the skill analysed and the coupling joints examined, CRP profiles between groups of differing performance levels may be: similar (Seifert et al., 2011), closer to in-phase in experts (Williams et al., 2016) or novices (Seifert, Leblanc, Chollet, & Delignières, 2010). These results suggest the need for more studies which analyse the influence of performance level on the CRP profile in order to determine if this can be effectively used to distinguish athletes of different performance levels.

Although in four of the parameters that analysed the CRP variability, a moderately increase in coupling variability was observed in the of non-runners group compared to runners group, most variables indicated unclear differences between groups. These results are in contrast to previous studies (Nakayama et al., 2010) that analysed the influence of running experience on the variability of gait cycle parameters but found that running experience was accompanied by lower variability in gait measures. For example, Nakayama et al. (2010) observed lower variability of stride time when comparing runners and non-runners groups, however, these apparently conflicting results may be due to the difference in the parameters analysed. Nakayama et al. (2010) analysed parameters related to end-point variability such as the spatio-temporal variables, while the present study analysed joint coordination variability. Reduced end-point variability can be expected in trained runners resulting from optimization of the task (Nakayama et al., 2010) whereas a higher level of coordination variability could be explained by greater flexibility in achieving a particular movement task (Hamill et al., 2012). Despite this, the results of this study showed that the variability of joint coupling during the stance phase was not dependent running experience or by consequence, training volume.

To our knowledge, no previous studies have investigated differences in coordination variability between runners with respect to skill level, while several studies have analysed the influence of skill level on the coordination variability in different sport skills (Cazzola, Pavei, & Preatoni, in press; L. Seifert et al., 2011; Ludovic Seifert, Leblanc, Chollet, & Delignières, 2010; Sides & Wilson, 2012; Williams et al., 2015). These studies suggested that coordination variability may be a useful surrogate measure for detecting skill-dependent factors in sports performance. However in the present study, very few differences were found in the coordination variability throughout the stance phase of running between runners and non-runners groups.

The apparent discrepancy between running and other skills could be explained by various factors. Since this study used a treadmill to evaluate the coordination variability in runners, the imposition of a constant velocity could have removed the tendency to adapt to sudden changes in the environment and less flexibility in movement was required by the participants (Cazzola et al., in press; Lindsay, Noakes, & McGregor, 2014; Wheat, Baltzopoulos, Milner, Bartlett, & Tsaopoulos, 2005). This factor could reduce the range of variability scores in both groups resulting in equalisation of the measures of coordination variability. Despite this, recent research on the coordination variability on a treadmill in race walkers (Cazzola et al., in press) found differences between race walkers of different skill levels. Translating these findings to running, suggests that the use of a treadmill to assess variability may not be the sole cause of similarity in CRP variability across groups.

The biomechanical differences between stance and swing phases in running could also provide some explanations for the results of this study. During the stance phase, the lower limb adjusts the movement pattern as a closed kinetic chain whereas during the swing, it behaves like an open kinetic chain. Similar to previous studies (Dierks & Davis, 2007; Foch & Milner, 2013; Hein et al., 2012), the present study analysed the coordination variability only in the stance phase. Nevertheless, closed kinetic chain activities could result in lower variability due to the reduced need for adaptability to environmental changes compared with open kinetic chain activities. Hamill et al. (1999) analysed the CRP variability between healthy and injured runners during the entire gait cycle and observed greater differences during the swing phase compared to stance phase. Although the highest peaks of variability were achieved in the transition periods between stance and swing. In the present study the variability was studied separately in the different functional sub phases in which the support phase can be divided.

The few differences found between groups did not concentrate on a single subphase. The three variables that showed differences between groups were distributed in three different subphases without showing a clear tendency.Therefore, the similar levels of coordination variability between the runners of different experience in this study could be due to the expected lower variability in closed kinetic chain tasks. Despite this, Sides & Wilson, (2012) observed differences in coordination variability in the closed kinetic chain task of cycling between cyclists of different levels of experience. Although the running stance phase and cycling can be considered as closed kinetic chain tasks, further studies are needed to determine if coordination variability can be used to distinguish between athletes of different skill level in closed kinetic chain tasks.

In this study the participants self-selected their running velocity and the mean velocities of the two groups were different. This difference was expected due to the differences in the levels of performance between groups. It is assumed that the self-selected velocity represented the velocity at which participants completed the largest volume of training and therefore represented the participants' most common kinematic patterns during running. It is possible that the differences in velocity could largely explain the results of this study. Previous research on coordination variability shows several studies that use self-selected running velocities (Hafer et al., 2015; Hamill et al., 1999; Kurz et al., 2005; Miller et al., 2008) and others that use specifically defined velocities (Dierks & Davis, 2007; Foch & Milner, 2013; Hein et al., 2012). Choosing the same velocity for both groups could result in changes in coordination variability and a change in the running velocity could also be accompanied by changes in the amplitude of movement or alterations in the timing of the movement. This could modify the predefined movement pattern and consequently change the variability in coordination patterns (Bartlett, Wheat, & Robins, 2007). Further studies are needed to advance the understanding of how the running velocity influences the coordination variability.

In summary, this study has demonstrated limited differences in the level of CRP and CRP variability among runners and non-runners groups and thus different levels of experience as estimated from weekly training volume. The few differences found in the CRP values suggest that the degree of coordination of the lower limb joints during running at a self-selected speed is not affected by the experience of the runners. Although few CRP variability parameters were different between groups, these differences were in the same direction: the runners group showed lower variability degree in the CRP profile. This suggests the need for more studies which analyse how the running experience affects the coordination variability.

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Figures

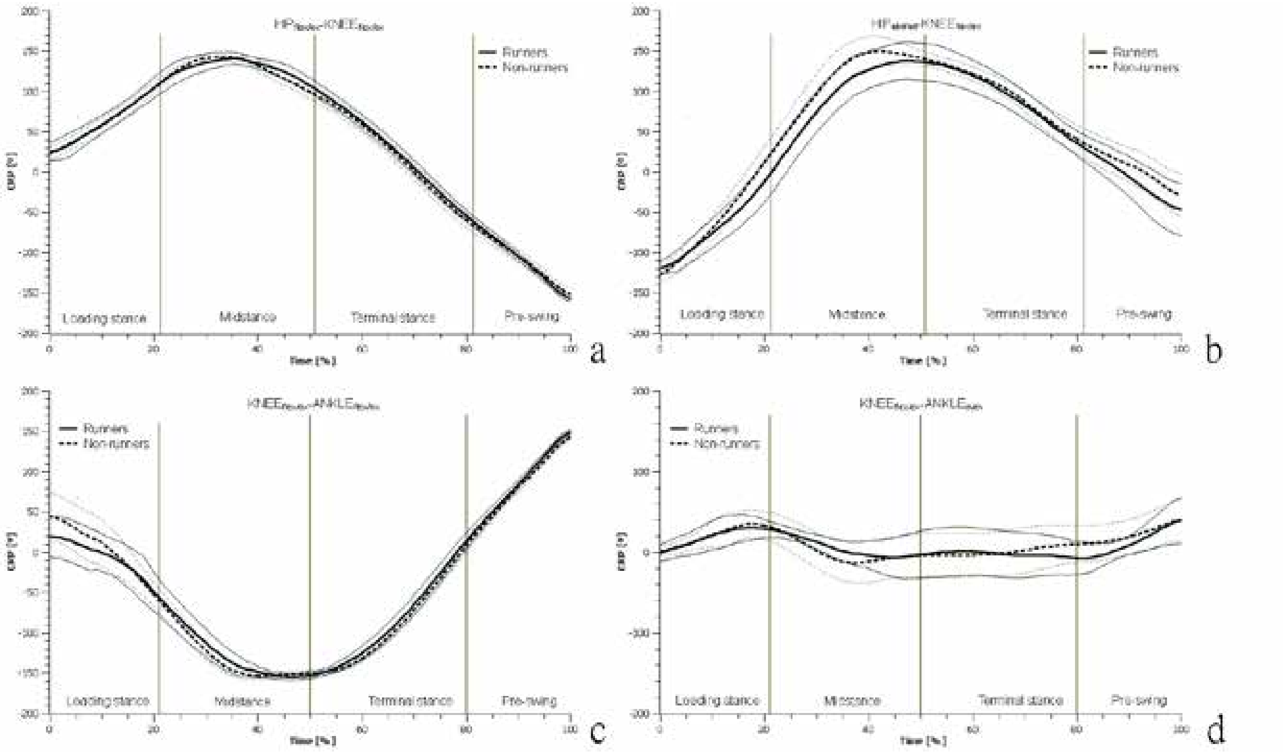

Figure 1. Average continuous relative phase for non-runners (dashed) and runners (black) groups normalized to stance phase: a) $HIP_{flex/ex}$-$KNEE_{flex/ex}$, b) $HIP_{abd/ad}$-$KNEE_{flex/ex}$, c) $KNEE_{flex/ex}$-$ANKLE_{flex/ex}$, d) $KNEE_{flex/ex}$-$ANKLE_{in/ev}$ 95% confidence intervals and effect sizes (ES) values are also presented. The vertical lines divide stance phase into four intervals according to (Perry & Burnfield, 2010)

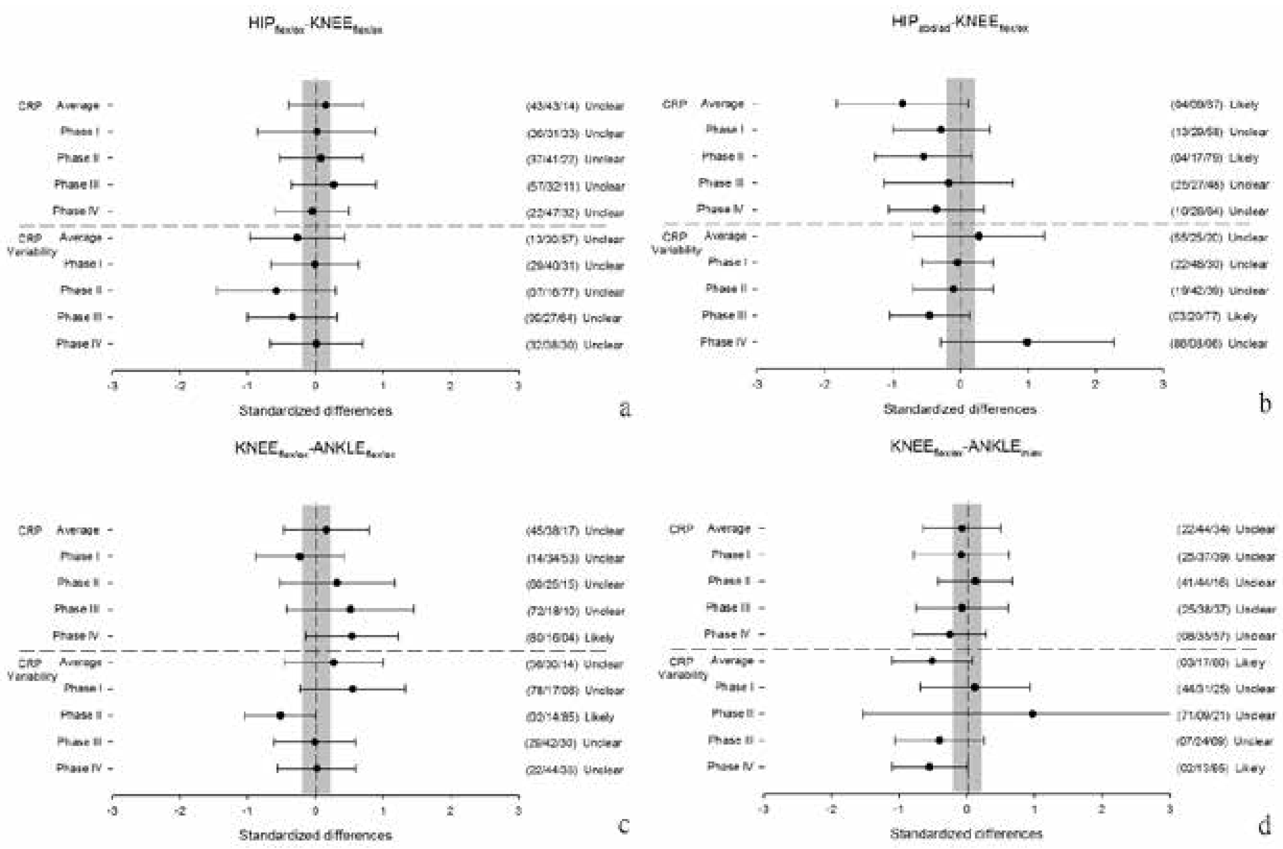

Figure 2. Differences (90% confidence intervals) in CRP and CRP variability for: a) HIP$_{flex/ex}$-KNEE$_{flex/ex}$, b) HIP$_{abd/ad}$-KNEE$_{flex/ex}$, c) KNEE$_{flex/ex}$-ANKLE$_{flex/ex}$, d) KNEE$_{flex/ex}$-ANKLE$_{in/ev}$. Shaded areas represent trivial differences

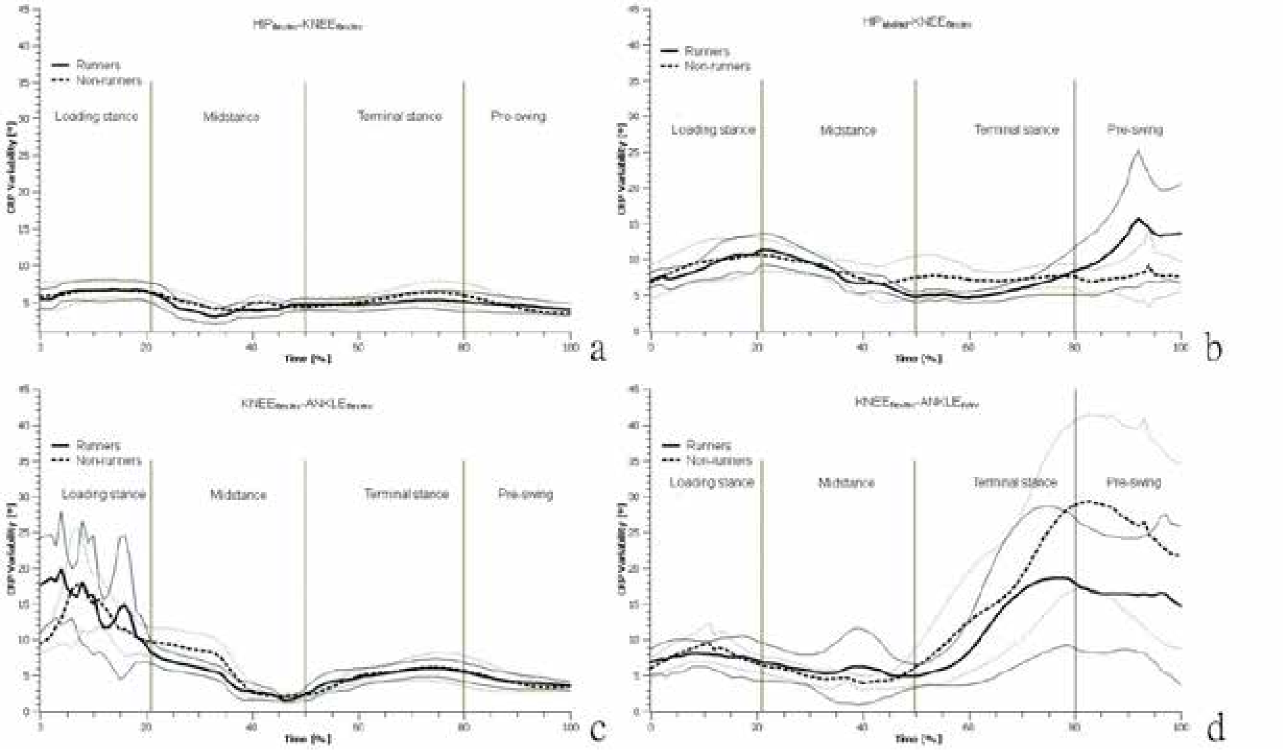

Figure 3. Average continuous relative phase variability for non-runners (dashed) and runners (black) groups normalized to stance phase: a) HIP$_{flex/ex}$-KNEE$_{flex/ex}$, b) HIP$_{abd/ad}$-KNEE$_{flex/ex}$, c) KNEE$_{flex/ex}$-ANKLE$_{flex/ex}$, d) KNEE$_{flex/ex}$-ANKLE$_{in/ev}$. 95% confidence intervals and effect sizes (ES) values are also presented. The vertical lines divide stance phase into four intervals according to (Perry & Burnfield, 2010)