CHANGES IN LOWER LIMB COORDINATION ACROSS RUNNING AT DIFFERENT SPEEDS AND INCLINATIONS: CONTINUOUS RELATIVE PHASE ANALYSIS

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CHANGES IN LOWER LIMB COORDINATION ACROSS RUNNING AT DIFFERENT SPEEDS AND INCLINATIONS: CONTINUOUS RELATIVE PHASE ANALYSIS

ABSTRACT. The aim of this study was to evaluate the changes in segmental coordination when running at different inclinations and speeds. 18 recreational runners performed running trials at three inclinations (0°, 3° and 6°) and three speeds (preferred speed, fast and slow) were measured with Vicon motion capturing system. The phase angle, continuous relative phase (CRP) and variability of CRP (VCRP) were calculated. Statistical models were performed to compare means for each running condition at each gait point: one-way ANOVA with Bonferroni post-hoc analysis for those data points with homogeneity of variances and Welch ANOVA with Games-Howell post-hoc analysis for those with heterogeneity of variance. Effect size (ω^2) was computed to indicate whether the significant effects were trivial. Our results demonstrated that compared with the running speeds, participants who ran on different inclined surfaces showed higher Ankle-Knee CRP but lower Knee-Hip CRP and its variability, which is susceptible to running related injuries. These data suggest that runners should have a higher concern on joint loading and sports recovery when running at inclined surfaces.

KEY WORDS: treadmill running, continuous relative phase, coordination pattern, running with inclinations, running injuries

MODIFICĂRI ALE COORDONĂRII MEMBRELOR INFERIOARE LA ALERGARE CU VITEZE ȘI ÎNCLINAȚII DIFERITE: ANALIZA FAZEI RELATIVE CONTINUE

REZUMAT. Scopul acestui studiu a fost de a evalua schimbările în coordonarea segmentară la alergare cu diferite înclinații și viteze. 18 alergători de agrement au efectuat probe de alergare la trei înclinații (0°, 3° și 6°) și s-au măsurat trei viteze (viteza preferată, rapidă și lentă) cu sistemul de captare a mișcării Vicon. S-au calculat unghiul de fază, faza relativă continuă (CRP) și variabilitatea CRP (VCRP). S-au efectuat modele statistice pentru a compara mediile pentru fiecare condiție de alergare la fiecare punct de mers: ANOVA unidirecțională cu analiză post-hoc Bonferroni pentru acele puncte de date cu varianță omogenă și ANOVA Welch cu analiză post-hoc Games-Howell pentru punctele de date cu varianţă eterogenă. Mărimea efectului (ω^2) a fost calculată pentru a indica dacă efectele au fost semnificative. Rezultatele noastre au demonstrat că, în comparație cu vitezele de alergare, participanții care au alergat pe diferite suprafețe înclinate au prezentat CRP mai mare în zona gleznă-genunchi, dar mai scăzută în zona genunchi-șold și variabilitatea acesteia, care este susceptibilă la leziuni legate de alergare. Aceste date sugerează că alergătorii ar trebui să pună un accent mai mare asupra încărcării articulațiilor și recuperării atunci când aleargă pe suprafețe înclinate.

CUVINTE CHEIE: alergare pe bandă, fază relativă continuă, model de coordonare, alergare pe suprafețe înclinate, leziuni legate de alergare

MODIFICATIONS DE LA COORDINATION DES MEMBRES INFÉRIEURS LORS DE LA COURSE À DIFFÉRENTES VITESSES ET INCLINAISONS : ANALYSE DE PHASE RELATIVE CONTINUE

RÉSUMÉ. Le but de cette étude était d'évaluer les changements dans la coordination segmentaire lors de la course à différentes inclinaisons et vitesses. 18 coureurs récréatifs ont effectué des essais de course à trois inclinaisons (0°, 3° et 6°) et trois vitesses (vitesse préférée, rapide et lente) qui ont été mesurées à l'aide du système de capture de mouvement Vicon. L'angle de phase, la phase relative continue (CRP) et la variabilité de la CRP (VCRP) ont été calculés. Des modèles statistiques ont été réalisés pour comparer les moyennes de chaque condition de course à chaque point de marche : ANOVA unidirectionnelle avec analyse post-hoc de Bonferroni pour les points de données présentant une homogénéité de variances et ANOVA de Welch avec analyse post-hoc de Games-Howell pour ceux présentant une hétérogénéité de variance. La taille de l'effet (ω^2) a été calculée pour indiquer si les effets significatifs étaient insignifiants. Nos résultats ont démontré que par rapport aux vitesses de course, les participants qui ont couru sur différentes surfaces inclinées ont présenté une CRP cheville-genou plus élevée mais une CRP genou-hanche plus faible et sa variabilité, susceptible de provoquer des blessures liées à la course. Ces données suggèrent que les coureurs devraient se préoccuper davantage de la charge articulaire et de la récupération sportive lorsqu'ils courent sur des surfaces inclinées.

MOTS CLÉS : course sur tapis roulant, phase relative continue, modèle de coordination, courir sur des surfaces inclinées, blessures liées à la course

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INTRODUCTION

Treadmill running is a popular fitness activity for recreational runners because of the low cost, few restrictions on space, and improvement of cardiovascular capability. This running is also widely used as supplementary training in elite athletes [1]. However, the poor running technique may cause chronic injuries in the knee and lower leg. Data showed that 33% to 50% of runners received at least 1 injury annually [2]. Most running injuries occurred in the joints of the lower limbs (Over 80%), including the legs, hip and feet, but knee injuries were the most common [3]. In studies over the past few years, high-impact forces from running have been identified as a significant cause of running injuries. Knee flexion and rotation could be effective in reducing joint impingement [4]. In response to incline running, the coordination of the movements of the small and large leg in the sagittal plane and the phase relationship produced flexion and extension suitable for the knee joint. In the frontal plane, the leg and foot coordinate their movements to produce anterior and posterior rotations of the subtalar joint as a means of ensuring stability of movement [5]. It could be found through existing studies that coordination between joints is necessary to ensure running and joint changes due to impact forces may be a dangerous movement pattern that predisposes runners to injury [3].

Running is a complex motor skill that involves numerous interacting joint segments or degrees of freedom; but coordination determines how these degrees of freedom are organized in an appropriate way [3]. Coordination analysis can provide insight into the mechanisms of running conditioning and running injury. Since the high frequency of joint movements presented by running and the relative positional relationships it brings, which are difficult to find out the relative positional differences between joints by kinematic analysis of single joints alone. Therefore; using a model of coordination, it helped researchers to gain further insight into the positional characteristics between the joints of the lower limbs in the running condition and to better understand the motor performance of the lower limbs during running movements [6]. Funato *et al*. concluded from an analysis of joint coordination during running that as the stride frequency increases, close relationship among the joints, reducing the production of joint degrees of freedom and leading to joint variability that can cause reduced performance and even injury [7]. In addition, the value of motor coordination for insight into running has been analyzed in several investigations by calculating continuous relative phase (CRP) angles. For example, by analyzing the coordination of the shank-foot and thigh-shank couplings in sagittal plane, it was found that the magnitude of coordination variability was significantly greater in backward running than in forward running, indicating that more degrees of freedom were involved in backward running [8]. CRP angles and CRP variability were calculated for key lower extremity kinematic couplings. It was found that subjects with lower limb injury disorders (iliotibial band syndrome) had abnormal segmental coordination patterns in running, particularly coupling involving knee abduction and tibia internal/external rotation. It was also suggested that changes in CRP in injury-prone runners may be associated with abnormal segmental coordination patterns [9]. Therefore, prospective studies assessing motor coordination will contribute to our understanding of the interplay between coordination, pain and running injuries. Since current methods in coordination assessment required multiple biomechanical variables, building an approach which can be measured and calculated in an easy way became critical in human dynamic analysis.

Commonly, therapists chose motor control and development mechanism in assessing motion performances and those theories emphasized the regulation of central nervous system [10]; however, some researchers suggested that the dynamic systems theory (DST) is a better explanation of how motor learning was optimized [11]. DST deems that motion behavior and its coordination are the outcomes of complex interactions within multiple segments and joints and it can be quantified by continuous relative phase (CRP), which is calculated by phase angle (PA) of a distal segment subtracting a proximal one through the time series of coupling angular displacements and velocities [12]. Several studies also approved that CRP is a practical protocol to investigate coordination of two coupling joints that fit the DST theory of interactions [11, 13].

In recent years, the effect of running speeds and inclinations on the lower limb coordination have been reported. When comparing biomechanical changes in long distance-running at different speeds, Aljohani *et al*. found a decrease in coupling angle variability in the sagittal plane of the knee joint and an increase in the proportion of hip flexion/extension movement patterns when speed was increased by 30%. This study concluded that speed changes were significantly correlated with an increase in risk factors for running-related injuries [14]. Bailey believed that increased movement speed affected coordination patterns and coordination variability. It was found that CRPV in the thigh decreased significantly with increasing speed and that this change was associated with an increase in the knee coupling range [15]. As the incline increases, the body adjusts its center of mass by leaning forward on its own to ensure the stability of movement. The length of the limb shortens in the oscillator and this change depends mainly on the movement of the knee joint, therefore the increase in incline reduces the range of motion of the knee joint [16]. Telhan *et al*. assumed that running on level and moderately inclined inclinations appeared to be a safe component of training regimens and return-to-run protocols after injury [17]. However, how the factors of speed, inclination and interaction would affect movement coordination during treadmill running was still vague.

This study aimed to investigate the effect of incline and speed on lower limb coordination during treadmill running. According to the current knowledge, Lam *et al*. investigated the effects of inclined motion on lower limb kinetic and kinematic variables. With increasing incline, peak vertical impact and loading rates, stride length and ankle coronal range of motion decrease, with the lowest sagittal knee mobility at an incline of 3°. Thus, running with a high incline resulted in more altered biomechanical variables compared to running with a low incline [18, 19]. The increase in speed produced a moderate change in the frequency of movement patterns, mainly in the form of changes in pelvic-trunk coordination. In addition, changes in each coordination pattern were only observed with increased velocity, suggesting that the effect of velocity on coordination depends not only on the amount of change but also on the direction of change. Therefore, to analyze the effect of coordination patterns on joints, the relationship between speed and coordination needs to be further investigated [18]. Hence, we hypothesized that both two factors would change the lower-limbs coordination patterns while running. For instance, the inclination would limit that of Knee-Ankle coupling, while speed would raise the range of motion of Hip-Knee coupling. Both those changes would be identified through the coordination pattern.

EXPERIMENTAL

Methods

Participants

18 healthy recreational male runners took part in this study. Their average age was 20.9±1.9 years with average mass and height of 70.4±6.3 kg and 1.79±0.07 m, respectively. They had an average running experience of 6.0±2.4 yrs, with current running exposure of 15.0 ±7.8 km/wk. None of the participants suffered from any musculoskeletal injuries at least six months prior to their participation. All study procedures complied with the principles of the Declaration of Helsinki for ethical research in human participants. Written informed consent was obtained from each participant prior to data acquisition.

Data Collection

After the 15 min warm-up, reflective markers (diameter 14 mm) were placed over the following anatomical landmarks: left and right sides of anterior superior iliac spine (ASIS) and Posterior superior iliac spine (PSIS), hip joint center, medial and lateral epicondyles of femur, medial and lateral malleolus, three calcaneus markers (posterior upper, posterior lower and lateral aspect of calcaneus), two-foot tracking markers (medial side of the first metatarsal head, upper side of the second metatarsal head and lateral side of the fifth metatarsal head) and two 4-marker rigid clusters which were attached to the thigh and leg segments (Fig. 1). A motion capture system of 10 cameras (200 Hz, Vicon, Metrics Ltd, Oxford, UK) was used to capture lower limb kinematics data for entire experiment.

An instrumented treadmill (Bertec Corp., Columbus, Ohio) was provided. The participants were first instructed to run at three inclinations (0°, 3°, 6°) with their preferred speed. The preferred speed of individual participant was determined by asking participants to run on the treadmill whilst gradually increasing the treadmill speed without letting them know the exact speed. They were instructed to verbally identify a running speed, which were the most comfortable and matched their preferred speed for an endurance run [20]. In the process of exploring the influence of inclination on running coordination, the preferred speed was determined at 0°, the same preferred speed was used for both 3° and 6° condition. The average preferred speed was 2.54 ± 0.34 m/s. After the completion of three inclination conditions, another fast speed (preferred speed +10%) and slow speed (preferred speed -10%) were performed with the level inclination. At least 1.5 min recording for running data was required in each test and 5 min rest was available between two tests. The order of inclination and speed conditions were randomly presented across participants.

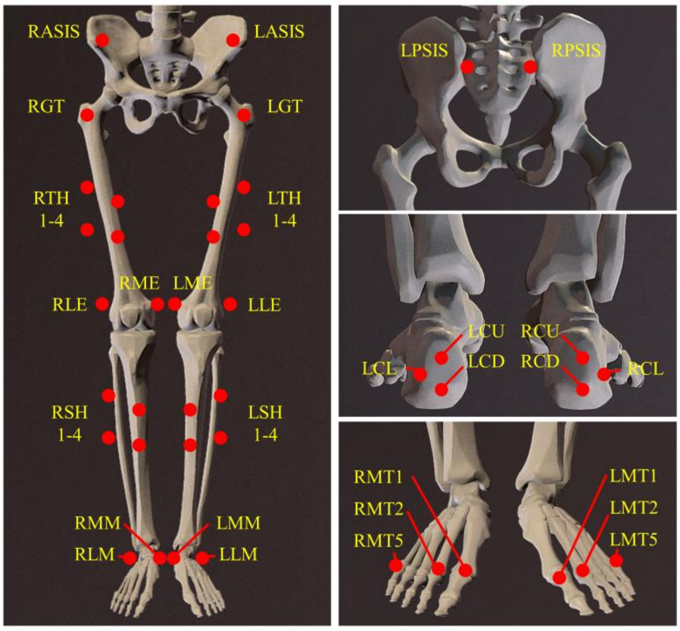

Figure 1. Demonstration of Markers' Installation

Data Processing

The biomechanical data were processed with Visual3D software (C-Motion Inc., Ontario, Canada) to define body segments and joint kinematic variables. A spline interpolation was performed to determine the minor missing data using three frames before and after the missing data. The contact phase was defined as the initial contact and toe-off by the force platform (Bertec Corp., Columbus, Ohio). A fourth-order Butterworth low-pass filter with cut-off frequencies of 10 Hz was used to filter the high-frequency noise. Each set of discrete joint angle data was normalized to 100 points using cubic spline interpolation which donated 100% of the gait cycle.

Continuous relative phase calculation procedure: Some researchers suggested that the dynamic systems theory (DST) is a better explanation of how motor learning was optimized [11]. DST deemed that motion behavior and its coordination are the outcomes of complex interactions, within multiple segments and joints, and it can be quantified by CRP which was calculated by the phase angle (PA) of a distal segment subtracting a proximal one through the time series of coupling angular displacements and velocities [12]. Several studies also approved that CRP is a practical protocol to investigate coordination of two coupling joints that fit the DST theory of interactions [11, 13].

We used Hilbert transform to calculate CRP by following four steps, which was introduced by Lamb [11].

(1) Shifting the center of phase portrait around zero

$$\theta_{c}(k)=\theta(k)-\min(\theta(k))-\frac{\max(\theta(k))-\min(\theta(k))}{2},\ (k=1,2,3...100) \tag{1}$$

where $\theta(k)=\{\theta(1),\theta(2),\theta(3)...\theta(100)\}$ denotes the interpolated 100 points Euler joint angle vector, and $\theta_c(k)$ refers to the Euler angle vector without zero-frequency component.

(2) Generating the analytic signal $\zeta(k)$ of $\theta_{c}(k)$ using Hilbert transform

$$\zeta(k)=\theta_{c}(k)+iH(k) \tag{2}$$

where $H(k)$ is the Hilbert transform of $\theta_{c}(k)$

(3) Computing the joint PA $\varphi(k)$ at each time k

$$\varphi(k)=\tan^{-1}(\frac{H(k)}{\theta_c(k)}) \tag{3}$$

(4) Calculating the continuous relative phase $CRP_{(1-2)}(k)$ between two joints

$$CRP_{(1-2)}(k)=\varphi_1(k)-\varphi_2(k) \tag{4}$$

where $\varphi_1(k)$ represents the PA of the proximal joint and $\varphi_2(k)$ represents the PA of the distal joint.

According to Equations (1) – (4), joint PA (hip, knee and ankle), Ankle-Knee CRP and Knee-Hip CRP of left and right lower limbs were calculated respectively. Ten successful trials were selected and averaged for each tested condition. An increasing CRP demonstrates that distal joint rotates faster than the proximal joint. Oppositely, a decreasing CRP represents that proximal joint rotates faster than the distal joint. This reversal tendency represents a change in relative rotation relationship between the proximal and distal joints. Furthermore, we computed standard deviation for each subject across 100 data points, among all participants as the variability of CRP (VCRP) [9], which represents a degree of variation in coordination between two joints [3].

Statistics Analysis

Since there were no significant differences between left and right leg data, the left and right leg data were merged for further statistical analysis. To investigate the impact of speed and inclination on lower limb coordination during running, analysis of variance (ANOVA) was used to explore if there was any difference between conditions. This method is a general method for evaluating differences in time series and has been applied by other scholars [21]. Due to the relatively small sample size (about 36 samples/group) and non-normal distribution of data at a small number of points, Brown-Forsythe's test was chosen to test the null hypothesis that the variances are equal across the three groups of data at three inclinations/speeds. For those points with homogeneity of variance, one-way ANOVA with Bonferroni multiple comparison test was performed to identify the significant difference. For those points for which the assumption of variance homogeneity was violated, Welch ANOVA was applied as it is proved to have a more robust performance than other non-parametric tests (Kruskal Wallis) [22] and post-hoc Games-Howell test was then applied for pairwise comparisons, which has greater power than traditional method. In addition, to estimate the degree of difference, effect size (ω^2) was computed at each point, which has less bias than (η^2) when heterogeneity of variance [23], interpreted as small ($\omega^2 < 0.06$), medium ($0.06 < \omega^2 < 0.14$), or large ($\omega^2 > 0.14$) [24].

For further investigation of the data, the running gait cycle was divided into four stages: (1) loading response (1%-20%), (2) mid-terminal stance (21%-60%), (3) initial swing (61%-80%), (4) mid-terminal swing (81%-100%) [25]. Furthermore, those points with significant differences ($p < 0.05$) were accumulated at each gait cycle stage separately between three conditions [26] and denoted by %P. Those points with large or medium effect ($\omega^2 > 0.14$ for large effect, $\omega^2 > 0.06$ for medium effect) were accumulated at each stage and denoted by %ES. All statistical analysis procedures were performed using MATLAB (R2020a, MathWorks, USA) with a significance level of 0.05 and a confidence interval of 95%.

RESULTS

Phase Angle (PA) Variables

As shown in Fig. 2, in terms of tendency, both speed and inclination affect the PA in knee rather than in ankle and hip, but slight off-set existed within loading response and early stance phase (around 0%-40% gait cycle) for ankle PA and whole stance and early swing (around 2%-80% gait cycle) for hip PA. With the running faster, knee PA increased; while slope became steep, knee PA decreased.

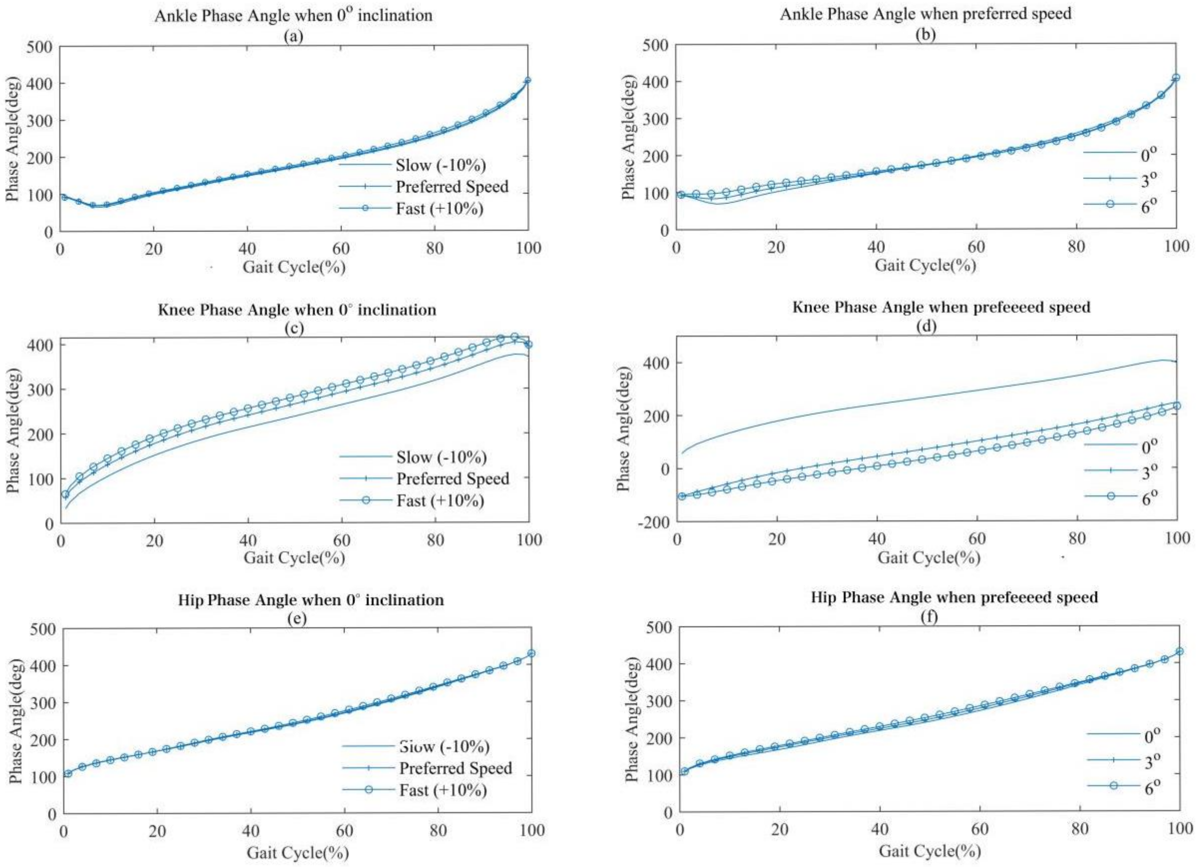

Figure 2. Curves of ankle (top), knee (middle) and hip (bottom) phase angle during running at different speeds (left panel) and inclinations (right panel)

Continuous Relative Phase (CRP) Variables

According to Table 1 and Fig. 3(a) and (b), in terms of speed, percentage of point (%P) and effect size (%ES) for both Knee-Hip and Ankle-Knee showed no significant differences or large effects among three speed conditions (fast, preferred and slow at level surface) across the entire gait cycle (Sig. %P = 0, %ES = 0 for both Ankle-Knee and Knee-Hip). But we found a statistically significant difference for those two couplings when inclination increased. In terms of CRP in Ankle-Knee, significant variations existed in 21-100% gait cycle (Sig. %P range 20-25, %ES around 20); however, CRP in Knee-Hip showed significance across the entire gait cycle (Sig. %P range 19-20, %ES range 7-20).

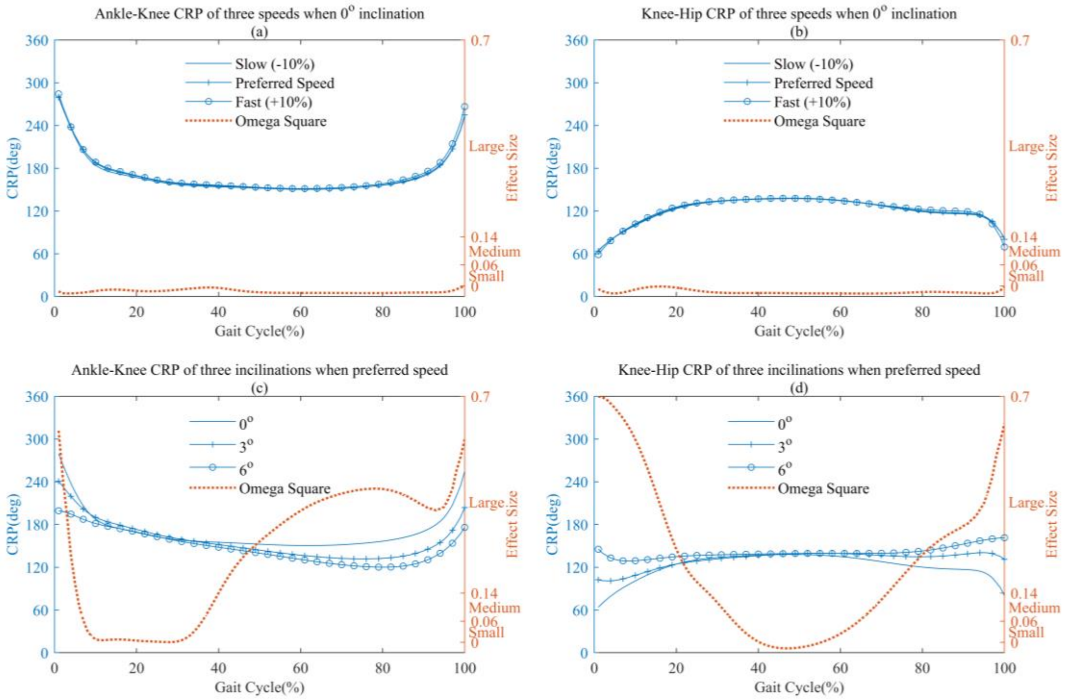

Figure 3. Curves of ankle-knee (left panel) and knee-hip (right panel) continuous relative phase (CRP) during running at different speeds (top) and inclinations (bottom)

Variability of Continuous Relative Phase (VCRP) Variables

In terms of VCRP in Ankle-Knee and Knee-Hip, as running faster, significant differences were only found in mid-terminal stance phase (%P = 11; %ES = 0 for Ankle-Knee; %P = 24; %ES = 0 for Knee-Hip; $p < 0.05$, $\omega^2 > 0.14$) and initial swing phase (%P = 3; %ES = 0 for Ankle-knee; %P = 2; %ES=0 for Knee-Hip; $p < 0.05$, $\omega^2 > 0.14$). When inclination angle increased, there were significant differences across the whole gait cycle (%P = 20, %ES = 15 for loading response; %P = 31, %ES = 12 for mid-terminal stance; %P = 20, %ES = 20 for initial swing; %P = 20, %ES = 20 for mid-terminal swing, for Ankle-Knee; %P = 15, %ES = 1 for loading response; %P = 19, %ES = 0 for mid-terminal stance; %P = 20, %ES = 19 for initial swing; %P = 20, %ES = 20 for a mid-terminal swing for Knee-Hip; $p < 0.05$, $\omega^2 > 0.14$) (Table 1 and Fig. 4).

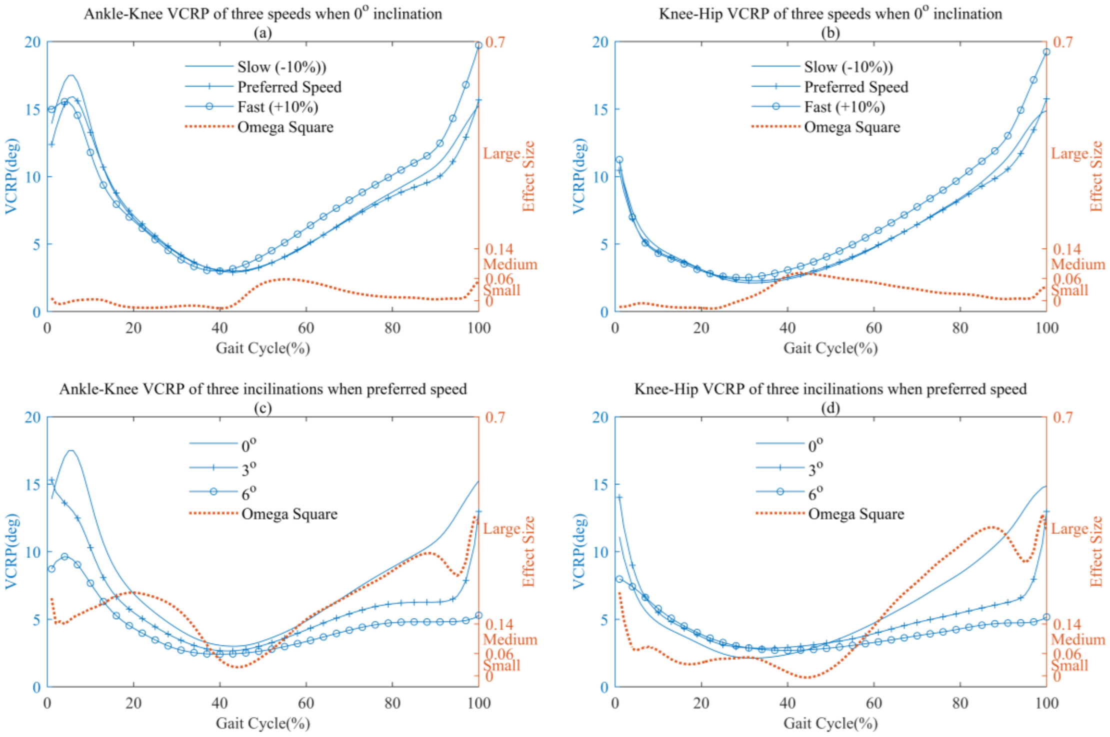

Figure 4. Curves of Ankle-Knee (left panel) and Knee-Hip (right panel) variability of continuous relative phase (VCRP) during running at different speeds (top) and inclinations (bottom)

Table 1: Statistical analysis results of CRP and VCRP

Item	Slope	Speed	Gait cycle											
			1%-20%			21%-60%			61%-80%			81%-100%		
			Mean (SD)	%P§	%ES* (%ES)**	Mean (SD)	%P§	%ES* (%ES)**	Mean (SD)	%P§	%ES* (%ES)**	Mean (SD)	%P§	%ES* (%ES)**
CRP Ankle-Knee	0°	Slow	197.51(24.71)	0	0 (0)	154.9(8.91)	0	0 (0)	152.18(13.81)	0	0 (0)	180.31(25.10)	0	0 (0)
	0°	Preferred	199.84(21.52)			155.87(8.50)			152.35(17.91)			181.44(32.85)		
	0°	Fast	200.90(20.78)			156.70(11.51)			153.66(11.51)			185.41(34.16)		
	0°	Preferred	199.84(21.52)	7	5 (7)	155.87(8.50)	25	21 (24)	152.35(17.91)	20	20 (20)	181.44(32.85)	20	20 (20)
	3°	Preferred	195.77(19.43)			152.05(7.60)			133.01(11.31)			151.33(14.76)		
	6°	Preferred	182.68(18.90)			148.19(8.46)			123.89(10.70)			135.45(10.54)		
CRP Knee-Hip	0°	Slow	99.04(9.83)	0	0 (0)	134.56(8.11)	0	0 (0)	126.69(15.36)	0	0 (0)	111.44(23.94)	0	0 (0)
	0°	Preferred	99.84(10.74)			135.17(7.83)			127.38(17.36)			112.54(30.32)		
	0°	Fast	100.12(10.57)			135.21(10.71)			127.83(10.71)			112.83(31.30)		
	0°	Preferred	99.84(10.74)	20	20 (20)	135.17(7.83)	19	7 (13)	127.38(17.36)	20	9 (16)	112.54(30.32)	20	20 (20)
	3°	Preferred	110.53(9.41)			135.23(6.42)			136.62(9.87)			137.36(13.97)		
	6°	Preferred	132.42(13.45)			138.27(6.74)			140.18(9.24)			152.98(11.67)		
VCRP Ankle-Knee	0°	Slow	12.66	0	0 (0)	4.03	11	0 (0)	7.01	3	0 (0)	11.48	1	0 (0)
	0°	Preferred	12.01			4.05			6.90			10.73		
	0°	Fast	11.45			4.29			8.31			13.38		
	0°	Preferred	12.01	20	15 (20)	4.05	31	12 (28)	6.90	20	20 (20)	10.73	20	20 (20)
	3°	Preferred	10.00			3.45			5.39			7.01		
	6°	Preferred	7.29			2.86			4.18			4.86		
VCRP Knee-Hip	0°	Slow	5.35	0	0 (0)	2.89	24	0 (14)	6.59	2	0 (0)	11.56	1	0 (0)
	0°	Preferred	5.04			3.01			6.56			11.04		
	0°	Fast	5.03			3.52			7.88			13.65		
	0°	Preferred	5.04	15	1 (10)	3.01	19	0 (6)	6.56	20	19 (20)	11.04	20	20 (20)
	3°	Preferred	6.36			3.18			4.78			6.85		
	6°	Preferred	5.80			2.97			3.80			4.69		

DISCUSSION

This study explored the influences of speed and inclination on lower limb coordination while running on the treadmill. Generally, the present findings demonstrated that changing a small range of running speed (±10% of preferred speed) would not cause significant impact on CPR, but increased its variations as speed went up. However, lower limb coordination across different phases of gait cycle was significantly affected by the changes in inclination angle. For the choice of inclination angle: when running with an incline angle, we could observe the feature of change for lower limbs' coordination. So, our purpose was not to explore the influence of extreme incline angle on the running performance. Further, running with an incline larger than 10° would become dangerous for participants on the treadmill for several minutes, since their center of mass was significantly modified. In conclusion, analyzing these variations can gain insights into how the neuromuscular system and skeletal system work when coping with different speed and inclination conditions.

Our results suggested that speed had limited influence on the CRP in Ankle-Knee and Knee-Hip, but the VCRP increased as running speed was added. As indicated by Chiu and Lamoth [27, 28], the change of speed caused the adaptations and adjustments in steps, so as to maintain their running rhythm. Since, the lower speed (relative to preferred one) led to a shorter stride length, which then reduced range of motion of the knee joint, so smaller knee PA was observed [29]; vice versa for the higher speed. However, when running faster than preferred speed, VCRP in Ankle-Knee and Knee-Hip occurred during 21%-80% gait cycle; this phenomenon suggested that when running with higher speed, segmental kinematics in the lower limb required much higher variability to maintain the coordination pattern in an optimal state that works best for each participant [18]. Meanwhile, human body used inertia and gravity acceleration to optimize energy efficiency whilst running, which was by the principle of the lowest energy consumption [30]. Thereby, we assumed that preferred speed is more controllable and safer while running.

Changing the inclination angle demonstrated a larger impact on lower limb coordination. Our results showed that the effect of incline on the ankle-knee joint had a large significant difference from the middle to the end of the gait cycle (20%-100% GC), thus confirming our first hypothesis.

When walking uphill, the center of gravity of the human body moved forward to the front end of the sole. At the same speed, the higher incline had a faster step frequency, and the hip joint cannot reach the fully extended state like walking on flat ground. In order to keep the balance of body, the natural forward flexion of the hip and knee joint increased the flexion angle in the standing position, and reduced the range of motion of the knee joint. So, the PA decreased with the increase of the incline [31]. A similar finding was made by Baida *et al*. [32].

When systematically analyzing differences in exercise variability between healthy and sport-injured populations, it was found that 64% of the articles reported a greater VCRP in the injured population. CRP was more significantly influenced by incline compared to speed. The range of knee-ankle CRP was found to decrease during uphill exercise during the support phase (0-60% GC), indicating a limitation of relative knee-ankle movement [32]. Floria *et al*. found through their study that experienced runners exhibited a higher proportion of in-phase movements in pelvic-thigh and knee-ankle coupling and greater CRP in hip-knee coupling as the incline increased. This result was consistent with the results obtained in this paper [33]. As the inclination increased, the time required for the knee to complete a full range of motion was reduced. Particularly, at the initial foot strike (10%) and terminal swing stages (80%), the knee joint was in full extension, which increased both Ankle-Knee and Knee-Hip CRP. Hence, we postulated that, when coping with running inclinations, runners preferred to adjust knee rotation, rather than ankle and hip motion to keep running status. As coordination played an important role in the alteration of posture and movement patterns during running, the study of the effect of gradient on coordination was beneficial to our understanding of the changes in the neuromuscular and skeletal systems during exercise. This had implications for the rehabilitation of lower limb disorders and for improving running safety.

The VCRP provided further support for this assumption. Since the VCRP reflects the stability within joints, VCRP corresponded to the capacity of the neuromuscular skeletal system to generate a stable movement. The low (high) VCRP indicated a stable (unstable) pattern in movement coordination [8, 34]. Our results showed that significant changes in Ankle-Knee and Knee-Hip VCRP across all four stages when the inclination changed, which implied that the adjustment between lower limb segments occurred in the entire running cycle. This coordination pattern increased the flexibility of lower limbs whilst coping with the inclined ground surface [19]; however, the high flexibility in fast running could be a potential risk factor, since highly varied coordination between ankle, knee and hip would have caused larger joint loading and thereby injury risks [12].

However, our study still had some limitations. Firstly, we did not consider the influence of speed in a higher intensity, such as ±20% preferred speed, as reported in Mehdizadeh's study [8]. Secondly, we did not include the fast (+10%) and slow (-10%) speed conditions at the two inclined surfaces (3° and 6°). If we included all the tests, the runner should have run a much longer time and fatigues were easily observed. So, we did not choose the orthogonal design.

CONCLUSIONS

Overall, higher incline running leads to higher ankle-knee CRP, versus lower knee-hip CRP and VCRP, so we speculate that these changes are a contributing factor to running-related injuries. At the same time, these data suggest that runners should be mindful of joint loading and recovery when running on inclines. It is safe for runners to choose a speed that is 10% faster than the preferred speed when running.

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