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Original Article

Effects of Running-induced Fatigue on the Trunk-pelvis-hip Coordination Variability During Treadmill Running at Different Speeds

Mehdi Khaleghi Tazji[1], Azam Valizadeh Ghale-beig[1], Hassan Sadeghi[1], George A. Koumantakis[2], Nikolaos Chrysagis[2], Ali Abbasi[1]

[1]Department of Biomechanics and Sports Injuries, Faculty of Physical Education and Sport Sciences, Kharazmi University, Tehran, Iran;
[2]Laboratory of Advanced Physiotherapy, Physiotherapy Department, School of Health and Care Sciences, University of West Attica, Athens, Greece

Abstract

Objective: The objective of this study was to examine the effects of fatigue on the coordination variability between the trunk, pelvis, and hips during treadmill running. **Methods**: The kinematics data were recorded during ten successive treadmill steps running at the preferred speed and at 80% and 120% of the preferred speed. The angle segment data obtained during the running cycles were normalized to 100 data points, and they were split into ten periods. The coordination variability was calculated using the continuous relative phase (CRP) and variability (VCRP) methods for the trunk, pelvic and hip segments before and after the fatigue protocol. **Results**: The repeated measures analysis of variance showed significant differences in the trunk-pelvic and trunk-hip CRPs and in the CRP variability during the last 30% of the treadmill running cycles after fatigue (p≤0.05). In addition, significant differences were observed in the pelvic-hip CRP and the CRP variability in 40% of the initial treadmill running cycles after fatigue (p≤0.05). **Conclusion**: According to the results of this study, fatigue reduces coordination and increases variability. The central nervous system probably exerts more control on the distal segments for maintaining moving patterns in fatigue conditions.

Keywords: Coordination, Fatigue, Running, Treadmill, Variability

Introduction

Running is a very popular form of exercise. Although running has several physiological benefits, it can result in musculoskeletal injuries in many runners[1]. Running is a complex movement requiring the motion coordination of the body segments to achieve specific joint positions[2]. Changes in the coordination can lead to overuse injuries through an abrupt (as opposed to gradual) shift of stress to the tissues that are not adapted to repetitive loading[3]. Instead, these changes are accompanied by a series of compensatory accommodative changes.

Fatigue, defined as the inability of muscles to produce the desired power, is a gradual process that results from the accompanying physiological changes occurring before and during the mechanical inefficiency of the body[4]. Changes in the limb mechanics following fatigue may cause injuries; however, adaptive movement reorganization can reduce the risk of injury. When fatigue occurs, the movement strategy of individuals changes to adapt to new situations to prevent possible tissue damage[5]. A three-dimensional analysis of running mechanics has shown that running-induced fatigue changes the number of steps per minute, the step length, and the lower extremity's kinematics[6]. Fatigue may affect coordination variability, an essential strategy when performing repetitive tasks. The cyclic nature of running causes repetitive lower limb loading, intensified with increasing speed and continued activity[7]. Increasing the coordination variability of the lower limbs using the

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Corresponding author: Mehdi Khaleghi Tazji, Department of Biomechanics and Sports Injuries, Faculty of Physical Education and Sport Sciences, Kharazmi University, Tehran, Iran
E-mail: mehdikhaleghi60@yahoo.com

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elongation-shortening cycle reduces the risk of damage due to overuse in the face of fatigue during a frequent activity or fast loading process[8]. Consequently, more studies are required to understand the relationship between inter-segmental coordination and fatigue during running.

In recent years, the variability and coordination of lower extremity such as gait, running, and cycling, have been considered by many researchers. As a principle of dynamic systems theory, variability in coordination patterns is a way to provide basic information about the motor system while performing an action, and it is also a description of the integrity of a motor strategy[9]. Variability is described as an indicator of the degree of stability in a person's movement pattern[10]. The variability in motion is the same as coordinated changes, which is described as the stability of motion patterns. For example, the loss of stability in a joint motion pattern is associated with increased variability[11]. According to dynamic systems theory, motion change is one of the fundamental characteristics of human behavior. The motor patterns of the neuromuscular system are dependent on a variety of morphological, biomechanical, and environmental factors and motor task constraints. Based on this theory, new studies have applied a number of tools and methods to better understand the function of the neuromuscular system using biomechanical variables to investigate its organization. One of these methods is the continuous relative phase (CRP), which includes two variables of velocity and displacement. It seems that the relative phase is a better criterion for organizing the neuromuscular system when compared to other biomechanical measures, such as angular displacement and velocity[12,13]. The CRP has been used in several research topics, such as segments coordination variability during treadmill and overground running at different speeds[14], lower extremity coordination while running over obstacles 13, coordination and variability in patients with total knee arthroplasties while rising from a chair[15], the comparison of motor coordination during bilateral forward reaching between healthy and low back pain individuals[16] and coordination and its variability with an increase in the running cadence[17]. Then analysis of CRP during dynamic movement such as running give insight about the mechanics of joints and segments coupling from a dynamical system theory perspective.

Changes in central body coordination are necessary for a consistent level of performing suitable movements. Therefore, fatigue and an change in running speed may affect the coordination and variability of the body segments. Due to the integrated nature of running and the anatomical communication between the trunk, pelvis, and hips, poorly coordinated movements in these parts can cause stress in the lumbar tissues and disturb the distal structures of the lower limbs. Research in integrated biomechanics on the trunk, pelvic, and hip complexes while running is rare, but there is evidence in this regard for walking[18,19]. Moreover, understanding the effect of fatigue on joints and segment coordination and its variability during running can lead to understand the change of dynamic of these structures which increases the risk for overuse injuries. Thus, the objective of this study was to examine the effects of running-induced fatigue on the trunk-pelvis-hip coordination variability during treadmill running at different speeds. It was hypothesized that: (1) fatigue can alter the trunk-pelvis-hip coordination variability during treadmill running, and (2) at different running speeds on the treadmill the coordination variability between the trunk-pelvis-hip segments changes.

Figure 1. Location of inertial sensors on the subject's body.

Materials and Methods

Participants and study design

Twenty-four college students (14 women [age: 21.64±2.02, height: 163±4.69 cm, weight: 56.42±5.54 kg] and 10 men [age: 21.60±2.42, height: 174±4.55, weight: 71.30±4.59]) participated in this quasi-experimental study. The inclusion criteria were not being a professional athlete nor having any history of musculoskeletal injuries or surgery in the lower extremities within the last six months. All of the subjects were informed about the purpose and content of the study. They each completed a consent form and health information questionnaire before participating in the study so that their essential information and medical/health records could be checked.

Procedures

A 3-dimensional analysis system (myoMOTION; Noraxon Inc., Scottsdale, AZ, USA) was used to record the kinematic

Figure 2. Execution of the running protocol on the treadmill by a subject.

data. According to the instructions, inertial sensors, with a system sampling frequency of 200 Hz, were placed on the line with the spinal column at the T12/L1 level, sacrum, and anterior portion of each thigh. The sensors were placed on the limbs using belts (myoMOTION System User Guide, 2014) (Figure 1).

Running protocol

The subjects were prepared to participate in the running protocol after placing the sensors on their bodies. Based on their preferred running speeds, the subjects ran at three speeds specific to each of them. In order to determine the running speed on the treadmill, the person was first asked to run on the treadmill at his or her preferred speed; then, 80% and 120% of the preferred speed were calculated, and each subject ran at these speeds before and after fatigue (Figure 2). The kinematic data were recorded at three speeds for 20 seconds.

Fatigue protocol

In this study, Koblbauer's fatigue protocol was applied[20]. The protocol started with treadmill walking at a speed of 6 km/h, which was increased by 1 km/h every 2 minutes. Each subject was asked to mention their Borg score during the fatigue protocol (0–20, 0 denoting no fatigue and 20 exhausted fatigue). The heartbeat was also observed and simultaneously controlled using a pulse rate meter. The subjects were blinded from seeing the speed and heart rate on the treadmill during the protocol. The treadmill speed increased continuously until the subject reported a Borg score of 13. After reaching a score of 13, the participant continued to run at the same time with a constant speed to reach a score of 17 at the Borg scale or 90% of their maximum heart rate (220-age). Then, running continued for 2 minutes with the same process until the protocol ended with a cool-down at a self-selected speed.

Data processing

The kinematics data from 10 successive cycles of treadmill running were extracted for the analysis and calculation of the coordination and variability. The coordination and variability were calculated in 10 phases of gait running. The kinematic data were filtered by the linear quadratic estimation method which was defined in the device software (KALMAN Filter) (MyoMOTION System User Guide, 2014). All data processing was conducted using MATLAB software (The MathWorks, Inc., Natick, MA, USA). After extracting the data from the device, the angular velocity and displacement were calculated in the MATLAB software to measure coordination and variability. We determined the beginning and end of each step according to the diagram of the changes in the hip joint during movement in the sagittal plane (flexion-extension), as well as according to the start and end of a step a separation was made for the pelvis and thorax. In the CRP method, the velocity of the segments is used in addition to the displacement. The CRP method shows coordination in a single cycle and successive steps, and the phase difference (position-velocity) is calculated between two oscillators.

The normalized angular position ($\theta inorm$) was first calculated to obtain a CRP:

$$\theta inorm=\left(\frac{2*[\theta i - \min(\theta i)]}{\max(\theta i) - \min(\theta i)}\right)$$

Then, we calculated the angular velocity from the following equation:

$$\omega inorm=\left(\frac{\omega i}{\max\{|\omega i|\}}\right)$$

Finally, the phase plane was constructed by plotting the angular position versus the angular velocity. Then, the phase angle could be obtained:

$$\varnothing=tan^{-1}=\left(\frac{\omega i}{\theta i}\right) \qquad i=1, 2,\ldots, n$$

All of the above steps were repeated for the three couplings.

The phase angle of the upper joints was then subtracted from the phase angle of the lower joints, and the CRP was extracted:

$$\theta\ relative\ phase=\varnothing\ distal\ joint - \varnothing\ proximal\ joint$$

The coordination was directly derived from the CRP, and the standard deviation of the CRP was considered to be the variability of coordination.

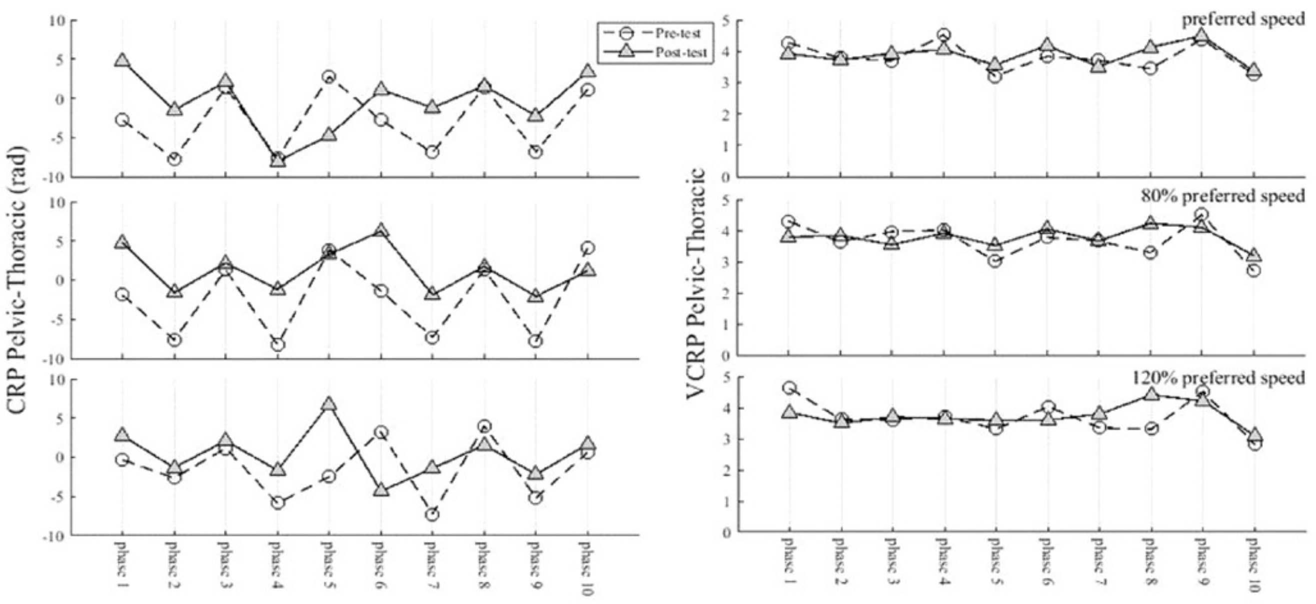

Figure 3. Coordination variability in a pelvic-thoracic couple in running gait cycle.

Statistical analysis

The statistical analyses were performed using IBM SPSS Statistics for Windows, Version 24.0 (IBM Corp., Armonk, NY, USA). A repeated-measures analysis of variance (ANOVA) and the Bonferroni test was used to determine the effects of the fatigue and speed on the kinematic data and to compare the two conditions, respectively. An alpha level of 0.05 was used to determine statistical significance in all comparisons.

Results

The repeated measures ANOVA showed that there were significant differences among three speeds in CRP in the pelvic-thoracic couple at the eighth, ninth and tenth phases. Moreover, the results showed that there were significant differences between pre-test and post-test fatigue protocol in VCRP in the pelvic-thoracic couple at the eighth, ninth and tenth phases. In the pelvic-thoracic couple, for the fifth ($F_{(1,23)}$=5.013, p=.01, η_p^2 =0.019) and sixth ($F_{(1,23)}$=3.676, p=.03, η_p^2=0.138) phases, the interaction between the time and the speed was significant in the CRP value, as well as for the sixth ($F_{(1,23)}$=0.082, p=.03, η_p^2=0.004) phase in the VCRP value (Figure 3).

In the hip-thoracic couple, the results of the ANOVA showed that the interaction between the time and speed on the CRP was not significant; nevertheless, the interaction between the time and speed on the VCRP in the first phase ($F_{(1,23)}$=3.393, p=.02, η_p^2=0.146) was significant. The effects of the time on the CRP and the VCRP were significant in the fifth, sixth, seventh and ninth phases and the eighth, ninth, and tenth phases, respectively. The speed effects on the CRP and the VCRP were significant in the sixth, seventh, eighth, ninth, and tenth phases and the second, third, fourth, ninth, and tenth phases, respectively (Figure 4).

The repeated measures ANOVA results showed that there were significant differences between pre-test and post-test fatigue protocol in CRP in the hip-pelvic couple at the first, second, third, seventh and eighth phases. The effects of the speed on the CRP and the VCRP were significant in the third and fourth phases and the first, second, third and fourth phases, respectively. For the fifth ($F_{(1,23)}$=3.188, p = .01, η_p^2 = 0.122), sixth ($F_{(1,23)}$=2.463, p=.04, η_p^2=0.970) and eighth ($F_{(1,23)}$=5.106, p=.01, η_p^2 =0.182) phases, the interaction between the time and speed was significant in the CRP value, as well as for the sixth($F_{(1,23)}$=4.856, p=.01, η_p^2=0.174) phase in the VCRP value (Figure 5).

Discussion

According to the research hypotheses, running-induced fatigue with different running speeds caused a change in the coordination variability. In addition, we observed that fatigue reduced the coordination and increased the variability in the trunk-pelvic coupling, and it decreased the variability in the trunk-hip coupling. The coordination pattern in the sagittal plane was in-phase in all three couples.

The coordination changes are a neuromuscular strategy for controlling the movement of the spine and maintaining postural stability in individuals. Increasing variability due

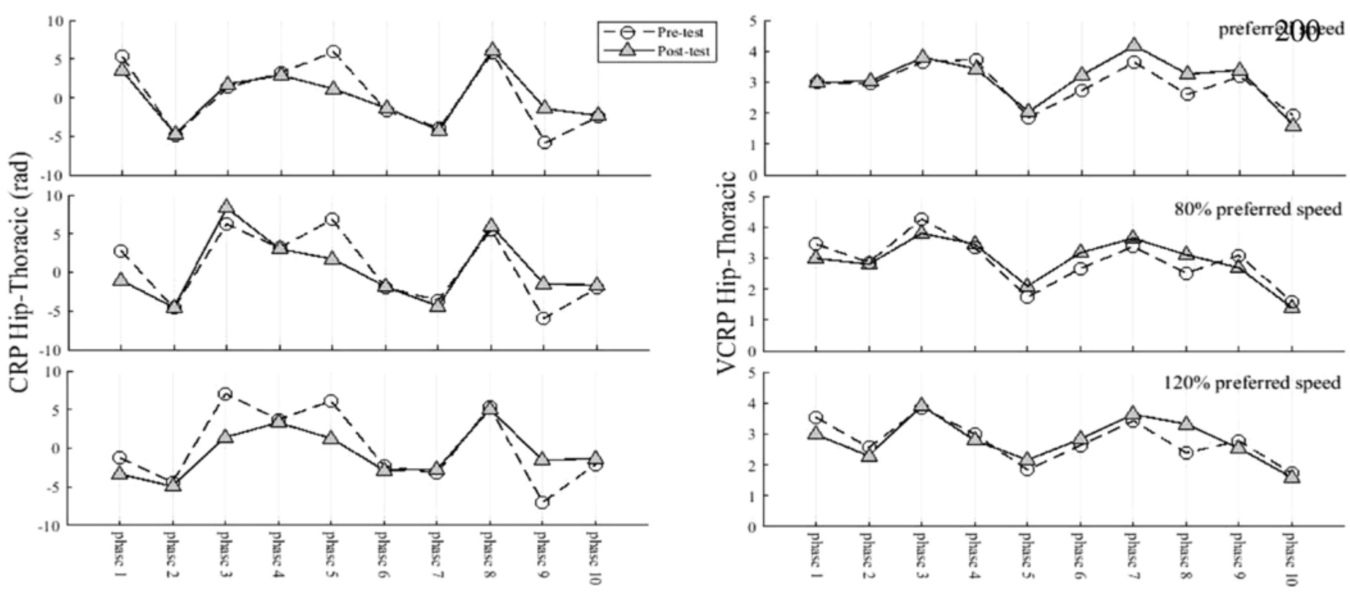

Figure 4. Coordination variability in hip- a thoracic couple in running gait cycle.

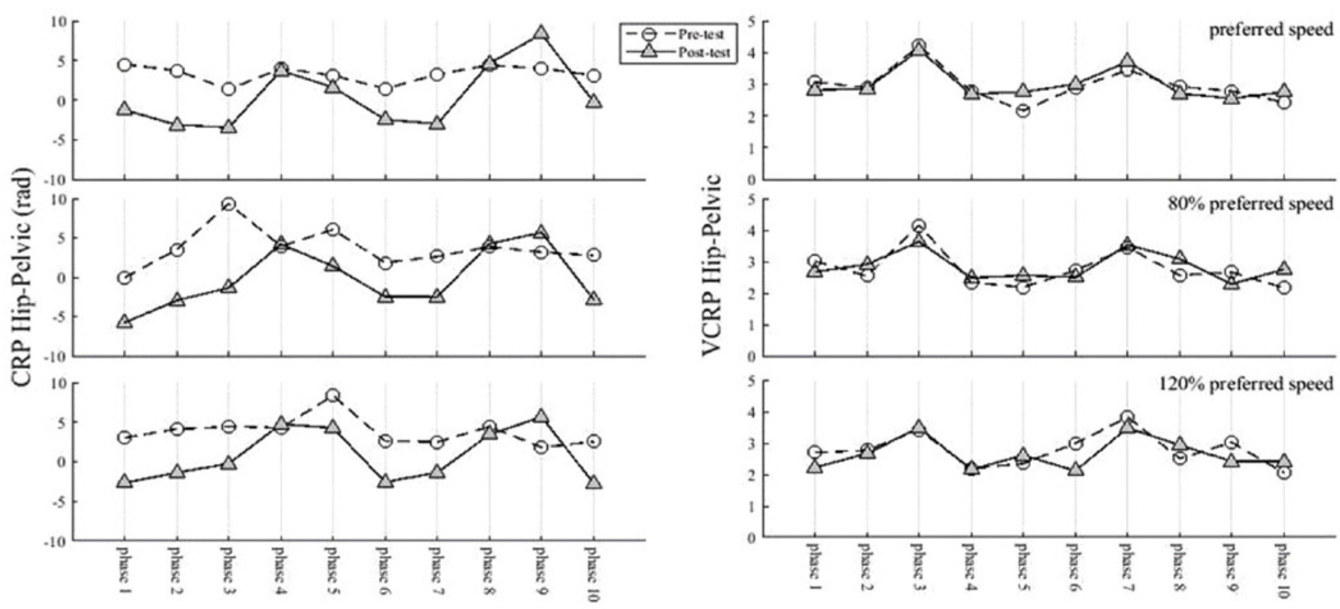

Figure 5. Coordination variability results in a hip-pelvic couple in running gait cycle.

to fatigue consequently increases the flexibility of the nervous system to control the joints and to reduce the risk of injury. Of course, biological stress rises with an increasing variability, and with neuromuscular and joint control it becomes more challenging to create an unstable motion pattern[21]. Less variability indicates a more stable motion pattern; however, decreasing variability and reduced joint mobility at high speeds leads to increased spine loading and backache during movement. The reduction in coordination caused by fatigue is noticeable when the foot touches the ground. Biomechanically, decreasing variability may lead to mechanical load increase and possibly injury in runners because of the association with an increasing or decreasing amount of tilt and the creation of asymmetrical movements[22].

It has been reported that long runs[23] and fatigue[19] lead to reduced coordination. However, Dierks et al. reported that the timing of the joints was maintained in the lower extremity during post-fatigue conditions[24]. Due to the integrated nature of running, decreasing coordination can cause stress in the tissues of the lower back and may also disturb the distal structure of the lower limbs.

At the end of the running cycle, the speed affected the coordination and variability. At higher speeds, the coordination was increased in the three couplings, while the variability was decreased in the trunk-hip and pelvic-hip couplings. As some studies have reported, decreasing variability in a specific task can indicate pathological conditions, and it seems that fatigue has created similar conditions. Farber et al. reported that the variability was increased during a frequent activity or rapid loading following fatigue[8,25]. The study by Asgari et al. showed that the variability was reduced with increasing speed, and that the relationship between the speed and variability was a negative linear relationship. At the same time, there was a positive relationship between speed and stability[26]. Seay et al.[26] reported that speeding up increased coordination, and they observed coordination patterns in phase in the sagittal plane of the trunk-pelvic coordination in people with low back pain.

Zhou et al.[11] also stated that the variability was decreased with increasing speed, and that a stability pattern was created as a result. The pelvis and hip as well as the lower extremities generally require a stable axis to perform motion and reduce damage, which is provided by the trunk[27]. Increased coordination between the spine and thighs due to increased speed is likely to increase the muscular control of the involved segments, controlling the forces entering the body when coming in contact with the ground, which helps maintain trunk stability. A reduction in variability during treadmill running at different speeds has been reported[28]. Decreasing variability, which, creates a sustainability condition, can facilitate limb movement while increasing speed. Overall, fatigue was more effective in the lower coupling (pelvis and hip).

Many changes in the hip joint's couplings occurred in the stance and early swing phases. According to the results, fatigue decreased coordination but increased with increasing speed. The variability was increased following fatigue and decreased by increasing the speed. In the couplings to which the trunk contributed, most of the changes occurred in the swing and late float phases.

In this study, the running was executed on a treadmill. The assessment of overground running with different speeds has given more insight into how fatigue can influence the coordination variability in the natural running speed. Therefore, further work is required to compare treadmill and overground running in future research on the coordination variability.

The coordination was decreased by fatigue and increased with an increasing speed. In addition, the variability was reduced by fatigue and an increasing speed. The coordination between the segments was changed following fatigue. It seems that the positioning of a limb in an open or closed kinetic chain can affect the coordination and variability. In addition, it seems that increasing the variability among our subjects could not help to maintain the motor pattern. It can be proposed that fatigue reduces joint coordination to control the limbs better and adapt to new conditions.

Ethics Approval

Prior to data collection, this study was approved by the research ethics committee of Kharazmi University.

Consent to Participate

All participants' parents were informed of the study procedures, and they signed an informed consent form obtained from a participant's parent prior to participating, in accordance with the Declaration of Helsinki.

Authors' Contributions

MK and AVG were responsible for the study conception, design, and data collection. Drafting of the article and data analysis was completed by GAK, HS, NC, and AA. They also assisted with the manuscript preparation. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

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