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Effects of Cycling-Induced Fatigue on Lower Extremity Coordination, Variability, and Proprioception in Semi-Skilled Male Cyclists

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ABSTRACT

Background: The research aims to investigate the impact of a single bout of functional fatigue on proprioception, coordination, and variability among lower extremity joints and segments in semi-skilled male cyclists. Cycling is recognized as a sport in both professional and public contexts, yet excessive activity and fatigue pose significant risks for injury during pedaling.
Methods: The present study utilized a semi-experimental design employing a pretest-posttest method. It involved 24 randomly selected semi-skilled male cyclists with a mean age of 26.32±5.72 years. Before inducing fatigue through cycling, participants underwent pretest and posttest assessments to evaluate coordination and variability among segments of the lower extremities and proprioception of the knee and ankle joints. These assessments were conducted using a three-dimensional optoelectronic system with six cameras operating at a sampling frequency of 200 Hz. This system facilitated the acquisition of kinematic data related to the lower extremities. Statistical analysis included a one-way repeated measures ANOVA test and dependent t-test to compare all variables.
Results: The significance level in all statistical tests was set at 0.05. The findings indicated a significant increase in knee and ankle proprioception ($P<0.001$) as well as coordination and variability among lower extremity segments ($P<0.001$).
Conclusion: The presence of heightened proprioceptive errors in the joints, decreased coordination, and increased variability between segments indicates their association with sports injuries. Consequently, prolonged cycling and fatigue may contribute to an elevated prevalence and diversity of sports injuries among semi-skilled cyclists.

Introduction

Cycling is widely recognized as a popular activity in professional and amateur sports. However, due to the repetitive nature and duration of the pedaling cycle, there is an increased risk of pedaling-related injuries, primarily caused by overexertion and fatigue [1-3]. Notably, the neck (48%) and knee (47%) are reported to have the highest prevalence of such injuries [2].

Fatigue can disrupt the body's movement and nervous systems, affecting each component of the neuromuscular and musculoskeletal systems responsible for controlling posture. Consequently, such disruptions may lead to various pedaling-related injuries [2, 3]. Moreover, various factors, such as changes in pedaling rate, body position and orientation, saddle height, and muscle fatigue, can influence pedaling biomechanics. These factors may ultimately result in alterations in the coordination and variability of joints or segments in the lower limbs [3, 4].

Scientific research underscores the importance of

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coordination among joints or segments during movement for performance enhancement and injury prevention. The timing and coordination of inter-segmental and joint movements are crucial for understanding the etiology of lower limb injuries. It is believed that any inconsistency in joint coupling or changes in coordination variability may predispose individuals to injury [5].

The coordination and variability of joint or segmental coordination indicate the musculoskeletal system's degree of freedom to select and execute tasks, thereby influencing performance and injury risk. Additionally, analyzing the variability and stability of kinematic parameters during pedaling not only aids in accurately describing muscle training programs but also offers insights into mitigating injury risks associated with excessive pedaling activity [1-3].

Previous research examining the relationship between coordination and coordination variability and overuse injuries suggests that alterations in movement variability may heighten injury risk [6]. Given the endurance nature of cycling, studying the coordination pattern and variability of lower limb segments can shed light on the system's degrees of freedom for achieving optimal performance. Identifying risk factors through such analysis can facilitate the development of appropriate training and performance strategies to reduce injury occurrence in athletes and enhance performance through targeted interventions, such as adjustments in training load [1-4].

Proprioception encompasses a broad and intricate spectrum, encompassing components such as joint position, movement, speed, and force application. It plays a pivotal role in shaping the pattern and variability of coordination. Proprioceptive feedback informs the programming of the neuromuscular system for movement control, including the contraction of relevant muscles, thereby contributing to dynamic joint stability. Any factor compromising proprioceptive feedback can lead to mechanical instability, rendering the joint vulnerable to minor trauma. Furthermore, chronic ligament damage in joints can impair proprioception [7, 8].

Joint position sense specifically refers to the ability to perceive the body's position in space without relying on visual or auditory cues. Both central and peripheral mechanisms regulate it. Sensory signals are transmitted to the central nervous system via afferent pathways by stimulating various receptors in muscles, tendons, joints, and skin, facilitating the perception of joint status [9, 10].

The majority of previous research has focused on investigating the coordination and variability of lower limb coordination during activities such as running [11-13], walking [14, 15], and comparing walking and running on a treadmill [16]. However, to date, no studies have explored the effects of fatigue on the coordination and variability of lower body coordination in cyclists.

DeMarchis et al. [17] studied the inter-individual variability of pedaling forces and muscle coordination in untrained individuals. Additionally, Daneshvar et al. [18] investigated the impact of general fatigue on the degree of coordination and variability between trunk area joints among elite rowers. They reported increased trunk area joint variability as a potential risk factor for professional rowers' performance, which could lead to various injuries and contribute to back pain among athletes in this sport.

In conclusion, given the repetitive nature of pedaling and cycling sports, analyzing pedaling kinematics following functional fatigue can provide insights into the underlying causes of chronic and prevalent injuries in these athletes. Moreover, investigating segments' coordination and variability patterns can elucidate the degrees of freedom required for optimal system performance.

Therefore, the present study addresses the following questions: (a) Does functional fatigue influence the proprioception of lower limb joints? (b) Does functional fatigue impact the coordination pattern among lower limb segments?

Methods

The present research design employed a semi-experimental approach utilizing a pretest-posttest method, which is practical and well-suited to achieve the study's objectives and application. A total of 24 male cyclists from Kerman city were selected as participants. Inclusion criteria required participants to have refrained from engaging in specific physical activities for 48 hours before the test, and they should have had no history of surgery, neuromuscular disorders, lower limb injuries, or structural or functional abnormalities.

Before participation, participants were fully informed about the research procedure and provided written consent to take part in the experiment. They also completed a physical health questionnaire. The current research project received ethical approval from Shahid Bahonr University of Kerman, with the ethics code IR.UK.REC.1401.004, ensuring compliance with ethical principles governing the test.

Figure 1 illustrates the methodology employed in the study. A pre-test was initially conducted, followed by a post-test administered after functional fatigue was induced in the cyclists. The experimental conditions remained consistent for all subjects before and after fatigue induction.

Before commencing the experiment, all subjects received instructions on the research design, methods for measuring kinematic parameters, and proper pedaling techniques on an ergometer. To assess joint proprioception and inter-segment coordination, fourteen markers were bilaterally positioned along the lower limb, including the sacrum, mid-thigh, lateral condyle of the knee, middle of the shank, lateral malleoli of the ankle, and fifth metatarsal of the foot.

Subjects began with a warm-up phase, pedaling at less than 150 watts for five minutes. The initial phase of the pre-test involved evaluating the subjects' perception of knee joint and superior ankle joint positions. The final angle was determined based on the subject's smallest difference between the initial angle and three repetitions. Each time, photographs of the subject's knee and ankle were taken using the motion system, and the Cortex software was used to identify the best angle with the smallest angle difference from the initial angle, deemed the final result.

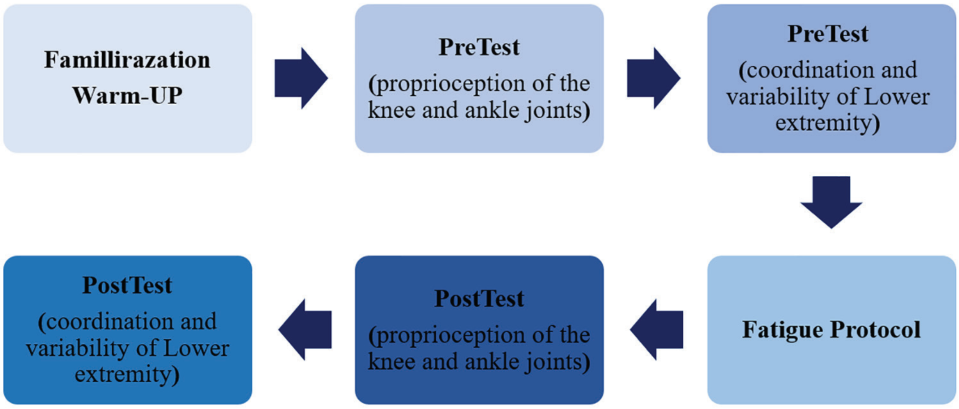

Figure 1: Study time line overview of events.

The absolute error was calculated by subtracting the value of the tested angle from the value of the reconstructed or response angle in each repetition of the angle test. Target angles for the knee joint included 15, 30, and 60 degrees, while for the ankle joint, they were 20 degrees of plantar flexion and 10 degrees of dorsiflexion [9, 10].

During the experiment, subjects pedaled an exercise bicycle at the desired speed for 30 seconds while being recorded by the motion system to gather data on coordination patterns and inter-joint coordination variability. To ensure optimal conditions, the bicycle saddle height was individually adjusted for each subject based on their sitting height. It was ensured that at the lowest point of the pedal stroke, the angle of knee flexion reached 150 degrees.

The subsequent step involved implementing the fatigue protocol, designed to induce cycling-induced fatigue using a modified 12-step protocol based on the study by Bonacci et al. [19]. Each subject pedaled with a load equivalent to one watt per kilogram of body mass.

The protocol concluded when the pedaling speed dropped below 90 to 100 revolutions per minute. To ensure subjects reached fatigue after each stage, the Rating of Perceived Exertion (RPE) index (6–20 Borg) was employed, where a score of 6 indicated no fatigue and scores of 17–20 indicated significant fatigue. If more than 17 cases of high fatigue (17–20 on the Borg scale) were reported at the end of each stage, the fatigue protocol was terminated [3]. Following the fatigue protocol, the post-tests were repeated in the same sequence as the pre-tests without any intervening rest period.

Kinematic data were captured using a 6-camera, 3D optoelectronic motion analysis system (Eagle; Motion Analysis Corp., Santa Rosa, CA, USA) with a sampling frequency of 200 Hz. The cameras were strategically positioned to cover the trial area, placed at a height of 1.5 meters in a semicircular arrangement. Cortex software recorded the xyz-coordinates of the local coordinate system origin relative to the global laboratory coordinate system. The Cartesian local coordinate system conventions were defined as follows: the x-axis represented the medial-lateral axis, the y-axis represented the anterior-posterior axis, and the z-axis represented the superior-inferior axis.

Coordinate data from the 14 bony anatomical landmarks were digitized and pre-processed using a fourth-order low-pass filter with a Butterworth cut-off frequency of 8 Hz. Subsequently, the raw angular position data were imported into MATLAB for analysis of coordination patterns and inter-segment coordination variability. Initially, the angular velocity of each joint was calculated using the following equation:

$$\omega i = \frac{(\theta) - \theta(i-1)}{t(i) - t(i-1)}$$

Furthermore, the displacement and angular velocity were normalized within the range of 1 to 1 to calculate the phase ratio of each joint in each frame, employing the following equations:

$$\theta inorm = \frac{2 \times [\theta i - \min(\theta i)]}{\max(\theta i) - \min(\theta i)x}$$

Plotting the angular velocity against the displacement function yielded a complex, fuzzy angular curve. Additionally, the phase angle value was determined by plotting the phase angle and calculating the slope of each point on the curve [16]:

$\phi(i)=\tan\}^{1-}\frac{\omega i}{\theta i}\}$

i=1,2,3……...n

Finally, the continuous relative phase (CRP) angle was computed to assess the coupling of two oscillators, utilizing the following formula. To calculate the CRP, the phase angle of the proximal limb was subtracted from the phase angle of the distal limb. In this equation, A represents the phase angle of oscillator A, and B represents the phase angle of oscillator B:

CRP(i)=ØA(i)-ØB(i)

Additionally, coordination was directly computed from CRP. In contrast, coordination variability was calculated using the standard deviation of CRP for pairs of thigh-leg, thigh-ankle, and leg-ankle joints across various movement planes (sagittal, frontal, and horizontal). These values for each variable corresponded to the angle difference between the distal and proximal joints.

The Shapiro-Wilk test was utilized to assess the normality of the data distribution using SPSS. Additionally, an ANOVA test with one-way repeated measurements and dependent t-tests was conducted to compare the effects of fatigue on joint proprioception, coordination, and variability between lower limbs. All statistical analyses adopted a significance level of 0.05.

Table 1: Dependent variables of joint proprioception before and after fatigue protocol.

Variables		Mean±SD		P value
Joint	Angle (deg)	Pre-Test	Post-Test	
Knee	15 (Flexion)	15.86±2.82	25.17±8.79	0.001*
	30 (Flexion)	30.05±3.28	39.89±5.76	0.001*
	60 (Flexion)	60.91±4.10	70.61±6.79	0.001*
Ankle	20 (Plantar Flexion)	18.52±4.03	27.12±4.51	0.001*
	10 (Dorsi Flexion)	13.40±5.42	19.20±6.27	0.001*

*Level of Significant

Table 2: Dependent variables of lower limb coordination and variability before and after fatigue protocol.

Variables	Mean±SD		P value
	Pre-Test	Post-Test	
Coordination of Thigh-Shank	177.14±1.34	121.28±1.99	0.001*
Variability of Thigh-Shank	194.67±1.47	132.07±2.16	0.001*
Coordination of Thigh-Foot	71.29±1.79	26.29±1.81	0.001*
Variability of Thigh-Foot	86.26±2.16	32.07±2.35	0.001*
Coordination of Shank-Foot	27.02±1.14	-18.57±2.07	0.001*
Variability of Shank-Foot	30.53±1.28	-14.67±2.24	0.001*

*Level of Significant

Results

As depicted in Table 1, significant differences were observed in the proprioception of knee flexion between the pre-test (15.86±2.82, 30.05±3.28, and 60.91±4.10) and post-test (25.17±8.79, 39.89±5.76, and 70.61±6.79) for angles of 15, 30, and 60 degrees, respectively (P<0.001). Additionally, significant differences were noted in the proprioception of the ankle joint between the pre-test (18.52±4.03 and 27.12±4.51) and post-test (13.40±5.42 and 19.20±6.27) for 20 degrees of plantar flexion and 10 degrees of dorsiflexion, respectively (P<0.001).

As presented in Table 2, significant differences were observed in the coordination and variability of thigh-shank between the pre-test (177.14±1.34 and 194.67±1.47) and post-test (121.28±1.99 and 132.07±2.16), respectively (P<0.001). Similarly, significant differences were noted in the coordination and variability of thigh-foot between the pre-test (71.29±1.79 and 26.29±1.81) and post-test (26.29±1.81 and 32.07±2.35), respectively (P<0.001). Furthermore, significant differences were observed in the coordination and variability of shank-foot between the pre-test (27.02±1.14 and 30.53±1.28) and post-test (-18.57±2.07 and -14.67±2.24), respectively (P<0.001).

Discussion

This study aimed to investigate the impact of functional fatigue on the proprioceptive abilities of the knee and ankle joints, as well as the coordination and variability among lower limb segments (thigh-leg, thigh-ankle, and leg-ankle) in semi-skilled cyclists. The findings revealed that fatigue led to an increase in reconstruction error and a reduction in knee joint position sense across various angles (15, 30, and 60 degrees) and ankle joint positions at 20 degrees of plantarflexion and 10 degrees of dorsiflexion. While no prior studies specifically examine fatigue's effect on knee joint proprioception in cyclists, these results align with existing literature suggesting that muscle fatigue can elevate reconstruction errors in target angle perception for hip and ankle joints [9, 10, 20, 21].

Muscle fatigue impacts both the processes of nerve-muscle connection and the involuntary activation of muscles and their contraction mechanisms. Fatigue leads to a rerouting of sensory messengers to the alpha motor neuron, impeding the joint's ability to fulfill its protective function aided by the muscle. As a result of decreased performance in metabolic and neuromuscular systems, sustained muscle contraction becomes challenging during episodes of muscle fatigue [9, 10, 20, 21]. It is plausible that the stimulation of deep sensory receptors within the Golgi tendon organ diminishes due to heightened knee joint reconstruction error resulting from fatigue and reduced muscle contraction. Another contributing factor to decreased knee joint proprioceptiveness may stem from the escalating influence of gravity on the limb with increasing movement angles. Consequently, when muscles fatigue, the decline in muscle strength and the impairment of mechanical receptors in transmitting messages to the central nervous system, alongside diminished efferent messages, curtails the excitability of motor units supplying the muscles, thereby diminishing organ control [9, 10, 20].

A functional fatigue protocol session induces a significant alteration in coordination and variability among thigh-leg, thigh-ankle, and leg-ankle, as per the findings of this study. Coordination variability serves as an indicator of stability, risk of falling, and likelihood of injury. Heightened variability correlates with increased instability and the potential for falls. In this context, Berger et al. [22] investigated the impact of fatigue induced by single-leg pedaling on an ergometer to the point of stagnation on body stability along the anterior-posterior and internal-external axes, revealing that such fatigue leads to instability along the internal-external axis. Additionally, in a study examining the effect of fatigue on lower limb variability, Ferber and Pohl [23] concluded that fatigue influences coordination variability crucial for repetitive tasks. Elevated variability in the lower extremities heightens the risk of overuse injuries during repetitive activities or rapid loading in the presence of fatigue.

In the thigh-leg coupling, the results indicate an initial phase of opposite movement direction; when transitioning out of phase, thigh movement predominates during the first half of the cycle, whereas during in-phase movement, leg movement takes precedence, reverting to the initial level by the cycle's end. Within this coupling, a significant increase in thigh range of motion due to fatigue-induced compensatory movements elevates pressure on the thigh segment, laying the groundwork for potential injury over time. Similarly, in the thigh-ankle coupling, thigh movement dominates during the initial quarter of pedaling, followed by ankle movement dominance in the second and third quarters, ultimately transitioning out of phase. Fatigue's effect on thigh-ankle coordination and variability prompts compensatory movements to expand thigh range of motion, potentially leading to injuries such as groin pain, patellar chondromalacia, patellar and quadriceps tendinitis, and stress on the Achilles tendon with prolonged and excessive use. Finally, in the leg-ankle coupling, movement initiates from an out-of-phase position, with leg movement dominating the first half of the cycle. During the second half, termed the rest phase, ankle movement prevails, and the joint returns to its initial state.

In general, the analysis of coordination and variability variables provides crucial data on changes in movement strategies. Fatigue, by altering the biomechanical properties of movement, induces new compensatory strategies at the neuromuscular level, developing novel coordination patterns [3, 8, 22]. Numerous studies indicate that altered coordination patterns in the joints can cause muscle damage, which further disrupts the coordination of segments and joints of the lower limbs during pedaling—a critical factor in sports performance [11, 18, 22, 23]. Previous research defines coordination as the process by which components of a motor system cooperate to enhance interaction with other components [4, 5, 18, 22, 23]. Effective coordination between joints and muscles ensures the proper application and distribution of force to the lower extremity joints. Moreover, the variability of coordination refers to the number of changes in the coordination patterns of athletes, highlighting the adaptability of movement pattern production systems. Inter-joint or inter-organ coordination facilitates neuromuscular function through deep and combined receptors, promoting symmetrical intra-organ and inter-organ coordination [2, 3, 12, 18].

Conclusion

In general, the findings of this research indicate that fatigue significantly affects the proprioception of the knee and ankle joints, as well as the coordination and variability of the lower extremity segments during cycling. These effects suggest that fatigue can lead to increased proprioceptive errors and altered movement patterns in cyclists. Moreover, heightened proprioceptive errors in the joints, decreased coordination, and increased variability between segments highlight their association with sports injuries. Consequently, prolonged cycling and fatigue may contribute to an elevated prevalence and diversity of sports injuries among semi-skilled cyclists.

It is essential to prioritize proprioception, coordination, and variability in training and exercise programs to address these concerns and mitigate injury risks in cycling athletes. Specifically, strategies aimed at reducing proprioceptive errors and variability while enhancing coordination should be incorporated. By adopting an approach that emphasizes minimizing proprioceptive errors and variability while maximizing coordination, the potential for sports injuries in cycling athletes can be reduced.

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