The Effect of One-Stage Global Fatigue on Coordination and Variability of Joints and Electrical Activity of Selected Lower-Limb Muscles of Elite Rowers: A Trauma Approach

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Submitted: 2020-05-14; **Accepted**: 2020-08-26; **Doi:** https://doi.org/10.22037/jcpr.v5i4.32907

Abstract

Introduction: Muscle fatigue due to exhaustive exercise is a common phenomenon that occurs during exercises and causes impaired motor function. The aim of the present study was to investigate the effect of one-stage global fatigue on the coordination and variability of joints and electrical activity of selected lower-limb muscles of elite rowers. **Methods and Materials:** A total of 14 rowers of the national men's rowing team participated in this quasi-experimental study. A rowing ergometer was used to induce global fatigue due to exhausting exercise. First, to measure mean power (MP), the subjects performed the 2000-m ergometer test. Fatigue protocol was performed after one week, (three 2-minute continuous tests with 60%, 90%, and 120% of MP). Electrical data of selected muscles were measured by electromyography and kinematic data were measured by IMU in 15 consecutive strokes at the beginning and end of the fatigue protocol. Shapiro-Wilk test was used to determine the normality of data distribution and dependent t-test was utilized to compare the dependent variables. P-value ≤0.05 was considered as the significant level in all tests. **Results**: The results showed a significant increase in the mean level of activity of biceps femoris, tibialis anterior, gastrocnemius medialis, and rectus femoris between pre-test and post-test ($P \leq 0.05$). The results also indicated a significant decrease in the coordination of ankle-knee and ankle-thigh joints in the sagittal plane and a significant increase in variability between ankle-knee joints in the sagittal plane and ankle-thigh joints in the sagittal and horizontal planes ($P<0.05$). **Conclusion**: Overall, fatigue seems to have a large effect on the mean activity and maximum activity of the muscles of the lower limbs in the sagittal and horizontal planes. Increased variability of the lower-limb joints following fatigue may be due to a decrease in strength or flexibility of the muscles in this area, which can adversely affect the performance of professional rowers and increase the risk of injury due to overactive musculoskeletal system.

Keywords: Electromyography; Fatigue, Joint coordination; Lower limb, Rowing; Variability

Please cite this paper as: Daneshvar A, Sadeghi H, Borhani Kakhki Z, Taghva M. The Effect of One-Stage Global Fatigue on Coordination and Variability of Joints and Electrical Activity of Selected Lower-Limb Muscles of Elite Rowers: A Trauma Approach. J Clin Physio Res. 2020; 5(4): e22. Doi: https://doi.org/10.22037/jcpr.v5i4.32907

Introduction

Muscle fatigue due to exhausting exercise is a common phenomenon that occurs during exercises and causes impaired motor function. Fatigue is defined as an unknown phenomenon leading to a decrease in force production capacity regardless of the action performed. Fatigue is deemed to be related to disruption of the chain of events from the central nervous system to the muscle fibers (1). Peripheral fatigue refers to exercise-related disorders that occur at the neuromuscular junction in the distal region and can be measured by reducing the force/torque produced by a muscle in response to cutaneous stimulation (2). Changes in muscle function is a possible strategy to counter the effects of fatigue (3). Most exercise injuries occur at the end of activities as well as competitions, indicating that strenuous exercise and fatigue may affect the dynamic stability of the knee joint and leads to a decrease in motor control function and increase in weakness of the knee joint (4).

Rowing is an activity with approximately 70 repetitive movements per minute. Therefore, the risk of injury increases with increasing volume and intensity of exercises (5). Considering the fact that many parts of the body are involved in rowing and the muscles of the upper and lower limbs are directly involved in the force production process, thus, compared to other rotational tasks such as cycling or walking, rowing used more compensatory strategies (changes in the distribution of muscle activity) between the upper and lower limbs during fatigue (6). The main role of extensor muscle of knee and ankle joints is emphasized in the force production during rowing stroke (6). It is also correct technique of stroke and coordination or rhythm of movement that rowers' performance can be optimal to achieve maximum speed (7).

There are very few studies that combine kinesiology and kinematic analysis in rowing related to mechanical efficiency (such as strength training exercises) (8). The rowing efficiency can be affected by angular corrections of the knee joint, which is possible by changing the height of the feet on the boat (pedal or footrest) during rowing. This claim was confirmed in a study carried out on 10 rowers. That study investigated acceleration and fatigue due to 3 minutes and 30 seconds of rowing at three different pedal heights and better results were obtained in the highest pedal position without change in speed, thereby causing increased efficiency by reducing fatigue (9). Electromyographic studies help trainers to technically teach excellent athletes so that they can focus muscle contraction more effectively on large muscle groups (10). Besides, observing the relationship between the combination of movement mechanics and fatigue (11) with the physiological characteristics of rowers can reveal differences in the kinematic pattern during training and improve performance using biofeedback (12). Electromyographic studies have also shown that ergometer rowing increases the risk of injury to the pelvis, spine, and knee. In addition, the results of neuromuscular activity assessment showed differences between different levels of competition, age and sex. Knee injuries significantly occur more frequently than other limbs in rowing (13). Hussey *et al.* (14) also found that most rowing injuries occurs in the knee (29%), low back (22%), ankle and upper limb (14%), and chest (9%).

Considering being new rowing of discipline in Iran, importance of fatigue in rowing, its significant role on the rowers' performance, and increasing the risk of injury, therefore, the aim of the present study was to investigate the effect of one-stage global fatigue of selected kinematic variables and electrical muscle activity of the lower-limb muscles (biceps femoris, tibialis anterior, gastrocnemius medialis, and rectus femoris) of elite rowers with a trauma approach.

Methods and Materials

Subjects: A total of 14 adult males in the camp of the national rowing team, Sculling sport (with mean±SD of age: 20.5±1.8 years, height: 1.85±0.07 m, mass: 85.70±6.5 kg) participated in this quasi-experimental study. Inclusion criteria included athletes who had the best record in 2019 based on the record of national team coaches, and top individuals whose names were announced by the rowing federation, attending the training camp of national teams. Rowers performed regular training under the supervision of national team coaches for 10 sessions per week on average (in the morning and afternoon) for at least 90 minutes per session. The research process was explained to the individuals. Prior to the laboratory tests, informed consent form was obtained from all athletes and a questionnaire including demographic characteristics (sex, age, weight) was completed by the participants. Ethical principles were observed during the tests performed in the medical school of Tehran Islamic Azad University of Medical Sciences and the research project was approved with the ethics ID (IR.IAU.TMU.REC.1399.230).

Test procedure: The activity of selected muscles was recorded using a 16-channel electromyographic device with a sampling frequency of 1000 Hz. Before installing the electrodes, the necessary measures were taken to prepare skin-electrode surface. Electrodes were placed on the right side of the body. European concerted action SENIAM was used to determine the location of electrode placement (tibialis anterior, gastrocnemius medialis, rectus femoris, and biceps femoris). In order to record the kinematic data (in sagittal, frontal and horizontal planes), myoMOTION analysis system made by Noraxon, United States was used and sensors were placed in the middle area of the subjects' thighs, legs, feet according to the instructions. The sampling rate of the myoMOTION system was set to 200 Hz.

Mean power (MP) should be used to implement the fatigue protocol. To measure MP, the subjects performed a 2000 m test on the ergometer (concept II) and ergometer monitor displayed time, calories burned, distance, exercise pattern, athlete's heart rate, mean athletic power, and number of strokes per minutes (spm) (10). One week later, each subject first performed global warm-up on a rowing ergometer for 5 minutes with the desired rhythm in each visit. Then, the fatigue protocol, which consists of three 2-minute tests with a constant load at 60%, 90%, and 120% of MP, was performed continuously and without rest. Athletes then continued the test until exhaustion with a constant load of their MP and a constant rowing stroke rate of 28-32spm. Output

Figure 1. Execution of rowing protocol

and stroke frequencies were displayed on a monitor in front of them. The test continued until exhaustion, or until reaching a 10% reduction in output power of rowing for more than 10-second rowing (10). Figure 1 shows the rowing protocol on a rowing ergometer.

Data processing

To process the data, first the raw electromyographic data of muscle activity in 15 consecutive strokes at the beginning and end of the fatigue protocol (7±3% of total time at the beginning and 93±2% of total time at the end of the fatigue protocol) was filtered using a 10-500 Hz bandpass filter (15). Then, to normalize the data in the domain, all values were divided by the maximum activity of the same muscle in maximum voluntary isometric contraction test (MVICT). The mean normalized activity of each muscle was calculated by the method of integral mean values and the maximum normalized activity by finding the maximum value was found. The median frequency of each muscle in this time period was also calculated using fast fourior transform (FFT) method with a frame width of 128 Hz. Finally, the dependent variables including mean normalized activity, maximum normalized activity, and median frequency were extracted for each pretest or posttest.

Noise reduction was performed using a fourth-order Butterworth low-pass filter with a cut-off frequency of 6 Hz on kinematic data of 15 consecutive strokes at the beginning and end of the fatigue protocol to analyze the lower-limb coordination and variability recorded by myoMOTION (16). All data processing were performed in MATLAB software. The data output of the ergometer was presented in the form of angular position of the joints that after being extracted from the device software, angular velocity and displacement were calculated in MATLAB software, and were then used to calculate coordination and variability. To make a time series for the above-mentioned calculations, the data of 15 consecutive strokes at the beginning and end of the fatigue protocol were selected from the strokes of each test. Then, angular displacement (knee-thigh, ankle-knee, and ankle-thigh) was separated during rowing in three planes (18).

The following equation was used to calculate the angular velocity:

Equation 1 $\theta i norm = \left(\frac{2*[\theta i - \min(\theta i)]}{\max(\theta i) - \min(\theta i)}\right)$

Also, to calculate the phase diagram of each joint, first the angular displacement and velocity in the range 1 to -1 were normalized through the following equations:

Equation 2 $\omega i norm = \left(\frac{\omega i}{\max\{I\ \omega i\ I\}}\right)$

Equation 3 $\omega i norm = \left(\frac{\omega i}{\max\{I\ \omega i\ I\}}\right)$

After plotting the angular velocity in the displacement function, the fuzzy angular curve of the joint was obtained. After plotting the phase angle and calculating the slope of each point of the angular velocity-angular position curve, the fuzzy angle value was obtained.

Equation 4 $i=1,2,\ldots,n \emptyset = tan^{-1}\left(\frac{\omega i}{\theta i}\right)$

The following equation was used to obtain a Continuous relative phase (CRP).

Equation 5 $CRP\ (i) = \phi_A(i) - \phi_B(i)$

Shapiro-Wilk test was used to evaluate the normality of data distribution. If the data were normal, dependent t-test was utilized to compare the effects of global fatigue (15 consecutive strokes at the beginning and end of the fatigue protocol) on coordination and variability between joints. Also, considering the non-normality of the data distribution, Wilcoxon test was utilized to compare the degree of variability between knee-thigh joints in the sagittal plane between pre-test and post-test (15 consecutive strokes at the beginning and end of the fatigue protocol). *P*-value≤0.05 was considered as the significance level in all statistical tests. Cohen's d method was used to investigate the effect of fatigue on coordination and variability (17).

Table 1. Mean and standard deviation of electromyographic variables before and after implementingglobal fatigue protocol (15 consecutive strokes at the beginning and end of the fatigue protocol) and dependent t-test results

Variable	Muscle	Pre-test (15 consecutivepre-strokes)	Post-test (15 consecutive post-strokes)	t-value	*P*-value	Effect size
Mean normalized activity	Rectus femoris	0.270 (0.067)	0.307 (0.086)	-2.011	0.066	0.484
	Biceps femoris	0.576 (0.129)	0.662 (0.146)	-4.044	0.001*	0.625
	Tibialis anterior	0.234 (0.064)	0.302 (0.096)	-3.635	0.003*	0.850
	Medialis gastrocnemius	0.438 (0.088)	0.498 (0.103)	-3.384	0.005*	0.628
Maximum normalized activity	Rectus femoris	0.548 (0.135)	0.631 (0.158)	-3.37	0.005*	0.56
	Biceps femoris	1.174 (0.245)	1.311 (0.291)	-2.18	0.048*	0.51
	Tibialis anterior	0.494 (0.111)	0.562 (0.137)	-3.9	0.002*	0.54
	Medialis gastrocnemius	1.036 (0.262)	1.196 (0.310)	-2.94	0.011*	0.55
Median muscle frequency	Rectus femoris	85.59 (11.31)	85.11 (14.97)	0.88	0.39	0.34
	Biceps femoris	95.36 (13.58)	88.12 (11.97)	-0.7	0.49	0.27
	Tibialis anterior	107.88 (18.52)	99.31 (15.39)	-1.17	0.26	0.24
	Medialis gastrocnemius	121.32 (19.88)	114.26 (21.08)	1.24	0.23	0.34

** Significance level≤0.05*

Results

Table 1 shows mean and standard deviation of muscle electromyographic variables (tibialis anterior, gastrocnemius medialis, rectus femoris, and biceps femoris) before and after the application of global fatigue protocol. All electromyographic data were normalized based on maximum voluntary activity. The results showed a significant increase between pre-test and post-test in terms of the mean activity of biceps femoris (P=0.001), tibialis anterior (P=0.003), gastrocnemius medialis (P=0.005), and also at the maximum activity of rectus femoris (P=0.005), biceps femoris (P=0.048), tibialis anterior (P=0.002), and gastrocnemius medialis (P=0.011) (P≤0.05).

Table 2 demonstrates mean and standard deviation of coordination and variability of thigh, knee and ankle joints in three planes before and after implementing the global fatigue protocol. The results of dependent t-test showed a significant decrease in the coordination of ankle-knee joints in the sagittal plane (P=0.034) and ankle-thigh joints in the sagittal plane (P=0.027) between pre-test and post-test. Also, the effect of global fatigue was greater on the coordination of ankle-knee joints in the sagittal plane (0.900) and ankle-thigh joints in the sagittal plane (0.826), respectively. The results of dependent t-test also showed a significant increase in the variability of ankle-knee joints in the sagittal plane (P=0.026), ankle-thigh joints in the sagittal plane (P=0.003), and ankle-thigh joints in the horizontal plane (P=0.046) between pre-test and post-test. Also, the effect of global fatigue was higher on the variability of ankle-thigh joints in the sagittal plane (P=0.942), ankle-knee joints in the sagittal plane (P=0.867), and ankle-thigh joints in the horizontal plane (0.592).

Discussion

The aim of the present study was to investigate the effect of one-stage global fatigue on selected kinematic variables and electrical activity of the lower-limb muscles (tibialis anterior, gastrocnemius medialis, rectus femoris, and biceps femoris) of elite rowers with a trauma approach. The results showed that mean and maximum activity of selected muscles of elite rowers significantly increased after one-stage global fatigue protocol (P≤0.05). These results are consistent with the results of Turpin *et al.* (10) who also showed the muscle activity level did not change or increase due to post-rowing fatigue (2). In contrast, the results of the present study are inconsistent with the results of the studies of Ferber & Pohl and Hajilou *et a*l. (18, 19). According to the literature review, the reasons for this discrepancy in the results may include subjects with different characteristics (such as sex, level of activity, different age, *etc.*) (20) and use of different methods to create the fatigue protocol (2, 21). On the other hand, it should be noted that different analysis methods can change the amount of myoelectric variables in muscles (especially mean and maximum activity variables) (15).

Also, one-stage global fatigue protocol did not significantly change the median frequency of tibialis anterior, gastrocnemius medialis, rectus femoris, and biceps femoris of elite rowers (P≤0.05). These results are consistent with the results of studies by Pinsiro *et al.* (22)as well as the statements made by Guyton & Hall and Robertson *et al.* (23, 24), all of which showed a decrease in the median frequency of muscles during fatigue. The results of the present study demonstrated the effectiveness of the protocol used to induce fatigue in selected lower-limb muscles. Overall, the implementation of the fatigue

Table 2. Results of dependent t-test used to compare the mean (standard deviation) of coordination and variability between lower- limb joints before and after global fatigue protocol (15 consecutive strokes at the beginning and end of the fatigue protocol)

Variable	Pre-test (15 consecutive pre-strokes)	Post-test (15 consecutive post-strokes)	t-value	*P*-value	Effect size
Knee-thigh coordination in the sagittal plane	3.64 (13.60)	2.99 (16.08)	0.171	0.867	0.044
Knee-thigh variability in the sagittal plane	25.98 (8.48)	31.17 (9.07)	-1.601	0.109	0.591
Ankle-knee coordination in the sagittal plane	-11.81 (15.29)	-25.06 (14.015)	2.374	0.034*	0.900
Ankle-knee variability in the sagittal plane	38.35 (10.87)	47.26 (9.68)	-2.522	0.026*	0.867
Ankle-thigh coordination in the sagittal plane	-7.03 (13.80)	-17.88 (12.47)	2.495	0.027*	0.826
Ankle-thigh variability in the sagittal plane	36.62 (7.71)	45.37 (10.87)	-3.681	0.003*	0.942
Ankle-thigh coordination in the frontal plane	-1.94 (16.17)	-4.92 (14.14)	0.751	0.466	0.197
Ankle-thigh variability in the frontal plane	29.87 (9.84)	33.56 (9.02)	-1.300	0.216	0.391
Ankle-thigh coordination in the horizontal plane	-4.52 (14.07)	-10.35 (13.80)	1.435	0.175	0.418
Ankle-thigh variability in the horizontal plane	21.58 (6.89)	26.01 (8.07)	-2.205	0.046*	0.592

** Significance level≤ 0.05*

protocol reduces the speed of neurotransmission in afferent and efferent nervous pathways leading to the target muscle group, which reduces the median frequency of the muscle after implementing the fatigue program (21). This can be accompanied by a decrease in the muscle force production as well as a decrease in muscle performance (24, 25).

Implementing one-stage global fatigue affects the coordination between the ankle-knee joints in the sagittal plane and the ankle-thigh in the sagittal plane. The results of the present study are consistent with the results of studies by Tamura *et al.* and Mansouri *et al.* (26, 27). They showed that kinematic characteristics of the thigh and knee joints of individuals changed and the coordination between the knee-ankle joints was significantly reduced following the onset of fatigue due to long-term activity.

In contrast, the results of a one-stage global fatigue on coordination of the lower limbs of the elite rowers are inconsistent with the results of studies by Janshen *et al.* and Talti & Anderson (28, 29). The reason for the discrepancy is probably related to the study population of the two studies. Another possible reason may be the type of exercise. Professional rowers performed strength training exercises targeting large muscles of the body and great motor skills during their training period. Janshan *et al.* (29) investigated the effects of fatigue caused by 2000-meter ergometer and observed no significant difference in the range of motion of thigh, knee, and ankle joints before and after fatigue. Talti & Anderson (28) investigated effect of fatigue following rowing ergometer on coordination variability between thigh-elbow joints among rowers at the national level. They showed that this type of fatigue had no effect on coordination variability between thigh-elbow joints in these individuals. However, it should be noted that sample size of their study consisted of only 3 rowers (two men and one woman), which is not enough to provide accurate results. As a result, the difference in sample size may be one of the reasons for the inconsistency in the results of that study compared to those of the present study. Also, the type of variables evaluated in the studies can be another reason for the existing discrepancies. Considering the importance of studying factors such as the angular velocity of the thigh and knee joints in identifying fatigue-related changes (26), there is a need for future studies to identify the effects of fatigue on other kinematic aspects of movement.

Overall, fatigue has a greater effect on the distal portion of the limbs that are responsible for fine motor movements. It is due to allocating a large part of the motor and premotor cortex areas to them and having thinner and more vulnerable muscle groups than other areas, which as a result are more affected by fatigue or functional disorders (30). In the present study, a global fatigue protocol similar to rowing exercise was used, which engaged all parts of the body. However, parts with finer motor skills (such as the distal portion of the limbs) seem to be more affected by this type of fatigue (such as changes in coordination and variability of ankle joint than others joints). It should be noted that proximal joints have larger motor skills with a stabilizing role, while the distal joints have fine motor skills and play a more important role in a motor movement during rowing (24, 31). This may be the reason why global fatigue has a greater effect on the distal portion of the limbs. To confirm this, Turpin *et al.* (10) showed that activity level of the thigh and knee muscles of 9 rowers did not change or increase due to rowing-induced fatigue; however, activity level of gastrocnemius medialis was significantly decreased. Results of another study showed that increased variability of the lower-limb joints during walking was due to factors such as loss of strength or flexibility of muscles in this area (32).

Coordination variability level provides information regarding situation stability and the risk of injury (33). Considering the increase in variability between lower-limb joints in the present study, these results are consistent with the results of studies by Ghram *et al.* and Johnston *et al.* (21, 34). Overall, fatigue can disrupt information received from sensory sources to the brain, leading to a slower transmission of afferent and efferent messages to the musculoskeletal system and affecting the ability to effectively compensate movements and balance body (35). Besides, reduced stability of different areas of the body during fatigue can have negative effects on performance (36). On the other hand, kinematic changes such as coordination or variability in the event of fatigue can act as risk factors for various injuries, including rupture of the anterior cruciate ligament of the knee joint (26). Elevated variability also increases the likelihood of dangerous movements outside the normal range in the joints and consequently the risk of injury (37).

In the present study, other muscles of the body were not examined that could play an important role in performing rowing motor activity. Also, the amount of force exerted on the paddle before and after fatigue was not studied, which can be conducted as a suggestion for future research. On the other hand, since there have been few studies on the effects of fatigue on muscle function, it is necessary to conduct further investigations to examine this biomechanical aspect as closely as possible. Also, considering the different effects of the fatigue protocol implementation, it is suggested that the fitness trainers of rowing athletes put more emphasis on strength and endurance training of the lower limbs (especially the calf muscles) to help reduce the effects of fatigue and its delay among athletes. Athletes should also be aware of the negative effects of fatigue on their performance and take the necessary precautions when suffering from fatigue to prevent various injuries.

Conclusion

Overall, fatigue seems to have a large effect on the average activity level and maximum activity of the lower-limb muscles in the sagittal and horizontal planes. Increased variability of the lower-limb joints following fatigue may be due to a decrease in strength or flexibility of the muscles in this area, which can adversely affect the performance of professional rowers and increase the risk of injury due to the overactive musculoskeletal system.

Acknowledgement

Hereby, the authors would like to express their gratitude to members of the national rowing team and rowing federation of the Islamic Republic of Iran for their assistance in conducting this research.

Conflict of interest:

None

Funding support:

None

Authors' contributions:

All authors made substantial contributions to the conception, design, and interpretation of data.

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