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The effects of triceps surae fatigue on the torque and electromyographic parameters in athletes compared with non-athletes

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Abstract. *Background and objectives:* The common description of muscular fatigue is the failure of muscle in maintaining a target force. Even in sustained contraction, when muscle force is held at a stable level, physiological, biomechanical and electromyographic changes can occur. The purpose of this study is to compare the effects of triceps surae (TS) fatigue on the torque, falling slope and electromyographic (EMG) parameters between athletes and non-athletes.
Materials and methods: Nineteen healthy women (10 non-athletes and 9 basketball players) participated in this study. After warm-up, subjects performed one maximum voluntary contraction (MVC) followed by fatigue test including sustained maximum isometric contraction of TS until the peak torque (PT) decreased to 50% of maximum value. Immediately after the test, subjects were asked to perform one MVC; then, root mean square (RMS), median frequency (MDF), median frequency slope (MDF slope), PT, falling slope (FSL) and the amount of pain were measured.
Results: In both groups shift of MDF slope to negative values, significant decrease of MDF and RMS occurred at the end of the fatigue test ($P < 0.05$). Immediately after the test, PT decreased significantly in both groups ($P < 0.05$), however, decrease of FSL was significant in non-athletes ($P < 0.05$) but not in athletes. After fatigue test, increase in Pain was significant in both groups ($P < 0.05$). Before fatigue test, at the end, and immediately after the test, MDF of non-athletes was more than athletes. There was no significant difference in RMS between the two groups.
Conclusion: Our findings suggest that TS fatigue affects EMG parameters, PT and pain in athletes and non-athletes similarly.

Keywords: Electromyography, isometric contraction, fatigue, triceps surae, torque

1. Introduction

Fatigue is distinguished by failure of muscle to maintain a target force [1,17,20,24]. Fatigue is an ongoing process that begins as the muscle starts its contraction. Some signs of fatigue such as physiological, biomechanical and electromyographic changes occur in fatigued muscle before reaching the failure point [1].

Several mechanisms such as muscle architecture, accumulation of metabolites and alteration in muscle circulation correlate with muscular fatigue [19]. Earlier muscle fatigue may occur by occlusion of blood flow during fatiguing contraction [1]. According to the theory of linear system identification, muscle is like a transducer which relates EMG (in units of μv) to torque (in units of Nm) [22]. Surface EMG is a noninvasive method of measuring the physiological processes that occur during muscular work for quantifying fatigue process [15]. The classical methods used for providing the information by EMG are calculating the root mean square of signal (RMS), mean frequency (MNF) and median frequency (MDF) during fatigue [21]. In fatigued muscle, the EMG power spectrum shifts to

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lower frequencies [7,21]. In fact, the shift is correlated with reduction in propagation velocity of the action potential along the muscle fibers [24]. Literature shows more complicated changes of signal amplitude that occur during fatigue [4,7]. At the beginning of voluntary contraction, the EMG signal amplitude increases due to compensatory mechanism of fatigue. It means that muscles tend to maintain the same amount of force by recruiting more motor units [6]. Increase in signal amplitude, which is a reflection of changes in muscle activity, shows that there is an increase in neural drive during fatigue process [14].

It has been shown that fatigue development depends on the muscle fiber composition [13]. Muscles with a higher percentage of type II fibers are more fatigable [11].

The frequency of the EMG signal is influenced by muscle fiber types and composition. Different studies have shown a significant association between mean power frequency (MPF) and median frequency (MDF) of EMG signals, with types of muscle fibers. Muscles with higher percentage of type II fibers have higher amounts of MPF or MDF and show more predominant changes during fatigue development and force increment. Such association reflects that high threshold type II fibers which are larger and more fatigable have higher conduction velocities which can influence action potential and the distribution of the EMG power spectrum [2,3]. Muscle fiber composition also influences the development of torque or rate of force production. Muscles with a higher percentage of type II fibers show a higher rate of torque/force development [2]. With regard to the structure and fiber types, the three heads of TS muscle are different from each other. Gastrocnemius crosses the knee joint; therefore its contribution to generating plantar flexion torque is greater in knee extension. The most physiological cross-sectional area belongs to the soleus, so that plantar flexion torque is influenced by the soleus, especially in knee flexion [11]. Fiber composition is different between the heads of TS muscle [8,16]. In non-athlete healthy subjects, the proportion of type II-x fibers in gastrocnemius is significantly larger than type I. There are some differences between trained and untrained muscles. Capillary to fiber area ratio increases with prolonged sub maximal training and consequently influences muscle blood flow and oxygen uptake [8] during muscle contraction. Athletes have more flexibility than non-athletes [23] and musculo-articular stiffness has an important role in motor control [18]. Until now there has been no information about the possible different effects of fatigue on the biomechanical and electromyographic parameters in athletes and non-athletes. The purpose of this study is to determine the probable different effects of TS fatigue on the torque, FSL and EMG parameters between athletes and non-athletes.

2. Subjects and methods

2.1. Subjects

Nintheen healthy women aged 20–30 years (10 non-athletes, 9 basketball players) participated in this study (Table 1). All subjects were right leg dominant. At the time of the test they were not pregnant and also they were not in monthly cycle. Subjects were instructed to refrain from having foods and drinks containing caffeine for two hours before the experimental sessions. All subjects were informed about the experimental procedure and participated in this study voluntarily. This study was approved by the ethical committee of Tehran University of Medical Sciences.

2.2. Torque measurement

An isokinetic dynamometer (Biodex sys.3 Medical, Inc, Shirly, New York) was used to measure the isometric peak torque of TS during MVCs and fatigue test. The output of dynamometer was displayed on-screen to provide a visual feedback for the participants.

2.3. EMG recording

Surface EMG signals were collected from three sites of the TS with three pairs of silver/silver chloride electrodes (diameter of 1 cm, center to center distance of 2 cm). The signals were passed through a differential amplifier (gain $= 1000$, input impedance $> 10^{15}$ ohms, CMRR > 96 dB, bandwidth $=$ 20–450 Hz) (Biometrics Ltd NOS.SX230, UK). The skin was prepared by shaving and wiping with alcohol. Recording electrodes were placed on the muscles according to surface electromyography for the noninvasive assessment of muscles (SENIAM) recommendations. Three pairs of electrodes were placed on the different heads of TS as below:

Two electrodes on the prominent bulge of the gastrocnemius medialis (GM). Two electrodes between the upper 1/3 and the lower 2/3 of the line along the head of the fibula and heel on the gastrocnemius lateralis (GL). Two electrodes between the upper 2/3 and the lower 1/3 of the line along the medial condyle of the femur and medial malleolus on the soleus (SOL).The reference electrode was placed over the lateral malleolus.

Table 1
Demographic characteristics of subjects (mean ± standard deviation are given)

Variable	Nonathletes ($n = 10$)	Athletes ($n = 9$)	All subjects ($n = 19$)
Age (year)	24.8 ± 3.22	24.11 ± 3.55	24.47 ± 3.30
Height (cm)	160.2 ± 5.28	170.77 ± 9.99	165.21 ± 9.37
Weight (kg)	54.3 ± 6.41	63.22 ± 10.23	58.52 ± 9.38
Body mass index (kgm^{-2})	21.19 ± 2.67	21.64 ± 2.39	21.4 ± 2.48

2.4. Protocol

After familiarization with instruments and experimental process, subjects lied in supine position on the dynamometer bench while their hip and knee joints were in full extension and their feet were placed on the force acceptance plate in 15° dorsiflexion. Adjustable belts were fastened across the chest and hips to prevent excessive movement of the body. Then, the subjects were asked to press their feet against the force acceptance plate as hard as possible in the direction of plantar flexion. Three maximum voluntary contractions (MVCs) were performed in this way. Duration of each MVC was 10 seconds, with 20 seconds of rest between them. While performing the MVCs, subjects received verbal encouragements. If there were more than 5% differences between the recorded MVCs, additional trials were performed. The maximum amounts were chosen as the subjects' MVC.

After 15 minutes, subjects performed warm-up comprised of 10 series of plantar flexion and dorsiflexion at the level of 20% of MVC at the speed of 210°/S; each series was separated by one minute of rest. After the warm-up and two minutes of rest, a pressure cuff was fastened at the distal end of the thigh and its pressure was increased to 140 mmHg, in order to reach fatigue in a short time. The subject was asked to perform one MVC before fatigue test (MVC_{bf}), while the ankle was in 15° dorsiflexion. The fatigue test consisting of a sustained maximum isometric contraction (at the level of 100% of MVC) was performed immediately afterward. The time of exhaustion was determined when the subject could not hold the torque above 50% of her MVC for at least 5 seconds. During the test, subjects were provided with continuous visual feedback on the monitor. After the fatigue test, the last MVC was recorded and used as the MVC after fatigue (MVC_{af}). Then, the pressure cuff was released.

2.5. Measurements

Before and after fatigue test, the amount of pain was determined by visual analogue scale (VAS). The amounts of RMS and MDF were computed on a three second period in the middle of MVC_{bf} and MVC_{af}. During the time of fatigue test, EMG signals and muscle torque were recorded by Data Log and Biodex instruments. Data link software was used to calculate median frequency slope (MDF slope). Determining the start and the end point of the fatigue test was based on the changes in muscle torque. The start point was the time in which the subject reached the steady state of her maximum torque and the end point was the time in which she reached 50% of her peak torque. Duration of the fatigue tests was between 3–4 minutes for different subjects which was divided into 10 windows of equal duration. Signals of EMG were processed using Hanning window for Fast Fourier Transform (FFT) and smoothed by 1024 samples per second. Average of median frequencies was obtained for each of 10 epochs. The slope of the MDF was measured across the 10 calculated median frequencies at the time of the fatigue test.

In the fatigue test initial and final RMS (RMS_i and RMS_f), and also initial and final MDF(MDF_i & MDF_f) were calculated during the first 500 ms of sustained activity and 500 ms prior to decrement of torque to 50% of the PT. The amounts of MDF, RMS and PT in MVC_{bf} and MVC_{af}, also MDF_f and RMS_f were normalized to the PT of each subject's MVC.

The parameter of falling slope (FSL) was used to determine the muscular fatigue. Falling slope is the ratio of torque (Nm) to time (s) and shows the changes of the torque slope during the period that a muscle reaches the rest state at the end of a contraction. Therefore, decrease in FSL is an indicator of muscular fatigue. The amounts of FSL in MVC_{bf} and MVC_{af} were determined and compared with each other.

3. Statistics

SPSS version 11.5 was used for statistical analysis. Descriptive statistics was used to determine mean ± standard deviation of sample characteristics, MDF, RMS, PT and pain. Repeated measures three-way

Table 2
Pure amounts of MDF, RMS and MDF slope during fatigue test in nonathletes and athletes (mean ± SD)

	Nonathletes ($n = 10$)			Athletes ($n = 9$)		
Variables	GL	GM	SoL	GL	GM	SoL
Initial MDF (HZ)	113.88 ± 16.7	135.67 ± 32.85	108.81 ± 15.86	108.76 ± 25.83	109.53 ± 29.46	95.06 ± 22.28
Final MDF (Hz)	75.87 ± 29.3	86.73 ± 34.05	82.69 ± 23.4	89.66 ± 32.78	97.25 ± 46.94	91.59 ± 31.14
MDF slope ($\frac{Hz}{s}$)	−%02	−%01	−%04	−%07	−%06	−%01
Initial RMS (μv)	46.92 ± 24.49	42.07 ± 31.09	47.25 ± 20.5	58 ± 26.67	48.91 ± 16.73	52.83 ± 20.45
Final RMS (μv)	11.77 ± 8.7	15.75 ± 5.81	15.37 ± 7.51	28.5 ± 16.89	35.88 ± 19.79	19.66 ± 10.05

ANOVAs (group × times of measurement × muscle) were used to determine the effects of fatigue on EMG parameters. Then, comparisons of RMS and MDF before, the end and immediately after the fatigue test were carried out. Differences between FSL and PT before and after fatigue were evaluated by Wilcoxon test. Mann-Whitney U test was used to evaluate the differences of PT between two groups. In all the tests, level of significance was 0.05.

4. Results

Before the test, none of the subjects had any pain in their calf muscles, although after fatigue, the average of pain in non-athletes was 6.4 ± 2.88 and 6.67 ± 2.10 in VAS in athletes.

4.1. Torque

There were significant group differences in PT before ($P = 0.002$) and after the fatigue test ($P = 0.001$), although there were not any significant differences in PT when data was normalized to the PT of each subject's MVC. After the fatigue test in comparison with before the test, a significant decrease in PT occurred in non-athletes ($P = 0.005$) and athletes ($P = 0.01$). Before the test, the mean PT for non-athletes was 32.28 ± 13.14 Nm while it decreased to 22.03 ± 10 Nm after the test. These values for athletes were 53.5 ±9 Nm and 37.91 ± 5.62 Nm, respectively.

4.2. Falling slope of MVC

The mean FSL of MVC_{af} (9.5 ± 6.59 Nm/s) in comparison with MVC_{bf} (14.87 ± 6.32 Nm/s) showed a significant decrease ($p < 0.005$) in non-athletes. These values in athletes were 18.39 ± 11.69 Nm/s and 26.6 ± 7.76 Nm/s respectively, but there were not any significant differences between them.

4.3. RMS, MDF and, MDF slope

Comparing with RMS_i and MDF_i, the amounts of RMS_f and MDF_f decreased and the MDF slope shifted to negative values (Table 2).

Repeated measures 3- way ANOVAs revealed no significant main effect of muscle for RMS and MDF, indicating that generally similar values of MDF and RMS were seen for different heads of TS muscle. No significant muscle × group and times of measurement × group interactions were found for RMS and MDF. It indicates that in both groups, similar values of RMS and MDF were seen for different heads of TS muscle at different times of measurement. Significant effects of times of measurement, and muscle× times of measurement interactions were found for MDF ($P = 0.000$, $P = 0.02$, respectively) and RMS ($P = 0.000$, $P = 0.009$, respectively). It indicates that at different times, different values of MDF and RMS were seen for the three heads of TS. Significant main effect of group factor and group × times of measurement × muscle interaction were for MDF ($P = 0.01$) (Figs 1, 2). However, there was not any group × times of measurement × muscle interaction for RMS (Figs 3, 4). This shows that generally similar values of RMS were seen in both groups at different times of measurement for the three heads of TS, however, these values were different for MDF.

5. Discussion

5.1. Torque

Before and after the fatigue test, absolute PT in athletes was significantly more than nonathletes. However, there was not any significant difference in normalized PT between the two groups. Larsson et al. (2006) found that there was significant difference between absolute PT of isokinetic plantar flexion in men and women, although there was not any significant difference

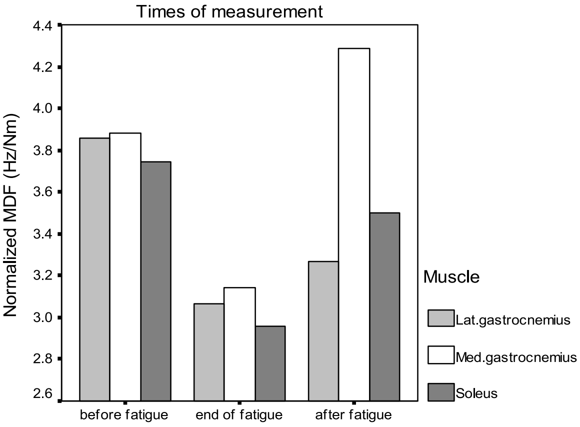

Fig. 1. Normalized MDF in nonathletes at the times of before, the end and after fatigue test.

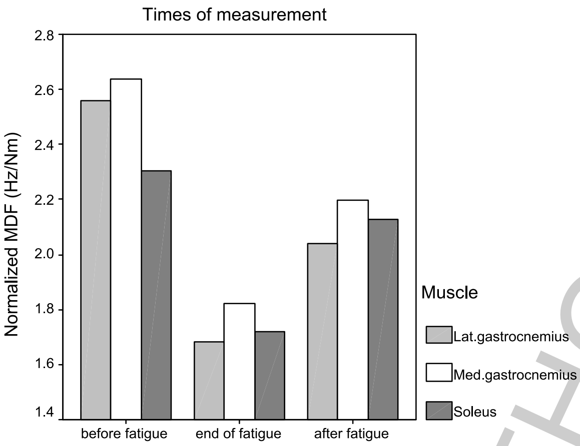

Fig. 2. Normalized MDF in athletes at the times of before, the end and after fatigue test.

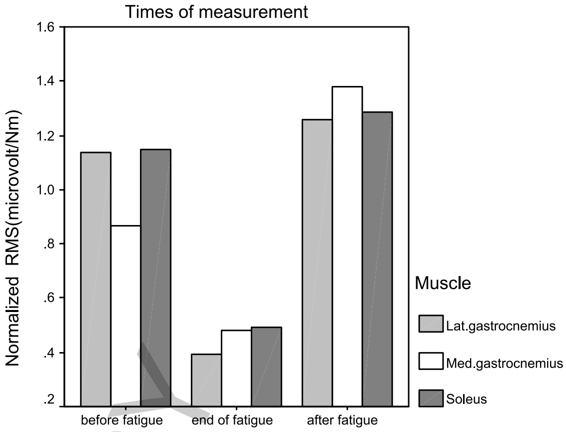

Fig. 3. Normalized RMS in nonathletes at the times of before, the end and after fatigue test.

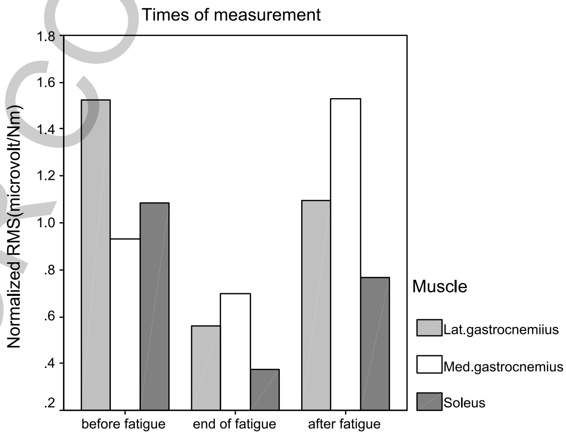

Fig. 4. Normalized RMS in athletes at the times of before, the end and after fatigue test.

between their normalized PT. They found that PT was associated with the area of large fibers and women with high proportion of type II fibers, had higher PT than men [13].

In the present study, after the fatigue test in comparison with before the test, PT decreased significantly in both groups. Non-athletes and athletes showed a 31% and 29% decrease of PT respectively. These results are almost similar with the results of the study of Svantesson et al. (1998). They reported a 25% decrease of PT in pure concentric test, 36% in the eccentric phase and 33% in the concentric phase of eccentric- concentric contraction of plantar flexors [24]. The magnitudes of PT in the present study were less than Svantesson's study; it may be due to individual differences between the participants and also different types of contractions in these studies.

5.2. FSL

When a muscle is fatigued, the slope of PT decrement is slow. At the end of a contraction, in a fresh strength muscle decrease in torque slope towards the rest state is steeper than a fatigued muscle. In this study FSL of MVC_{af} compared with FSL of MVC_{bf} decreased significantly ($P = 0.005$) in non-athletes. However, among athletes this decrease was not significant. In both groups, there were not any significant differences between the duration of reaching the maximum torque to the rest state. In all times of measurement, the PT of athletes was more than non-athletes. It seems that the greater amount of PT in athletes was the cause of less FSL among them. Unfortunately, there were not any studies about FSL and it was not possible to compare this finding with the results of other publications.

5.3. MDF

In both groups MDF of TS muscle decreased significantly at the end of the fatigue test in comparison with the beginning of the activity. Although MDF of MVC_{af} increased significantly in comparison with the MDF_f, it was still less than MDF in MVC_{bf}. In previous studies it has been reported that in sustained isometric contractions, shift of EMG power spectrum to lower frequencies is an indicator of muscular fatigue [4,7,21] and is in relationship with peripheral fatigue [14]. It has been shown that pain decreases firing rates of active motor units during constant force contractions [5]. In the present study after the fatigue test, pain increased significantly in both groups.

After fatigue test, in non-athletes MDF of GM was more than before the test, however, it was not statistically significant. In isometric and dynamic contractions, MDF is influenced by the type of muscle fibers and is more in muscles with a higher percentage of type II fibers [3]. It is probable that the proportion of muscular activity is different among the different heads of TS. Hof et al. (1977) showed that in isometric contraction the distribution of torque between GL and GM was not constant [9]. Kinugasa et al. (2005) found that in isokinetic contraction the area of activated muscle for GM was 46% and for GL and SOL were 35%. They also showed that GM had shorter fascicles with larger fascicle angles than GL and consequently had a greater force producing capacity in comparison with GL or SOL [12]. Therefore, it is probable that even after the fatigue test the activity of GM is more than the other heads of TS. Our results are almost similar to the results of Bilodeau et al. (2003) study on the quadriceps. They found that fatigue had a distinguished effect on the vastus lateralis (VL) compared to the vastus medialis (VM) and the rectus femoris (RF). They suggested that after fatigue, insignificant increase of vastus lateralis MDF could be explained with the fact that the VL may contain a higher proportion of type II fibers. In addition, biomechanical difference could influence MDF. Conduction velocity of type II fibers is more than type I fibers due to their electrophysiological properties and larger diameter. It has been revealed that MDF is influenced by the fiber conduction velocity. Muscles with larger areas of type II fibers or greater content of type II fibers show more MDF decrease with fatigue [3].

In our study, MDF was more among non-athletes in comparison with athletes. It may be due to their need for a higher firing rate of motor units to postpone early fatigue.

5.4. RMS

In both groups at the end of fatigue test compared with the beginning of the test, RMS of TS decreased significantly. Although the RMS in MVC_{af} increased significantly in comparison with RMS_f, it did not reach its level in MVC_{bf}. In different studies changes of RMS are reported as increasing, unchanging and decreased during the fatigue test [4]. Svantesson et al. (1998) in their study on the isokinetic contraction of TS did not report any significant differences in RMS during fatigue [24]. In the present study, decrease of RMS_f in comparison with RMS in MVC_{bf} in athletes was more than non-athletes, however, this difference was not significant. Bilodeau et al. (2003) in their study on the serial sustained isometric contraction of quadriceps reported the decrease of RMS in all heads of quadriceps during fatigue test. They suggested that due to a higher percentage of type II fibers in men, decrease of RMS following fatigue was more prominent in men than women [3]. From the aspect of restriction of blood flow, the present study is similar to Karabulut et al. (2010) study. They found that low intensity exercise of knee extensors combined with vascular restriction resulted in significant decrease in EMG amplitude from pre- to post- exercise. They suggested that neuromuscular fatigue during vascular restriction might be due to a combination of central and peripheral fatigue [10].

6. Conclusion

Our findings suggest that TS fatigue affects EMG parameters, PT and pain in athletes and non-athletes similarly. Significant decrease of FSL due to fatigue in non-athletes but not in athletes, may have been due to the fact that their PT were less than athletes in all times of measurement.

The reaction of different heads of TS in relation to the fatigue among two groups was different. In both groups after the fatigue test, RMS of GM was more than before the test.

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