EMG frequency content changes with increasing force and during fatigue in the quadriceps femoris muscle of men and women

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Abstract

The purpose of this study was to determine the effect of gender on changes in electromyographic (EMG) signal characteristics of the quadriceps muscles with increasing force and with fatigue. A total of fourteen healthy adults (seven men, seven women) participated in the study. Subjects had to perform isometric ramp contractions in knee extension with the force gradually increasing from 0 to 100% of the maximal voluntary contraction (MVC) in a 6-s period. Subjects then performed a fatigue task, consisting of a sustained maximum isometric knee extension contraction held until force decreased below 50% of the pre-fatigue MVC. Subjects also performed a single ramp contraction immediately after the fatigue task. The Root Mean Square (RMS) amplitude, mean power frequency (MPF) and median frequency (MF) of EMG signals obtained from the vastus lateralis, vastus medialis and rectus femoris were calculated at nine different force levels from the ramp contractions (10, 20, 30, 40, 50, 60, 70, 80 and 90% MVC), as well as every 5 s during the fatigue task. The main results were a more pronounced increase in EMG RMS amplitude for the three muscles and in MPF for the VL muscle with force in men compared with women. No significant effect of gender was found with regards to fatigue. These observations most likely reflect a moderately greater type II fiber content and/or area in the VL muscle of men compared to that of women.

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1. Introduction

Fiber composition (% fiber type) and fiber size (area or diameter) have been reported to be different between men and women for the vastus lateralis (VL) muscle. Several studies report a greater type I fiber content (%) in women compared to men [23,28,29], with the overall range of values for type I fiber content between 25% and 70%, and with women showing, on average, about 5–6% more type I fibers. However, others report no such gender-related differences [9,10]. In general men have larger fibers (all types) compared to women. For example, Gerdl et al. [9] report that fibers are about 30% larger in men compared with women in the VL muscle. Also, there are a number of studies where type II fibers have been shown to be larger than type I fibers in men, whereas the opposite can be observed in women [9,10,11,18,23,28,29]. Variations in fiber composition have also been noted between the different muscles forming the quadriceps complex. Edgerton et al. [5] report a greater type I fiber proportion in the vastus medialis (VM) (~50%) compared with the VL (~30%). However, Johnson et al. [14] report a 30–40% type I fiber composition for rectus femoris (RF), VL and VM. Polgar et al. [26] report the following diameter for type I and II fibers of 6 males: VL (I: 63 um, II: 63 um), VM (I: 61.6 um, II: 64.7 um) and RF (I: ~65 um, II: 74 um). Only the difference for the RF reached significance.

Fiber composition and size have been shown to influence the frequency content of the electromyographic (EMG) signals. In general, higher values of the median (MF) or mean power frequency (MPF) of the EMG power spectrum are observed for muscles with a greater percentage of type II fibers [7,9,10,11,21,32] or greater relative area of type II fibers [16]. In addition, changes
in the MF or MPF with increasing force or fatigue are also influenced by fiber composition or fiber size [7,9,10,16,32]. For example, a more pronounced decrease in MF during fatigue is observed in muscles with a larger area of type II fibers [16] or greater type II fiber content (%) [9,10]. A more pronounced increase in MF or MPF with increasing force in muscles with a higher percentage of type II fibers has also been reported [7]. This has been explained by the progressive recruitment of type II fibers which, because they have a greater diameter than type I fibers or due to intrinsic electrophysiological properties [27], would have a higher conduction velocity [22]. It should be noted, however, that confounding factors, such as skinfold thickness, can significantly influence the behavior of spectral statistics with increasing force [3], and should therefore be controlled.

With regards to the quadriceps muscle group, Gerdle [7] report differences in MPF between the VL, VM and RF, with the RF showing higher values (10 Hz) than the two vastii. In contrast, Pincivero et al. [25] reported higher MF values for the VL compared to the VM, with the RF showing values between those of the two vastii. Other studies have also reported no difference in these frequency statistics between the three muscles of the quadriceps [10,31]. Pincivero et al. [25] also report a significant increase in MF with increasing force for the VL muscle but not for the VM and RF. They explained the greater increase in MF with force for the VL compared to the VM (and RF) by the reported greater type II fiber content in the former compared to the later muscles. In the same study, they report that men tended to present with a more pronounced increase in MF with force (VL). They explained this gender difference by the higher type I fiber content (and smaller fibers) in women compared to men, which would limit the range of MF values (through the smaller range in conduction velocity values). In contrast, Gerdle et al. [10] and Gerdle et al. [9] report no difference between men and women in the change in EMG frequency parameters with fatigue, however this is reported in the text and no data is presented in either study [9,10].

Therefore, the potential influence of gender-related differences in muscle fiber characteristics for the quadriceps muscle group remains unclear. The purpose of the present study was to determine the effect of gender on the changes in EMG RMS amplitude and MF or MPF with increasing force and with fatigue in the quadriceps muscle group.

2. Methods

2.1. Subjects

Fourteen healthy adults (7 women, 7 men; age ranging between 22 and 43 years) participated in this study. Subjects were all right leg dominant (leg used to kick a ball). All subjects signed a written informed consent. The study was approved by the University of Iowa Institutional Review Board.

2.2. Materials

2.2.1. Force recording

Subjects were seated comfortably on an experimental chair, with their hip and knee joints flexed to 90°. A leather ankle cuff was placed just proximal to the right leg malleoli and connected to a load cell (Genesco AWU-500, Simi Valley, CA) at a right angle with a steel cable. The pelvis was stabilized with a seatbelt and the right thigh with a wide Velcro strap. The signal from the load cell (range 0–2230 N) was then amplified and low-pass filtered at 30 Hz. The force signal (knee extension) was then fed through an analog-to-digital converter and stored on computer with a sampling frequency of 1000 Hz.

2.2.2. EMG recordings

EMG signals from the RF, VM and VL were recorded with pairs of bipolar silver–silver chloride surface electrodes (8 mm electrode diameter, fixed inter-electrode distance of 20 mm). Following skin abrasion with an alcohol soaked cotton pad, electrodes were placed as follows on the respective muscle bellies: RF—6 cm proximal to the superior pole of the patella; VM—on the medial aspect of the thigh, 4 cm proximal to the superior pole of the patella; VL—on the lateral aspect of the thigh, 4 cm proximal to the superior pole of the patella. All electrode pairs were placed in a direction parallel to the general direction of muscle fibers for a given muscle. A reference electrode was positioned approximately 6 cm distal to the inferior pole of the patella, over the bony surface of the tibia. EMG signals were pre-amplified at the electrode site (X35) and then fed into a differential amplifier with adjustable gain setting (×100 to ×100 000; 15–4000 Hz; CMRR: 87 dB at 60 Hz; Therapeutics Unlimited, Iowa City, Iowa). EMG signals were stored on computer with a sampling frequency of 2000 Hz.

2.3. Procedures

All procedures were performed in the same experimental session. Prior to testing, skin thickness measurements were taken with a skinfold caliper over the recording site for the VM and VL. Subjects were first allowed to warm-up the quadriceps muscle group by performing a minimum of one slow ramp (linear increase in force) isometric knee extension contraction at each of 20, 40, 60 and 80% of their perceived maximum voluntary contraction (MVC). This allowed subjects to get familiar with the performance and control of ramp contractions through the matching of their exerted force and
a visual target displayed on an oscilloscope facing them. Additional warm-up contractions were allowed until subjects were proficient with the performance of ramp contractions. Subjects then performed knee extension MVCs lasting 2–3 s. At least two MVC trials were performed to ensure that the force recorded was representative of a subject’s maximum effort. If there was a difference greater than 10% between the first two MVCs, additional trials were performed as needed. All subject were provided with loud verbal encouragement during the MVC trials. A 3-min rest period was allowed between MVCs.

Next, the maximum force obtained during the two MVC trials deemed representative of a subject’s maximal capacity was averaged and used to set the target maximal force for the ramp template on the oscilloscope. The template consisted of a 2-s baseline (horizontal line) followed by a linearly increasing force period lasting 6 s and ending with a 2-s plateau at the maximum target force. Subjects were asked to perform two to five ramp contractions (0–100% MVC). A 3-min rest period was allowed between each ramp contraction. The two ramps that best satisfied the following criteria, were used for later analysis: 1) maximal force reaching at least 80% of MVC, and 2) smooth linear increase in force as per visual inspection.

After another 3-min rest period, subjects had to perform a fatigue task consisting of a sustained maximum isometric contraction held until force decreased below 50% of the calculated pre-fatigue MVC force for at least 5 continuous seconds. Loud verbal encouragement was provided to the subject throughout the fatigue task. Immediately after the fatigue task, subjects were asked to perform a ramp contraction using the same template on the oscilloscope facing them.

2.4. Data analysis

For the ramp contractions, EMG Root Mean Square (RMS) value and MF and MPF of the power spectrum (512 points, raised cosine window processing, Fast Fourier Transform) were calculated from a 0.5-s window at each the following force levels: 10, 20, 30, 40, 50, 60, 70, 80 and 90% of maximum. For the fatigue task, EMG Root Mean Square (RMS) value and MF and MPF of the power spectrum (512 points, raised cosine window processing, Fast Fourier Transform) were calculated for consecutive 5-s windows throughout the whole fatigue task.

Mixed-design 2-way ANOVAs were used to determine the effect of gender (independent factor) and force or fatigue (repeated measures factors) on EMG RMS values and MF or MPF. For the ramp contractions, values obtained at 10, 30 and 60% of maximum were used in the statistical analyses. Those three levels were chosen because for the majority of subjects, MF and MPF increased with force up to about 60% of maximum and then leveled-off or even decreased slightly. Because subjects presented with different times to fatigue, each subject’s fatigue task was divided in five parts of equal duration. All data from the 5-s windows in a given section were averaged to yield a single value. Values from the first, middle (third) and fifth sections were used in the statistical analyses. Differences across the three muscles were also evaluated using three-way ANOVAs where in addition to the gender and force or fatigue factors, a muscle factor was included in the model. The level of significance chosen for all tests was 0.05. Pearson-product moment correlation analyses were also performed to test the association between skinfold thickness and MF or MPF variables.

3. Results

The MVC force produced by men (479.7 ± 100.8 N) was significantly greater than that produced by women (257.2 ± 42.6 N).

3.1. Ramp contractions

3.1.1. RMS amplitude

EMG RMS amplitude increased progressively with increasing force in all muscles. When expressed as a percent of the RMS value obtained during the brief pre-fatigue MVCs, the increase was similar between the different muscles, and this was the case for both men and women (Fig. 1; no muscle × force or gender × force interactions). The increase expressed in absolute value (voltage), however, was more pronounced in men compared to women for all muscles (Fig. 2; significant gender × force interactions for the VM and RF, but not for the VL (p = 0.06)). When the increase in absolute EMG amplitude was expressed in relation to the increase in absolute force (N), there were no longer any significant differences between men and women.

3.1.2. MF or MPF

No significant effect of the muscle factor was found for either MPF or MF (p > 0.05), indicating that generally similar values were observed for the three muscles. Increases in MPF and MF with force were observed for all muscles (force factor, p < 0.05; Fig. 3). No significant interaction between the muscle and force factors were found, reflecting the similar increase in MF or MPF with force for all muscles. Even though both central tendency statistics were generally higher in men compared with women for both VL and VM, no main effect of gender was found (p > 0.05). A significant interaction between the gender and force factor was found for the MPF of the VL, with men showing a more pronounced increase with force compared with women.


Fig. 1. Normalized group EMG RMS amplitude data (mean ± standard deviation) plotted as a function of force for the pre-fatigue ramp contractions. Data has been normalized to the RMS EMG amplitude obtained during the brief maximal voluntary contractions and is presented for the vastus lateralis (VL), vastus medialis (VM) and rectus femoris (RF) muscles. Similar increases in normalized RMS amplitude are observed across muscles and between women (top panel) and men (bottom panel).

A similar trend was observed for the MF of this muscle, but this did not reach significance (gender × force interaction; $p = 0.09$). The percent increase in MPF and MF for each muscle is given in Table 1.

3.2. Fatigue task

No difference was found between men (40.2 ± 7.3 s) and women (45.5 ± 11.7 s) in endurance time ($p > 0.05$; t-test for independent samples). There was a weak, non-significant negative relationship ($r = -0.41$, $n = 13$) between MVC force and endurance time.

3.2.1. RMS amplitude

RMS amplitude decreased with fatigue in all muscles. This decrease was slightly more pronounced for men (Fig. 4), however, this did not reach statistical significance.

3.2.2. MF or MPF

Similarly, both the MPF and MF decreased with fatigue in all muscles. There was no difference between
men and women in the behavior of either statistic with fatigue (Fig. 5).

3.2.3. Post-fatigue ramp

Data from the ramp performed after the fatigue task generally showed lower MF or MPF values for each muscle compared to pre-fatigue values (Fig. 6). Also, the main effect of force and the gender × force interaction present before fatigue for the VL, were not significant for the post-fatigue ramp. This points out to the fact that after fatigue, there was no significant change in MPF or MF with increasing force for the VL (Figs. 6 and 7). The post-fatigue relative increases are also given in Table 1.

3.3. Skinfold thickness

Significant differences were found in skinfold thickness between men and women, with men (VL: 15.3 ± 8.1 mm, VM: 16.3 ± 5.1 mm) having a thinner skin layer compared with women (VL: 29.3 ± 10.7 mm, VM: 26.5 ± 9.1 mm). However, no correlations were found between skinfold thickness and the initial value or the behavior of MPF or MF with force or fatigue (p > 0.05 for all correlations). A significant correlation was found between skinfold thickness and RMS amplitude (measured during MVC trials) for the VL muscle (r = −0.74), but not for the VM (r = −0.45).

4. Discussion

Generally, few differences were observed between men and women with regards to the EMG variables studied. Amongst the significant differences found were a greater increase in EMG RMS amplitude for all three muscles of the quadriceps of men compared with women with increasing force, and a more pronounced increase in MF or MPF with force for the VL muscle of men compared with women. Also, no difference between the three muscles and between men and women were observed concerning the effect of fatigue on the EMG variables, except for the VL, where the effects of the force factor and the gender × force interaction were no longer significant for the post-fatigue ramp.

4.1. Gender

Men presented with a greater increase in EMG RMS amplitude with relative force (% MVC) compared with women, and this was observed for all three muscles. Gerdle et al. [7] report a significant association between the increase in EMG RMS amplitude (%) of the VL with force and the size (area) of fibers as obtained from biopsy data. Therefore, the greater increase in signal amplitude for the men (from similar values at low force) could be explained by the presence of larger type II fibers, as compared to those of women [9], with less gender-related differences in the size of type I fibers [28]. This would suggest that the observed gender related difference in fiber size reported for the VL [23,28,29].

Fig. 3. Group mean power frequency (MPF) data (mean ± standard deviation) plotted as a function of force (% ramp maximum) for the pre-fatigue ramp contractions. Data shown separately for men and women for the three muscles. Note the more pronounced increase in MPF for the men compared with the women for the vastus lateralis muscle.
Table 1
Percent increase in MF or MPF with force for both men and women

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<tr>
<td>VL</td>
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would also hold for the VM and RF. The generally larger fibers found in men, and mostly type II fibers [28], compared with women could also partly explain the greater force-generating capacity of the former group compared to the later, as reflected in our MVC force data. However, differences in the maximum knee extension force produced by men versus women would have to be assessed by taking differences in overall muscle size between the two groups into consideration. The thorough measurement of muscle size (e.g., through imaging methods) was beyond the scope of the present study.

Because the MF or MPF data only presented with a gender-related difference for the VL (significant gender × force interaction), it appears that factors other than those related to fiber composition/size may also have contributed to the observed difference between men and women in EMG RMS amplitude. For example, a difference between men and women in discharge frequency could give rise to differences in EMG RMS amplitude if it is calculated over a long enough time period (e.g., 0.5 s here). The more pronounced increase in MF or MPF with force in men compared with women could therefore be due to the greater type II fiber content in men [23,28,29] or to the lesser difference in diameter between type I and II fibers in women compared with men [9,10,23,28,29].

The current results and those of Pincivero et al. [25] concerning the observation of a gender-related difference in the MF or MPF versus force relationship of the VL, suggest that the difference in fiber composition size between men and women is more pronounced for this muscle. However, the magnitude of the difference in MF or MPF increase with force between men and women (8% for this study and 11% for the Pincivero et al. study) is relatively small, which would agree with available data on muscle fiber composition, where only modest differences (or no differences) between men and women in fiber composition or size are reported for knee extensor muscles (with more data available on the VL). In addition, the potential gender-related differences in fiber composition were not important enough to lead to significant differences between men and women in our fatigue-related measurements (endurance time and EMG variables), which is consistent with previous findings [9,10,20]. Men did present with a trend toward a greater decrease in EMG RMS amplitude with fatigue compared with women (most noticeable for the VL), which would be consistent with a greater type II fiber content in the former versus the later group of subjects [9]. However, this was not accompanied by gender-related differences in MF or MPF changes with fatigue, which had been reported for other muscles [19].

4.2. VL versus VM versus RF

Interestingly, Pincivero et al. [25] did not find an increase in MF with force for the VM and RF muscles. In contrast, we found significant increases in both MPF and MF for these two muscles in the present study. An increase in MF was also found for all of VM, VL and
RF by Gerdle et al. [7]. These different results could be explained by the fact that the effect of increasing force was assessed using gradually increasing contractions (ramp) in the present study and in Gerdle et al. [7], whereas Pincivero et al. [25] used steady contractions performed at various force levels. Bilodeau et al. [2] have shown that more pronounced increases in MF or MPF with force can be observed with ramp versus step contractions. However, Bernadi et al. [1] also observed an increase in MF with force for the RF muscle using “step-wise” increasing contractions. The use of a different type of contraction could potentially also explain the fact that we observed a similar increase in RMS amplitude between the three muscles, whereas Pincivero et al. [25] reported a more pronounced increase in amplitude.
Fig. 6. Group mean power frequency (MPF) data (mean ± standard deviation) plotted as a function of force (% ramp maximum) for the post-fatigue ramp contractions. Data shown separately for men and women for the three muscles. Note that compared with pre-fatigue data (Fig. 3), the increase in MPF with force is less apparent for the VL (not significant).

for the VM compared to the two other muscles at high force levels. In the current study, no significant differences were found in the general MPF or MF values between the three different muscles. In contrast, Gerdle et al. [7] reported higher MPF values for the RF compared to VM and VL. Pincivero et al. [25] observed greater values for the VL compared to the VM and RF.

The differences between our results and those of these two studies could reflect the high variability in fiber characteristics across individuals and even within a given muscle for the quadriceps [17], and underscore the reliance of the MF or MPF on the specific location of the electrodes on the muscles.

Data from the ramp contraction performed immedi-
ately after the fatigue task suggest that fatigue had a differential effect on the VL compared to the other two muscles. Whereas MPF and MF increased significantly with force before fatigue in the three muscles, it did so only for the VM and RF after fatigue. The smaller (non-significant) increase in MF or MPF in the VL after fatigue could be explained by the fact that this muscle may have a higher type II fiber content compared to the VM (and possibly RF) [5], and that it has been suggested that biochemical changes in mainly these fibers would influence the MPF [6]. Gerdle and Karlsson [8] previously reported a similar effect of fatigue on the force-dependency of the MPF for the VL and RF muscles (their Figs. 2 and 3). However, these authors used fatigue tasks performed at different force levels, which most likely led to the involvement of different fatigue mechanisms for each task. In contrast, a single fatigue task was used in the present study, and consequently, the same fatigue mechanism(s) (most likely the build-up of metabolites, because of the performance of a relatively short sustained maximum contraction [24]) affected the data obtained at all force levels during the post-fatigue ramp. Therefore, our results cannot be directly compared with those of this previous study [8].

Finally, it was shown that the MPF was more sensitive than the MF with regards to gender differences in the VL. For this muscle, a significant gender × force interaction was found for the MPF, whereas it did not reach significance for the MF. Greater gender-related differences in the MPF/force relationship compared to the MF/force relationship have previously been reported for upper limb muscles [3]. The study by Bilodeau et al. [3] showed greater differences between men and women for the MPF compared to the MF of the triceps brachii muscle, and this was explained by the greater influence of skinfold thickness on the former compared to the later frequency parameter. This is related to the fact that the skin layer acts as a low-pass filter and that the MPF is more sensitive to the high frequency content in the power spectrum compared to the MF [12]. In the present study, even though a significant difference in skinfold thickness was found between men and women, no correlations were found between skinfold thickness and MPF or MF and their behavior with force or fatigue. Therefore, we believe that this factor does not explain the gender-related differences observed, which most likely reflect a moderately greater type II fiber content and/or area in the VL muscle of men compared to that of women.

In summary, men showed a greater increase in VL MPF with force compared with women. No such gender-related differences were observed for the VM or RF muscles and for EMG changes associated with fatigue. These results may reflect the relatively small difference in fiber composition/size between men and women reported in the literature for the quadriceps muscle complex.

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References


