Influence of contraction intensity, muscle, and gender on median frequency of the quadriceps femoris

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The results demonstrate that the largest change in differences or differences between the latter two muscles was significantly higher than the VM and RF, with no gender length. The intuitive 512-ms epochs overlapping each other by one-half their length. The f med for each of the 11 epochs was then determined, followed by calculation of the mean and SD. The major findings of this study demonstrated that overall f med was significantly highest for the VL and lowest for the VM, whereas RF f med was between that of the other two muscles. Similar findings were observed for f med variability as the VL was significantly higher than the VM and RF, with no gender differences or differences between the latter two muscles. The results demonstrate that the largest change in f med as a function of contraction intensity occurred for the VL in men (18.6%) and women (7.6%). These findings suggest that muscle fiber-type homogeneity may exist in the VM and RF, which displayed negligible changes in f med, whereas the VL may possess greater morphological variability.

The primary function of the quadriceps femoris (QF) muscle is to generate knee extensor torque and to stabilize the patella (29). As this muscle group plays a key role during ambulatory and functional activities, interest in the recruitment characteristics of its different components has escalated. One method that has been used to enhance the understanding of QF muscle function is surface electromyography (EMG), which has proven to be a valid and reliable tool of muscle recruitment (21, 36). Many anatomic and physiological factors that mediate QF recruitment behavior, such as contraction intensity, muscle fiber type, or motor unit activation pattern, can be manifested in the surface EMG signal. The QF muscle is unique in that the different components have been shown to display varying fiber-type compositions (20, 40) and divergent tension (10), while all receiving innervation from the femoral nerve (18). Differential recruitment of the superficial components of the QF muscle has also been recently demonstrated to be a function of contraction intensity (1, 31). Furthermore, potential gender differences that may exist in the surface EMG signal have yet to be conclusively established for this muscle group, despite demonstrated differences in fiber-type proportions (35).

The expression and quantification of the surface EMG signal in the frequency domain, via the median frequency (f med), has displayed a positive relationship to muscle fiber conduction velocity (23, 25, 37) as a function of a larger fiber diameter (23). Defined as the frequency at which the EMG spectrum is divided into two parts of equal power (4), the f med has been shown to increase with higher contraction intensities as a result of additional recruitment of larger diameter fibers (4, 6). As limited evidence regarding typical muscle fiber-type proportions of the vastus medialis (VM) and rectus femoris (RF) muscles exists (20, 40), compared with that for the vastus lateralis (VL) (35), the f med may provide insight into specific EMG patterns for these different muscles. Typically, shifts to lower frequencies have been demonstrated during fatiguing contractions (2, 24, 25), yet a pattern of f med changes at different contraction intensities for the different portions of the QF muscle has yet to be shown. The potential of a gender difference in f med as a function of contraction intensity has been shown in select muscles (anconeus, tibialis anterior) by previous studies (4, 6). Such a finding was not evident, however, during maximal voluntary isometric contractions of the QF muscle, in which our laboratory demonstrated f med of the super-

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ficial portions of the QF muscle that was not gender specific (32). The implications of varying recruitment patterns of the QF muscle between men and women, as a function of contraction intensity, may lend insight into gender-specific factors affecting physical activity and function, such as discrepant rates of athletic-related knee injury (14). Therefore, the purpose of this study was to examine the influence of gender and contraction intensity on the $f_{med}$ statistic of the VM, VL, and RF muscles in healthy individuals.

MATERIALS AND METHODS

Subjects. The present study incorporated a repeated-measures design. Subjects for this study consisted of 30 healthy male ($n = 15$, mean age = 26.5 ± 4.7 yr, mean height = 178.1 ± 6.1 cm, mean mass = 88.6 ± 16.1 kg) and female ($n = 15$, mean age = 24.9 ± 3.7 yr, mean height = 165.4 ± 5.6 cm, mean mass = 61.4 ± 8.4 kg) volunteers. All subjects were physically active but had not actively taken part in an intensive resistance training program (i.e., >2 days/wk) for the lower extremity for at least 6 mo before the study. Individuals with a history of cardiovascular disease, hypertension, or orthopedic pathology were excluded from participating in this study. All subjects provided written, informed consent as approved by the Institutional Review Board at Eastern Washington University.

Measurement of isometric torque. Before the measurement of isometric torque, all subjects completed a warm-up period that consisted of submaximal cycling for 3–5 min. Isometric torque was measured on the Biodex System II isokinetic dynamometer (Biodex Medical, Shirley, NY). Subjects sat in a comfortable, upright position on the Biodex accessory chair and were secured with the use of thigh, pelvic, and torso straps to minimize extraneous body movements. The lateral femoral epicondyle was used as the bony landmark for matching the axis of rotation of the knee joint with the axis of rotation of the dynamometer resistance adapter. Gravity correction was obtained by measuring the torque exerted on the dynamometer resistance adapter with the knee in a relaxed state at full extension. Values for isometric torque were automatically adjusted for gravity by the Biodex Advantage software program (version 3.2.6). During the assessment of isometric torque, subjects were required to fold their arms across their chest and were given verbal encouragement, as well as visual feedback from the Biodex computer monitor, in an attempt to achieve a maximal voluntary effort (16, 22, 27). All of the procedures and verbal encouragement were administered by the same investigator for all subjects. Calibration of the Biodex dynamometer was performed before every testing session according to the manufacturer’s specifications.

Once the subjects were seated in the chair, their knee was fixed at an angle of 60° flexion, which has been demonstrated to be the angle of maximal isometric force generation (38, 39). After two to three submaximal, followed by two to three maximal, contractions for familiarization purposes, subjects were asked to contract their quadriceps as hard as they could {maximal voluntary contraction (MVC)} and to hold this contraction for 5 s. This contraction was repeated two more times with a minimal rest of 2 min in between each contraction. The average peak torque of the three MVCs was calculated to yield a representative estimate of an individual’s maximal voluntary effort. The mean absolute torque level (± SD) for each of the three MVCs was as follows: MVC 1, 214.25 ± 63.26 N·m; MVC 2, 218.96 ± 62.64 N·m; and MVC 3, 218.77 ± 63.40 N·m. The calculated intraclass correlation coefficient among the three MVCs was 0.98, and the SE of measurement was 8.92 N·m, or 4.1% of the mean value. The 95% confidence interval for the SE of measurement value was found to be 3.4–4.8% (32).

Subjects were then asked to perform one voluntary isometric contraction of their quadriceps at the following intensities: 10, 20, 30, 40, 50, 60, 70, 80, and 90% of their MVC. All subjects performed each contraction for 5 s with a minimal rest period of 2 min in between each bout. Subjects were asked to match a horizontal line on the Biodex computer monitor that corresponded to the torque level at each intensity. The order of contraction intensity was randomized. During all testing, the subjects were blinded to the absolute torque values that they were generating.

Measurement of $f_{med}$. The $f_{med}$ was assessed through surface EMG for the VM, VL, and RF muscles. Pre amplified bipolar circular surface electrodes (Ag/AgCl, 0.8 cm diameter) were placed on each muscle with a fixed interelectrode distance (center to center) of 2 cm. Before electrode placement, the skin area was shaved, cleaned with isopropyl alcohol, and abraded with coarse gauze to reduce skin impedance. Electrode placement for the VM was 20% of the distance from the medial joint line of the knee to the anterior superior iliac spine (44). The reference electrode was placed over the medial shaft of the tibia ~6–8 cm below the inferior pole of the patella. EMG activity was collected by a four-channel unit (Therapeutics Unlimited, Iowa City, IA) at a rate of 1,000 Hz for each muscle. The common mode rejection of the current system is 87 dB at 60 Hz with an input impedance of >25 MΩ at direct current. The gain range used in this study was 10,000, and signals were band-pass filtered between 20 and 500 Hz. Raw EMG signals were digitized and stored on computer disks for subsequent analysis by the Acknowledge software program (version 3.2.6, Biopac Systems, Santa Barbara, CA). The signals collected within the first and last second of each 5-s isometric contraction were not used for analysis because of knee movement that may have occurred at the initiation and completion of the test. Therefore, a 3-s window of EMG signals was used for analysis. A power spectral analysis was performed on the 3-s window for each muscle. A fast Fourier transformation of 512 points (Hamming window processing) was performed on 11 consecutive 512-ms segments, overlapping each other by one-half their length (256 ms), over the middle of each contraction (4). The $f_{med}$ was determined from each of the 11 overlapping windows. The $f_{med}$ mean and SD of the 11 windows during each contraction were then calculated for each muscle. These two values were then used for statistical analyses. The integration algorithm utilized to calculate the area of the power frequency spectrum in the software is as follows

$$f_{output}(n) = \sum_{k=1}^{n-1} f_{input}(k) + [(f_{input}(n-1) + f_{input}(n))/2] \cdot \Delta t$$

where $f$ is frequency, $f(n)$ represents the data values (mV/s), $\Delta t$ is the change in time and represents the horizontal sampling interval (s) (MP100 Systems Guide, Biopac), and $k$ is a variable.
Descriptive data for the median frequency variability across 11 overlapping epochs for the vastus medialis, vastus lateralis, and rectus femoris muscles of men and women at submaximal contraction intensities

<table>
<thead>
<tr>
<th>MVC, %</th>
<th>Vastus Medialis</th>
<th>Vastus Lateralis</th>
<th>Rectus Femoris</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Men</td>
<td>Women</td>
<td>Men</td>
</tr>
<tr>
<td>10</td>
<td>7.57 ± 2.75</td>
<td>9.06 ± 3.83</td>
<td>9.53 ± 3.45</td>
</tr>
<tr>
<td>20</td>
<td>6.58 ± 1.72</td>
<td>8.13 ± 3.70</td>
<td>9.70 ± 2.57</td>
</tr>
<tr>
<td>30</td>
<td>7.22 ± 1.35</td>
<td>7.68 ± 2.62</td>
<td>9.51 ± 3.40</td>
</tr>
<tr>
<td>40</td>
<td>7.46 ± 3.58</td>
<td>7.26 ± 2.72</td>
<td>9.20 ± 2.31</td>
</tr>
<tr>
<td>50</td>
<td>8.33 ± 4.17</td>
<td>6.44 ± 2.19</td>
<td>9.28 ± 2.24</td>
</tr>
<tr>
<td>60</td>
<td>7.28 ± 3.42</td>
<td>6.78 ± 2.20</td>
<td>10.04 ± 3.13</td>
</tr>
<tr>
<td>70</td>
<td>8.78 ± 3.03</td>
<td>7.71 ± 4.26</td>
<td>9.96 ± 3.32</td>
</tr>
<tr>
<td>80</td>
<td>7.42 ± 3.58</td>
<td>6.62 ± 5.18</td>
<td>9.34 ± 2.11</td>
</tr>
<tr>
<td>90</td>
<td>6.99 ± 2.58</td>
<td>7.24 ± 2.99</td>
<td>11.45 ± 3.48</td>
</tr>
</tbody>
</table>

Values are means ± SD in Hz.
The major findings of this study demonstrated that the superficial components of the QF muscle display distinctive differences in $f_{\text{med}}$ mean and variability across the spectrum of submaximal contraction intensities. The most notable distinction occurred with the $f_{\text{med}}$ mean of the VL muscle, as men displayed a significantly greater increase from 10 to 90% MVC (average 18.6% increase) than women (average 7.6% increase). Although the effect size of this interaction is considered to be small ($\eta^2 = 0.09$), the effect of contraction intensity on $f_{\text{med}}$ when pooled across all subjects was larger ($\eta^2 = 0.51$). Significantly higher $f_{\text{med}}$ variability was shown for the VL compared with the RF and VM, with these latter two muscles displaying no significant differences. The significantly greater change in VM $f_{\text{med}}$ mean (i.e., decrease) in the women compared with the men was quantified as a small effect size ($\eta^2 = 0.09$; Fig. 1) and should, therefore, be interpreted with caution. In other words, the inherent variability of $f_{\text{med}}$ within a contraction (Table 2) may be used as the “yardstick” in lieu of statistically significant results. Within this context, the demonstrated significant effects for the RF and VM muscles approximate to a 5- to 8-Hz and a 5- to 6-Hz difference, respectively. These statistical differences in mean $f_{\text{med}}$ fall within the range of expected $f_{\text{med}}$ variability for any given contraction (Table 2). In regard to $f_{\text{med}}$ variability, it was assumed in the present investigation that a systematic change (i.e., a decrease due to fatigue) across the 11 epochs was not present because of the short nature of the contraction. The possibility of a systematic change, however, was not specifically investigated in this study.

**Effects of contraction intensity.** To reiterate the function of the QF muscle, its role as a generator of knee extensor torque is critical for normal activities of daily living. Moreover, the relative activation of its different components has been shown to alter patellofemoral mechanics significantly (10) and may ultimately impact the presence of various knee pathologies (13, 33). The examination of an EMG frequency-domain statistic ($f_{\text{med}}$) to describe intermuscular differences within the QF may provide additional evidence toward the understanding of this muscle’s characteristics under voluntary conditions. This notion is deduced from experimental evidence regarding: 1) the presence of a greater number and higher density of Na$^+$ channels within the sarcolemma of fast-twitch muscle fibers, compared with slow-twitch muscle fibers (26); 2) the generation of higher frequency action potentials, and hence EMG signals, from fast-twitch muscle fibers (23); 3) the significant relation between the EMG $f_{\text{med}}$ and muscle fiber conduction velocity (23, 37); and 4) the progressive recruitment of fast-twitch muscle fibers at higher contraction intensities (7, 9, 17). Although it is well known that the surface EMG signal, as measured in the present study, provides limited evidence of specific motor unit recruitment or rate-coding changes, the observed $f_{\text{med}}$ statistic can be considered to be, in part, a reflection of muscle fiber-type activation (11, 23).
scientific literature, however, has not yielded absolutely consistent findings regarding $f_{\text{med}}$ changes as a function of contraction intensity. Petrofsky and Lind (30) demonstrated no relationship between contraction intensity and mean power frequency (MPF) of the forearm muscles. Similarly, Hagberg and Ericson (15) found that the MPF of the elbow flexors increased only at low-contraction intensities and became independent of contraction intensities >30% MVC. Subsequently, however, Broman et al. (5) demonstrated a significant increase in $f_{\text{med}}$ in the tibialis anterior muscle in eight healthy men during isometric contractions ranging from 10 to 100% MVC. It was not until the work of Moritani and Muro (28) that the raw data (i.e., frequency statistics) were presented to illustrate the magnitude of the contraction intensity effect. During a linearly increasing contraction (0–80% MVC) of the biceps brachii muscle, a significant increase in the MPF was observed in the 12 male subjects (MPF increase range = 89 ± 4.4 to 123 ± 7.8 Hz). It was also shown that the increase in MPF occurred concomitantly with greater motor unit spike amplitudes and firing frequencies, as detected by intramuscular recordings. To support the findings of Moritani and Muro regarding the tibialis anterior muscle, Cioni et al. (6) observed significant increases in $f_{\text{med}}$ of this muscle in both healthy men ($n = 15$) and women ($n = 15$) across isometric contraction intensities ranging from 10 to 100% MVC. Based on the data presented by Cioni et al., it appeared that $f_{\text{med}}$ increased from ~85 Hz at 10% MVC to 125 Hz at 100% MVC. Thus far, these observations suggest that sensitivity of $f_{\text{med}}$ to changes in contraction intensity may largely be dictated by the muscle in question. For instance, Bilodeau et al. (4) found statistically significant increases in $f_{\text{med}}$ in the anconeus and triceps brachii muscle isometric contractions that ranged from 10 to 90% MVC in 10% increments ($n = 13$ men, $n = 16$ women). However, the graphical representation of these data suggest only a moderate rise in $f_{\text{med}}$ (i.e., ~10–15 Hz), with the exception of the anconeus muscle in the male subjects (~35 Hz). These discrepant findings within the scientific literature appear to be present in the present investigation. Whereas only small changes in mean $f_{\text{med}}$ were observed across the contraction intensities for the VM and RF muscles, larger and consistent increases were only noted for the VL muscle. It can be reasonably speculated that contraction intensity differences for the VM and RF are attributable to the inherent nature of the EMG as a “quasi-random” signal (32) and to the observed variability within the present study (Table 2). As very limited data suggest that the VM muscle contains a relatively higher proportion of slow-twitch muscle fibers (20, 40), research with larger sample sizes demonstrates a wide variation in muscle fiber types of the VL muscle (36). As a result, increasing contraction intensities that progressively recruit fast-twitch fibers may give rise to higher frequency EMG signals if a high degree of muscle fiber-type heterogeneity were present.

Effects of QF muscle differences. Optimal function of the knee joint is highly dependent on the coordinated action within the QF complex. It is becoming ever more apparent that the components of the QF exhibit different cross-sectional areas (43), fiber angles (29, 33), muscle fiber types (20, 40), contributions to knee extensor torque (10, 29, 34), and activation characteristics (1, 31). The examination of the EMG signals from the present experimental procedure in the time domain (i.e., full-wave rectified, integrated, and normalized to the MVCs) demonstrated nonparallel increases in activation of these muscles at higher contraction intensities (31), which were recently supported by the findings of Alkner et al. (1). The overall higher $f_{\text{med}}$ values for the VL, compared with the VM and RF muscles, concur with the findings recently published during the performance of the three MVCs of the present subjects (32). These results are, however, contrary to the findings of Weir et al. (42) during a sustained 50% MVC, Ebenbichler et al. (8) during three successive MVCs, and Gerdle et al. (11) during 25 and 75% MVCs, in which intramuscle differences were not present. It is noteworthy to point out that $f_{\text{med}}$ values reported in previous studies (3, 8, 41) are typically lower (i.e., 68–105.7 Hz) than those in the present investigation. The methodology of the present investigation incorporated a 2-cm interelectrode distance, which is narrower than that used by others (3, 41), that may account for the observed higher values. This is due to the fact that a larger interelectrode spacing acts as a low-pass filter, thereby attenuating higher frequency signals and biasing the $f_{\text{med}}$ toward a lower value. It may also be argued that a better representation of $f_{\text{med}}$ was obtained in the present investigation as a result of the 11 overlapping epochs. The variability of $f_{\text{med}}$ within a single contraction illustrates a relative fluctuation of power spectral density statistics, even for brief, submaximal, isometric, constant-force contractions. Such variability should be taken into consideration in cases in which these statistics are used to objectify the effects of various interventions, such as training or disease, on neuromuscular function. The $f_{\text{med}}$ values that are comparable with the present investigation have been shown for the anconeus muscle (160–180 Hz) and the tibialis anterior muscle (75–125 Hz) (4, 6). The differences among the superficial QF portions in the present study may be reflective of existing variations in muscle fiber types among these muscles.

Gender differences. The examination of a gender difference in muscle characteristics has partially been fueled by recent data demonstrating the higher incidence of knee injuries in female athletes than in their male counterparts (14). The results from the present study demonstrated that the increase in VL $f_{\text{med}}$ from contraction intensities of 10–90% MVC was significantly greater in men than women. These results appear to be supported by the findings of Cioni et al. (6), who observed that women exhibited a “slower” increase in $f_{\text{med}}$ than do men. Similar findings were also presented by Bilodeau et al. (4), namely, that men dis-
played a significantly greater increase in $f_{\text{med}}$ of the anconeous muscle across the submaximal intensity spectrum than did women. As female VL muscle has been typically shown to exhibit a greater proportion and smaller type I muscle fibers than male (35), the potential range of $f_{\text{med}}$ values may be limited. It is critical to highlight that the characteristics of the surface EMG signal are a manifestation of a progressive increase in type I to type II muscle fiber recruitment as contraction intensity increases. Because the $f_{\text{med}}$ statistic is commonly used to quantify muscle fatigue, for instance, consideration of a contraction intensity effect should be made evident in such an evaluation. Unfortunately, very little data are apparent in the scientific literature regarding $f_{\text{med}}$ of the superficial QF muscle across the range of submaximal contraction intensities in men and women. It should also be pointed out that such differences in EMG $f_{\text{med}}$ between men and women are likely affected by the low-pass-filtering effect of subcutaneous tissue. This relationship has been demonstrated by Bilodeau et al. (4) during submaximal contraction of the triceps brachii and anconeous muscles. Significantly higher levels of skinfold thickness in women were correlated with lower EMG frequency measures. Although the present study is limited by the fact that skinfold thickness was not obtained, such an effect may have been manifested in the VL muscle only, as a gender-specific pattern regarding $f_{\text{med}}$ was not clearly evident for the other muscles. However, the findings from the present study suggest that previously demonstrated differences in muscle fiber-type profiles of the VL muscle between men and women (35) are reflected in the $f_{\text{med}}$ statistic as contraction intensity increases from low (10% MVC) to near-maximal levels. This presumption, coupled with the established effect of skinfold thickness on attenuation of high-frequency components, provides ample rationale for the VL muscle to be a unique muscle for EMG investigations between men and women.

Summary. Distinct differences in QF muscle structure and function are clearly apparent, as outlined. The results of the present study demonstrated that this fact is also reflected in the surface EMG signal. It is speculated that the sensitivity of $f_{\text{med}}$ to reflect progressive muscle fiber recruitment is dependent on the profile of the muscle. Muscles that contain a relatively greater proportion of type I fibers may not demonstrate increases in $f_{\text{med}}$ with greater forces, despite the additional recruitment of these fibers. As a result, the ability to document progressive muscle fiber recruitment with the $f_{\text{med}}$ statistic may be limiting in muscles with significant muscle fiber-type homogeneity. It is apparent, however, that this measure is useful and may be applicable to many different situations when muscle activation characteristics of the VL muscle are examined.

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