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ORIGINAL ARTICLE

Danny M. Pincivero · Alan J. Coelho
Robert M. Campy · Yuliya Salfetnikov · Ashley Bright

The effects of voluntary contraction effort on quadriceps femoris electromyogram median frequency in humans: a muscle and sex comparison

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Abstract The purpose of this study was to examine the effect of voluntary contraction efforts on the median frequency (f_{med}) of the electromyogram (EMG) recorded from the quadriceps femoris muscle in healthy men and women. A group of 30 healthy volunteers (15 men, 15 women) were assessed for EMG activity of the vastus medialis (VM), vastus lateralis (VL), and rectus femoris (RF) muscles during isometric contractions with the knee at 60° flexion. Subjects performed a series of 5 s maximal voluntary isometric contractions that anchored the perceptual range with a "10" on a 10-point scale. Sub-maximal isometric contractions were then separately performed at the following perceived effort levels on the 10-point scale: 1, 2, 3, 4, 5, 6, 7, 8 and 9, in a random order. Subjects were instructed to maintain the contraction at each perceived level of effort for 5 s. The f_{med} of the three muscles was assessed using a power spectrum analysis performed over 11 consecutive, 512 ms, epochs overlapping each other by half their length during the middle 3 s of each contraction. The f_{med} for each of the 11 epochs was then determined for each muscle, followed by calculation of the means and normalized coefficients of variation [(standard deviation/mean)×100%] for each contraction. The results demonstrated that the mean f_{med} of VL was significantly greater than those of the other two muscles, and that f_{med} of RF was significantly greater than that of VM. The VL muscle demonstrated a significant increase in mean f_{med} across the contraction efforts, compared to the VM and RF muscles that displayed a significant decrease. The men displayed significantly higher f_{med} values for the VM muscle than did the women, as well as showing a significantly greater increase across the contraction efforts for the VL muscle. The variability of f_{med} was shown to be significantly higher for the VM muscle, compared to the VL and RF muscles. The findings of this study suggest that the f_{med} statistic is most sensitive to contraction intensity efforts for the VL muscle, and that men display significantly higher values for the VL and VM muscles, compared to women.

Keywords Vastus medialis · Vastus lateralis · Rectus femoris · Median frequency of electromyogram

D.M. Pincivero (✉)
Human Performance and Fatigue Laboratory,
Department of Kinesiology, The University of Toledo,
Toledo, OH 43606 USA
E-mail: danny.pincivero@utoledo.edu
Tel.: +1-419-5305291
Fax: +1-419-5302759

A.J. Coelho · R.M. Campy · Y. Salfetnikov · A. Bright
Department of Physical Health and Recreation,
Eastern Washington University, Cheney, WA, USA

Introduction

The quadriceps femoris (QF) muscle is a unique group of four anatomically distinct muscles that share a common nerve innervation (i.e. the femoral nerve) and function (i.e. generating knee extensor torque, Hollinshead and Rosse 1985; Linnamo et al. 2001). Given that the vastus medialis (VM), vastus lateralis (VL), vastus intermedius, and rectus femoris (RF) muscles are the constituents of this major muscle group, it has been speculated that insufficient function of any, or all, of these muscles may significantly compromise lower extremity function (Grabiner et al. 1994; Raimondo et al. 1998). It may, therefore, be surmised that inter-muscle differences in force generating ability (Salzman et al. 1993; Farahmand et al. 1998), muscle fiber angle (Raimondo et al. 1998; Linnamo et al. 2001), muscle fiber type (Johnson et al. 1973; Travnik et al. 1995), and electromyogram (EMG) parameters (Alkner et al. 2000; Pincivero and Coelhho 2000; Pincivero et al. 2000, 2001), are compensated to allow well-coordinated actions maintaining the efficiency of the knee joint. One specific factor that has demonstrated a significant effect on the pattern of differential muscle activation is the level of intensity of the contraction (Alkner et al. 2000; Pincivero and Coelhho 2000; Pincivero et al. 2000). Recent investigations by Alkner et al. (2000), and Pincivero and Coelho (2000) showed a significantly greater increase in VM activation at relatively higher levels of torque, as evidenced by the normalized time-domain EMG signal, compared to the VL and RF muscles. An approach that has not been utilized extensively when examining the EMG signal in the frequency-domain is magnitude production, in which individuals contract their muscles or exercise to intensities that are gauged by their perceptual feelings of exertion. Although a pattern of muscle activation to a progressive increase in knee extensor torque has been demonstrated, such patterns during perceptually guided contractions have not been shown. The performance of voluntary muscle contractions as guided by perceptual cues may lend insight into the mechanisms driving motor control of sub-maximal tasks.

The most widely used and, perhaps, the most valid parameter of the EMG signal in the frequency-domain is the median frequency (f_{med}) statistic, as significantly higher correlations with the proportions of muscle fiber-types have been observed when this has been estimated compared to the mean power frequency (MPF, Kupa et al. 1995). The f_{med} refers to the frequency in the sampled EMG bandwidth that divides the power spectrum into halves (Bilodeau et al. 1995), and is considered to reflect the conduction velocity of the action potential of the muscle fiber (Kupa et al. 1995). As mentioned, the scientific literature has revealed some inconsistent findings regarding the effects of the level of intensity of contraction on the f_{med} of the EMG. Some investigations have shown a negligible effect of the level of muscle force on the EMG f_{med} for the triceps brachii (Bilodeau et al. 1995), biceps brachii (Hagberg and Ericson 1982), muscles of the forearm (Petrofsky and Lind 1980), and the VM and RF muscles (Pincivero et al. 2001). It appears, however, that certain muscles generate spectrum parameters of the EMG (i.e. f_{med}) that are a function of the intensity of contraction (Broman et al. 1985; Bilodeau et al. 1992, 1995; Cioni et al. 1994; McNair et al. 1996; Pincivero et al. 2001). In a recent investigation by Pincivero et al. (2001), it was specifically demonstrated that the f_{med} of the VL EMG increased as a function of the level of intensity of the voluntary contraction during constant forces, and that the increase was found to be significantly greater in men compared to women. In addition to these findings, it was shown that the VL muscle displayed significantly higher f_{med} than the RF and VM muscles. As that recent study examined the f_{med} at constant levels of knee extensor torque, the present study sought to investigate this particular EMG statistic of the superficial QF muscle during muscle contractions guided by levels of perceived effort. In many instances, the intensity of a muscle contraction is often gauged by perceived levels of effort, rather than by contracting to a fixed level of force. As such, the relative torque output resulting from a perceptually guided muscle contraction should, theoretically, increase as the effort of voluntary contraction increases. In this regard, the f_{med} of the recorded EMG signal should demonstrate a pattern that reflects the degree of torque output. Therefore, the purpose of this study was to examine the effects of levels of perceived voluntary contractions on relative torque output, and inter-muscle and between sex differences in EMG f_{med}. It was, therefore, hypothesized that knee extensor torque would increase at relatively higher levels of perceived effort, thereby revealing a f_{med} pattern that reflects higher levels of constant torque.

Methods

Subjects

The present study incorporated a repeated measurements design. Subjects for this study consisted of 30 healthy male [mean (SD)] [$n=15$, age 24.6 (4.14) years, height 177.97 (9.77) cm, mass 77.79 (11.18) kg] and female [$n=15$, age 24.33 (5.16) years, height 166.96 (6.87) cm, mass 60.52 (6.19) kg] volunteers. It should be noted that the 30 subjects in the present investigation were different to those used in our recent study (Pincivero et al. 2001). All subjects were physically active, and no individuals with a history of cardiovascular disease, hypertension, or orthopedic pathology participated in this study. The experiment procedures were conducted in accordance with the Declaration of Helsinki, and all subjects provided written informed consent as approved by the Institutional Review Board at Eastern Washington University.

Measurement of isometric torque

Prior to the measurement of isometric torque, all subjects completed a warm-up that consisted of sub-maximal cycling for 5 min. Isometric torque was measured on the Biodex System II Isokinetic Dynamometer (Biodex Medical, Inc., Shirley, N.Y.). Subjects sat in a comfortable, upright position on the Biodex Accessory Chair and were secured using 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 chests and were given verbal encouragement, as well as visual feedback from the Biodex computer monitor, in an attempt to achieve a maximal voluntary effort (Hald and Bottjen 1987; McNair et al. 1996; Kim and Kramer 1997). The same investigator administered all tests and gave the verbal encouragement to all subjects. Calibration of the Biodex dynamometer was performed according to the manufacturers' specifications prior to every test. Once the subjects were seated in the chair, their knees were fixed at an angle of 60° flexion, which has been demonstrated to be the angle that generates maximal isometric force (Thorstensson et al. 1976; Tihanyi et al. 1982). Following two to three sub-maximal, followed by two to three maximal, contractions for familiarization purposes, subjects were asked to contract their QF as hard as they could (maximal voluntary contraction, MVC) and to hold this contraction for 5 s. This contraction was repeated four more times with a minimal rest of 2 min in between each contraction.

Constant effort contractions

The constant effort (sub-maximal) contractions were performed using a modified category-ratio scale (CR-10), as developed by Borg (1982). A modification of the CR-10 scale in the present study eliminated the numerical rating of 0.5 and all verbal descriptors, including "maximal". The use of this scale has been previously found to correlate positively with increasing levels of lactate accumulation, and it has also been suggested that qualitative changes in motor unit recruitment may be perceived (Noble et al. 1983). To provide the subjects with a context through which sensation intensities could be evaluated, anchor intensities at one high and one low level were applied under isometric conditions (Noble and Robertson 1996; Pincivero et al. 1999). Immediately following each MVC, subjects were instructed to "think about the feelings in your quadriceps during the contraction, and assign a rating of 10 to those feelings". Following the 2 min rest, subjects were asked to sit quietly while their knees were flexed to 60° (supported passively by the resistance adapter) and to "think about the feelings in your quadriceps and assign a rating of 0 to those feelings". Subjects then performed a single voluntary isometric contraction of the QF muscle at the following perceptual intensities: 1, 2, 3, 4, 5, 6, 7, 8, and 9. For example, subjects were instructed to "contract your muscles to a level that feels like 5, and to hold it at a 5". During each contraction, subjects were instructed to view the 10-point scale while the investigator pointed to the selected number. All subjects performed each contraction for 5 s with a rest of at least 2 min between contractions. The order of execution of the various exercise intensities was randomized. During none of the tests did the subjects have knowledge of the values of the absolute torques they were generating. For each contraction at the different perceived exertion levels, the average torque over the middle 3 s of the contraction (Newton meters) was calculated, and subsequently normalized to the average of the three highest MVC.

Measurement of f_{med}

The f_{med} was assessed using surface EMG for the VM, VL, and RF muscles. Pre-amplified bi-polar circular surface electrodes (Ag-AgCl-0.8 cm diameter) were placed on each muscle at a fixed inter-electrode distance (center to center) of 2 cm. Prior to 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 (ASIS) (Zipp 1982). This electrode was placed at an approximate 45° angle between the anatomical horizontal and sagittal planes in order to be oriented towards the longitudinal direction of the muscle fibers. Electrode placement for the VL was the mid-point between the head of the greater trochanter and the lateral femoral epicondyle (Housh et al. 1996), and electrode placement for the RF was 50% of the distance from the ASIS to the superior pole of the patella (Zipp 1982). The reference electrode was placed over the medial shaft of the tibia approximately 6–8 cm below the inferior pole of the patella. The EMG activity was collected at a rate of 1,000 Hz for each muscle (Therapeutics Unlimited, Iowa City, Iowa). The common mode rejection of this EMG system was 87 dB at 60 Hz with an input impedance greater than 25 MΩ at d.c. The gain range used in this study was 5,000 and signals were bandpass filtered between 20–500 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 Inc., Santa Barbara, Calif.) The signals collected within the first and last seconds of each 5 s isometric contraction were not used for analysis because of the 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 the power spectrum analysis. A fast Fourier transformation (FFT) of 512 points (Hamming window processing) was performed on 11 consecutive, 512 ms segments, overlapping each other by half their length (256 ms), over this portion (i.e. middle 3 s) of each contraction (Bilodeau et al. 1997; Pincivero et al. 2000). The f_{med} was determined from each of the 11 overlapping windows. The mean and normalized coefficients of variation [CV, (standard deviation/mean)×100%] of f_{med} in the 11 windows during each contraction was then calculated for each muscle. These two values were then used for statistical analyses. The integration algorithm used to calculate the area of the power frequency spectrum in the software program is as follows:

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

In this integration algorithm, $f(n)$ represents the data values (millivolts per second), and the Δt represents the horizontal sampling interval (seconds) (MP100 Systems Guide, Biopac Inc.).

Statistical analysis

A 3 factor repeated measurements ANOVA (sex×muscle×intensity) was performed on the mean and variability of f_{med}. When the overall F-test revealed an intensity or muscle main effect, or significant interaction, separate ANOVA were performed across the repeating levels of contraction intensity, and the Bonferroni-Dunn inequality was invoked to ensure the family-wise error rate (Glass and Hopkins 1996). To examine specifically the effects of contraction intensity and sex on changes in the f_{med}, separate two-way ANOVA (intensity×sex) were performed on each muscle to compare the values obtained at each intensity with 10% of perceived maximal effort. This was performed to examine significant changes across the range of contraction intensities. All tests of significance were carried out to ensure a family-wise error rate of 0.05.

Results

Descriptive data [means (standard deviations)] for the means of f_{med} and their variabilities for the VM, VL and RF muscles at each level of effort for the men and

Table 1. Descriptive data [means (SD)] for the mean median frequency (Hz) across 11 overlapping epochs for the vastus medialis, vastus lateralis, and rectus femoris muscles of men and women at sub-maximal levels of effort

Effort level	Vastus medialis		Vastus lateralis		Rectus femoris	
	Men	Women	Men	Women	Men	Women
1	128.65 (24.0)	122.29 (34.14)	156.33 (25.88)	162.74 (25.11)	128.43 (7.44)	169.24 (46.22)
2	121.57 (17.07)	108.83 (22.01)	153.19 (26.21)	155.94 (13.82)	128.84 (9.76)	143.39 (24.40)
3	117.81 (13.79)	104.50 (25.64)	158.95 (30.16)	152.37 (24.42)	132.81 (8.18)	137.32 (16.54
4	116.02 (15.32)	102.09 (15.79)	161.16 (29.73)	153.40 (20.48)	131.44 (11.09)	136.53 (16.86)
5	115.37 (19.18)	101.10 (17.20)	160.50 (32.25)	154.02 (22.54)	133.34 (11.73)	130.20 (15.43)
6	116.23 (16.27)	97.65 (12.07)	165.65 (31.29)	158.51 (20.88)	131.76 (12.11)	131.38 (18.32)
7	114.26 (17.46)	98.31 (12.17)	168.96 (27.87)	157.39 (21.64)	134.03 (14.81)	131.42 (17.00)
8	114.77 (15.93)	98.70 (14.73)	171.51 (29.70)	164.41 (24.62)	134.76 (15.60)	129.90 (19.01)
9	114.58 (16.19)	94.73 (12.13)	175.63 (29.73)	162.52 (19.79)	130.07 (14.30)	129.86 (17.33)

Table 2. Descriptive data [means (SD)] for the median frequency (Hz) normalized coefficients of variation (%) for 11 overlapping epochs of the vastus medialis, vastus lateralis, and rectus femoris muscles of men and women at sub-maximal levels of effort

Effort level	Vastus medialis		Vastus lateralis		Rectus femoris	
	Men	Womens	Men	Women	Men	Women
1	7.20 (2.98)	10.03 (7.03)	5.83 (2.29)	6.12 (2.22)	6.57 (2.04)	5.57 (1.47)
2	7.01 (1.51)	8.08 (2.25)	6.50 (1.74)	6.04 (2.15)	5.95 (1.57)	5.65 (1.44)
3	7.50 (2.97)	7.00 (2.59)	6.35 (1.72)	7.11 (2.14)	6.48 (1.74)	7.67 (4.25)
4	6.91 (1.66)	6.62 (1.88)	5.99 (2.07)	7.18 (2.29)	6.24 (2.14)	6.09 (2.30)
5	6.68 (2.08)	6.07 (2.11)	6.46 (1.81)	6.31 (1.81)	6.94 (2.65)	5.80 (1.52)
6	6.43 (1.82)	8.11 (3.83)	5.63 (0.87)	7.11 (3.49)	5.55 (1.28)	6.54 (2.75)
7	6.29 (1.24)	7.28 (2.02)	5.72 (2.38)	5.84 (1.70)	5.81 (2.91)	5.82 (2.66)
8	6.54 (2.03)	6.70 (1.74)	6.46 (1.76)	7.39 (3.07)	6.16 (2.21)	6.40 (1.61)
9	6.64 (2.51)	6.74 (2.24)	6.18 (2.24)	6.70 (1.71)	5.13 (1.29)	6.22 (1.32)

women are presented in Tables 1 and 2, respectively. The results demonstrated that the average torque output normalized to the three highest MVC increased significantly across the levels of perceived effort (Fig. 1).

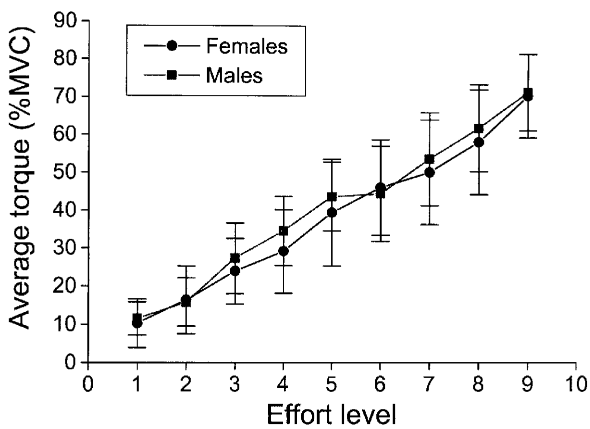

Fig. 1. Mean (SD) average knee extensor torque in men ($n = 15$) and women ($n = 15$) at levels of perceived effort from 1–9 (significant perceived effort main effect). MVC Maximal voluntary contraction

Muscle differences

The results demonstrated an overall significant main effect for muscle ($F_{2,\,56} = 61.30$, $P < 0.001$, $\eta^2 = 0.67$, $1-\beta = 0.99$) as mean f_{med} was significantly the highest for VL and the lowest for VM, with the value for RF in between the other two muscles (i.e. greater than VM and less than VL). The results also demonstrated a significant effort by muscle interaction ($F_{16,\,448} = 9.52$, $P < 0.001$, $\eta^2 = 0.25$, $1-\beta = 0.99$). Specifically, f_{med} was found to decrease significantly across successive levels of effort for the VM muscle compared to the increase in the VL muscle (Fig. 2).

The results for the variability of f_{med} (normalized CV) across the 11 overlapping epochs demonstrated a significant muscle main effect ($F_{2,\,56} = 8.06$, $P = 0.001$, $\eta^2 = 0.22$, $1-\beta = 0.95$) and a significant muscle by effort interaction ($F_{16,\,448} = 1.82$, $P = 0.03$, $\eta^2 = 0.06$, $1-\beta = 0.95$). The results indicated that the variability of f_{med} was highest for the VM muscle, compared to the VL ($F_{1,\,28} = 10.14$, $P = 0.004$, $\eta^2 = 0.27$, $1-\beta = 0.87$) and RF ($F_{2,\,56} = 27.47$, $P = 0.005$, $\eta^2 = 0.25$, $1-\beta = 0.84$) muscles. Following adjustment for the a priori family-wise α level (0.05/3 comparisons = 0.02), the overall muscle differences were found to be significant. The VL and RF muscles were not significantly different.

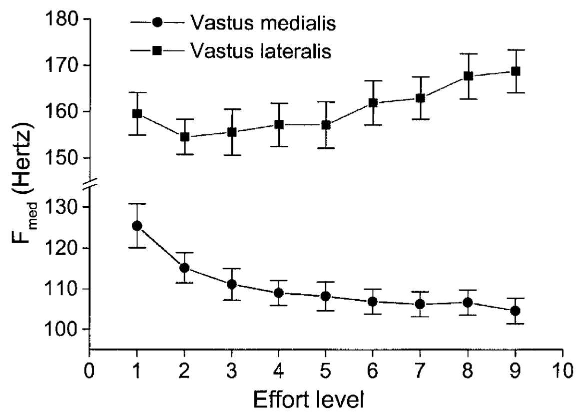

Fig. 2. Mean (SEM) median frequency (F_{med}) of the vastus medialis and vastus lateralis muscles ($n = 30$) at effort levels from 1 to 9 (significant effort×muscle interaction)

VM muscle

The results demonstrated a significant effort ($F_{8,\,224} = 10.25$, $P < 0.001$, $\eta^2 = 0.27$, $1-\beta = 0.99$), and sex main effect ($F_{1,\,28} = 6.64$, $P = 0.016$, $\eta^2 = 0.19$, $1-\beta = 0.70$), and no significant effort×sex interaction. The f_{med} was found to decrease significantly from effort levels 1–9 (VM muscle, Fig. 2), while the overall values across the effort levels were significantly higher in men than in women.

VL muscle

The results for the VL muscle demonstrated a significant effort main effect ($F_{8,\,224} = 6.74$, $P < 0.001$, $\eta^2 = 0.19$, $1-\beta = 0.99$), a significant effort×sex interaction ($F_{8,\,224} = 2.44$, $P = 0.015$, $\eta^2 = 0.08$, $1-\beta = 0.90$), and no significant main effect of sex. These findings show a significantly greater increase in f_{med} of VL across the range of effort levels in men compared to women (Fig. 3).

RF muscle

The results for the RF muscle demonstrated a significant effort main effect ($F_{8, 224}=5.11$, $P<0.001$, $\eta^2=0.15$, $1-\beta=0.99$), a significant effort×sex interaction ($F_{8, 224}=8.31$, $P<0.001$, $\eta^2=0.23$, $1-\beta=0.99$), and no significant main effect of sex. Overall, the main effect for effort demonstrated a significant decrease in f_{med} across effort levels 1–9. However, the significant interaction demonstrated that women displayed a significant decrease in f_{med} from effort level 1 to effort levels 3–9, compared to the men who demonstrated a minimal change in f_{med} across the effort levels (Fig. 4). Following the Bonferonni-Dunn adjustment to maintain the family-wise error rate (0.05/8 comparisons = 0.006), these interactions were found to be statistically significant.

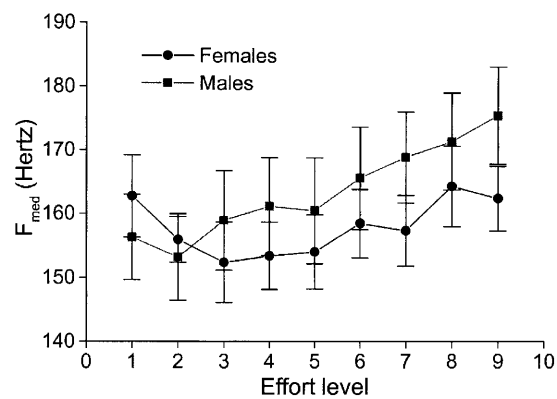

Fig. 3. Significantly greater increase in median frequency (F_{med}) of the vastus lateralis muscle in men ($n=15$) compared to women ($n=15$), across the range of levels of effort (mean and SEM)

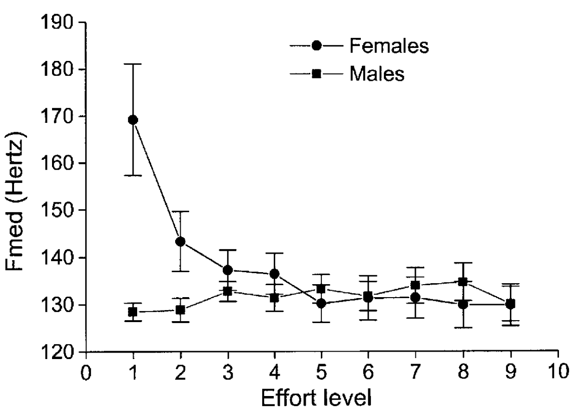

Fig. 4. Significantly greater decrease in median frequency (F_{med}) of the rectus femoris muscle in women ($n=15$) compared to men ($n=15$), across the range of levels levels (mean and SEM)

Discussion

The major findings of this study demonstrated that the overall f_{med} of the VL muscle was significantly higher than the RF and VM muscles, while the f_{med} of RF was greater than that of VM. It was also apparent that the only muscle that demonstrated a consistent increase in f_{med} across the successive effort levels was the VL muscle; in this particular case, the increase was found to be significantly greater for men than women. The f_{med} was also shown to be significantly higher in men than women for the VM muscle, which did not appear to be sensitive to the effort level. Another important, yet potentially misleading, finding relates to the significant decrease in the f_{med} of RF for the female subjects (Fig. 3), and the decrease in f_{med} of VM in all subjects (Fig. 2). This result clearly demonstrates (Fig. 3) that this decrease occurred across the first two effort levels, where very low knee extensor torque was generated. In this manner, it is speculated that a small signal to noise ratio at these low effort levels skewed the mean of f_{med} to higher values (Weir et al. 1996). The calculated variability about the 11 overlapping epochs for the calculation of a mean f_{med} was shown to be significantly the higher for the VM muscle, while the VL and RF muscles were not significantly different. Relative torque output was observed to increase across the levels of perceived contraction.

QF muscle differences

As indicated earlier, the QF muscle group receives a common nerve innervation (i.e. the femoral nerve), and its individual muscle components function in a concerted fashion to generate knee extensor torque during many different types of daily and exercise-related activities. Despite these two common characteristics, the individual muscles comprising the QF group have been shown to display a different EMG pattern (i.e. time-domain parameters) during isolated contractions. During constant torque, sub-maximal isometric contractions (10%–90% MVC, 10% increments), Pincivero and Coelho (2000) demonstrated a significantly greater increase in VM activation at near maximal intensities compared to the VL and RF muscles. Alkner et al. (2000) also observed an effect of contraction intensity on the VM muscle during isometric contractions. Descriptions of the EMG signals in the frequency-domain, however, have revealed conflicting findings regarding differences within the QF muscle. No differences in f_{med} of the superficial QF components have been observed during a maintained 50% MVC (Weir et al.1996), three successive MVC (Ebenbichler et al. 1998), or 25% and 75% MVC (Gerdle et al. 1997). However, in a recent investigation, f_{med} of the superficial QF was examined during a series of sub-maximal isometric constant torques in 30 healthy subjects, in which evidence was presented that corroborates the results of the current study

(Pincivero et al. 2001). The normalized average torque illustrated in Fig. 1 demonstrates an increase at progressively higher levels of perceived effort, supporting the pattern of f_{med} for the VL muscle. In the light of these findings, it is tempting to conclude that there exists a definitive frequency profile for the EMG of the QF muscle. Contrary results were reported by Mannion and Dolan (1996), in 10 healthy volunteers performing isometric QF contractions at intensities ranging from 20% to 60% MVC in which the f_{med} of the RF muscle was significantly higher than that of the VL muscle. Using an experimental approach similar to that of the present study, Linnamo et al. (2001) recently reported no significant differences in f_{med} between the superficial QF muscles during brief contraction efforts at 40%, 60% and 80% MVC in 10 healthy men. Methodologically, a number of other factors could provide a viable explanation for the different results of these numerous studies; such factors include electrode type (i.e. size, shape and inter-electrode distance) and location on the muscle sampled (Baratta et al. 1998; Merletti et al. 2001). In addition, the length of the sampling window for the FFT analysis, which differed between the present study and Linnamo et al. (2001), may have contributed to these discrepant findings. From a physiological perspective, however, it may be speculated that the higher f_{med} for the VL muscle may be a reflection of a significantly greater proportion of fast-twitch (FT) muscle fibers, compared to the other two muscles. This notion is based on evidence demonstrating that:

1. The larger FT muscle fibers exhibit higher conduction velocities of the action potential that give rise to higher f_{med} (Sadoyama et al. 1988; Kupa et al. 1995)
2. The VM muscle has been shown to be composed predominantly of slow twitch (ST) muscle fibers (Johnson et al. 1973; Travnik et al. 1995).

Such an explanation may be plausible given the additional role of the VM muscle in medial patellar stabilization (Grabiner et al. 1994; Levangie and Norkin 2001), in which this muscle is recruited cyclically at low contraction intensities during most ambulatory activities. In this case, the predominance of ST muscle fibers would prove to be an advantage due to their ability to generate force at relatively lower levels for a long period of time. Such a presumption, however, necessitates additional investigation into the morphology of the different components of the QF muscle.

Contraction effort and sex differences

The influence of the level of contraction effort on time-domain parameters of the EMG signal (i.e. amplitude) has demonstrated definitive linear and non-linear relationships. Such an effect on the frequency statistics of the EMG signal, however, has yielded more subtle results. The most notable finding in the present study in this regard is the significantly greater increase in the f_{med} of VL in the men, compared to the women. This result concurs with that of our previous study which demonstrated this effect during isolated, isometric contractions of QF ranging from 10% to 90% MVC, in 10% increments (Pincivero et al. 2001). Such findings, however, are contrary to those of Mannion and Dolan (1996), who demonstrated small, yet statistically significant, increases in the f_{med} of VL and RF in 10 healthy men and women from contraction intensities of 20%–60% MVC. Much larger effects of contraction effort on the MPF of the EMG were demonstrated by Moritani and Muro (1987) in the biceps brachii muscle from contraction intensities of 0%–80% MVC. The effect, however, was not observed for the superficial muscles of QF by Linnamo et al. (2001) at 40%, 60%, 80% and 100% MVC. As indicated earlier, methodological differences may have accounted for the contrary findings specific to the VL muscle compared to the present investigation. In other studies examining the combined effects of sex and contraction intensity on the f_{med} of the EMG, the outcome appears to have been muscle specific. Cioni et al. (1994) observed a significant increase in the f_{med} of the tibialis anterior muscle in 15 men and 15 women during isometric contractions ranging from 10% to 100% MVC, with a steeper increase occurring in the male subjects. Bilodeau et al. (1992) also demonstrated a significantly greater increase in the f_{med} of the triceps brachii, anconeus, and biceps brachii muscles in men from contraction intensities of 10%, 20%, 40%, 60%, and 80% MVC. The f_{med} of RF and VM did not display any sensitivity to contraction effort, with the exception at the lower effort contractions in the present study, which is also in agreement with our previous investigation (Pincivero et al. 2001).

As speculated earlier regarding possible muscle fiber-type differences between the component muscles of QF, this pattern may also be present between the sexes. The successive recruitment of more FT muscle fibers at higher contraction efforts (Henneman 1979; DeLuca et al. 1982) may skew the f_{med} of the EMG to higher values (Merletti et al. 2001). As men have been shown to display a significantly greater proportion of FT muscle fibers in the VL muscle compared to women (Simoneau and Bouchard 1989), that VM and RF muscle have not demonstrated this profile may mainly be due to the inherent limitations of obtaining samples in these latter two muscles. Therefore, this physiological rationale underlying the results of the present investigation remains plausible, yet speculative.

f_{med} variability

As the f_{med} statistic of the EMG is widely used as an indicator of progressive muscle fatigue, it is prudent to obtain accurate results for this parameter. One such attempt to enhance accuracy, as used in the present study, is the use of successive, overlapping epochs during a maintained contraction (Bilodeau et al. 1992;

Pincivero et al. 2000, 2001). The use of this procedure also allows for the documentation of the variability of f_{med}. The results of the present study demonstrated that this variability, as calculated through the normalized CV, was significantly greater for the VM than the VL and RF muscles, and was affected only to a small degree ($\eta^2 = 0.06$) by the level of effort. Although these results are contrary to our recent studies (Pincivero et al. 2000, 2001), in which the variability of f_{med} was highest for the VL muscle, it should be highlighted that normalization was not performed. In relative terms, the data from the present study suggests an inherent 5%–10% variability in f_{med} for the superficial QF muscles within a given brief sub-maximal contraction. Similar results were reported by Linnamo et al. (2001), in which the f_{med} statistic varied between 16.7 and 23.2 Hz over a 1 s period during brief isometric contractions of QF. What should also be of concern is the possibility of a systematic change (i.e. decrease due to fatigue) in the f_{med} of the EMG during the 3 s period analyzed. Recently, Lariviere et al. (2001) examined this potential factor in four back muscles during sub-maximal isometric contractions at 10%, 20%, 40%, 60%, and 80% MVC. The results from this study demonstrated that only the left multifidus muscle showed a small (i.e. approximately 10 Hz), yet statistically significant decrease in f_{med}, at the third sampled 250 ms epoch at the end of the 3 s contraction. Although this decrease in f_{med} appears to correspond to the upper limit of absolute variability parameters (Pincivero et al. 2000), this result was found for only one muscle, and the f_{med} was determined for a smaller sampling epoch (250 ms), which is known to increase variability (Bilodeau et al. 1997). From a physiological perspective, variability in f_{med} is probably of limited value due to the inherent nature of the surface EMG signal as "quasi-random" (Knaflitz and Bonato 1999; Pincivero et al. 2000). Practically, however, variability in f_{med} is a very important consideration when attempting to use this frequency statistic to differentiate between variables or interventions.

Summary

As outlined, the superficial components of the QF muscle have demonstrated specific structural, mechanical and myoelectric characteristics. The findings of the present study appear to corroborate our previous investigation (Pincivero et al. 2001) regarding contraction effort and sex effects on the VL muscle. In comparison with other studies in the scientific literature, the current findings also suggest that sensitivity of the f_{med} of the EMG to an increase in contraction intensity is muscle specific. Although the practical, or clinical, application of the f_{med} statistic of the surface EMG signal is not yet clearly defined, the results of the present investigation as well as findings in the scientific literature suggest the presence of a muscle-specific pattern. In this context, application of this muscle-specific pattern to more commonly studied aspects of the f_{med} of the EMG, such as muscle fatigue, may lend greater insight into muscle function. An ever-important consideration, however, when interpreting frequency parameters of surface EMG is the inherent signal variability and specific technical details of the methodological approach.

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