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Sex Differences in Quadriceps & Hamstrings EMG-Moment Relationships

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Abstract

Purpose—To evaluate sex differences in quadriceps and hamstrings muscle EMG-moment relationships when the muscles were acting as agonists and antagonists across the range of contraction intensity.

Methods—Twenty-two age and activity-level matched young people (11 females, 11 males) with no history of serious lower extremity injuries participated in this study. Muscle specific EMG-moment relationships were determined for the quadriceps and hamstrings muscles when acting as agonists and antagonists during isometric target matching at ten loads ranging from 10% to 100% peak moment. Sex differences in quadriceps and hamstrings muscle activation were assessed across the normalized moment spectrum.

Results—Females had significantly higher vastus medialis activity than males during knee extension trials at 10%, 20%, and 30% peak moment ($P < .05$). Significant sex differences were broadly observed in the subjects' quadriceps muscle EMG-moment relationships (females displayed higher activity) during knee flexion trials ($P < .05$). Conversely, no sex differences were observed in the subjects' hamstrings muscle EMG-moment relationships. The shape of the EMG-moment relationships in agonist contractions were variable with linear patterns observed in the rectus femoris, semitendinosus, and biceps femoris muscles, and nonlinear patterns observed in the vastus medialis and vastus lateralis muscles. Antagonistic muscle activity increased with increases in moment magnitude.

Conclusions—The results of this study provide evidence of some sex differences in quadriceps muscle EMG-moment relationships. Conversely, the activation patterns for the hamstrings muscles were similar between the sexes. The consistent association between antagonist activity patterns and moment magnitudes supports the idea that the control of agonist-antagonist activity in the thigh muscles is linked.

Keywords

knee moment; isometric; sex; muscle activation; thigh; neuromuscular control

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Introduction

Neuromuscular function has been implicated as a primary contributor to the higher incidence of non-contact ACL injuries and patellofemoral disorders in females when compared with their male counterparts (2,8). Several research reports indicate that females exhibit higher quadriceps activity, altered coactivity patterns between the quadriceps muscle and its antagonists, and-or differences in the timing of quadriceps muscle recruitment when compared with males performing the same tasks (4,12,16,20,32). The natural tendency is to conclude that the higher quadriceps activity observed in females may alter knee joint loads and thereby increase their risk for knee injury. This is a reasonable hypothesis considering the results of the above studies and related epidemiology; however, there is an underlying assumption that the relative load associated with each unit of normalized quadriceps activity is similar in males and females.

Recent research provides evidence that athletic females generate significantly higher quadriceps activity than age and activity-level matched males when performing isometric knee extension at the same relative target load (30% maximum, the only load evaluated in the study) (12). Additional evidence indicates that females display higher antagonistic quadriceps activity than males when performing isometric flexion contractions (13,34). Together the results of these studies suggest that males and females may characteristically have different agonist and antagonist EMG-moment relationships. Therefore, the higher quadriceps muscle activity and altered coactivity patterns often observed in females may simply be related to their force production strategies and may produce no greater loads at the knee than are observed in their male counterparts. Hence, it is possible that the increased/ altered quadriceps activity often observed in females is in fact benign. It is important to note, however, that the results of these studies were obtained at a narrow range of forces/moments (either 30% maximum or maximum). It was unknown whether the observed sex differences in quadriceps activity were unique to certain parts of the EMG-moment spectrum or a more global phenomenon. A more complete understanding of thigh muscle activity patterns over the range of contraction intensity was needed to clarify this issue and its potential implications. Moreover, further definition of thigh muscle activation strategies of males and females across the moment spectrum would add to our current understanding of human physiology and have relevance to anatomical, physiological, and biomechanical theory. Therefore, the purpose of this study was to examine and contrast the quadriceps and hamstrings muscle activation of females and males during isometric knee extension and flexion across the moment spectrum (10% to 100% peak moment). Based on pilot tests in our laboratory we hypothesized that females would display higher magnitudes of vastus medialis and vastus lateralis activity than males in the lower half of the knee extensor moment spectrum and also exhibit higher magnitudes of antagonistic quadriceps activity throughout the range of flexion moments. Conversely, we hypothesized that no significant differences would be observed in the hamstrings muscle EMG-moment relationships of the two groups.

Materials and Methods

Subject Screening

Twenty-two subjects with no history of serious lower extremity injuries volunteered to participate in this study. The sample consisted of 11 males (mean age: 24.0 ± 2.19) and 11 females (mean age: 24.18 ± 2.48) who were regular participants in sports or fitness activities (Tegner Activity Scores: male 6.45 ± 0.69 , female 6.0 ± 1.0) (30). Prior to enrollment, subjects completed a brief questionnaire regarding their activity profile and lower extremity health status. A brief lower extremity physical examination was then performed bilaterally to confirm the subjects had no signs of conditions that would exclude them from participation. Exclusion criteria included a history of: significant lower extremity muscle injury, major knee ligament injury, knee surgery, abnormal KT-2000™ evaluation (> 3 mm side-to-side difference in laxity) (6), ankle sprain or fracture within the prior six months, lower extremity nerve injury, knee joint effusion, abnormal gait pattern, or evidence of any health condition that would adversely impact the validity of the study. No potential subjects were excluded from the study based on physical exam or medical history. All subjects provided written informed consent to participation using a form approved by the University of Iowa Human Subjects Research Institutional Review Board.

Subjects were asked to refrain from any strenuous physical activity for 24 hours prior to testing. Testing began by having subjects perform a 5-minute warm-up on a cycle ergometer followed by self-directed stretching of the thigh musculature. Voluntary activation of the quadriceps muscles was then evaluated using a burst interpolated twitch technique (17,24). This test was performed so that we would be able to assess whether completeness of quadriceps muscle activation was a contributing factor to any differences in quadriceps activity patterns observed between the sexes. The test was performed on a HUMAC NORM Testing and Rehabilitation System (Computer Sports Medicine, Inc., Stoughton, MA, USA) with the subject secured according to the manufacturer's recommendations. The knee was positioned at 60° of flexion and the hip at approximately 90° of flexion. After cleansing the skin of the thigh with isopropyl alcohol, two self-adhesive surface electrodes ($2.75 \text{ in} \times 5 \text{ in}$, Dura-Stick II, Chattanooga Group, Hixson, TN, USA) were applied over the vastus lateralis muscle proximally and largest part of the vastus medialis distally (27). The current intensity of the burst of electrical stimulation imposed during the test was set at subject-specific levels that were determined by gradually increasing the intensity of the stimulator in steps of 100 mA until the torque associated with the stimulus-induced muscle contraction plateaued and decreased. The current intensity was then decreased by 50 mA and a final stimulus was introduced. The current intensity producing the largest torque was selected for use in testing. After a three minute rest period, subjects performed three knee extension and three knee flexion maximal voluntary isometric contractions (MVICs) in alternating fashion with three minutes of rest between each like trial. Loud verbal encouragement and visual feedback of the real-time torque curves were provided during testing to facilitate maximal effort. Approximately three seconds after the onset of each knee extension MVIC, a train of electrical pulses (10 pulse, 100 Hz, 200 μs pulse duration, 400V) at the predetermined stimulus intensity (range = 250 to 400 mA) was superimposed on the subjects' maximal effort using a high voltage constant current stimulator (model DS7AH, Digitimer Ltd.,

Hertfordshire, England). The stimulator was triggered using a program written in LabVIEW v. 7.0 (National Instruments Corp., Austin, TX, USA). The magnitude of quadriceps activation was calculated with the following equation:

$$\% \text{Activation} = \left[1 - \frac{\text{stimulation induced torque during MVIC}}{\text{stimulation induced torque at rest}} \right] \times 100 \quad [1]$$

After testing voluntary quadriceps activation, a 3-inch fiberglass cylinder cast was applied to the distal shank with its mid-point approximately 7.5 cm proximal to the medial malleolus and then rigidly fixed to a 6-axis force/torque transducer (model Delta F/T DAQ SI-660-60, ATI Industrial Automation, Apex, NC, USA) using a custom-designed clamping device (Figure 1). Muscle specific EMG-moment relationships were determined by having subjects match knee extension and knee flexion moment targets at ten normalized magnitudes (10% to 100% peak voluntary torque in 10% increments). Subjects viewed the moment targets and real-time feedback of their target matching efforts on a LCD monitor placed in front of them. To match the targets, subjects moved a cursor from the center of the monitor and positioned it over the target by applying loads against the force/moment transducer (Figure 2). Subjects were provided with several practice trials at 30% of their peak torque to familiarize them with the methods and minimize the effects of task novelty and learning. Subjects then matched targets at the 10 moment magnitudes. These moment magnitudes appeared one at a time at the 12 o'clock position (extension) and subsequently the 6 o'clock position (flexion) until the entire range moments had been tested. The distance from the cursor origin in the center of the screen to the moment targets was constant irrespective of the moment magnitude being tested; the load required to move cursor one pixel (the unit of distance) varied proportionately with magnitude. The moment targets were presented in random order to minimize systematic error associated with the presentation of target loads. Electromyographic (EMG) data were recorded from the muscle bellies of the semitendinosus, biceps femoris, vastus lateralis, rectus femoris, and vastus medialis during the 200 milliseconds target matching period using differential surface preamplifiers (model 544, Therapeutics Unlimited, Inc., Iowa City, IA, USA; 35× differential gain, 87 dB common-mode rejection at 60 Hz, input impedance > 25 MΩ, noise < 2 μV RMS). Electrode placement sites were selected according to the recommendations of Perotto (22). Subjects sat on a small platform placed on the test system's chair to minimize the potential for electrical noise associated with pressure on the EMG preamplifiers fixed over the hamstrings muscles. A common ground was placed over the skin of the patella. Two extension and two flexion trials were performed at each torque target. The average of the two trials at each load was used in analysis. After testing was completed on the first leg, the subjects' opposite side was tested in the same fashion.

Signal Sampling, Conditioning, and Processing

Signals were sampled at a frequency of 1000 Hz. The EMG signals were conditioned using an 8th order analog Butterworth low-pass filter (SCXI-1143, National Instruments Corp., Austin, TX, USA) with a 500 Hz cut-off frequency. The signals from the HUMAC NORM Testing System were low-pass filtered at 10 Hz and then converted to torque values (N·m) using calibrated conversion factors that were validated onsite prior to testing. The EMG

signals were baseline removed, full-wave rectified, and averaged during the 200 millisecond target-matching epoch. Normalization of the EMG recordings was performed using maximal EMG values recorded during MVIC testing that took place just before the target matching tests. The magnitude of antagonist muscle activity present during testing (hamstrings muscle activity in extension trials and quadriceps muscle activity in flexion trials) was determined by representing the values recorded when the muscles were antagonists as a percentage of the respective values recorded when the muscles were agonists.

Data Analysis

All statistical analyses were performed using SPSS for Windows version 15.0 (SPSS Inc., Chicago, IL, USA). A one-way ANOVA was used to evaluate whether significant differences existed in the demographic profiles of the male and female subjects. Repeated measures ANOVA with side as a within-subjects factor and sex as a between subjects factor was performed for each dependent variable to identify significant differences in agonist and antagonist activity of the knee muscles between sexes across the moment spectrum. Repeated measures ANOVA was also used to test for differences in peak quadriceps voluntary activation values between the sexes. Pearson product moment correlation was used to evaluate the association between voluntary activation test results and magnitude of quadriceps muscle activity at each sub-maximal moment target level where significant differences were observed between the sexes. Pearson product moment correlation was also used to examine the relationship between antagonist activity levels and moment magnitudes. Lack of fit tests were used to evaluate whether or not a linear model would explain the EMG-moment relationships of the agonist and antagonist muscles. Statistical significance was set at $\alpha = 0.05$.

Results

Subject Demographics

The demographics of the male and female participants were similar with the exception of their height (females: 1.66 ± 0.06 m, males: 1.80 ± 0.07 m; $P < .001$) and weight (females: 63.63 ± 4.96 Kg, males: 80.24 ± 8.40 Kg; $P < .01$).

Muscle Activation across Contraction Intensities

Females had significantly higher vastus medialis activity than males during knee extension at the 10% ($9.39\% \pm 5.21\%$ vs. $5.92\% \pm 2.44\%$, $P = 0.014$), 20% ($16.35\% \pm 7.95\%$ vs. $12.13\% \pm 3.31\%$, $P = 0.05$), and 30% ($23.85\% \pm 10.74\%$ vs. $17.39\% \pm 6.33\%$, $P = 0.03$) moment targets (Figure 3). All muscles displayed antagonistic muscle activity patterns that increased with moment magnitude (Figure 4). This association was statistically significant ($r = .63$ to $.70$, $P < .01$). Females had significantly higher antagonistic vastus lateralis and vastus medialis muscle activity than males at all moment targets ($P < 0.01$ to $P = 0.04$). Females also displayed significantly higher antagonistic rectus femoris muscle activity than males at the 50% ($P = 0.03$), 70% ($P = 0.02$), and 100% ($P = 0.02$) moment targets. The activity patterns of the hamstrings muscles were similar between sexes at each moment level tested during both agonist and antagonist contractions ($P > .05$). There were no significant

differences in muscle activation values by side ($P = 0.07$ to 0.89) and no side by sex interactions ($P = 0.21$ to 0.96).

Linearity vs. Nonlinearity of EMG-Moment Relationships

Lack of fit tests indicated that the EMG-moment relationships for agonist contractions of the vastus lateralis and vastus medialis were nonlinear ($P < 0.01$), whereas those for the rectus femoris, semitendinosus, and biceps femoris were linear ($P = 0.14$ to 0.96). The EMG-moment relationships for the antagonist contractions followed the opposite patterns with linear relationships observed in the vastus lateralis and vastus medialis muscles ($P = 0.14$ and $P = 0.40$, respectively) and nonlinear relationships ($P < 0.05$) in the rectus femoris, semitendinosus, and biceps femoris muscles.

Voluntary Activation Testing

No significant differences were observed in the peak quadriceps voluntary activation values of the male ($91.02\% \pm 7.56\%$) and female ($93.37\% \pm 6.48\%$) subjects ($P = 0.35$). There was also no significant difference in quadriceps activation level by side ($P = 0.31$) and no side by sex interaction ($P = 0.53$). There was no correlation between voluntary activation of the quadriceps muscles and the vastus medialis agonist values at any of the moment levels ($r = -0.04$ to 0.05 , $P = 0.77$ to 0.95). There were also no significant correlations between peak quadriceps voluntary activation values and antagonistic quadriceps activity ($r = -0.15$ to 0.08 , $P = 0.35$ to 0.95).

Discussion

This study contributes the following valuable information to the literature: 1) a detailed report of sex-specific thigh muscle EMG-moment relationships when the muscles are acting as agonists and antagonists throughout the moment spectrum, 2) more evidence demonstrating differences in quadriceps EMG-Moment relationships between the sexes, 3) evidence indicating that hamstrings muscle activation is similar in females and males throughout the moment spectrum, and 4) evidence supporting the theory that the nervous system's control of the quadriceps and hamstrings muscle groups is linked.

The female participants in this study displayed significantly higher magnitudes of vastus medialis muscle activity than males at lower contraction intensities (10% to 30%). This finding is consistent with the results of Krishnan et al (12) who reported that females display higher magnitudes of vastus medialis and vastus lateralis muscle activity than males when performing isometric knee extension at 30% MVIC. The results are also consistent with Cioni et al's (5) report of significantly higher normalized tibialis anterior activity in females at contraction intensities between 20% and 40% MVIC. Although the sex differences reaching statistical significance in the current study were isolated to the vastus medialis muscle during agonist contractions, significant differences in quadriceps activity levels were observed throughout the moment spectrum during flexion contractions when the muscle group was acting as an antagonist. These data expand on the results of prior studies demonstrating sex differences in antagonistic quadriceps activity during maximum voluntary isometric contractions (13,34). The data now available clearly indicate that women and men

have measurable differences in their quadriceps muscle physiology. These sex differences in quadriceps activation are particularly interesting when considering basic lower extremity anatomy, physiology, and biomechanics.

Although the picture is far from clear, the literature offers some explanatory insights related to the observed sex differences in quadriceps muscle activation. Evidence supports the presence of differences in the relative composition, distribution, and location of slow vs. fast muscle fibers in the quadriceps muscles of males and females (25,28). Evidence also indicates that females recruit a larger number of motor units than males at a given contraction intensity and tend to preferentially use a strategy of recruiting new motor units prior to substantially increasing motor unit firing rates when increasing force (5,33). Hence, it is likely that the observed differences are associated with multiple factors including differences in muscle composition and neuromotor control.

The experimental methods used in this study involved the generation of knee extension and flexion moments during isometric contractions over the range of contraction intensity. Although this was a fitting design for the current study, it is important to note that the relationship between the EMG-moment relationships observed in the present study and those typical in functional activities such as walking, running, or landing from a jump are unclear. Defining EMG-moment relationships with confidence during such functional tasks is difficult as there are many potentially confounding factors such as the kinematic and kinetic variability associated with the movement of joint segments above and below the muscles of interest and increased likelihood of volume conduction due to skin motion. Based on the consistent findings in isometric studies, it seems likely that females will also display higher levels of quadriceps activity than males in low intensity functional tasks. Most activities of daily living performed by individuals are in fact low intensity in terms of quadriceps activity requirements. For example, walking on level ground typically requires quadriceps activity levels that range between 15% and 40% of the maximum values recorded in MVIC trials (14,31). This fact highlights the potential importance of the sex difference in quadriceps activity observed in the present study.

Discussion of the clinical meaningfulness of the observed differences and the potential relationship of these differences to the high incidence of certain knee pathologies in the female population is beyond the scope of this study. The observation of higher vastus medialis muscle activity in females at the same relative loads used in males does, however, have implications for biomechanical studies related to sports injury prevention and treatment. The results of this study suggest that higher vastus medialis activity should be expected in females during low intensity knee extension and that it is unlikely that this increased activity puts females at increased risk for knee injury as the higher activity is associated with the same relative extension moments as lower levels of activity in males. Given these findings, care should be taken when considering the injury risk associated with muscle activity if the moments transferred to the knee are not directly measured or modeled. It is important to note, however, that the magnitude of quadriceps activation differences observed between the sexes in studies of dynamic tasks are often much greater than those in the current study (32). With higher magnitudes of quadriceps activity and greater differences between the sexes in high intensity activities, there may be increased risk of knee injury

although this cannot be assumed. Considering the growing body of evidence demonstrating neuromuscular differences between the sexes, it seems likely that comparisons between females who sustain injuries and those who do not will yield greater insights related to the risk factors associated with knee injury than comparisons with the male population.

Testing of voluntary quadriceps activation levels was included in this study because it was recognized that dissimilarity in the completeness of quadriceps activation could have been a confounding factor when assessing sex differences in thigh muscle EMG-moment relationships. The EMG data acquired during testing were normalized using values recorded during MVIC trials, which is the most common method normalization used in the applied sciences. If the females and males had significant differences in maximal quadriceps activation levels, the EMG normalization process could have been compromised resulting in artificially increased normalized EMG values in the group with lower voluntary activation levels. Hence, a Type II error could have resulted. The burst superimposition interpolated twitch test results clearly indicate there was no significant difference in maximal voluntary quadriceps muscle activation levels between the sexes. Moreover, there were no significant associations between the completeness of quadriceps activation and the vastus medialis agonist values recorded at each of the contraction intensities. Therefore, the observed differences in vastus medialis activity between the sexes were independent of the subjects' ability to voluntarily activate their quadriceps muscles.

The effect of contraction intensity on antagonist muscle activity is not well documented in the literature. This study contributes evidence describing antagonistic quadriceps and hamstrings muscle activity patterns across the spectrum of intensity. Antagonist muscle activity increased with increasing contraction intensity in each of the muscles tested. The observed proportional increase in the antagonist muscle activity with increasing excitation of the agonist muscles supports the idea that quadriceps and hamstrings activation is linked. A number of theories that support this concept have been put forth in studies related to the regulation of agonist and antagonist muscle activity. One theory holds that the central nervous system controls the motoneuron pools of the agonist-antagonist muscle pairs with a single input as if they both belong to the same motoneuron pool (i.e., agonists and antagonist are under "common drive") (7). A pre-synaptic mechanism has also been described in which the excitation of antagonist motoneuron pools is controlled by active inhibition of the disynaptic Ia inhibitory pathway through descending commands (21,23). In addition, antagonist muscle activity can be mediated through peripheral mechanisms via afferent inputs (group II, III, and IV muscle afferents, high and low threshold cutaneous afferents, and joint afferents) of the flexion-extension reflex pathways or via interneuronal connections in the spinal cord circuitry (Renshaw cells) (9,26). Renshaw cells, a class of spinal interneurons, are known to be excited by input from agonist muscle α -motoneurons and in turn produce signals that result in coactivation of the antagonist muscles via an inhibitory process (18,29). Since the excitation of Renshaw cells is directly related to the activity of α -motoneurons of the agonist muscle, increases in agonist muscle activity result in increases in antagonist activity. Although the exact mechanisms underlying the association between agonist and antagonist activity remain theoretical, the results of this study provide further evidence supporting a direct association in the agonist and antagonist activity patterns of the quadriceps and hamstrings muscles.

Antagonist muscle activity levels can be affected by several factors including the type of muscle action, the velocity of the moving segment, angular position, level of effort, age, level of training, and task novelty (10,11). It is unlikely, however, that these factors contributed to the sex differences in antagonistic quadriceps activity observed in this study. The male and female participants were similar in age and activity level. Methodological factors such as the type of muscle action, knee joint position, and task novelty were equivalent. The two groups also had similar levels of peak quadriceps activation. The idea that the observed sex differences may be associated with increased volume conduction in the female subjects due to the fact that females typically have more subcutaneous tissue than age-matched males is also an unlikely explanation as the differences in antagonistic muscle activity were isolated to the quadriceps muscles rather than being observed in both of the muscle groups. The logical conclusion, therefore, is that the observed differences in antagonist activity are a product of inherent differences in the quadriceps muscle control strategies used by males and females.

Surface EMG-force relationships for human muscles have long been debated. Both linear and nonlinear EMG-force relationships have been reported in isometric conditions (1,3). Early evidence from theoretical investigations suggested that the amplitude of the EMG signal is linearly related to the square root of force generated by the muscle (19). However, most of the empirical evidence argues against the square-root relationship and instead suggests that the amplitude of the EMG signal either increases linearly with force levels or increases disproportionately at higher levels of contractions (3,35). The results of this study support the presence of both linear and nonlinear EMG-force relationships in the thigh muscles depending on the muscle examined, which is consistent with the findings of others (1,15,35).

In summary, the results of this study make several meaningful contributions to the literature. EMG-moment relationships are provided for the vastus medialis, vastus lateralis, rectus femoris, semitendinosus (medial hamstrings), and biceps femoris (lateral hamstrings) throughout the moment spectrum when the muscles were acting as agonist and antagonists during isometric knee extension/flexion. The results provide evidence supporting the presence of neuromechanical differences in the quadriceps muscles of females and males. These differences were isolated to lower intensity contractions of the vastus medialis muscle in knee extension, but observed broadly in knee flexion where the quadriceps act as antagonists. No significant sex differences were observed in the subjects' hamstring muscle activation patterns. The shapes of the EMG-moment relationships from agonist contractions were muscle-dependent with some muscles displaying linear patterns and others nonlinear patterns. Antagonist activity increased proportionally with increasing knee extension/flexion moments in all of the muscles tested. This finding supports the idea that agonist and antagonist quadriceps and hamstrings muscle activity are associated. Although it is currently unclear if the findings of this study have implications directly related to the female predisposition to knee pathology, the results are meaningful in terms of our basic understanding of anatomy, physiology, and neuromuscular function.

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Figure 1.
Subject positioned for testing with instrumentation attached.

Figure 2.

Screen shots of the LCD monitor depicting the cursor, target, and successful positioning of the cursor over the target in extension (A) and flexion (B). Each trial begins with the cursor in the center of the screen. The subject's objective is to move the cursor (dashed line) over the target (the space between two circles of slightly different size) and hold it there for 200 ms. The dashed circle in Figures 2A & 2B depicts a successfully matched target in the respective load direction. Data recorded during the 200 ms epoch associated with successfully matching each target was saved for analysis. After successfully matching each target the subjects returned the cursor to the origin and then began the next trial.

Figure 3. EMG-moment relationships for the subjects' thigh muscles when acting as agonists (quadriceps muscles in knee extension, hamstrings muscles in knee flexion). Asterisks (*) identify statistically significant differences ($P < 0.05$).

Figure 4.

EMG-moment relationships for the subjects' thigh muscles when acting as antagonists (quadriceps muscles in knee flexion, hamstrings muscles in knee extension). Asterisks (*) identify statistically significant differences ($P < 0.05$). Mean antagonistic vastus medialis and vastus lateralis muscle activity values were statistically significant between sexes across the entire contraction intensity spectrum.