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original research

Fatigue and the Electromechanical Efficiency of the Vastus Medialis and Vastus Lateralis Muscles

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Context: The relationship between the amplitudes of the mechanomyographic (MMG) and electromyographic (EMG) signals has been used to examine the "electromechanical efficiency" (EME) of normal and diseased muscle. The EME may help us to better understand the neuromuscular relationship between the vastus medialis and vastus lateralis muscles.

Objective: To examine the EME of the vastus medialis and vastus lateralis muscles during a fatiguing task.

Design: Repeated-measures design.

Setting: Research laboratory.

Patients or Other Participants: Ten healthy males (age = 23.2 ± 1.2 years) with no history of knee injury.

Intervention(s): Seventy-five consecutive, maximal concentric isokinetic leg extensions at a velocity of 180°/s.

Main Outcomes Measure(s): Bipolar surface EMG electrodes were placed over the vastus medialis and vastus lateralis muscles, with an MMG contact sensor placed adjacent to the superior EMG electrode on each muscle. The MMG and EMG amplitude values (root mean squares) were calculated for each of the 75 repetitions and normalized to the highest value from the 75 repetitions. The EME was expressed as the ratio of the log-transformed normalized MMG amplitude to the normalized EMG amplitude. For each muscle, the linear relationship for the normalized-group mean EME was determined across the 75 repetitions.

Results: Linear regression indicated decreases in torque (R^2 = .96), vastus medialis EME (R^2 = .73), and vastus lateralis EME (R^2 =.73). The slopes for the vastus medialis and vastus lateralis EME were not different ($P > .10$).

Conclusions: The similarities in the fatigue-induced decreases in EME for the vastus medialis and vastus lateralis muscles suggested that symmetry was present between the muscles in the electric and mechanical responses to repeated, maximal muscle actions. The EME measurements may provide a unique insight into the influence of fatigue on the contractile properties of skeletal muscle, including alterations that occur to the intrinsic electric and mechanical components. The EME may be useful in assessing and quantifying clinically relevant asymmetries in vastus medialis and vastus lateralis muscle function in those with knee injuries.

Key Words: mechanomyography, electromyography

Key Points

- In healthy muscle, the electromechanical efficiency of the vastus medialis and vastus lateralis muscles decreased concurrently with decreased torque. Thus, as suggested by others, electromechanical efficiency may provide an index of changes in electromechanical coupling.
- Electromechanical efficiency may offer insight into the influence of fatigue on skeletal muscle function and be a useful tool to assess and quantify clinically relevant asymmetries in vastus medialis and vastus lateralis muscle function in those with knee conditions.

Mechanomyography (MMG) is a relatively new, noninvasive technique that records and quantifies the low-frequency lateral oscillations produced by active skeletal muscle fibers.[1–5] It has been suggested that the lateral oscillations are the result of (a) gross lateral movement of the muscle as it moves toward or away from its line of pull during contraction or relaxation, (b) smaller subsequent lateral oscillations generated at the resonant frequency of the muscle, and (c) dimensional changes of the active muscle fibers.[1,3] The lateral muscle fiber oscillations (quantified at the skin as MMG) reflect the intrinsic mechanical property of motor unit activity and are independent of motor unit electric activity as measured by electromyography (EMG).[5] The MMG signal has been suggested to be influenced by factors such as muscle length, temperature, stiffness, mass, and intramuscular pressure. However, mounting evidence suggests that MMG is generated primarily from muscle activity.[1] Specifically, the MMG amplitude is thought to reflect motor unit recruitment, whereas the EMG amplitude reflects both motor unit recruitment and firing rate.[1,3] Thus, simultaneous measures of EMG and MMG provide unique insight into the electromechanical function of active skeletal muscle.

Previous investigators[6–11] have used EMG and MMG to examine the electric and mechanical aspects, respectively, of muscle function during a given task, both in clinical and nonclinic populations. For example, MMG has been used to noninvasively provide diagnostic information about muscular diseases such as spastic cerebral palsy,[6] pediatric neuromuscular disorders,[7] and muscular dystrophy,[8,9] as well as to determine age-related changes in muscle function[10] and to assess muscle fiber composition.[11] In nonclinical populations, authors[2,12–14] have reported a close relationship between MMG amplitude and torque production during repeated, concentric muscle actions. Decreases in MMG amplitude at maximal or near-maximal torque levels across time have been attributed to decreases in the lateral oscillations due to increases in muscle fiber relaxation time,[3] decreases in motor unit recruitment or fusion of motor unit twitches (or both),[3] as well as a fatigue-induced decrease in the contribution of type II fibers to torque production.[14] Furthermore, the results of Ebersole et al[13] and Perry-Rana et al[14] suggest that the MMG amplitude-isokinetic torque relationship may be muscle specific. Thus, MMG amplitude provides a noninvasive way to monitor muscle-specific changes in observed torque production during a fatiguing activity.

"Efficiency of electrical activity" (EEA) was initially described by Lenman[15] and deVries[16] as a method of evaluating the functional state of muscle by plotting the integrated electric activity as a function of the force of an isometric muscle action. In general, EEA was determined to improve (ie, greater force production was accompanied by decreases in EMG amplitude) with training-induced increases in strength and deteriorated with a fatiguing task.[15,16] Barry et al[7] suggested the dissociation between the electric and mechanical events of muscle function (ie, electromechanical coupling) might be better captured through examination of changes in the ratio of MMG to EMG amplitudes, which creates an index of "electromechanical efficiency" (EME).

Recent investigators have used EME to evaluate the symmetry of the low back paraspinal muscles[17] and discriminate healthy from diseased muscle in patients with cerebral palsy[6] and muscular dystrophy.[8,9] Clinically, changes in neuromuscular function (measured by EMG) of the vastus medialis (VM) and vastus lateralis (VL) muscles are often associated with conditions such as patellofemoral pain. The EME is an index that reflects the excitation-contraction couple process in active skeletal muscle. It is possible that EME may provide a unique insight relative to the electromechanical function of the VM and VL, potentially advancing our understanding of the relationship of the VM and VL to lower extremity conditions such as patellofemoral pain syndrome. Further, the close relationship between MMG amplitude and isokinetic torque[2] and the reported muscle-specific responses during a fatiguing task,[13,14] suggest that examination of EME during a fatiguing task may add to our ability to assess muscle-specific changes in the electromechanical function of the VM and VL, which may not be present in a shorter, nonfatiguing bout of maximal repetitions. To date, however, no authors have examined the EME responses of the VM and VL in healthy individuals as well as during a fatiguing task. Thus, our purpose was to examine the influence of fatigue on the EME of the VM and VL.

METHODS

Participants

Ten healthy males (age = 23.2 ± 1.2 years, height = 177.1 ± 76.1 cm, mass = 75.0 ± 10.1 kg) volunteered to participate in this investigation. This study was approved by the university's institutional review board for human subjects. All participants completed a health history questionnaire and signed a written informed consent before testing.

Isokinetic Strength Testing

The participants reported to the laboratory on 2 occasions. The first visit was an orientation and practice session, during which the participants were allowed to become familiar with the strength testing procedures. On the second visit, each participant performed 75 consecutive, maximal concentric muscle actions of the dominant leg extensors at 180°/s on a calibrated Biodex System 3 dynamometer (Biodex Medical Systems, Shirley, NY). A 5-minute warm-up on a cycle ergometer was completed before testing. The torque, velocity, and position signals from the dynamometer were integrated with a general-purpose signal-interface unit (model DI-220; DATAQ Instruments Inc, Akron, OH).

Electromyographic Procedures

Bipolar surface electrodes (model MeshTrode [rectangular solid gel, silver-silver chloride snap connector]; Verimed International Inc, Coral Springs, FL) were placed along the longitudinal axis of the VL and VM muscles of the dominant leg in accordance with the *European Recommendations for Surface Electromyography*.[18] The electrode placements on the VL were at approximately two thirds of the distance between the anterior superior iliac spine and the lateral aspect of the patella. For the VM, the electrodes were placed at approximately 20% of the distance between the medial gap of the knee joint and the anterior superior iliac spine. The electrodes were placed directly adjacent to each other to minimize the interelectrode distance within each muscle. A single reference electrode was placed over the iliac crest. Interelectrode impedance was minimized by shaving, gently rubbing the area with sterile gauze, and wiping the area clean with alcohol. The EMG signal was acquired and amplified (gain = 2000) with the Telemyo 900 System (Noraxon U.S.A. Inc, Scottsdale, AZ; bandwidth of 10 to 500 Hz) before passing through the DI-220 signal interface unit at a sampling frequency of 1000 Hz.

Mechanomyographic Procedures

The MMG signal was detected by a piezoelectric crystal contact sensor (model 21050A; Philips Medical Systems, Bothell, WA; bandwidth = 0.02 to 2000 Hz). For each muscle (VL and VM), 1 contact sensor was placed adjacent to the superior border of the proximal EMG electrode. A stabilizing ring and double-sided adhesive tape were used to ensure consistent contact pressure of the sensor. The raw MMG signals were integrated with the DI-220 signal interface unit with a sampling frequency of 1000 Hz.

Data Acquisition and Signal Processing

The EMG, MMG, and torque signals were recorded onto a personal laptop computer (Inspiron 7500; Dell, Round Rock, TX) with WinDaq Software (WinDaq/Pro+; DATAQ Instruments, Akron, OH). The data were digitized and stored on the computer for subsequent analysis.

Data analysis was performed with custom programs written with LabView software (version 7.0; National Instruments, Austin, TX). For each of the 75 repetitions, the MMG and EMG amplitude (root mean square) as well as peak torque (TQ) were calculated over the middle third of each repetition (approximately a 30° range of motion; 0.25 s for 180°/s). The MMG signal was bandpass filtered from 5 to 150 Hz before signal analysis.

Statistical Analyses

The EMG and MMG amplitude and torque data were normalized to the repetition that resulted in the highest value. Electromechanical efficiency was calculated as the ratio of the normalized MMG amplitude to the normalized EMG amplitude at each of the 75 repetitions. The normalized group mean data (EME versus repetitions) were then regressed against muscle action number using polynomial regression models (linear, quadratic, cubic; version 11.5; SPSS Inc, Chicago, IL), where X = muscle action number, Y = EME or TQ and a_0, a_1, a_2, and a_3 = statistically determined regression coefficients. The models were as follows:

$$Y = a_0 + a_1X \text{ (linear model)}$$

$$Y = a_0 + a_1X + a_2X^2 \text{ (quadratic model)}$$

$$Y = a_0 + a_1X + a_2X^2 + a_2X^3 \text{ (cubic model)}$$

The statistical significance ($P < .05$) for the increment in the proportion of the variance that would be accounted for by a higher-degree model was determined using the following F test:

$$F = \frac{(R_2^2 - R_1^2)/(K_2 - K_1)}{(1 - R_2^2)/(n - K_2 - 1)}$$

The polynomial regression analysis indicated different EME patterns for the VM (quadratic) and VL (cubic). To allow for comparisons of slopes, the EME and torque data were natural-log transformed and then fit with a linear curve. The slope coefficients for the EME of the VM and VL were compared statistically using the procedures of Pedhazur[19]: an α level of .10 was used to reduce the chance of committing a type II error when testing the differences between slope coefficients.

RESULTS

Linear decreases in torque ($R^2 = 0.96$, b = −.011), VM EME ($R^2 = 0.73$, b = −.009), and VL EME ($R^2 = 0.73$, b = −.013) were noted across the 75 repetitions at 180°/s (Figure 1). A test of the regression coefficients indicated that the slopes for the VM and VL EME were not different ($P > .10$).

DISCUSSION

In our investigation, the 58% and 66% decreases in EME for the VM and VL, respectively, occurred concurrently with the 47% decline in torque production. The decline in torque production was similar to that found by previous researchers, who reported decreases in peak torque ranging from 34% to 63% during repeated concentric leg extensions.[13,14,20–25] The similar patterns in the fatigue-induced decreases in EME for the VM and VL were consistent with those of Wright and Stokes,[17] who reported similar declines in EME between the right and left paraspinal

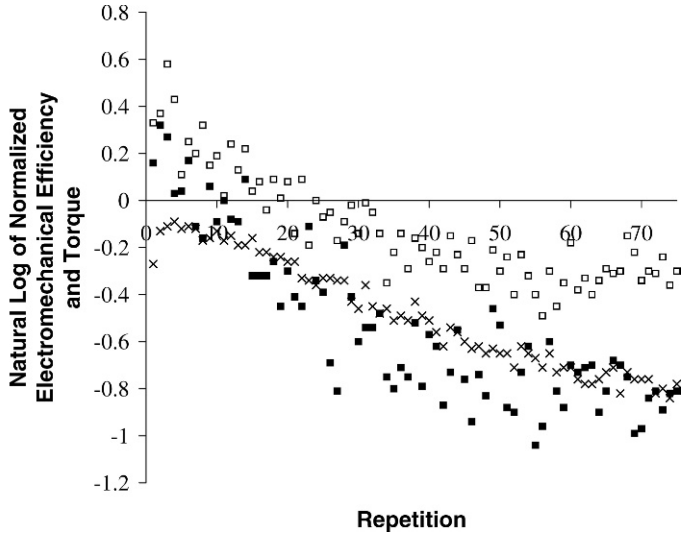

Figure 1. The relationship between repetition number and the natural log of the normalized torque (x) and electromechanical efficiency responses for the vastus medialis (□) and vastus lateralis (■) muscles.

muscles groups in healthy adult males during an isometric fatiguing task.

Barry et al[7] suggested that the reduced EME in adolescent patients with various neuromuscular diseases may have been due to atrophy of fibers that generated electric activity but little mechanical activity. Akataki et al[6] and Orizio et al[8] proposed that the reduced EME in patients with cerebral palsy and myotonic dystrophy was due to a reduced percentage of type II fibers. Further, Nonaka et al[10] attributed the reduced EME in healthy adolescents compared with healthy adults to immature development of type II muscle fibers in the adolescent population. The force-velocity relationship is influenced by muscle fiber type, such that a faster rate of force decline is associated with a greater percentage of type II fibers in the active muscles.[21,24] The VM and VL are generally considered muscles composed of mixed fibers, with reported percentages of type II fibers ranging from 38% to 57% and 31% to 59% for the VM and VL, respectively.[26–29] Thus, the decrease in force production may reflect a reduction in the number of active type II fibers. As a result, the magnitude of the lateral oscillations was attenuated (MMG amplitude decreased), thereby reducing the EME for the VM and VL.

The reduced EME for the VM and VL in our study may have also been associated with a change in motor unit activation strategies. We observed a dissociation between the electric and mechanical events of muscle function when the EMG and MMG amplitudes from each muscle were plotted separately, such that EMG amplitude increased while MMG amplitude decreased across the 75 repetitions (Figure 2). Increases in EMG amplitude during a maximal fatiguing activity may be due to the recruitment of additional motor units, while the overall contribution of type II fibers is reduced.[21] A reduction in the MMG amplitude during near-maximal muscle actions has been attributed to the development of a fusion-like state in the active muscle.[3,30–32] As a result of the fusion, the magnitude of the dimensional changes of the active muscle fibers decreased, thereby decreasing MMG amplitude.[30,31]

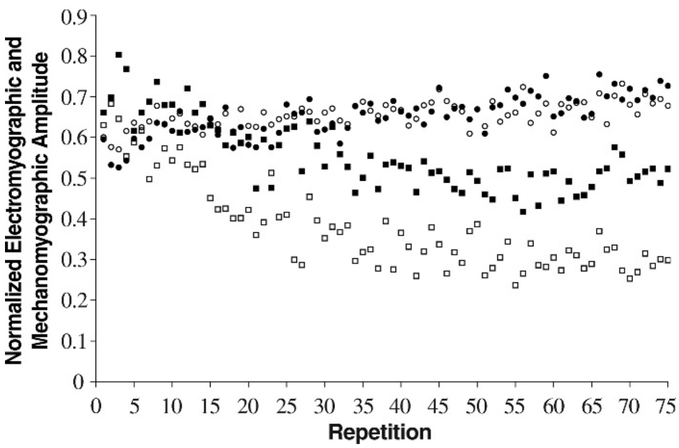

Figure 2. The normalized vastus medialis electromyographic (●), vastus lateralis electromyographic (○), vastus medialis mechanomyographic (■), and vastus lateralis mechanomyographic (□) amplitude responses across the 75 repetitions.

In our investigation, the reduction in type II fiber contribution plus the fusion of the motor units in the active muscle fibers may have contributed to the decrease in EME for the VM and VL. Orizio et al[8] suggested that the potential advantage of EME is that it may provide a method for estimating "the efficiency of the mechanical transduction of the motor unit electrical activities." Changes in muscle function during a fatiguing task have been attributed to impairment of the electromechanical coupling process.[6] Our findings suggest that decreased efficiency of the intrinsic mechanical aspect of motor unit function may have played a greater role in the decline in torque production than the intrinsic electric events.

In healthy muscle, the EME of the VM and VL decreased concurrently with a decrease in torque. Thus, as suggested by Barry et al,[7] the EME may provide an index of changes in electromechanical coupling. Wright and Stokes[17] indicated that when applied to patients with unilateral back pain, asymmetry in the EME would be expected in the paraspinal muscles on the affected side. Further, the return to symmetry (ie, similar EME responses) between 2 muscle groups could be applied to monitoring either a rehabilitation protocol or the efficacy of specific tasks designed to improve neuromuscular control of the VM and VL. Thus, the EME may be sensitive to discriminating between healthy and injured muscle in a population having atrophy or other dysfunction of the VM or VL (or both) as potential contributing factors, such as with patellofemoral pain. Examination of the EME in the VM and VL may also provide insight into the contributions that functional differences between these muscles have on knee joint disorders, as well as serve as an index of underlying change in neuromuscular muscle function before injury and in conjunction with injury treatment and rehabilitation. Future researchers should examine EME from these muscles in a clinical population as well as in response to specific interventions.

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