JOURNAL OF APPLIED BIOMECHANICS, 2005, **21**, 96-109

Gender Comparisons of Mechanomyographic Amplitude and Mean Power Frequency Versus Isometric Torque Relationships

Travis W. Beck[1], Terry J. Housh[1], Glen O. Johnson[1], Joseph P. Weir[2], Joel T. Cramer[3], Jared W. Coburn[1], and Moh H. Malek[1]

[1]University of Nebraska–Lincoln; [2]Des Moines University Osteopathic Medical Center; [3]University of Texas at Arlington

This study compared the patterns of mechanomyographic (MMG) amplitude and mean power frequency vs. torque relationships in men and women during isometric muscle actions of the biceps brachii. Seven men (mean age 23.9 ± 3.5 yrs) and 8 women (mean 21.0 ± 1.3 yrs) performed submaximal to maximal isometric muscle actions of the dominant forearm flexors. Following determination of the isometric maximum voluntary contraction (MVC), they randomly performed submaximal step muscle actions in 10% increments from 10% to 90% MVC. Polynomial regression analyses indicated that the MMG amplitude vs. isometric torque relationship for the men was best fit with a cubic model (R^2 = 0.983), where MMG amplitude increased slightly from 10% to 20% MVC, increased rapidly from 20% to 80% MVC, and plateaued from 80% to 100% MVC. For the women, MMG amplitude increased linearly (r^2 = 0.949) from 10% to 100% MVC. Linear models also provided the best fit for the MMG mean power frequency vs. isometric torque relationship in both the men (r^2 = 0.813) and women (r^2 = 0.578). The results demonstrated gender differences in the MMG amplitude vs. isometric torque relationship, but similar torque-related patterns for MMG mean power frequency. These findings suggested that the plateau in MMG amplitude at high levels of isometric torque production for the biceps brachii in the men, but not the women, may have been due to greater isometric torque, muscle stiffness, and/or intramuscular fluid pressure in the men, rather than to differences in motor unit activation strategies for modulating isometric torque production.

Key Words: mechanomyography, muscle function, recruitment, firing rate, males and females

[1]Dept. of Nutrition and Health Sciences, University of Nebraska-Lincoln, Lincoln, NE 68588-0229; [2]Applied Physiology Lab, Des Moines University Osteopathic Medical Center, Des Moines, IA 50312; [3]Dept. of Kinesiology, The University of Texas at Arlington, Arlington, TX 76019-0259.

Mechanomyography (MMG) involves recording and quantifying the low-frequency lateral oscillations of contracting skeletal muscle fibers (Barry & Cole, 1990; Orizio, 1993; Stokes, 1993), and Gordon and Holbourn (1948) indicated that these oscillations reflect the “mechanical counterpart” of the motor unit electrical activity as measured by electromyography (EMG). Barry and Cole (1988) and Orizio (1993) have indicated that the lateral oscillations recorded as MMG are a function of: (a) a gross lateral movement of the muscle at the initiation of a contraction generated by the nonsimultaneous activation of muscle fibers, (b) smaller subsequent lateral oscillations generated at the resonant frequency of the muscle, and (c) dimensional changes of the active fibers. The amplitude of the MMG signal, however, is influenced by many factors, including muscle temperature, stiffness, mass, intramuscular pressure, the viscosity of the intracellular and extracellular fluid mediums, and the firing rates of the active motor units (Marchetti, Felici, Bernardi, Minasi, & Di Filippo, 1992; Orizio, 1993; Orizio, Gobbo, Diemont, Esposito, & Veicsteinas, 2003; Orizio & Veicsteinas, 1992; Stokes, 1993).

The MMG signal can provide information about many aspects of muscle function. Simultaneous measurements of MMG and EMG have been used to examine the dissociation between the electrical and mechanical events (excitation-contraction coupling) that occurs with fatigue (Stokes & Dalton, 1991) and to examine factors related to electromechanical and phonomechanical delay (Petitjean, Maton, & Cnockaert, 1992). In addition, recent studies have examined the MMG amplitude and frequency responses during maximal concentric and eccentric isokinetic muscle actions (Cramer et al., 2002b; 2002c; Ebersole et al., 2000; Evetovich et al., 1999), as well as maximal and submaximal cycle ergometry (Housh et al., 2000; Perry et al., 2001a; 2001b; Shinohara, Kouzaki, Yoshihisa, & Fukunaga, 1997; Stout, Housh, Johnson, Evetovich, & Smith, 1997). These studies have found that during maximal concentric and eccentric isokinetic muscle actions, MMG amplitude increases with velocity (Cramer et al., 2002c; Evetovich et al., 1999).

The pattern for MMG mean power frequency, however, has been reported to decrease (Cramer et al., 2002b) or remain unchanged (Ebersole et al., 2000) with increases in velocity during maximal concentric and eccentric isokinetic muscle actions, respectively. Furthermore, during maximal and submaximal cycle ergometry, MMG amplitude increases with power output (Perry et al., 2001a; Stout et al., 1997), while MMG mean power frequency decreases (Perry et al., 2001b). Clinically, MMG may be used to examine neuromuscular disorders (Rhatigan, Mylrea, Lonsdale, & Stern, 1986) including cerebral palsy (Akataki, Mita, Itoh, Suzuki, & Watakabe, 1996), myotonic dystrophy (Orizio et al., 1997), cranio-mandibular disorders (L’Estrange, Rowell, & Stokes, 1993), chronic and severe low back pain (Yoshitake, Ue, Myazaki, & Moritani, 2001), diaphragmatic fatigue (Petitjean & Bellemare, 1994), skeletal muscle atrophy (Marchetti, Salleo, Figura, & Del Gaudio, 1974), and as a control mechanism for externally powered prostheses (Barry, Leonard, Gitter, & Ball, 1986).

During voluntary contractions, the asynchronous motor unit activities are summated to form the surface MMG, and it has been suggested that the time and frequency domains of the MMG signal may provide information regarding the unique motor unit activation strategies (motor unit recruitment and firing rate) that modulate isometric torque production in various muscles (Akataki, Mita, Watakabe, & Itoh, 2003; Orizio, 1993; Orizio et al., 2003; Orizio, Liberati, Locatelli, De Grandis, & Veicsteinas, 1996; Orizio, Perini, Diemont, Figini, & Veicsteinas, 1990;

Orizio, Perini, & Veicsteinas, 1989). Specifically, it has been shown that MMG amplitude is related to motor unit recruitment, while the frequency domain of the MMG signal may contain information about motor unit firing rate (Akataki et al., 2003; Orizio, 1993; Orizio et al., 2003; Orizio, Solomonow, Baratta, & Veicsteinas, 1993).

For the biceps brachii, several recent studies have reported increases in both MMG amplitude and MMG mean power frequency with submaximal isometric torque (Akataki, Mita, Watakabe, & Itoh, 2001; Akataki et al., 2003; Beck et al., 2004; Orizio et al., 1989; 1990). At torque levels ≥ 60–80% MVC, however, MMG amplitude for the biceps brachii plateaus or decreases (Akataki et al., 2001; 2003; Beck et al., 2004; Orizio et al., 1989; 2003). Although the exact mechanisms are unclear, it has been hypothesized that a plateau or decrease in MMG amplitude at high levels of isometric torque may be due to muscle stiffness and intramuscular fluid pressure and/or fusion of motor unit twitches at high firing rates (Akataki et al., 2001; 2003; Beck et al., 2004; Orizio et al., 1989; 2003).

Given that males typically generate greater forearm flexion torque (which is related to muscle stiffness and intramuscular fluid pressure) than females (Singh & Karpovich, 1968), and the possibility for examining motor control strategies with the time and frequency domains of the MMG signal, examination of the influence of gender-related differences in strength on the MMG amplitude and mean power frequency vs. isometric torque relationships may provide information regarding the mechanism(s) responsible for the plateau or decrease in MMG amplitude at high torque levels during voluntary muscle actions. Therefore, the purpose of the present study was to examine the MMG amplitude and mean power frequency vs. torque relationships in men and women during submaximal to maximal isometric muscle actions of the biceps brachii.

Methods

Seven men (mean ± *SD*: age = 23.9 ± 3.5 yrs; body mass = 78.5 ± 5.2 kg; height = 182.9 ± 4.5 cm) and 8 women (age = 21.0 ± 1.3 yrs; body mass = 63.8 ± 6.8 kg; height = 170.0 ± 8.3 cm) volunteered to participate in this study. The study was approved by the University Institutional Review Board for Human Subjects, and all participants completed a health history questionnaire and signed a written informed consent document prior to testing.

An orientation session familiarized the participant with the protocol for isometric testing. The isometric muscle actions of the dominant forearm flexors (based on throwing preference) were performed on a calibrated Cybex II dynamometer at a joint angle of 115° between the arm and the forearm (Orizio et al., 1989; 1990; 2003). For all muscle actions, the participants were in a supine position and used a neutral handgrip in accordance with the Cybex II instruction manual (*Isolated joint testing and exercise*, 1980). Following a 6-second isometric maximum voluntary contraction (MVC), the participants practiced submaximal isometric muscle actions at 10, 30, 50, 70, and 90% MVC. Verbal feedback regarding torque production was provided after each isometric muscle action.

Prior to the isometric testing session, the participants undertook a warm-up of five 6-sec isometric muscle actions. They were instructed to provide an effort corresponding to approximately 50% of their maximum during each muscle action.

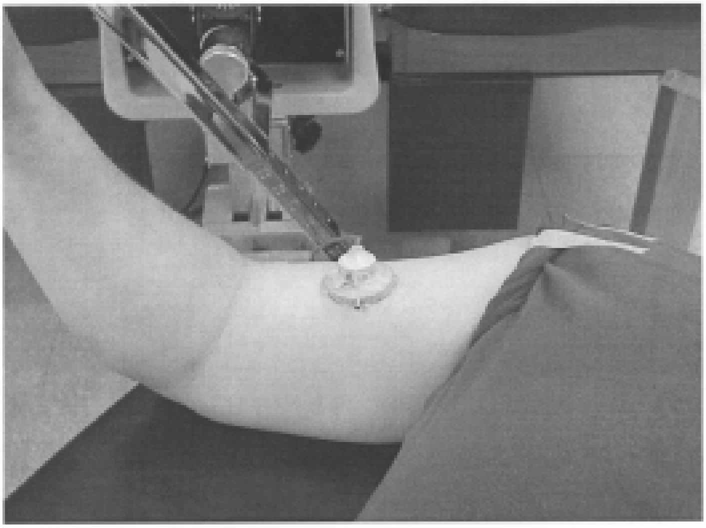

Figure 1 — Example of the MMG sensor placement.

Following the warm-up trials and 2 minutes of rest, the participants performed two maximal, 6-sec isometric muscle actions at a joint angle of 115º between the arm and forearm (Orizio et al., 1989; 1990; 2003) to determine MVC. They then performed a series of randomly ordered submaximal muscle actions in 10% increments from 10% to 90% MVC. Trials were repeated if the actual submaximal torque was not within ±5% of the calculated value. A 2-min rest was allowed between each muscle action. Following the submaximal muscle actions, two additional maximal efforts were performed in order to determine whether the testing had affected the MVC.

The MMG signal was detected by a piezoelectric crystal contact sensor (Hewlett-Packard, 21050A, bandwidth 0.02-2000 Hz, Andover, MA) placed over the belly of the biceps brachii muscle (Orizio et al., 1989; 1990) (Figure 1). A stabilizing ring, double-sided foam tape, and microporous tape were used to ensure consistent contact pressure of the MMG sensor (Bolton, Parkes, Thompson, Clark, & Sterne, 1989).

The raw MMG signal was digitized at 1,000 Hz and stored in a personal computer (Macintosh 7100/80 AV Power PC, Apple Computer, Inc., Cupertino, CA) for subsequent analysis. All signal processing was performed using custom programs written with LabVIEW programming software (version 6.1, National Instruments, Austin, TX). The MMG signal was bandpass filtered (fourth-order Butterworth) at 5–100 Hz and the amplitude (root-mean-square, rms) and mean power frequency values were calculated for a 2.0-second time period (Figure 2) corresponding to the middle 33% of the 6-sec isometric muscle action to assure that the MMG signal was measured at the desired torque level. For the mean power frequency analyses, each data segment was processed with a Hamming window and a discrete Fourier transform (DFT). The mean power frequency was selected

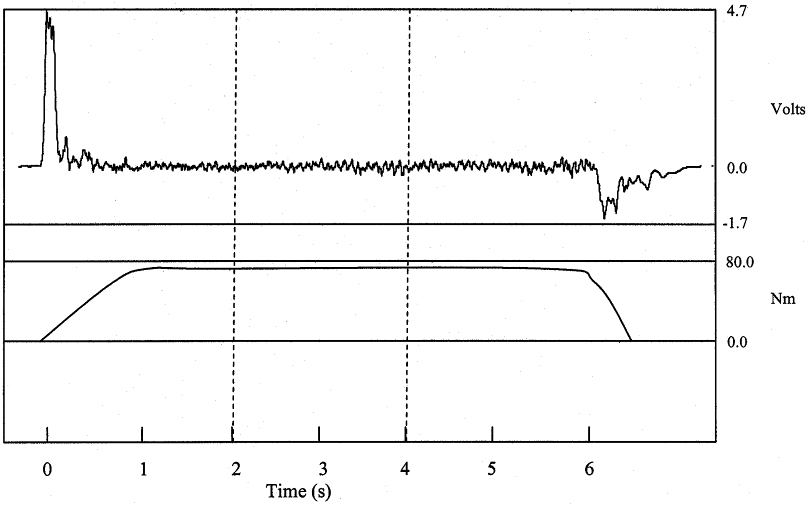

Figure 2 — Example of the raw MMG signal from the biceps brachii and the isometric torque production curve. The portions of the MMG and torque signals between the dashed vertical lines were selected for analysis.

to represent the power spectrum on the basis of the recommendations of Diemont, Figini, Orizio, Perini, and Veicsteinas (1988) and was calculated as described by Kwatny, Thomas, and Kwatny (1970).

The relationships for average MMG amplitude and MMG mean power frequency vs. %MVC for both sexes were examined using polynomial regression models (linear, quadratic, cubic; SPSS software program, Chicago). Using X = % MVC, Y = MMG amplitude or MMG mean power frequency, and a_0, a_1, a_2, and a_3 = statistically determined regression coefficients, these models are:

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

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

$$Y = a_0 + a_1X + a_2X^2 + a_3X^3 \text{ (cubic model)}$$

The statistical significance ($p \leq 0.05$) for the increment in the proportion of the variance that would be accounted for by a higher-degree polynomial was determined using the following *F*-test (Pedhazur, 1997):

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

where n is the number of data points, K_2 is the number of predictors from the larger R^2, and K_1 is the number of predictors from the smaller R^2. Paired *t*-tests were used to determine whether there were differences between the means for the MVC values measured prior to and following the submaximal isometric muscle actions. An alpha of 0.05 was considered statistically significant for all comparisons.

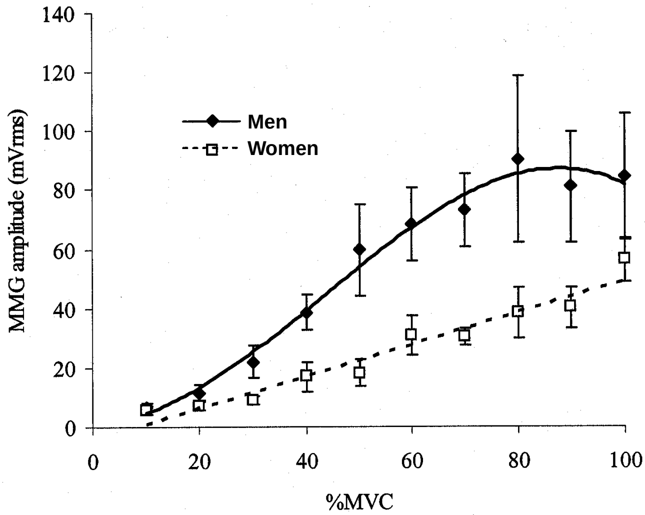

Figure 3 — The relationships between MMG amplitude (mVrms) and %MVC for the male and the female samples. Values are mean ± *SEM*.

Results

The mean (± *SEM*) isometric MVC values were 71.8 ± 3.1 Nm for the men and 30.9 ± 8.5 Nm for the women. Following the submaximal isometric muscle actions, the mean (± *SEM*) MVC values were 75.5 ± 3.0 Nm for the men and 31.1 ± 1.8 Nm for the women. There were no significant ($p > 0.05$) differences between the mean MVC values measured prior to and following the submaximal isometric muscle actions for either gender.

The MMG amplitude (mVrms) vs. %MVC relationship for the men was best fit with a cubic model (Figure 3, $R^2 = 0.983$), where MMG amplitude increased slightly from 10% to 20% MVC, increased rapidly from 20% to 80% MVC, and plateaued from 80% to 100% MVC. For the women, the relationship between MMG amplitude (mVrms) and %MVC was best fit with a linear model (Figure 3, $r^2 = 0.949$). Linear models provided the best fit for the MMG mean power frequency (Hz) vs. %MVC relationship (Figure 4) in both the men ($r^2 = 0.813$) and women ($r^2 = 0.578$).

Discussion

The amplitude of the MMG signal is determined by the number of active motor units and their firing rates (Orizio, 1993; Orizio et al., 2003), and although not directly verified (Akataki et al., 2003), it has been suggested that the MMG frequency content qualitatively reflects the global firing rate of the unfused activated motor units (Akataki et al., 2001; Bichler, 2000; Bichler & Celichowski, 2001; Orizio, 1993; Orizio et al., 2003). Thus, examination of the MMG amplitude and mean power frequency vs. isometric torque relationships may provide information regarding the unique motor unit activation strategies (recruitment and firing rate)

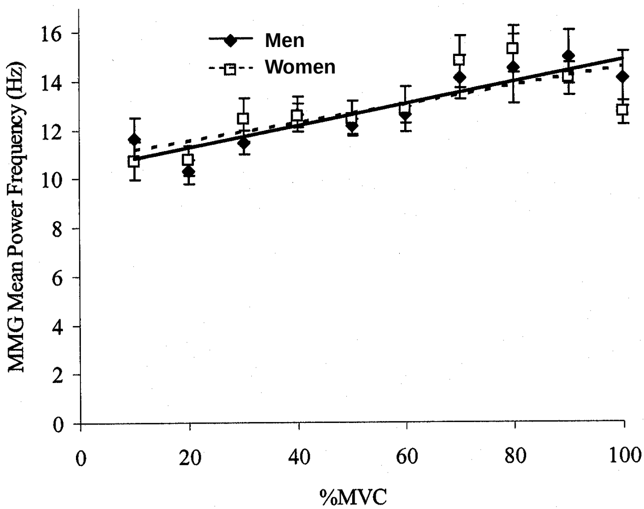

Figure 4 — The relationships between MMG mean power frequency (Hz) and % MVC for the male and the female samples. Values are mean ± *SEM*.

that modulate torque production in various muscles (Akataki et al., 2003; Kukulka & Clamann, 1981; Madeleine, Bajaj, Søgaard, & Arendt-Nielsen, 2001; Orizio et al., 1989; 1990; Shinohara, Kouzaki, Yoshihisa, & Fukunaga, 1998; Zhang, Frank, Rangayyan, & Bell, 1992).

Previous studies have reported that the MMG amplitude vs. isometric torque relationship: (a) increases linearly to MVC (Shinohara et al., 1998); (b) increases curvilinearly to MVC (Maton, Petitjean, & Cnockaert, 1990); (c) increases in an S-shaped pattern to MVC (Lammert, Jorgensen, & Einer-Jensen, 1976); or (d) increases to 60–80% MVC (Akataki et al., 2001; 2003; Coburn et al., 2004; Ebersole et al., 1998; 1999; Esposito, Malgrati, Veicsteinas, & Orizio, 1996; Orizio et al., 1989; 2003) and then plateaus or decreases at higher torque levels. Furthermore, although Maton, Petitjean, and Cnockaert (1990) reported an increase in MMG mean power frequency from 10% to 40% MVC and then a plateau, most previous studies have found linear (Esposito et al., 1996; Shinohara et al., 1998) or curvilinear (Coburn et al., 2004; Orizio et al., 1990; Orizio, Esposito, & Veicsteinas, 1994; Shinohara et al., 1998) increases in MMG mean power frequency to MVC.

A number of factors can influence the MMG amplitude and/or MMG mean power frequency vs. isometric torque relationships including the muscles involved, the time windows chosen for signal analysis, the possibility of fatigue during sustained isometric muscle actions, muscle fiber type characteristics, and the joint angle at which the muscle action is performed (Akataki et al., 2003; Ebersole et al., 1998; 1999; Lammert et al., 1976; Maton et al., 1990; Orizio, 1993; Yoshitake & Moritani, 1999). For example, Ebersole et al. (1999) found that MMG amplitude increased to MVC for the rectus femoris and vastus medialis muscles at 25 and 50° of leg flexion and for the vastus lateralis at 50° of leg flexion. At 75° of leg flexion, however, MMG amplitude for each muscle (rectus femoris, vastus lateralis, and vastus medialis) increased to 75% MVC, and then plateaued between 75%

and 100% MVC. It was hypothesized that greater isometric torque production, and thus muscle stiffness, may have caused the plateau in MMG amplitude for each muscle at 75° of leg flexion, but not at 25 and 50° of leg flexion (Ebersole et al., 1999).

For the biceps brachii, Maton et al. (1990) reported an increase in MMG amplitude to 100% MVC, while Orizio et al. (1989) found a decrease in MMG amplitude above 80% MVC. These disparate findings may have been due to differences in the joint angle at which the isometric muscle actions were performed. The participants in the studies by Maton et al. (1990) and Orizio et al. (1989) performed the isometric muscle actions at 90° and 115° of forearm flexion, respectively.

For the MMG mean power frequency vs. isometric torque relationship from the biceps brachii, Orizio (1993) suggested that the discrepancy in the patterns reported by Maton et al. (1990) and Orizio et al. (1990) may have reflected the different time windows chosen for signal analysis and the possibility of fatigue during sustained isometric muscle actions. In the study by Maton et al. (1990), a 10-sec window corresponding to the most stable part of the torque signal was analyzed from each 15-sec isometric muscle action, while Orizio et al. (1990) examined the middle 2 seconds from each 4-sec isometric muscle action. In addition, the MMG mean power frequency vs. isometric torque relationship is also affected by the muscle that is tested. Akataki et al. (2003) reported that during an isometric ramp muscle action from 15% to 70% MVC, MMG mean power frequency increased linearly for the first dorsal interosseous, but curvilinearly for the biceps brachii. It was hypothesized (Akataki et al., 2003) that the different MMG mean power frequency patterns may have reflected unique motor unit activation strategies for modulating isometric torque production in the biceps brachii and first dorsal interosseous muscles.

In the present study, although the MMG mean power frequency vs. isometric torque relationship was best fit with linear models for both sexes, MMG mean power frequency decreased from 80% (women) or 90% (men) to MVC (Figure 3). There was a clear gender difference, however, in the MMG amplitude vs. isometric torque relationship. For the women, MMG amplitude increased to 100% MVC, while the men exhibited an increase to 80% MVC, and a plateau from 80% to 100% MVC (Figure 3).

These findings were not consistent with those from previous studies of maximal concentric and eccentric isokinetic muscle actions (Cramer et al., 2002a; 2002c; 2004), during which MMG amplitude increased with velocity in a similar manner for both sexes. Esposito et al. (1996) reported that in young males and females, MMG amplitude and MMG mean power frequency for the biceps brachii increased to 80% MVC. From 80% to 100% MVC, however, MMG amplitude decreased for the males and plateaued for the females, while MMG mean power frequency continued to increase (Esposito et al., 1996). It is likely that the torque-related increases in MMG amplitude and MMG mean power frequency to at least 80% MVC for the men and women in the present study, as well as those of Esposito et al. (1996), reflected concurrent modulation of the number of active motor units and their firing rates (Akataki et al., 2003; Orizio, 1993; Orizio et al., 1989; 2003). It has been suggested that a plateau or decrease in MMG amplitude at high torque levels (such as ≥ 80% MVC for the men in the present study) may be due to (a) muscle stiffness and intramuscular fluid pressure, and/or (b) fusion of motor unit twitches at high firing rates (Akataki et al., 2001; Beck et al., 2004; Coburn et al., 2004; Ebersole et al., 1998; 1999; Orizio, 1993; Orizio et al., 1989).

Muscle stiffness is primarily a function of the number of attached, force-exerting cross-bridges (Ettema & Huijing, 1994) and, although the exact mechanism(s) are unclear, it has been suggested that high levels of intramuscular fluid pressure occur when curved muscle fibers generate an inward force during contraction (Hill, 1948). Previous studies (Barry & Cole, 1990; Ford, Huxley, & Simmons, 1981; Sadamoto, Bonde-Petersen, & Suzuki, 1983; Sejersted et al., 1984) have indicated that during isometric muscle actions, muscle stiffness and intramuscular fluid pressure increase to MVC.

Furthermore, Barry and Cole (1990) reported that during an isometric twitch of isolated frog gastrocnemius, muscle stiffness dominated the changes in the resonant frequency of the muscle and, therefore, the MMG signal may be used "to monitor muscle stiffness changes during isometric contractions" (p. 530). In addition, Barry (1987) indicated that the lateral muscle fiber oscillations that generate the MMG signal are limited by the internal compliance of the muscle. Therefore, it has been suggested that at high levels of isometric torque production, muscle stiffness and intramuscular fluid pressure may impair the lateral oscillations of the active muscle fibers, thereby attenuating the MMG signal (Akataki et al., 2001; Orizio, 1993; Orizio et al., 1989). In the present study, the isometric MVC for the women was only 43.0% of that of the men, and thus it is likely that muscle stiffness and intramuscular fluid pressure were substantially greater in the men than in the women. Therefore, the gender differences in the MMG amplitude vs. isometric torque relationship above 80% MVC may have been due to higher levels of isometric torque, muscle stiffness, and intramuscular fluid pressure in the men than in the women.

The MMG signal is also affected by motor unit activation strategies. During voluntary isometric muscle actions, torque production is modulated by recruitment of additional motor units and/or increases in firing rates (Adrian & Bronk, 1929; Enoka & Fuglevand, 2001). When all available motor units have been recruited, increases in firing rates are used to generate additional torque. For the biceps brachii, Kukulka and Clamann (1981) reported motor unit recruitment through at least 90% MVC, although the relative contribution of increases in firing rates may be greater at this high level of torque production. Since the surface MMG is a summation of the mechanical activities of individual motor units (Orizio et al., 1996), the amplitude of the MMG signal reflects the number of unfused activated motor units and their firing rates. Furthermore, Orizio et al. (1989; 1993; 2003) have reported that during voluntary, incremental step and ramp isometric muscle actions of the biceps brachii as well as electrically stimulated ramp contractions of the cat gastrocnemius, MMG amplitude increased to the end of motor unit recruitment.

A number of studies (Akataki et al., 2001; 2003; Orizio, 1993; Orizio et al., 1989; 2003) have hypothesized that a plateau or decrease in MMG amplitude at high torque levels (such as ≥ 80% MVC for the men in the present study) may reflect high firing rates, which cause fusion of motor unit twitches and impair the oscillations of the active muscle fibers. For the women in the present study, however, MMG amplitude and MMG mean power frequency increased to MVC. Therefore, if a plateau or decrease in MMG amplitude at high torque levels is due solely to fusion of motor unit twitches, the plateau in MMG amplitude for the men and the increase in MMG amplitude for the women from 80% to 100% MVC in the present study suggested that there may have been a gender difference in the motor unit activation strategy for modulating isometric torque production.

Although gender differences in motor control strategies have been reported during fatiguing isometric muscle actions (Hunter, Critchlow, Shin, & Enoka, 2004a, 2004b), there is no evidence that there are differences between men and women in the motor unit activation strategy that modulates incremental isometric torque production. Furthermore, the similarities for the men and women in the present study for the MMG mean power frequency vs. isometric torque relationships suggested that there was no gender difference in the torque-related pattern of motor unit firing rate. Therefore, it is likely that the plateau in MMG amplitude for the men above 80% MVC in the present study was due to high levels of isometric torque, muscle stiffness, and/or intramuscular fluid pressure, rather than fusion of motor unit twitches at high firing rates. This hypothesis could be tested further by examining the MMG amplitude from the biceps brachii vs. isometric torque relationships in high- and low-strength men and women.

In summary, the results of the present study demonstrated gender differences in the MMG amplitude vs. isometric torque relationship for the biceps brachii muscle. Specifically, MMG amplitude increased from 10% to 80% MVC and then plateaued from 80% to 100% MVC in the men, while the women demonstrated an increase in MMG amplitude to 100% MVC. Furthermore, although the MMG mean power frequency vs. isometric torque relationship was best fit with a linear model in both sexes, MMG mean power frequency decreased from 80% (women) or 90% (men) to MVC.

We hypothesize that from 80% to 100% MVC, the discrepancy between the men and the women in the MMG amplitude responses, but not in the MMG mean power frequency patterns, may have reflected a gender difference in muscle stiffness and/or intramuscular fluid pressure, rather than dissimilar motor unit activation strategies for modulating isometric torque production. It is also possible that the difference between the sexes for the torque-related patterns for MMG amplitude found in the present study was due to the difference between the groups in absolute isometric torque levels and was not a true gender effect. Future studies should examine the MMG amplitude and/or mean power frequency vs. isometric torque relationships in strength-matched men and women.

References

Adrian, E.D., & Bronk, D.W. (1929). The discharge of impulses in motor nerve fibers. Part II. The frequency discharge in reflex and voluntary contractions. *The Journal of Physiology*, **67**, 119-151.

Akataki, K., Mita, K., Itoh, K., Suzuki, N., & Watakabe, M. (1996). Acoustic and electrical activities during voluntary isometric contraction of biceps brachii muscle in patients with spastic cerebral palsy. *Muscle & Nerve*, **19**, 1252-1257.

Akataki, K., Mita, K., Watakabe, M., & Itoh, K. (2001). Mechanomyogram and force relationship during voluntary isometric ramp contractions of the biceps brachii muscle. *European Journal of Applied Physiology*, **84**, 19-25.

Akataki, K., Mita, K., Watakabe, M., & Itoh, K. (2003). Mechanomyographic responses during voluntary ramp contractions of the human first dorsal interosseous muscle. *European Journal of Applied Physiology*, **89**, 520-525.

Barry, D.T. (1987). Acoustic signals from frog skeletal muscle. *Biophysical Journal*, **51**, 769-773.

Barry, D.T., & Cole, N.M. (1988). Fluid mechanics of muscle vibrations. *Biophysical Journal*, **53**, 899-905.

Barry, D.T., & Cole, N.M. (1990). Muscle sounds are emitted at the resonant frequencies of skeletal muscle. *IEEE Transactions on Bio-medical Engineering*, **37**, 525-531.

Barry, D.T., Leonard, J.A., Gitter, A.J., & Ball, R.D. (1986). Acoustic myography as a control signal for externally powered prosthesis. *Archives of Physical Medicine and Rehabilitation*, **67**, 267-269.

Beck, T.W., Housh, T.J., Johnson, G.O., Weir, J.P., Cramer, J.T., Coburn, J.W., & Malek, M.H. (2004). Mechanomyographic amplitude and mean power frequency versus torque relationships during isokinetic and isometric muscle actions of the biceps brachii. *Journal of Electromyography and Kinesiology*, **14**, 555-564.

Bichler, E. (2000). Mechanomyograms recorded during evoked contractions of single motor units in the rat medial gastrocnemius muscle. *European Journal of Applied Physiology*, **83**, 310-319.

Bichler, E., & Celichowski, J. (2001). Mechanomyographic signals generated during unfused tetani of single motor units in the rat medial gastrocnemius muscle. *European Journal of Applied Physiology*, **85**, 513-520.

Bolton, C.F., Parkes, A., Thompson, T.R., Clark, M.R., & Sterne, C.J. (1989). Recording sound from human skeletal muscle: Technical and physiological aspects. *Muscle & Nerve*, **12**, 126-134.

Coburn, J.W., Housh, T.J., Cramer, J.T., Weir, J.P., Miller, J.M., Beck, T.W., Malek, M.H., & Johnson, G.O. (2004). Mechanomyographic time and frequency domain responses of the vastus medialis muscle during submaximal to maximal isometric and isokinetic muscle actions. *Electromyography and Clinical Neurophysiology*, **44**, 247-255.

Cramer, J.T., Housh, T.J., Evetovich, T.K., Johnson, G.O., Ebersole, K.T., Perry, S.R., & Bull, A.J. (2002a). The relationships among peak torque, mean power output, mechanomyography, and electromyography in men and women during maximal, eccentric isokinetic muscle actions. *European Journal of Applied Physiology*, **86**, 226-232.

Cramer, J.T., Housh, T.J., Weir, J.P., Johnson, G.O., Berning, J.M., Perry, S.R., & Bull, A.J. (2002b). Mechanomyographic and electromyographic amplitude and frequency responses from the superficial quadriceps femoris muscles during maximal, eccentric isokinetic muscle actions. *Electromyography and Clinical Neurophysiology*, **42**, 337-346.

Cramer, J.T., Housh, T.J., Weir, J.P., Johnson, G.O., Berning, J.M., Perry, S.R., & Bull, A.J. (2004). Gender, muscle, and velocity comparisons of mechanomyographic and electromyographic responses during isokinetic muscle actions. *Scandinavian Journal of Medicine and Science in Sports*, **14**, 116-127.

Cramer, J.T., Housh, T.J., Weir, J.P., Johnson, G.O., Ebersole, K.T., Perry, S.R., & Bull, A.J. (2002c). Power output, mechanomyographic, and electromyographic responses to maximal, concentric, isokinetic muscle actions in men and women. *Journal of Strength and Conditioning Research*, **16**, 399-408.

Diemont, B., Figini, M.M., Orizio, C., Perini, R., & Veicsteinas, A. (1988). Spectral analysis of muscular sound at low and high contraction level. *International Journal of Biomedical Computing*, **23**, 161-175.

Ebersole, K.T., Housh, T.J., Johnson, G.O., Evetovich, T.K., Smith, D.B., & Perry, S.R. (1998). The effect of leg flexion angle on the mechanomyographic responses to isometric muscle actions. *European Journal of Applied Physiology*, **78**, 264-269.

Ebersole, K.T., Housh, T.J., Johnson, G.O., Evetovich, T.K., Smith, D.B., & Perry, S.R. (1999). MMG and EMG responses of the superficial quadriceps femoris muscles. *Journal of Electromyography and Kinesiology*, **9**, 219-227.

Ebersole, K.T., Housh, T.J., Weir, J.P., Johnson, G.O., Evetovich, T.K., & Smith, D.B. (2000). The effects of leg angular velocity on mean power frequency and amplitude of the mechanomyographic signal. *Electromyography and Clinical Neurophysiology*, **40**, 49-55.

Enoka, R.M., & Fuglevand, A.J. (2001). Motor unit physiology: Some unresolved issues. *Muscle & Nerve*, **23**, 4-17.

Esposito, F., Malgrati, D., Veicsteinas, A., & Orizio, C. (1996). Time and frequency domain analysis of electromyogram and sound myogram in the elderly. *European Journal of Applied Physiology*, **73**, 503-510.

Ettema, G.J.C., & Huijing, P.A. (1994). Skeletal muscle stiffness in static and dynamic contractions. *Journal of Biomechanics*, **27**, 1361-1368.

Evetovich, T.K., Housh, T.J., Weir, J.P., Johnson, G.O., Smith, D.B., & Ebersole, K.T. (1999). Mean power frequency and amplitude of the mechanomyographic signal during maximal eccentric isokinetic muscle actions. *Electromyography and Clinical Neurophysiology*, **39**, 123-127.

Ford, L.E., Huxley, A.F., & Simmons, R.M. (1981). The relation between stiffness and filament overlap in stimulated frog muscle fibres. *Journal of Physiology,* **311**, 219-249.

Gordon, G., & Holbourn, A.H.S. (1948). The sounds from single motor units in a contracting muscle. *Journal of Physiology*, **107**, 456-464.

Hill, A.V. (1948). The pressure developed in muscle during contraction. *Journal of Physiology*, **107**, 518-526.

Housh, T.J., Perry, S.R., Bull, A.J., Johnson, G.O., Ebersole, K.T., Housh, D.J., & deVries, H.A. (2000). Mechanomyographic and electromyographic responses during submaximal cycle ergometry. *European Journal of Applied Physiology*, **83**, 381-387.

Hunter, S.K., Critchlow, A., Shin, I.S., & Enoka, R.M. (2004a). Fatigability of the elbow flexor muscles for a sustained submaximal contraction is similar in men and women matched for strength. *Journal of Applied Physiology*, **96**, 195-202.

Hunter, S.K., Critchlow, A., Shin, I.S., & Enoka, R.M., (2004b). Men are more fatigable than strength-matched women when performing intermittent submaximal contractions. *Journal of Applied Physiology*, **96**, 2125-2132.

Isolated joint testing and exercise…A handbook for using CYBEX II and the U.B.X.T. [owner's manual]. (1980). Bay Shore, NY: Cybex.

Kukulka, C.G., & Clamann, H.P. (1981). Comparison of the recruitment and discharge properties of motor units in human brachial biceps and adductor pollicis during isometric contractions. *Brain Research*, **219**, 45-55.

Kwatny, E., Thomas, D.H., & Kwatny, H.G. (1970). An application of signal processing techniques to the study of myoelectric signals. *IEEE Transactions on Bio-medical Engineering*, **17**, 303-312.

Lammert, O., Jorgensen, F., & Einer-Jensen, N. (1976). Accelerometermyography (AMG). I. Method for measuring mechanical vibrations from isometrically contracted muscles. In P.V. Komi (Ed.), *Biomechanics V* (pp. 152-158). Baltimore: University Park.

L'Estrange, P.R., Rowell, J., & Stokes, M.J. (1993). Acoustic myography in the assessment of human masseter muscle. *Journal of Oral Rehabilitation*, **20**, 353-362.

Madeleine, P., Bajaj, P., Søgaard, K., & Arendt-Nielsen, L. (2001). Mechanomyography and electromyography force relationships during concentric, isometric and eccentric contractions. *Journal of Electromyography and Kinesiology*, **11**, 113-121.

Marchetti, M., Felici, F., Bernardi, M., Minasi, P., & Di Filippo, L. (1992). Can evoked phonomyography be used to recognize fast and slow twitch muscle in man? *International Journal of Sports Medicine*, **13**, 65-68.

Marchetti, M., Salleo, A., Figura, F., & Del Gaudio, V. (1974). Electromyographic and phonomyographic patterns in muscle atrophy in man. In R.C. Nelson & C.A. Morehouse (Eds.), *Biomechanics IV* (pp. 388-393). Baltimore: University Park.

Maton, B., Petitjean, M., & Cnockaert, J-C. (1990). Phonomyogram and electromyogram relationships with isometric force reinvestigated in man. *European Journal of Applied Physiology*, **60**, 194-201.

Orizio, C. (1993). Muscle sound: Bases for the introduction of a mechanomyographic signal in muscle studies. *Critical Reviews in Biomedical Engineering*, **21**, 201-243.

Orizio, C., Esposito, F., Sansone, V., Parrinello, G., Meola, G., & Veicsteinas, A. (1997). Muscle surface mechanical and electrical activities in myotonic dystrophy. *Electromyography and Clinical Neurophysiology*, **37**, 231-239.

Orizio, C., Esposito, F., & Veicsteinas, A. (1994). Effect of acclimatization to high altitude (5,050 m) on motor unit activation pattern and muscle performance. *Journal of Applied Physiology*, **77**, 2840-2844.

Orizio, C., Gobbo, M., Diemont, B., Esposito, F., & Veicsteinas, A. (2003). The surface mechanomyogram as a tool to describe the influence of fatigue on biceps brachii motor unit activation strategy. Historical basis and novel evidence. *European Journal of Applied Physiology*, **90**, 326-336.

Orizio, C., Liberati, D., Locatelli, C., De Grandis, D., & Veicsteinas, A. (1996). Surface mechanomyogram reflects muscle fibres twitches summation. *Journal of Biomechanics*, **29**, 475-481.

Orizio, C., Perini, R., Diemont, B., Figini, M.M., & Veicsteinas, A. (1990). Spectral analysis of muscular sound during isometric contraction of biceps brachii. *Journal of Applied Physiology*, **68**, 508-512.

Orizio, C., Perini, R., & Veicsteinas, A. (1989). Muscular sound and force relationship during isometric contraction in man. *European Journal of Applied Physiology*, **58**, 528-533.

Orizio, C., Solomonow, M., Baratta, R., & Veicsteinas, A. (1993). Influence of motor unit recruitment and firing rate on the soundmyogram and EMG characteristics in cat gastrocnemius. *Journal of Electromyography and Kinesiology*, **2**, 232-241.

Orizio, C., & Veicsteinas, A. (1992). Soundmyogram analysis during sustained maximal voluntary contraction in sprinters and long distance runners. *International Journal of Sports Medicine*, **13**, 594-599.

Pedhazur, E.J. (1997). *Multiple regression in behavioral research: Explanation and prediction* (3rd ed.). Fort Worth: Harcourt Brace College Publ.

Perry, S.R., Housh, T.J., Johnson, G.O., Ebersole, K.T., Bull, A.J., Evetovich, T.K., & Smith, D.B. (2001a). Mechanomyography, electromyography, heart rate, and ratings of perceived exertion during incremental cycle ergometry. *Journal of Sports Medicine and Physical Fitness*, **41**, 183-188.

Perry, S.R., Housh, T.J., Weir, J.P., Johnson, G.O., Bull, A.J., & Ebersole, K.T. (2001b). Mean power frequency and amplitude of the mechanomyographic and electromyographic signals during incremental cycle ergometry. *Journal of Electromyography and Kinesiology*, **11**, 299-305.

Petitjean, M., & Bellemare, F. (1994). Phonomyogram of the diaphragm during unilateral and bilateral phrenic nerve stimulation and changes with fatigue. *Muscle & Nerve*, **17**, 1201-1209.

Petitjean, M., Maton, B., & Cnockaert, J-C. (1992). Evaluation of human dynamic contraction by phonomyography. *Journal of Applied Physiology*, **73**, 2567-2573.

Rhatigan, B.A., Mylrea, K.C., Lonsdale, E., & Stern, L.Z. (1986). Investigation of sounds produced by healthy and diseased human muscular contraction. *IEEE Transactions on Bio-medical Engineering*, **33**, 967-971.

Sadamoto, T., Bonde-Petersen, F., & Suzuki, Y. (1983). Skeletal muscle tension, flow, pressure, and EMG during sustained isometric contractions in humans. *European Journal of Applied Physiology,* **51**, 395-408.

Sejersted, O.M., Hargens, A.R., Kardel, K.R., Blom, P., Jensen, O., & Hermansen, L. (1984). Intramuscular fluid pressure during isometric contraction of human skeletal muscle. *Journal of Applied Physiology*, **56**, 287-295.

Shinohara, M., Kouzaki, M., Yoshihisa, T., & Fukunaga, T. (1997). Mechanomyography of the human quadriceps muscle during incremental cycle ergometry. *European Journal of Applied Physiology,* **76**, 314-319.

Shinohara, M., Kouzaki, M., Yoshihisa, T., & Fukunaga, T. (1998). Mechanomyogram from the different heads of the quadriceps muscle during incremental knee extension. *European Journal of Applied Physiology,* **78**, 289-295.

Singh, M., & Karpovich, P.V. (1968). Strength of forearm flexors and extensors in men and women. *Journal of Applied Physiology,* **25**, 177-180.

Stokes, M.J. (1993). Acoustic myography: Applications and considerations in measuring muscle performance. *Isokinetics and Exercise Science,* **3**, 4-15.

Stokes, M.J., & Dalton, P.A. (1991). Acoustic myography for investigating human skeletal muscle fatigue. *Journal of Applied Physiology*, **71**, 1422-1426.

Stout, J.R., Housh, T.J., Johnson, G.O., Evetovich, T.K., & Smith, D.B. (1997). Mechanomyography and oxygen consumption during incremental cycle ergometry. *European Journal of Applied Physiology,* **76**, 363-367.

Yoshitake, Y., & Moritani, T. (1999). The muscle sound properties of different muscle fiber types during voluntary and electrically induced contractions. *Journal of Electromyography and Kinesiology*, **9**, 209-217.

Yoshitake, Y., Ue, H., Myazaki, M., & Moritani, T. (2001). Assessment of lower-back muscle fatigue using electromyography, mechanomyography, and near-infrared spectroscopy. *European Journal of Applied Physiology*, **84**, 174-179.

Zhang, Y-T., Frank, C.B., Rangayyan, R.M., & Bell, G.D. (1992). A comparative study of simultaneous vibromyography and electromyography with active human quadriceps. *IEEE Transactions on Biomedical Engineering,* **39**, 1045-1052.