Neuroscience

The Effects of Gender on Fatigue-Induced Changes in Electromechanical Efficiency and Torque

Ethan C. Hill[*], Terry J. Housh, Cory M. Smith, Richard J. Schmidt, and Glen O. Johnson

Department of Nutrition and Health Sciences, Human Performance Laboratory, University of Nebraska-Lincoln, Lincoln, NE 68505, USA

Electromechanical efficiency ($efficiency_{E\text{-}M}$) has been used to detect changes in neuromuscular function and track decreases in torque production as a result of muscle fatigue. No previous investigations, however, have applied $efficiency_{E\text{-}M}$ to examine gender-specific decreases in torque as a result of fatigue. Therefore, the purpose of the present investigation was to examine gender differences in the fatigue-related effects on $efficiency_{E\text{-}M}$ (mechanomyographic amplitude ÷ electromyographic amplitude) during repeated, submaximal, concentric forearm flexion muscle actions. Eleven men and eleven women performed 50 consecutive submaximal (65% of concentric peak torque), concentric muscle actions of the forearm flexors at $60°\cdot s^{-1}$. There were decreases in pretest versus posttest concentric peak torque for both the men (30.5%) and women (22.3%) as a result of the fatiguing exercise bout, but the decrease was greater for the men. During the fatiguing exercise bout, torque output remained unchanged at 65% of concentric peak torque, while $efficiency_{E\text{-}M}$ decreased for both the men and women. Thus, $efficiency_{E\text{-}M}$ did not track torque production during the submaximal fatiguing protocol.

Gender | Muscle Fatigue | EMG | MMG

Introduction

It has been well established that men and women respond differently to fatiguing exercise (11, 12). For example, women can perform a greater number of repetitions to exhaustion than men at the same relative intensity during isometric and concentric muscle actions (13-15). These gender-specific responses as a result of fatiguing exercise have been attributed to differences in muscle blood flow and motor unit activation strategies, and may be a function of the intensity of the exercise task, muscular strength of the subjects, and speed of the muscle actions (12, 16, 22). For example, during low intensity fatiguing exercise, men experienced greater fatigue-induced decreases in maximal voluntary isometric contraction (MVIC) than women, but at higher intensities there were no gender-specific differences in the decreases for MVIC (27). Furthermore, gender-specific decreases in MVIC as a result of submaximal muscle actions were due, in part, to differences in absolute muscle strength (14). In addition, women completed a greater number of repetitions than men during fatiguing submaximal dynamic muscle actions performed at a slow velocity of $60°\cdot s^{-1}$ (26). As a result of maximal velocity (per subject) submaximal dynamic muscle actions, however, men and women experienced similar reductions in MVIC (23).

Gender-specific fatigue responses have also been examined using electromyography (EMG) and mechanomyography (MMG) to make inferences regarding differences in the motor unit activation strategies that modulate torque production in men versus women (10). For example, during fatiguing submaximal muscle actions EMG amplitude tends to increase and has been associated with increases in motor unit recruitment and/or firing rate (7). In addition, MMG amplitude increases during fatiguing submaximal muscle actions at intensities of 20-60% of MVIC, but decreases at 60-80% of MVIC (20). Thus, the simultaneous assessment of EMG and MMG can be used to describe the fatigue-induced changes in torque as a function motor unit recruitment and/or firing rate. Regarding gender-specific neuromuscular responses, men and women manifested similar reductions in MVIC and EMG amplitude for the forearm flexors, but men experienced greater reductions in MVIC and EMG amplitude than women for the leg extensors (23) as a result of fatiguing, submaximal dynamic muscle actions. Furthermore, for the leg extensors, Hakkinen (9) reported that voluntary activation decreased to a greater extent in men than women as a result of a fatiguing bout of maximal effort back squats. Hill et al. (10), however, reported no gender-specific differences in EMG amplitude or MMG amplitude as a result of fatiguing, submaximal isometric muscle actions of the forearm flexors, but gender-specific decreases in MVIC. Thus, under some conditions there were gender-specific neuromuscular responses as a result of fatiguing submaximal exercise bouts. No previous investigations, however, have examined gender-specific neuromuscular responses during fatiguing submaximal muscle actions.

Barry et al. (2) suggested that electromechanical efficiency ($efficiency_{E\text{-}M}$), the ratio of MMG amplitude to EMG amplitude, provides a muscle-specific measurement of the impairment of electrochemical coupling as a result of muscle fatigue. Specifically, electromechanical coupling is a function of the electrical and mechanical components of muscle contraction and provides an indirect assessment of the efficiency of excitation-contraction coupling (2, 17). During fatiguing tasks in healthy muscle, $efficiency_{E\text{-}M}$ may also be impaired by a fatigue-induced buildup of metabolic byproducts which adversely effects excitation-contraction coupling (6, 25). For example, $efficiency_{E\text{-}M}$ has been shown to track torque production during maximal concentric and submaximal isometric muscle actions (6, 25) and may reflect the electromechanical impairment of fatigable motor units (6, 17). Thus, $efficiency_{E\text{-}M}$ may provide insight regarding fatigue-induced effects on torque production that are unique from EMG amplitude and MMG amplitude when examined individually. No previous investigations, however, have examined $efficiency_{E\text{-}M}$ during submaximal concentric exercise in men and women. Therefore, the purpose of the present investigation was to examine gender differences in the fatigue-related effects on $efficiency_{E\text{-}M}$ during repeated, submaximal, concentric forearm flexion muscle actions. Based on previous investigations (6, 25), we hypothesized that $efficiency_{E\text{-}M}$ would remain unchanged during the fatiguing protocol in both men and women.

Conflict of Interest: No conflicts declared.

* Corresponding Author: Ethan C. Hill. Department of Nutrition and Health Sciences, 110 Ruth Leverton Hall, University of Nebraska-Lincoln, Lincoln, NE 68583-0806, USA.

Phone: 402-472-2690. Email: ethan.hill@unl.edu

© 2017 by the Authors | Journal of Nature and Science (JNSCI).

Methods

Subjects

Eleven men (n = 11; mean age ± SD = 22.2 ± 1.8 yrs; body mass = 84.6 ± 8.6 kg; height = 179.5 ± 9.3 cm) and 11 women (n = 11; mean age ± SD = 22.2 ± 2.7 yrs; body mass = 62.2 ± 6.4 kg; height = 168.3 ± 7.3 cm) volunteered to participate in this investigation (Table 1). The number of subjects selected was based on a priori sample size calculations to detect gender differences in torque production with 80% power and type-I error rate of 5%. The subjects had no known cardiovascular, pulmonary, metabolic, muscular, and/or coronary heart disease, or regularly used prescription medication. In addition, all subjects at the time of testing were actively participating in resistance training for at least the past six months (men = 7.3 ± 2.6 $hrs \cdot wk^{-1}$ and women = 6.3 ± 3.3 $hrs \cdot wk^{-1}$ with no mean difference between genders [$p > 0.05$]). The subjects visited the laboratory on two occasions separated by at least 48-h within a 1-week period and performed the testing procedures at the same time of day. The subjects were instructed to avoid performing upper body exercise 48-h prior to the testing visit. The study was approved by the University Institutional Review Board for Human Subjects and all subjects completed a health history questionnaire and signed a written informed consent prior to testing.

Procedures

Familiarization. The first laboratory visit consisted of an orientation session to familiarize the subjects with the testing protocols. During the orientation, the subjects performed submaximal and maximal concentric, isokinetic muscle actions of the forearm flexors at $60° \cdot s^{-1}$. The subjects visually tracked torque production using real-time torque displayed on a computer monitor programmed using LabVIEW 13.0 software (National Instruments, Austin, TX) and practiced performing concentric muscle contractions at 65% of concentric peak torque.

Determination of Concentric Peak Torque and Submaximal Fatigue Protocol. During visit two, the subjects performed a warm-up consisting of 15 submaximal (approximately 50% of maximum effort), concentric muscle contractions of the dominant (based on throwing preference) forearm flexors at $60° \cdot s^{-1}$ on a calibrated Cybex II dynamometer. After 2-min of rest, the subjects performed five concentric peak torque trials through a 90° range of motion (0-90° of flexion at the elbow, where 0° corresponds to full extension at the elbow). Consistent with the recommendations of Brown (5), concentric peak torque was determined as the highest torque produced from the five trials, excluding the first trial. Following the determination of the pretest concentric peak torque, the subjects performed 50 submaximal (each repetition at 65% of their pretest concentric peak torque), concentric muscle actions at $60° \cdot s^{-1}$ and each repetition was followed by passive extension that was assisted by the investigator. Real-time torque was displayed on a computer monitor and a light bulb indicated the start and end of each repetition which was displayed on the same computer monitor as the real-time torque. Immediately after completing the 50 submaximal, concentric muscle actions, the subjects performed five posttest concentric peak torque trials using the same procedures as the pretest.

Electrode and Accelerometer Placements. A bipolar (30 mm center-to-center) surface EMG electrode (circular 4 mm diameter silver/silver chloride) arrangement was placed on the dominant arm over the biceps brachii according to the recommendations of Barbero et al. (1) and the reference electrode was placed over the acromion process. Prior to each electrode placement, the skin was shaved, carefully abraded, and cleaned with alcohol. The MMG signals from the biceps brachii were detected using an accelerometer (Entran EGAS FT 10, dimensions: 1.0 x 1.0 x 0.5 cm, mass: 1.0 g) that was placed between the proximal and distal EMG electrodes of the bipolar arrangement using double-sided adhesive tape.

Signal Processing and Determination of EMG Amplitude, MMG Amplitude, Eccentric Torque, and Efficiency$_{E\text{-}M}$. The raw EMG and MMG signals were digitized at 1000 Hz with a 32-bit analog-to-digital converter (Model MP150, Biopac Systems, Inc.) and stored in a personal computer (ATIV Book 9 Intel Core i7 Samsung Inc., Dallas, TX) for subsequent analyses. The EMG signals were amplified (gain: x 1000) using differential amplifiers (EMG 100, Biopac Systems, Inc., Santa Barbara, CA) and both the EMG and MMG signals were digitally bandpass filtered (fourth-order Butterworth, zero-phase shift) at 10-500 Hz and 5-100 Hz, respectively. All signal processing was performed using custom programs written with the LabVIEW programming software. The EMG amplitude (μV root-mean-square, μVrms) and MMG amplitude ($m \cdot s^{-2}$) values for the concentric muscle contractions were calculated for the middle one-third of each contraction (30-60° of flexion at the elbow, where 0° corresponds to full extension at the elbow). Furthermore, the EMG amplitude and MMG amplitude values were normalized to the initial repetition (i.e. repetition 1 of the 50 submaximal muscle actions). Efficiency$_{E\text{-}M}$ was calculated as the ratio of MMG amplitude to EMG amplitude (6).

Statistical Analyses

Independent samples *t*-tests were used to examine differences in weight, height, age, pretest concentric peak torque, and resistance training $hrs \cdot wk^{-1}$ between the men and women. A 2 (Gender [men, women]) × 2 (Time [pretest, posttest]) mixed factorial ANOVA was used to analyze the absolute concentric peak torque values. A significant interaction was decomposed with follow-up independent and dependent samples *t*-tests. Polynomial regression analyses (first, second, and third order) were used to examine the individual and composite patterns of responses for the normalized (to repetition 1 of the 50 submaximal, concentric muscle actions) EMG amplitude, MMG amplitude, and efficiency$_{E\text{-}M}$ during the fatiguing protocols. The F-test was used to determine if the increment in proportion of variance accounted for by a higher-order polynomial was significant at $p \leq 0.05$ (21). All statistical analyses were performed using IBM SPSS v. 21 (Armonk, NY) and an alpha of $p \leq 0.05$ considered statistically significant for all comparisons.

Results

Figure 1 displays the individual pretest and posttest absolute concentric peak torque responses for the men and women. Table 1 includes the descriptive characteristics of the men and women and Table 2 displays the individual and composite results of the polynomial regression analyses for the normalized EMG amplitude, MMG amplitude, and efficiency$_{E\text{-}M}$ during the 50 repetitions for the men and women.

Concentric Peak Torque Responses. There was a significant ($p < 0.001$, $\eta_p^2 = 0.747$) Gender × Time interaction for absolute concentric peak torque. Analyses of the simple main effects indicated that the decreases in concentric peak torque from pretest to posttest were significantly greater for the men (pretest = 78.7 ± 18.2 Nm vs. posttest 54.7 ± 14.5 Nm; 30.5% decrease) than the women (pretest = 40.2 ± 6.2 Nm vs. posttest 31.2 ± 5.9 Nm; 22.3% decrease). The individual responses indicated that concentric peak torque decreased from pretest to posttest for all subjects (Figure 1).

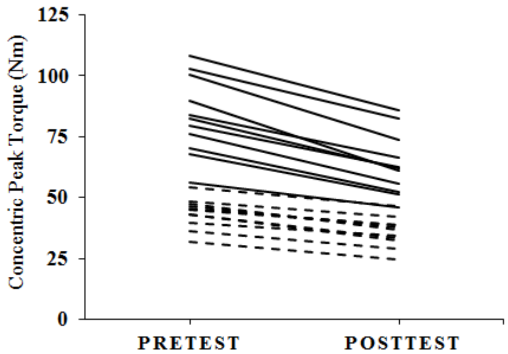

Figure 1. Individual fatigue-related responses for the men (solid line) and women (dashed line) for pretest and posttest concentric peak torque values. There were significant mean ($p \leq 0.05$) decreases for both the men (30.5%) and women (22.3%), but the decrease was greater for the men.

Table 1. Descriptive statistics for the men and women.

	Men	Women
Age	22.2 ± 1.8	22.2 ± 2.7
Weight (kg)*	84.6 ± 8.6	62.2 ± 6.4
Height (cm)*	179.5 ± 9.3	168.3 ± 7.3
Resistance training (hr·wk-¹)	7.3 ± 2.6	6.3 ± 3.3

*$p \leq 0.05$, men > women

Patterns of Responses for EMG Amplitude, MMG Amplitude, and Efficiency$_{E\text{-}M}$ during the 50 Submaximal Concentric Muscle Actions. The polynomial regression analyses of the composite data indicated that there were significant quadratic increases for normalized composite EMG amplitude versus repetition for the men (p = 0.002, R = 0.985) and women (p = 0.027, R = 0.855) during the fatiguing protocol (Figure 2a). In addition, for individual subjects there were linear (3 increases, 1 decrease), quadratic (3 increases, 1 decrease) as well as no relationships (3 of 11) for the men and linear (5 increases, 1 decrease), quadratic (1 increase), and cubic (1 increase) as well as no relationships (3 of 11) for the women (Table 2).

For composite normalized MMG amplitude, there was a significant linear decrease for the men (p < 0.001, r = -0.759) during the fatiguing protocol, but no change for composite normalized MMG amplitude versus repetition for the women (p = 0.429, r = 0.114) (Figure 2b). In addition, for individual subjects there were linear (1 decrease), quadratic (1 decrease), and cubic (2 decreases) as well as no relationships (7 of 11) for the men and linear (1 increase, 1 decrease) and quadratic (1 decrease) as well as no relationships (8 of 11) for the women (Table 2).

For composite efficiency$_{E\text{-}M}$, there were significant quadratic decreases for efficiency$_{E\text{-}M}$ versus repetition for the men (p = 0.016, R = -0.919) and the women (p = 0.006, R = -0.605) during the fatiguing protocol (Figure 2c). For individual subjects, there were linear (2 decreases), quadratic (5 decreases), and cubic (2 decreases) as well as no relationships (2 of 11) for the men and linear (3 increases, 2 decreases), quadratic (2 decreases), and cubic (1 decrease) as well as no relationships (3 of 11) for the women (Table 2).

Table 2. The individual and composite results of the polynomial regression analyses for the normalized (to initial repetition) electromyographic (EMG) amplitude, mechanomyographic (MMG) amplitude, and electromechanical efficiency (efficiency$_{E\text{-}M}$) for the men and women.

		EMG Amplitude		MMG Amplitude		Efficiency$_{E\text{-}M}$	
	Subject	Relationship	Correlation	Relationship	Correlation	Relationship	Correlation
Men	1	Quadratic	0.902	Linear	-0.758	Quadratic	-0.889
	2	NS	0.004	NS	0.057	NS	-0.053
	3	Quadratic	0.730	NS	-0.117	Quadratic	-0.627
	4	Linear	0.713	NS	-0.163	Cubic	-0.742
	5	Linear	0.354	NS	0.005	Quadratic	-0.420
	6	NS	0.095	Cubic	-0.736	Linear	-0.459
	7	Quadratic	-0.714	Cubic	-0.759	Cubic	-0.868
	8	Quadratic	0.664	NS	0.002	Quadratic	-0.637
	9	NS	0.092	NS	-0.201	NS	-0.062
	10	Linear	-0.442	NS	-0.229	Linear	-0.523
	11	Linear	0.533	Quadratic	-0.530	Quadratic	-0.511
	Composite	Quadratic	0.985	Linear	-0.759	Quadratic	-0.919
Women	1	Linear	-0.419	NS	0.085	Linear	0.371
	2	Linear	0.328	NS	0.236	NS	0.059
	3	Linear	0.635	Linear	-0.342	Linear	-0.526
	4	Cubic	0.805	NS	0.142	Cubic	-0.714
	5	Linear	0.673	NS	0.203	Linear	-0.358
	6	NS	0.014	NS	0.100	NS	0.112
	7	Quadratic	0.475	NS	-0.202	Quadratic	-0.573
	8	Linear	0.706	Quadratic	-0.404	Quadratic	-0.514
	9	NS	0.165	NS	-0.246	Linear	-0.406
	10	Linear	0.404	NS	0.254	NS	-0.096
	11	NS	0.007	Linear	0.432	Linear	0.326
	Composite	Quadratic	0.855	NS	0.114	Quadratic	-0.605

Note: NS corresponds to non-significant.

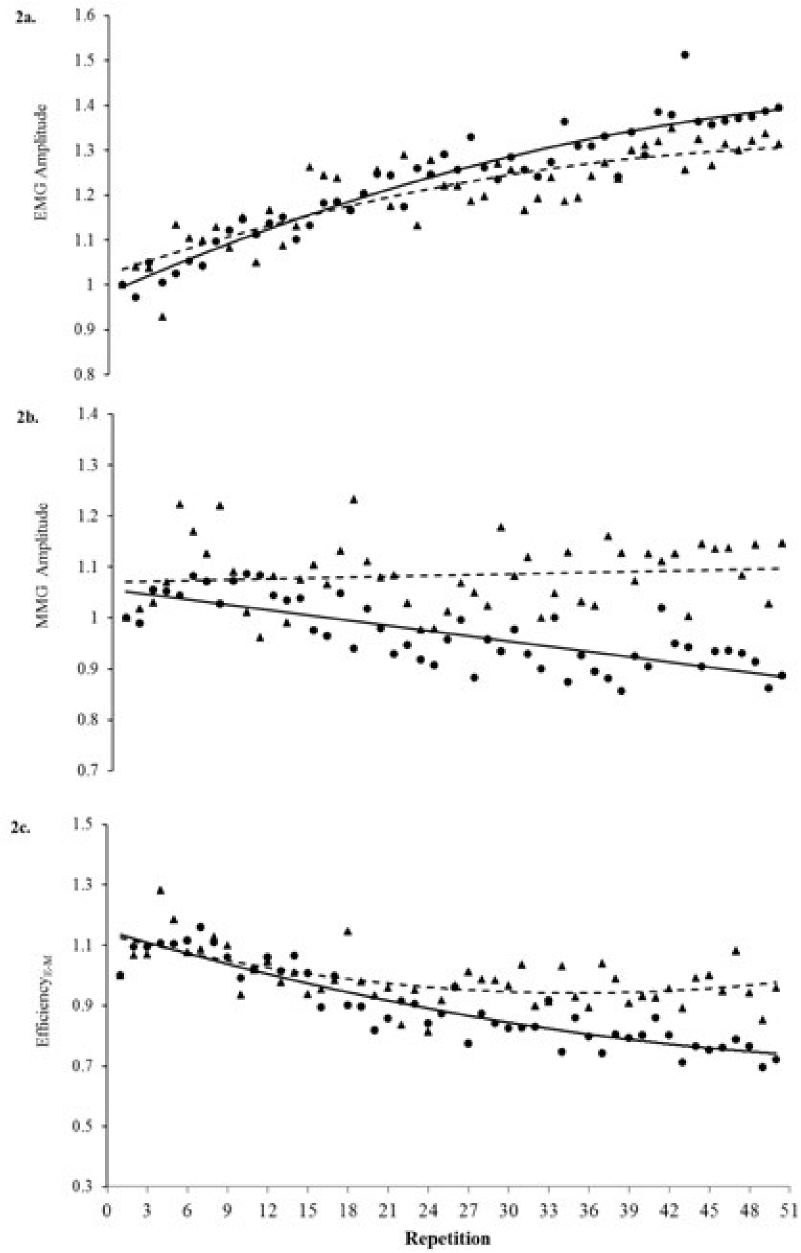

Figure 2. The composite results of the polynomial regression analyses for the normalized (to the initial repetition) electromyographic (EMG) amplitude (µV), mechanomyographic (MMG) amplitude ($m \cdot s^{-2}$) and electromechanical efficiency (efficiency_{E-M}) during the 50 submaximal, concentric muscle actions for the men (circles with solid line) and women (triangles with dashed line).

Discussion

The results of the present study indicated that the men exhibited a greater mean fatigue-induced reduction in absolute concentric peak torque than the women (30.5% vs. 22.3%, respectively). The individual analyses, however, indicated that concentric peak torque decreased from pretest to posttest for all subjects. Thus, for both the men and women, there were fatigue-induced decreases in posttest concentric peak torque as a result of the fatiguing submaximal protocol.

The decreases in concentric peak torque for both the men and women confirmed the fatiguing nature of the task. That is, despite the maintenance of torque production during 50 submaximal concentric muscle actions, concentric peak torque decreased from pretest to posttest. In addition, the gender-specific decreases in concentric peak torque were consistent with previous investigations (12, 16, 23, 26) that have also reported gender differences in peak torque or MVIC following fatiguing tasks. Generally, gender-specific decreases in torque production following fatiguing dynamic exercise have been associated with the intensity of the fatiguing task, muscle strength differences between men and women, and speed of the muscle action (12, 16, 23, 26). Therefore, the gender-specific differences in the concentric peak torque responses may have been a function of muscle strength (which was greater in the men than women), the intensity of the fatiguing task, and/or the speed of the muscle actions.

No previous investigations have examined gender-specific efficiency_{E-M} responses, but efficiency_{E-M} has been shown to track concentric and isometric torque during fatiguing exercise. For example, efficiency_{E-M} and concentric peak torque decreased during maximal, concentric leg extensions (6) and efficiency$_{E-M}$ and isometric torque remained unchanged during submaximal, isometric back extensions (25). Contrary to our hypothesis and previous investigations (6, 25), efficiency$_{E-M}$ did not track torque production during the submaximal fatiguing protocol. Specifically, efficiency$_{E-M}$ decreased during the fatiguing protocol, while torque production remained unchanged at 65% of concentric peak torque. The decreases in efficiency$_{E-M}$ during the fatiguing submaximal protocol, however, indicated that despite the maintenance in torque production, fatigue was manifested by simultaneous changes in EMG amplitude (increased for both the men and women) and MMG amplitude (decreased for the men and remained unchanged for the women). Thus, efficiency$_{E-M}$ did not track torque production during the submaximal concentric fatiguing protocol. For the women, however, MMG amplitude tracked the lack of changes in torque production. Therefore, for women, MMG amplitude may track torque production during fatiguing submaximal concentric muscle actions.

The composite decrease in efficiency$_{E-M}$ for the men was associated with an increase in EMG amplitude, but a decrease in MMG amplitude. For the women, however, the composite decrease in efficiency$_{E-M}$ was associated with an increase in EMG amplitude, but no change in MMG amplitude. The increases in EMG amplitude for both the men and women may have been due to fatigue-induced increase in motor unit recruitment and/or firing rates required to maintain 65% of concentric peak torque. Fatigue-induced decreases in MMG amplitude for the men may have been associated with muscle wisdom and/or decreased muscle compliance (3, 18, 19). It is unlikely, however, that the decrease in MMG amplitude reflected decreased motor unit recruitment since torque production remained unchanged and EMG amplitude increased during the fatiguing task. Thus, the decrease in MMG amplitude with no change in torque production may have been a function of muscle wisdom. Muscle wisdom is a motor unit activation strategy characterized by decreased muscle relaxation times and motor neuron discharge rates (decreased motor unit firing rate) as well as greater fusion of motor unit twitches to optimize force production (decreased lateral oscillations of the activated motor units) (8). It is also possible, however, that the decrease in MMG amplitude for the men was a function of deceased muscle compliance. For example, increased intramuscular fluid pressure from repeated and prolonged muscle actions can decrease muscle compliance (24) and restrict the lateral oscillations of the activated muscle fibers, thereby, decreasing MMG amplitude (4). Thus, the decrease in MMG amplitude for the men may be related to the effects of muscle wisdom and/or decreased muscle compliance. The lack of change in MMG amplitude for the women may have been due competing influences such as increased motor unit recruitment, the effects of muscle wisdom, and decreased muscle compliance. It is also possible that the fatigue-induced effects of muscle contractility are different between men and women during submaximal fatiguing concentric muscle actions.

There were, however, individual increases, decreases, and no changes in efficiency$_{E-M}$ for both the men and women which was likely due to the individual EMG amplitude and MMG amplitude responses that included increases, decreases, and no changes. Thus, despite overall decreases in efficiency$_{E-M}$ for both the men and women, the individual responses indicated that fatigue was manifested uniquely for each subject. For example, for both genders there were significant (linear, quadratic, and cubic) and non-significant relationships for EMG amplitude, MMG amplitude, and efficiency$_{E-M}$ that resulted in different patterns of responses. Therefore, inferences regarding electromechanical coupling (efficiency$_{E-M}$) and/or the motor unit activation strategies (EMG and MMG) during fatiguing tasks using composite data may not reflect the individual variability.

Conclusion

As a result of the fatiguing concentric muscle actions, pretest versus posttest concentric peak torque decreased to a greater extent in men than women. During the fatiguing submaximal protocol, torque production remained unchanged at 65% of concentric peak torque, while efficiency$_{E-M}$ decreased for both the men and women. The decreases in efficiency$_{E-M}$ were associated with increases in EMG amplitude for both the men and women, while MMG amplitude decreased for the men and remained unchanged for the women. Thus, despite similar EMG amplitude responses and gender-specific MMG amplitude responses during the fatiguing task, efficiency$_{E-M}$ decreased for both men and women. These findings indicated that both the men and women experienced fatigue-induced increases in muscle activation and impairment on electrical-mechanical coupling during the fatiguing intervention.

1. Barbero, M., Merletti, R., Rainoldi, A. *Atlas of Muscle Innervation Zones Understanding Surface Electromyography and its Applications*. New York, NY; Springer, 2012.
2. Barry, D. T., Leonard, J. A., Jr., Gitter, A. J., and Ball, R. D. Acoustic myography as a control signal for an externally powered prosthesis. *Arch Phys Med Rehabil* 67: 267-269, 1986.
3. Beck, T. W., Housh, T. J., Johnson, G. O., Weir, J. P., Cramer, J. T., Coburn, J. W., and Malek, M. H. Mechanomyographic amplitude and mean power frequency versus torque relationships during isokinetic and isometric muscle actions of the biceps brachii. *J Electromyogr Kinesiol* 14: 555-564, 2004.
4. Beck, T. W., Housh, T. J., Johnson, G. O., Weir, J. P., Cramer, J. T., Coburn, J. W., and Malek, M. H. Mechanomyographic and electromyographic amplitude and frequency responses during fatiguing isokinetic muscle actions of the biceps brachii. *Electromyogr Clin Neurophysiol* 44: 431-441, 2004.
5. Brown, L. E. *Isokinetics in Human Performance.* Champaign, Ill.: Human Kinetics, 2000.
6. Ebersole, K. T. and Malek, D. M. Fatigue and the Electromechanical efficiency of the vastus medialis and vastus lateralis muscles. *J Athl Train* 43: 152-156, 2008.
7. Enoka, R. M. and Duchateau, J. Muscle fatigue: what, why and how it influences muscle function. *J Physiol (Lond)* 586: 11-23, 2008.
8. Garland, S. J. and Gossen, E. R. The muscular wisdom hypothesis in human muscle fatigue. *Exerc Sport Sci Rev* 30: 45-49, 2002.
9. Hakkinen, K. Neuromuscular fatigue and recovery in male and female athletes during heavy resistance exercise. *Int J Sport Med* 14: 53-59, 1993.
10. Hill, E. C., Housh, T. J., Smith, C. M., Cochrane, K. C., Jenkins, N. D., Cramer, J. T., Schmidt, R. J., and Johnson, G. O. Effect of sex on torque, recovery, EMG, and MMG responses to fatigue. *J Musculoskelet Neuronal Interact* 16: 310-317, 2016.
11. Hunter, S. K. Sex differences in human fatigability: mechanisms and insight to physiological responses. *Acta Physiologica (Oxford, England)* 210: 768-789, 2014.
12. Hunter, S. K. Sex differences in fatigability of dynamic contractions. *Exp Physiol* 101: 250-255, 2016.
13. Hunter, S. K., Critchlow, A., Shin, I. S., and Enoka, R. M. Men are more fatigable than strength-matched women when performing intermittent submaximal contractions. *J Appl Physiol* 96: 2125-2132, 2004.

14. Hunter, S. K. and Enoka, R. M. Sex differences in the fatigability of arm muscles depends on absolute force during isometric contractions. *J Appl Physiol* 91: 2686-2694, 2001.
15. Hunter, S. K., Ryan, D. L., Ortega, J. D., and Enoka, R. M. Task differences with the same load torque alter the endurance time of submaximal fatiguing contractions in humans. *J Neurophysiol* 88: 3087-3096, 2002.
16. Maughan, R. J., Harmon, M., Leiper, J. B., Sale, D., and Delman, A. Endurance capacity of untrained males and females in isometric and dynamic muscular contractions. *Eur J Appl Physiol Occup Physiol* 55: 395-400, 1986.
17. Orizio, C., Esposito, F., Paganotti, I., Marino, L., Rossi, B., and Veicsteinas, A. Electrically-elicited surface mechanomyogram in myotonic dystrophy. *Neurol Sci* 18: 185-190, 1997.
18. Orizio, C., Gobbo, M., Diemont, B., Esposito, F., and Veicsteinas, A. The surface mechanomyogram as a tool to describe the influence of fatigue on biceps brachii motor unit activation strategy. Historical basis and novel evidence. *Eur J Appl Physiol* 90: 326-336, 2003.
19. Orizio, C., Perini, R., Diemont, B., Maranzana Figini, M., and Veicsteinas, A. Spectral analysis of muscular sound during isometric contraction of biceps brachii. *J Appl Physiol* 68: 508-512, 1990.
20. Orizio, C., Perini, R., and Veicsteinas, A. Musuclar sound and force relationship during isometric contraction in man. *Eur J Appl Physiol Occup Physiol* 58: 528-533, 1989.
21. Pedhazur, E. J. *Multiple Regression in Behavioral Research: Explanation and Prediction.* Harcourt Brace College Publishers, 1997.
22. Russ, D. W. and Kent-Braun, J. A. Sex differences in human skeletal muscle fatigue are eliminated under ischemic conditions. *J Appl Physiol* 94: 2414-2422, 2003.
23. Senefeld, J., Yoon, T., Bement, M. H., and Hunter, S. K. Fatigue and recovery from dynamic contractions in men and women differ for arm and leg muscles. *Muscle Nerve* 48: 436-439, 2013.
24. Sjogaard, G. and Saltin, B. Extra- and intracellular water spaces in muscles of man at rest and with dynamic exercise. *Am J Physiol* 243: R271-280, 1982.
25. Wright, F. and Stokes, M. J. Symmetry of electro- and acoustic myographic activity of the lumbar paraspinal muscles in normal adults. *Scand J Rehabil Med* 24: 127-131, 1992.
26. Yoon, T., Doyel, R., Widule, C., and Hunter, S. K. Sex differences with aging in the fatigability of dynamic contractions. *Exp Gerontol* 70: 1-10, 2015.
27. Yoon, T., Schlinder, Delap B., Griffith, E. E., and Hunter, S. K. Mechanisms of fatigue differ after low- and high-force fatiguing contractions in men and women. *Muscle Nerve* 36: 515-524, 2007.