2017

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International Journal of EXERCISE SCIENCE

Original Research

The Effects of Work-to-Rest Ratios on Torque, Electromyographic, and Mechanomyographic Responses to Fatiguing Workbouts

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ABSTRACT

International Journal of Exercise Science 10(4): 580-591, 2017. The purpose of the present study was to examine the effects of 2 different work-to-rest ratios, but the same mean load, cycle time, and total duration of the exercise bout, on maximal voluntary isometric contraction torque and neuromuscular responses to fatiguing, intermittent, submaximal, isometric, forearm flexion muscle actions. Ten men performed 2 fatiguing protocols with different work-to-rest ratios (4 s contraction, 4 s rest vs. 4 s contraction, alternating 6 and 2 s rest) that consisted of 50 intermittent, submaximal (65% of maximal voluntary isometric contraction), isometric, forearm flexion muscle actions. Electromyographic and mechanomyographic signals from the biceps brachii were recorded before, during, immediately and 5 min after performing the fatiguing protocols. In addition, maximal voluntary isometric contraction torque was assessed before, immediately and 5 min after. Both protocols resulted in decreases in maximal voluntary isometric contraction torque, electromyographic mean power frequency, and mechanomyographic mean power frequency, but no changes in electromyographic amplitude or mechanomyographic amplitude. The results of the present study indicated that differences in work-to-rest ratio did not affect maximal voluntary isometric contraction torque or the associated neuromuscular parameters as a result of fatiguing, intermittent, isometric muscle actions when mean load, cycle time, and total duration of exercise were equivalent.

KEY WORDS: Neuromuscular fatigue, alternating rest, muscle fatigue, EMG, MMG

INTRODUCTION

A commonly used definition of neuromuscular fatigue by Bigland-Ritchie and Woods (7) is "…any reduction in the force generating capacity of the total neuromuscular system regardless of the force required in any given situation". Fatigue is multifaceted and there is no single mechanism that can account for the effects on muscular performance under all conditions (15, 43). Thus, the mechanisms underlying fatigue are dependent upon the characteristics of the physical activity that is performed (15).

Time-dependent changes in electromyographic (EMG) and mechanomyographic (MMG) time and frequency domain parameters have been used to describe the patterns and time course of neuromuscular responses to fatigue and make inferences regarding the motor unit activation strategies that modulate torque production during fatiguing tasks (31, 40, 43, 45). Specifically, it has been suggested that, within limitation, the root-mean-squared amplitude (AMP) of the EMG signal reflects the level of muscle activation and the frequency content is associated with muscle fiber action potential conduction velocity (2, 9, 10, 17). The AMP of the MMG signal, however, can provide information regarding motor unit recruitment and the frequency content is qualitatively related to the global firing rate of the activated motor units (22, 35, 36). Thus, simultaneous assessments of timing and patterns of responses for the AMP and frequency characteristics of EMG and MMG signals may provide insight regarding fatigue-related changes in motor unit activation strategies.

Factors such as the mode of muscle action (intermittent isometric, sustained isometric, and dynamic), cycle time (length of exercise period + length of pause period), mean load (exercise period load × length of exercise period ÷ cycle time), and duty cycle (length of exercise period ÷ cycle time) can affect the performance and neuromuscular responses to fatigue (31, 41, 46). For example, Rohmert (41) and Mathiassen (31) found that the time to exhaustion was inversely related to mean load and duty cycle during intermittent, submaximal, isometric muscle actions of the forearm flexors and arm abductors. Furthermore, Seghers and Spaepen (43) reported that EMG AMP from the biceps brachii increased, while EMG median frequency (MDF) decreased during 60 intermittent, submaximal, isometric, forearm flexion muscle actions at 50% of maximal voluntary isometric contraction (MVIC) and a duty cycle of 0.25. At 25% of MVIC and a duty cycle of 0.50, however, EMG AMP increased, but EMG MDF remained unchanged (43). The findings of Seghers and Spaepen (43) were in partial agreement with those of Mathiassen (31) who reported increases in EMG AMP from the upper trapezius, but decreases in EMG frequency during intermittent, submaximal, isometric, arm abduction muscle actions performed to exhaustion at 15% of MVIC and duty cycles of 0.50 and 0.67. At 15% of MVIC and duty cycles of 0.33 and 0.83, however, there were increases in EMG AMP, but no changes in EMG frequency (31). In addition, Madeleine, et al. (28) reported that during 180 intermittent, submaximal, isometric, forearm flexion muscle actions, MMG AMP from the biceps brachii increased and MMG mean power frequency (MPF) decreased at 10 and 30% of MVIC and duty cycles of 0.6 and cycle times of 10 s. Therefore, previous investigations (28, 31, 41, 43) have indicated that the characteristics of a fatiguing task can affect the performance as well as the EMG and MMG time and frequency domain responses to fatiguing intermittent, submaximal, isometric muscle actions.

No previous investigations, however, have examined the effects of different duty cycles on EMG and MMG time and frequency domain responses during intermittent, submaximal, isometric muscle actions when mean load, cycle time, and total duration of exercise bouts are held constant. Furthermore, the duty cycles used in previous investigations (28, 31, 41, 43) have generally involved large work periods as well as large rest times at light contraction intensities (≤ 50% of MVIC). Human movements in sport and work places, however, vary by duration and intensity which generally include short work periods followed by short rest periods (14, 41). Thus, there is a need to further examine the effects of duty cycle with short work and rest periods and at higher contraction intensities that may be applicable to typical sport- and work-related activities. Therefore, the purpose of the present study was to examine the effects of 2 different work-to-rest ratios, but the same mean load, cycle time, and total duration of the exercise bout, on MVIC torque and neuromuscular responses to fatiguing, intermittent, submaximal, isometric, forearm flexion muscle actions. Based on previous investigations (28, 31, 41, 43), we hypothesized that there would be no difference in the patterns of responses for torque or any of the neuromuscular parameters as a result of the 2 fatiguing workbouts. As a result of the fatiguing workbouts, however, we hypothesized that MVIC torque, EMG MPF, MMG AMP, and MMG MPF would decrease, while EMG AMP would remain unchanged. During the fatiguing workbouts, we hypothesized that EMG AMP, MMG AMP, and MMG MPF would increase, while EMG MPF would decrease.

METHODS

Participants

Ten men (mean age ± SD = 23 ± 2 yrs; body weight = 85.4 ± 7.1 kg; height = 179.2 ± 6.3 cm) volunteered to participate in this investigation. Sample size was selected based on a priori sample size calculations with 80% power and type-I error rate of 5%. The subjects regularly participated in resistance training and had no known cardiovascular, pulmonary, metabolic, muscular and/or coronary heart disease, or regularly used prescription medication or nutritional supplements. The subjects visited the laboratory on 3 occasions separated by at least 48 h and were instructed not to perform upper body exercise 48 h prior to each 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.

Protocol

Familiarization (Visit 1) - The first laboratory visit consisted of an orientation session to familiarize the subjects with the testing protocols. During the orientation, the subjects practiced maximal and submaximal (65% of MVIC), isometric, forearm flexion muscle actions. The subjects visually tracked torque production using real-time torque displayed on an external computer monitor that was programmed using LabVIEW 13.0 software (National Instruments, Austin, TX).

Determination of MVIC and Submaximal, Isometric Muscle Actions (Visits 2 and 3). During visits 2 and 3, the subjects performed a warm-up consisting of 10 – 15 submaximal (50 – 75% max), isometric muscle actions of the dominant (based on throwing preference) forearm flexors on a calibrated Cybex II dynamometer (Medway, Massachusetts). Each warm-up muscle action was sustained for 4 s followed by 10 s of rest. After 2 min of rest, the subjects performed 2 pretest MVIC trials held for 4 s and separated by 2 s of rest at an elbow joint angle of 115°. The highest isometric torque from the 2 trials was selected as the pretest MVIC. Following the determination of the pretest MVIC, the subjects performed 50 intermittent, submaximal, isometric muscle actions at 65% of their Visit 2 pretest MVIC using 1 of the 2 randomly ordered protocols (4-4 or 6-2). Based on preliminary findings, intensity was selected to allow for the completion of all 50 repetitions and sufficiently high enough to induce decreases in MVIC torque. Protocol 4-4 consisted of 50 intermittent, 4 s isometric contractions at 65% MVIC with each contraction followed by 4 s of rest. Protocol 6-2 consisted of 50 intermittent, 4 s isometric contractions at 65% MVIC with each contraction followed by alternating 6 or 2 s of rest. Like the familiarization visit, real-time torque was displayed on an external computer monitor. In addition, for all visits a virtual 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 (posttest) and 5 min after (5 min recovery) completing the 50 submaximal, isometric muscle actions, the subjects performed MVIC trials using the same procedures as the pretest.

Electrode and Accelerometer Placements - During visits 2 and 3, a bipolar (30 mm center-to-center) surface EMG electrode (circular 4 mm diameter silver/silver chloride, BIOPAC Systems, Inc., Santa Barbara, CA) arrangement was placed on the dominate arm over the biceps brachii muscle according to Barbero, et al. (1). 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 signal from the biceps brachii was detected using an accelerometer (Entran EGAS FT 10, dimensions: 1.0 x 1.0 x 0.5 cm; mass: 1.0 g; sensitivity: 654.6 mV/g) that was placed between the proximal and distal EMG electrodes of the bipolar arrangement using double-sided adhesive tape.

Signal Processing - The raw EMG and MMG signals were digitized at 1000 Hz with a 12-bit analog-to-digital converter (Model MP100, 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). The EMG and MMG signals were digitally bandpass filtered (fourth-order Butterworth) 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 (μV root-mean-square, μVrms) and MMG ($m \cdot s^{-2}$) AMP and MPF (Hz) values for the MVIC and submaximal, isometric muscle actions were calculated for the middle third of each contraction. Thus, signal epochs of 1.33 s were used to calculate the AMP and MPF values of the EMG and MMG signals. This portion of the signal was selected to avoid initial gross lateral movement of the muscle at the onset of muscle contraction (35) and to ensure that the subject was at MVIC or 65% of MVIC. For the submaximal, isometric muscle actions, repetition 5 was the average of repetitions 1 – 5, repetition 10 was the average or repetitions 6 – 10, and so on (Figure 1). Average values across each of the 5 repetitions were used for subsequent analyses. For the MPF analyses, each data segment was processed with a Hamming window and the

Discrete Fourier transform algorithm (12, 26). The MPF was selected to represent the power spectrum in accordance with the recommendations of Hermens, et al. (23).

Statistical Analysis

Five separate 3 (Time [pretest, posttest, 5 min recovery]) × 2 (Protocol [4-4, 6-2]) repeated measures analysis of variance (ANOVAs) were used to analyze the MVIC torque values as well as the EMG AMP, EMG MPF, MMG AMP, and MMG MPF values assessed during the MVIC muscle actions. In addition, four separate 10 (Time [5, 10, 15, 20, 25, 30, 35, 40, 45, 50]) × 2 (Protocol [4-4, 6-2]) repeated measures ANOVAs were used to analyze the EMG AMP, EMG MPF, MMG AMP, and MMG MPF values assessed during the submaximal, isometric muscle actions. Post-hoc analyses were performed using Fischer's Least Significant Difference. Greenhouse Geisser corrections were applied when sphericity was not met according to Maulchy's Test of Sphericity and partial eta squared effect sizes (η_p^2) were calculated for each ANOVA and interpreted using Cohen's D as small (0.2), medium (0.5), or large (0.8) (39). For all analyses, the torque and neuromuscular parameters were normalized to the pretest MVIC during Visit 2. Furthermore, all statistical analyses were performed using IBM SPSS v. 21 (Armonk, NY) and an alpha of $p \leq 0.05$ was considered statistically significant.

RESULTS

MVIC - Table 1 includes the pretest, posttest, and 5 min recovery responses for MVIC and associated neuromuscular parameters. There were no significant Time × Protocol interactions for torque ($p = 0.958$, $\eta_p^2 = 0.005$) or any of the neuromuscular ($p = 0.335$-0.828, $\eta_p^2 = 0.021$-0.115) parameters. There were, however, significant main effects for Time (collapsed across Protocol) for torque (pretest > 5 min recovery > posttest; $p < 0.001$, $\eta_p^2 = 0.886$),EMG MPF (pretest > posttest; $p = 0.001$, $\eta_p^2 = 0.516$), and MMG MPF (pretest > posttest; $p = 0.015$, $\eta_p^2 = 0.373$), but not EMG AMP ($p = 0.135$, $\eta_p^2 = 0.199$) or MMG AMP ($p = 0.150$, $\eta_p^2 = 0.190$). Furthermore, there were no significant main effects for Protocol (collapsed across Time) for torque ($p = 0.793$, $\eta_p^2 = 0.008$) or any of the neuromuscular ($p = 0.277$-0.892, $\eta_p^2 = 0.002$-0.129) parameters.

Table 1. Marginal means ± SD (collapsed across Protocol) for pretest, posttest, and 5-min recovery.

	Pretest	Posttest	5-min Recovery
MVIC Torque (Nm)	84.1 ± 8.6[a]	65.8 ± 6.9[b]	72.5 ± 5.9[c]
EMG AMP (μVrms)	1210.5 ± 733.3	1331.8 ± 556.5	1282.4 ± 397.8
EMG MPF (Hz)	84.9 ± 22.1[a]	70.4 ± 19.7[b]	81.0 ± 19.6
MMG AMP ($m \cdot s^{-2}$)	0.64 ± 0.19	0.76 ± 0.29	0.76 ± 0.43
MMG MPF (Hz)	31.8 ± 6.3[a]	25.5 ± 7.3[b]	33.1 ± 6.3

[a]Significant at $p \leq 0.05$ for pretest > posttest, [b]Significant at $p \leq 0.05$ for posttest < 5-min recovery, [c]Significant at $p \leq 0.05$ for 5-min recovery < pretest

Intermittent, Submaximal, Isometric Muscle Actions. Figure 1 displays the neuromuscular responses from the 50 intermittent, submaximal, isometric muscle actions for associated neuromuscular parameters. There were no significant Time × Protocol interactions for any of the neuromuscular parameters. There were, however, significant main effects for Time (collapsed across Protocol) for EMG AMP ($p = 0.013$, $\eta_p^2 = 0.516$) which increased, and for EMG MPF ($p = 0.001$, $\eta_p^2 = 0.712$) and MMG MPF ($p = 0.020$, $\eta_p^2 = 0.467$) which decreased.

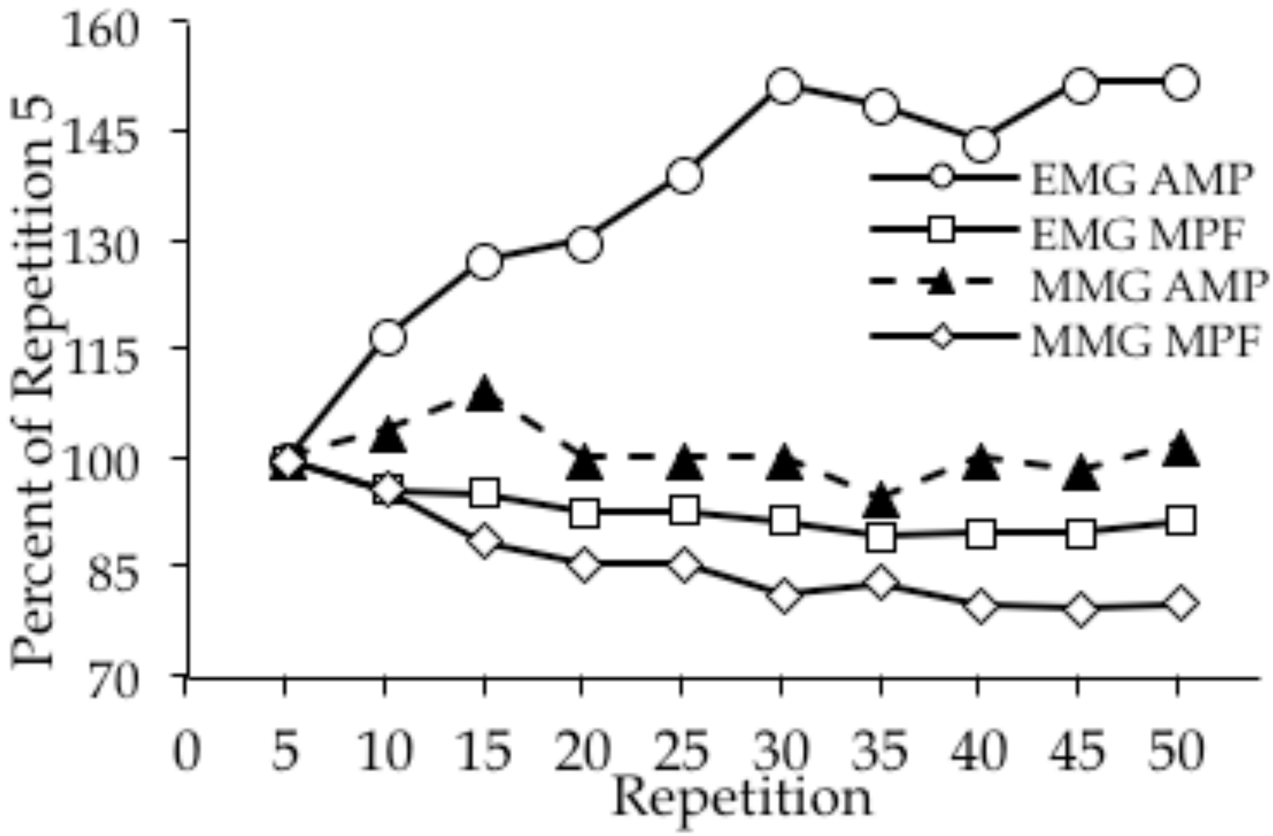

Figure 1. Marginal means (collapsed across Protocol) for electromyographic (EMG) amplitude (AMP), EMG mean power frequency (MPF), mechanomyographic (MMG) AMP, and MMG MPF from the biceps brachii across the 50 submaximal, isometric muscle actions. Each repetition is the average of 5 repetitions (i.e. repetition 5 = mean of repetitions 1-5; repetition 10 = mean of repetitions 6-10; and so on). *Significant ($p \leq 0.05$) changes from baseline (i.e. repetition 5) are denotated by a solid line and empty symbols.

DISCUSSION

The primary findings of the present study indicated that the 2 work-to-rest ratios resulted in similar fatigue-induced effects on MVIC, EMG AMP, EMG MPF, MMG AMP, and MMG MPF. For example, averaged across subjects, similar average torque (64.8±1.9% and 65.1±2.2%) was performed as a result of the 4-4 and 6-2 protocols, respectively, over a time period of 5 min and 40 s. These findings indicated that when total work performed and duration of the tasks was equivalent, work-to-rest ratios were not related to fatigue-related effects on torque or neuromuscular responses as a result of performing fatiguing submaximal isometric muscle actions. Thus, the subsequent interpretations and discussion were based on fatigue-induced effects of performing submaximal isometric muscle actions.

The decreases in MVIC torque (22.1 and 21.3%) for both protocols (4-4 and 6-2) in the present study were in agreement with previous investigations (6, 29, 43, 45) that have reported 15 – 50% decreases following 27 – 180 intermittent, submaximal (10 – 50% of MVIC), isometric muscle actions in various muscle groups. Furthermore, for the pretest versus posttest neuromuscular responses during the MVIC muscle actions, EMG MPF and MMG MPF decreased, while EMG AMP and MMG AMP remained unchanged for both protocols (4-4 and 6-2). After 5 min of recovery, however, all neuromuscular parameters returned to pretest levels. These findings were not consistent with Søgaard, Blangsted, Jorgensen, Madeleine and Sjogaard (45) who reported decreases in EMG AMP, increases in EMG MPF, but no changes in MMG AMP or MMG MPF from the biceps brachii following a bout of intermittent, submaximal, isometric muscle actions at 30% of MVIC. The differences in neuromuscular responses between the present study and those of Søgaard, Blangsted, Jorgensen, Madeleine and Sjogaard (45) may be related to differences in load intensity (65 vs. 30% of MVIC), work-to-rest ratio (4 s contraction, 4 s rest and 4 s contraction, 2 or 6 s rest vs. 6 s contraction, 4 s rest) cycle time (8 s vs. 10 s), number of repetitions (50 vs. 180), and/or total duration of exercise (400 s vs. 1800 s). Furthermore, in the present study the neuromuscular responses were assessed pretest, posttest, and 5 min post exercise at 100% of MVIC, while Søgaard, Blangsted, Jorgensen, Madeleine and Sjogaard (45) assessed the neuromuscular responses pretest, 10 and 30 min post exercise at a submaximal level of 80% of MVIC.

In the present study, the decreases in EMG MPF and MMG MPF during the MVIC muscle actions were consistent with the decreases in MVIC torque, but EMG AMP and MMG AMP remained unchanged. These findings indirectly suggested that muscle activation (EMG AMP) was unaffected by the intermittent, submaximal, isometric muscle actions when assessed during the MVIC muscle actions, while action potential conduction velocity (EMG MPF) and global motor unit firing rate (MMG MPF) decreased. Fatigue-induced decreases in action potential conduction velocity (EMG MPF) have been associated with the buildup of metabolic byproducts which can adversely affect excitation-contraction coupling (13, 27) and may lead to the dropout (inability to contribute to force production despite activation) of fatigable fast-twitch motor units (8, 34, 38, 42) which have higher firing rates (35, 36). In the present study, the decrease in MMG MPF which reflects motor unit firing rate and the decrease in MVIC torque were consistent with the potential fatigue-induced dropout of fast-twitch motor units, while the lack of change in MMG AMP which reflects motor unit recruitment was not (35, 36). The dissociation between the MMG AMP and MMG MPF responses may have been due to competing influences on the MMG signal. Specifically, fatigue-induced dropout of fast-twitch motor units (which decreases MMG AMP and MMG MPF) may have been counterbalanced by decreased muscle stiffness which is proportional to the number of attached cross-bridges (4, 16) and, therefore, allowed greater oscillations of the activated motor units (which increases MMG AMP) (4). These fatigue-related mechanisms (dropout of fatigable fast-twitch motor units and decreased action potential conduction velocity), however, were not consistent with MVIC torque measured 5 min post exercise. That is, at 5 min post exercise EMG MPF and MMG MPF returned to pretest levels, while MVIC torque at 5 min post exercise remained depressed, although was greater than MVIC torque assessed posttest. Previous investigations have reported that during recovery, EMG MPF returned to pretest levels and may reflect the clearance of metabolic byproducts (29, 32, 33). No previous investigations have examined MMG MPF 5 min post exercise, however, the current findings suggested that global motor unit firing rate may have returned to pretest levels due to the recovery in the ability of previously fatigued fast-twitch motor units to again contribute to torque production as evidenced by the increases in MVIC torque. Collectively, these findings suggested that the EMG MPF and MMG MPF responses were consistent with the fatigue-induced decreases in MVIC torque posttest, and 5 min of recovery was enough time to restore EMG MPF and MMG MPF to pretest levels, but was not sufficient for MVIC torque. Thus, the recovery patterns of these neuromuscular parameters were not consistent with the recovery of MVIC torque.

During the intermittent, submaximal, isometric muscle actions, EMG MPF and MMG MPF decreased, MMG AMP remained unchanged, while EMG AMP increased. These findings were in partial agreement with previous investigations that have reported increases in EMG AMP (6, 29, 43, 45), and decreases or no changes in EMG MPF (25, 29, 43) during intermittent, submaximal, isometric muscle actions. Increases in EMG AMP have been attributed to fatigue-induced increases in muscle activation (increased motor unit recruitment, firing rate, and/or synchronization) to maintain force production, while fatigue-induced decreases in EMG MPF and MMG MPF have been attributed to decreases in action potential conduction velocity and global motor unit firing rate, respectively (3, 5, 15, 36, 37, 42). In the present study, the decreases in action potential conduction velocity (EMG MPF) and global motor unit firing rate (MMG MPF) may be related to the effects of muscle wisdom including decreased muscle relaxation times and motor neuron discharge rates as well as a greater fusion of motor unit twitches to optimize force production (18-21, 30). In addition, the increase in muscle activation was likely the result of motor unit synchronization (as evidenced by the lack of change in motor unit recruitment (MMG AMP) and decreased firing rate (MMG MPF)) which results in a more efficient and synchronous activation of motor units to optimize force production (2, 11, 24, 34, 44, 47). Thus, it is plausible that the maintenance in torque across the 50 intermittent, submaximal, isometric muscle actions was a function of muscle wisdom and/or motor unit synchronization which optimized force production during the fatiguing muscle actions.

The present findings indicated that there was no difference in MVIC torque responses between the 4-4 and 6-2 intermittent isometric protocols. Thus, alternating the work-to-rest ratio for consecutive repetitions did not affect the MVIC torque responses to fatiguing exercise bouts when mean load (32.5% of MVIC), cycle time (8 s), and the total duration of the exercise (400 s) were equivalent. The results of the present study were in agreement with Seghers and Spaepen (43) who reported decreases of 15.2 and 15.3% in MVIC torque for the forearm flexors, following two intermittent isometric protocols with different work-to-rest ratios (10 s contraction, 10 s rest vs. 5 s contraction, 15 s rest), but equal mean load (12.5% of MVIC), cycle time (20 s), and total duration of exercise (1200 s). Thus, the present findings, in conjunction with Seghers and Spaepen (43), indicated that work-to-rest ratios did not affect the MVIC torque responses when mean load, cycle time, and total duration of exercise were equivalent.

Like MVIC torque, the work-to-rest ratios of the 4-4 and 6-2 intermittent isometric protocols did not affect the neuromuscular responses during the MVIC or intermittent, submaximal, isometric muscle actions. Specifically, during the MVIC muscle actions EMG MPF (18.7 and 15.5%) and MMG MPF decreased (15.0 and 23.9%), while EMG AMP and MMG AMP remained unchanged for the 4-4 and 6-2 protocols, respectively. During the intermittent, submaximal, isometric muscle actions, EMG AMP increased (57.3 and 46.7%), EMG MPF (8.3 and 8.4%) and MMG MPF (19.9 and 19.8%) decreased, and MMG AMP remained unchanged for the 4-4 and 6-2 protocols, respectively. These findings were in partial agreement with Seghers and Spaepen (43) who reported no change from pretest to posttest for EMG AMP during MVIC muscle actions, but increases in EMG AMP during the intermittent, submaximal, isometric muscle actions. Unlike the present study, however, Seghers and Spaepen (43) reported a difference in the EMG MDF responses during the repeated, submaximal, isometric muscle actions between a low versus high torque protocol. Specifically, during the low torque protocol (10 s contraction, 10 s rest at 25% of MVIC), Seghers and Spaepen (43) reported decreases for EMG MDF, while during the high torque protocol (5 s contraction, 15 s rest at 50% of MVIC) EMG MDF remained unchanged. The differences in EMG MDF responses reported by Seghers and Spaepen (43) were likely due to the torque-related differences in protocols (25 vs. 50% of MVIC), and not the work-to-rest ratios, since the present study indicated that work-to-rest ratios did not affect EMG MPF. Therefore, the present findings, in conjunction with Seghers and Spaepen (43), suggested that MVIC torque and the associated neuromuscular parameters respond similarly to differences in work-to-rest ratios between protocols. During repeated, submaximal, isometric muscle actions, however, center frequency of the EMG signal (EMG MDF and EMG MPF) may reflect torque-related differences between protocols. Further research is needed to examine MMG AMP and MMG MPF during high versus low force protocols with equal mean load, cycle time, and total duration of exercise.

In summary, the results of the present study indicated that workS-to-rest ratios had no effects on torque or any of the neuromuscular parameters assessed during and as a result of performing the intermittent, submaximal, isometric muscle actions. Thus, work-to-rest ratios may not be a mediating factor of muscle fatigue when mean load, cycle time, and total duration of exercise are equivalent. As a result of the intermittent, submaximal, isometric muscle actions, however, there were decreases in MVIC torque that were consistent with EMG MPF and MMG MPF which also decreased, but were not consistent with EMG AMP or MMG AMP which remained unchanged. After 5 min of recovery, however, EMG MPF and MMG MPF returned to pretest levels, but MVIC torque had not fully returned to pretest levels. These findings suggested that the decreases in MVIC torque measured posttest were the result of fatigue-induced excitation-contraction failure which limited the number of motor units available to contribute to force production, while the partial, but incomplete recovery of MVIC torque suggested that 5 min of recovery was enough time to restore some of the previously fatigued motor units. During the intermittent, submaximal, isometric muscle actions there were decreases in EMG MPF and MMG MPF, an increase in EMG AMP, and no change in MMG AMP. These findings indirectly suggested that the maintenance in torque across the intermittent muscle actions was a function of muscle wisdom and/or motor unit synchronization.

ACKNOWLEDGEMENTS

There were no funding sources associated with the completion of this manuscript nor were there any professional relationships with companies or manufactures that may benefit from the results of this investigation.

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