

Effects of KAATSU on muscular function during isometric exercise

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Int. J. KAATSU Training Res. 2006; 2: 19-28

Generally, a threshold intensity of 65% 1-RM will induce muscle hypertrophy; however, recent studies using low-intensity (20% 1-RM) exercise combined with vascular restriction (KAATSU) have demonstrated increases in muscle size and strength. **PURPOSE:** To investigate the EMG and MMG responses, and percent voluntary activation (PVA) of the vastus lateralis (VL) following exposure to low-intensity intermittent isometric exercise in combination with moderate vascular restriction. **METHODS:** Twelve males (Age = 23.7 ± 4.1 yrs) participated in 1 familiarization trial and 2 experimental trials (with or without KAATSU) each separated by 48 h. Testing order was: a) Resting blood pressure after 5 min rest; b) 5 min warm-up on a cycle ergometer (50 W, 50-70 rpm); c) 2 pre-exercise 5-s isometric MVCs, 1 min rest between trials; d) 5 sets of 20 intermittent isometric contractions (2-s on / 1-s off) at 20% of MVC, 30-s interset rest periods; and e) 2 post-exercise isometric 5-s MVCs. **RESULTS:** There were no significant interactions or main effects for time or session for pre- and post-exercise isometric MVCs, with and without KAATSU, for the following parameters: MVC, PVA, EMG amplitude, EMG mean power frequency (MPF), MMG amplitude, and MMG MPF. Average normalized EMG amplitude increased significantly from repetitions 1-4 to 5-8 to 9-12 and MMG amplitude increased significantly from set 1 to 2 for both the KAATSU and no-KAATSU sessions. **CONCLUSION:** Intermittent isometric contractions at 20% 1-RM, with or without vascular restriction, are not intense enough to cause significant muscular fatigue. **Key words:** blood restriction, EMG, MMG, isometric contraction.

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INTRODUCTION

Skeletal muscle has the ability to adapt to mechanical stress, however, the response can vary between different modes of exercise (Kay et al., 2000). The general response to intense resistance exercise is an increase in strength and muscle hypertrophy, but if the exercise stimulus is inadequate or absent, then muscular atrophy will occur (Kandarian and Stevenson, 2002). It is generally accepted that the threshold intensity needed to induce muscle hypertrophy needs to exceed 65% 1-RM (Baechle and Earle, 2000; McDonagh and Davies, 1984), however, recent studies using low-intensity resistance exercise (20% 1-RM) combined with vascular restriction (KAATSU) have also been able to demonstrate increases in muscle size and strength (Takarada et al., 2002; Takarada et al., 2004). Typically, the effects of externally applied vascular restriction has been used in combination with low intensity dynamic resistance exercise, however, the response of muscle to the combined effects of KAATSU and low intensity intermittent isometric exercise (IIE) has not been investigated.

Disuse atrophy normally occurs from cast-immobilization (Takarada et al., 2000b), however,

Takarada et al. (2004) found that the application of vascular restriction (VR), even without exercise, had a positive effect on skeletal muscle and decreased the magnitude of post-operative atrophy, but did not eliminate it completely. Therefore, the authors suggest that an exercise stimulus is essential during vascular restriction in order to induce muscular hypertrophy. What is not understood at the present time is the level of muscle activation needed in combination with vascular restriction to ensure an optimal benefit to skeletal muscle.

The mechanomyogram (MMG) records and quantifies the low-frequency lateral oscillations of active skeletal muscle fibers (Barry and Cole, 1990; Orizio, 1993). Gordon and Holbourn (1948) suggested that these oscillations represent the mechanical counterpart of motor unit electrical activity, as measured by electromyography (EMG). MMG signals recorded during voluntary muscle actions can be separated into three components, which include: (a) the gross lateral movement of the muscle at the initiation of the contraction due to the non-simultaneous activation of muscle fibers, (b) smaller subsequent lateral oscillations occurring at the resonant frequency of the muscle, and (c) dimensional changes of active muscle fibers (Barry

and Cole, 1990; Orizio, 1993).

During voluntary muscle actions, the MMG signal represents the summation of the mechanical activity from individual motor units. The time and frequency domains of the MMG signal have been suggested to reflect motor unit recruitment and firing rate, respectively (Beck et al., 2006; Orizio, 1993). Surface EMG, however, reflects the linear algebraic summation of muscle action potentials that propagate within the electrode recording areas. The time and frequency domains of the EMG signal may reflect muscle activation (combination of motor unit recruitment and firing rate) and motor unit action potential conduction velocity via the global shape of the action potentials (Basmajian and De Luca, 1985), respectively. Therefore, EMG and MMG signals have been used simultaneously to provide unique and complimentary noninvasive physiological information regarding neuromuscular fatigue (Beck et al., 2004; Perry-Rana et al., 2002), motor control strategies during dynamic (Cramer et al., 2002) and isometric muscle actions (Akataki et al., 2004), muscle fiber type distribution patterns (Marchetti et al., 1992; Orizio and Veicsteinas, 1992), and clinical neuromuscular disorders (Barry et al., 1990; Orizio et al., 1997).

Another noninvasive technique that is used to differentiate the central vs. peripheral contributions to muscle activation is *twitch interpolation* (Allen et al., 1995). Perhaps regarded as a criterion method, twitch interpolation involves the supramaximal stimulation of the muscle or peripheral nerve during the course of an isometric maximal voluntary contraction (MVC) to estimate the level of muscle inactivation. As a result of the utility of the twitch interpolation technique, it has been used to examine neuromuscular fatigue (Biro et al., 2006), neural activation strategies (Desbrosses et al., 2006), neural resistance training adaptations (Jubeau et al., 2006), and clinical neural deficits associated with diseases (Molloy et al., 2006). Therefore, the simultaneous use of EMG, MMG, and twitch interpolation may help to determine the optimal level of resistance exercise intensity during isometric muscle actions that is necessary when used in conjunction with moderate vascular restriction (KAATSU).

Therefore, the purposes of this study were twofold: (a) investigate the EMG and MMG time and frequency domains of the vastus lateralis during low intensity intermittent isometric exercise in combination with KAATSU and (b) determine the changes in percent muscle activation of the vastus lateralis in an attempt to determine if the decrease in muscle torque can be attributed to central and/or peripheral mechanisms of fatigue.

METHODS

Study design

A randomized, counterbalanced, within-subjects experimental design was used to investigate the effects of KAATSU on muscular function during and after voluntary intermittent isometric exercise. Each participant visited the laboratory three times: one familiarization trial and two experimental trials, separated by at least 48 h. The two experimental trials consisted of the same testing and isometric exercise protocol, however, the participants experienced either the KAATSU or control (no-KAATSU) conditions in random order. For the familiarization trial, each participant was asked to practice the isometric maximum voluntary contractions (MVCs) and experience the nerve stimulation procedure prior to the experimental trials in order to decrease the potential for a learning effect. For the experimental trials, the following procedures were performed in order: a) resting blood pressure assessment after 5 min rest (for the KAATSU trial only), b) five-minute warm-up on a stationary cycle ergometer with a power output of 50 W and a pedaling cadence of 50-70 rpm, c) two pre-exercise 5-s isometric MVCs with 1 min rest between trials, d) five sets of 20 intermittent isometric contractions (2-s on and 1-s off) at 20% of MVC with a 30-s interset rest period, and e) two post-exercise isometric 5-s MVCs with 1 min rest between trials. For the KAATSU session, the KAATSU cuffs were inflated prior to the first pre-exercise MVC trial and were deflated immediately after the last post-exercise MVC trial.

Subjects

Twelve healthy men volunteered to participate in this study (mean±SD age = 23.7±4.1 years; height = 180.7±7.9 cm; mass = 86.6±17.9 kg). The age range was from 19 to 34 years. The participants were active with different levels of activity (1-3 times a week), but none were engaged in any specific training for an athletic event for at least 6 months prior to study. The physical characteristics of the participants are presented in the Table 1. The participants reported no current or recent (within the past 6 months) knee- or hip-related injuries. This study was approved by the University Institutional Review Board for Human Subjects, and all participants read, completed, and signed a health questionnaire (PAR-Q) and informed consent form before testing.

Table 1. Descriptive Statistics (mean ± SD).

	N	Minimum	Maximum	Mean ± SD
Age (yr)	12	19.0	34.0	23.7 ± 4.1
Height (cm)	12	166.0	191.5	180.7 ± 7.9
Weight (kg)	12	66.8	121.8	86.6 ± 17.9

Isometric Strength Assessments

A calibrated Biodex System 3 isokinetic dynamometer (Biodex Medical Systems, Inc., Shirley, NY) was used to assess isometric MVC torque of the right leg extensors before (pre) and after (post) the isometric exercises for both the KAATSU and no-KAATSU sessions. Each participant was seated in an upright position in the dynamometer chair and secured with restraining straps around the trunk and hips in accordance with the Biodex User's Guide (Biodex Pro Manual, Applications/Operations. Biodex Medical Systems, Inc., Shirley, NY). The right knee joint was aligned with the rotational axis of the dynamometer and the lever arm was secured to the leg just superior to the malleoli. A standard hand-held goniometer was used to determine the knee joint angle, which was set at 80° below the horizontal plane for all isometric testing and exercise (Takarada et al., 2002; Takarada et al., 2004).

For each isometric strength assessment, each participant performed two 3-5 s MVCs with a 1-min rest between trials. These MVC trials were used to assess maximal voluntary (MVC) torque (before the superimposed twitch) as well as percent voluntary activation (see below). The participants were instructed to give a maximum effort for both trials and strong verbal encouragement was provided by the investigators. The highest MVC torque accomplished between the two trials was used as the 100% MVC torque value for the calculation of each participant's target submaximal torque (i.e. 20% MVC) used during the isometric exercises.

Percent Voluntary Activation

The twitch interpolation technique was used to determine percent voluntary activation (%VA) (Allen et al., 1995). This technique involves electrical stimulations applied to the muscle or nerve during and after an isometric MVC (see Figure 1) (Shield and Zhou, 2004). In the present study, transcutaneous electrical stimuli were delivered using a high-voltage (maximal voltage= 400 V) constant-current stimulator (Digitimer DS7, Herthfordshire, UK). The cathode was a metal probe (8 mm diameter) with the tip covered in a saline-soaked sponge, which was pressed into the lateral portion of the femoral triangle over the femoral nerve. The anode was a 9 x 5 cm rectangular self-adhesive electrode (Durastick Supreme, Chattanooga Group, Hixton, TN) that was positioned midway between the greater trochanter and the inferior border of the iliac crest (Babault et al., 2005). Single stimuli were used to determine the optimal probe location (20 mA) and the maximal compound muscle action potential (M-wave) with incremental amperage increases (20-100 mA). Once a plateau in the peak-to-peak M-wave was determined, despite amperage increases, 20% was

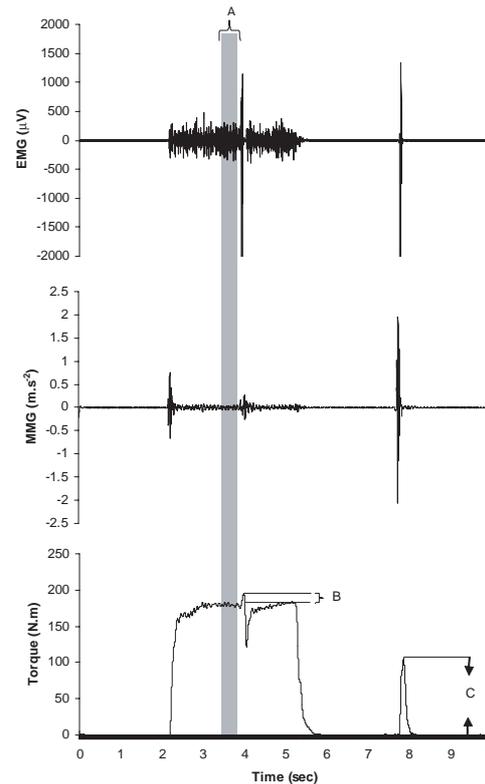


Figure 1. An example of the mechanomyographic (MMG) and electromyographic (EMG) signals from the vastus lateralis (VL) muscle during an isometric MVC for 1 participant. The shaded area A. represents the 0.5 sec epoch taken to determine the average torque as well as the time and frequency domain estimates for the EMG and MMG signals during the MVC trials. B. and C. represent the superimposed and potentiated twitches, respectively.

added to the amperage that yielded the highest peak-to-peak M-wave to assure a supramaximal stimulus. A single stimulation was a 1-ms duration square wave impulse, while a doublet consisted of two single stimuli delivered successively at 100 Hz. Doublets were administered with the supramaximal stimulus intensity during the MVC trials to increase the signal-to-noise ratio and minimize the series elastic effects on torque production (Desbrosses et al., 2006). In accordance with the twitch interpolation procedure, a supramaximal doublet was administered 350-500 ms into the MVC plateau (superimposed twitch) and then again 3-5 s after the MVC trial at rest (potentiated twitch). %VA was calculated with the following equation (Allen et al., 1995):

$$\%VA = \left[1 - \left(\frac{\text{superimposed twitch}}{\text{potentiated twitch}} \right) \right] \times 100$$

Isometric Exercises

The exercise session consisted of five sets of 20 repetitions of intermittent isometric leg extension muscle actions (2-s on 1-s off) performed at 20%

MVC with a 30-s interset rest period. The 20% MVC was chosen based on the methods of previous studies (Takarada et al., 2000b; Takarada et al., 2004). A custom written computer program (LabVIEW v.7.1, National Instruments, Austin, TX) was used to display the target torque (i.e., 20% MVC) as a horizontal line across a computer screen placed directly in front of the participants. The digital torque signal was also displayed on the monitor, and the participants were asked to contract their leg extensor muscle so that their torque met, but did not exceed, the target torque line. Each set was performed as a duty cycle, where the participants contracted at 20% MVC for 2-s and rested for 1-s (to mimic previously published dynamic contraction protocols (Takarada et al., 2000a; Takarada et al., 2004)) until 20 repetitions were reached. The total time required for each isometric exercise intervention was always between 8 and 10 min.

Blood Flow Restriction Protocol

For one of the laboratory visits, blood flow to the lower body was restricted with a KAATSU device (KAATSU-Master, Sato Sports Plaza, Tokyo, Japan). Specially-designed elastic cuffs (50 mm width) were placed around both thighs at 1-2 cm distal to the inguinal folds. Each cuff is equipped with a pneumatic bag along the inner surface and is connected to an electronic air pressure control system that monitors and maintains consistent restriction pressures set by the investigator. The cuff pressure used to restrict blood flow in the present study was determined with the following equation:

$$\text{Kaatsu Pressure} = (\text{SBP} \times 1.2) \times 1.2$$

Where SBP is the systolic blood pressure measured from the arm, and $\text{SBP} \times 1.2$ is the estimated systolic blood pressure of the legs. Therefore, the final KAATSU pressure was 20% higher than the estimated leg systolic blood pressure and was kept constant throughout the testing session. To inflate the cuffs to their appropriate pressures, the pressure was increased by 20 mmHg (starting at 120 mmHg), held for 30 s and released for 10 s between increments until the desired target exercise pressure was reached (Abe et al., 2006). The mean \pm SD KAATSU pressure throughout the testing period was 183.3 ± 11.54 mmHg. The cuffs were inflated before the first pre-exercise MVC trial and deflated immediately after the last post-exercise MVC trial.

EMG Measurements

A bipolar surface EMG electrode arrangement was placed parallel to the long axis of the femur 25 mm distal to a mark that was made at 50% of the distance between the greater trochanter and the lateral femoral epicondyle on the lateral-anterior edge of the

contracted vastus lateralis (VL) muscle. The EMG signals were recorded with pre-amplified, active electrodes (TSD150B, Biopac Systems Inc., Santa Barbara, CA) with a fixed center-to-center interelectrode distance of 20 mm, built-in differential amplifier with a gain of 350 (nominal), input impedance of 100 M Ω , common mode rejection ratio of 95 dB (normal), bandwidth of 12-500 Hz, electrode diameter of 11.4mm, sensor dimensions of 17.4 mm (wide) x 51 mm (long) x 6.4 mm (high), and mass of 9.5 grams. A single pre-gelled, disposable electrode (Ag-Ag Cl, Quinton Quick Prep, Quinton Instruments Co., Bothell, WA) was placed on the cleaned and lightly abraded skin over the spinous process of the 7th cervical vertebrae to serve as a reference electrode.

MMG Measurements

The MMG signals were recorded with an active miniature accelerometer (EGAS-FS-10-/VO5, Measurement Specialties, Inc., Hampton, VA) that was pre-amplified with a gain of 200, frequency response of 0 to 200 Hz, sensitivity of 70 mV/m·s⁻², and range of ± 98 m·s⁻². The accelerometer was placed 25 mm proximal to the active EMG electrode configuration over the VL at the half distance between the greater trochanter and lateral epicondyle of the femur. The accelerometer was fixed to the skin with 3M double-sided foam tape to ensure consistent contact pressure.

Signal Processing

The EMG, MMG, and torque signals were recorded simultaneously with a Biopac data acquisition system (MP150WSW, Biopac Systems, Inc., Santa Barbara, CA) during each isometric MVC trial as well as during the isometric exercises. The torque (Nm) signal from the dynamometer and the EMG (μ V) and MMG (m·s⁻²) signals recorded from the VL were sampled at 2 kHz. All signals were stored on a personal computer (Dell Inspiron 8200, Dell, Inc., Round Rock, TX), and processing was completed off-line using custom written software (LabVIEW v 7.1, National Instruments, Austin, TX). The EMG and MMG signals were digitally filtered (zero-phase 4th-order Butterworth filter) with a pass band of 10-500 Hz and 5-100 Hz, respectively. The torque signal was low-pass filtered with a 10 Hz cutoff (zero-phase 4th-order Butterworth filter) and gravity corrected so that the baseline torque value was 0 Nm (Figure 1). All subsequent analyses were performed on the filtered signals.

Isometric MVC torque (Nm) was calculated as the average torque value during the 0.5 s epoch taken immediately prior to the superimposed twitch. Consequently, the same (concurrent) 0.5 s epochs were selected from the EMG and MMG signals to

calculate the time and frequency domain estimates during the MVC trials (Figure 1). For the isometric exercises, 1.0 s EMG and MMG signal epochs were selected from the middle of the 2.0 s torque plateaus at 20% MVC for all 20 repetitions during all sets. The averages of 4 consecutive repetitions for the EMG and MMG values were used to analyze the patterns of response across each set.

For each EMG and MMG signal epoch during the MVC trials or the isometric exercises, the time domain was represented as the root mean square (RMS) amplitude value. For the frequency domain, each epoch was processed with a Hamming window and a discrete Fourier transform. The mean power frequency (MPF) was calculated as described by Kwatny et al. (1970) to represent the power spectrum based on the recommendations of Hermens et al. (1999) due to the high signal-to-noise ratios of the EMG and MMG signals in the present study.

Statistical Analyses

Six separate two-way repeated measures ANOVAs (time [pre- vs. post-exercise] x session [KAATSU vs. no-KAATSU]) were used to analyze the MVC torque, %VA, EMG amplitude, EMG MPF, MMG amplitude, and MMG MPF values. Two separate three-way repeated measures ANOVAs (session [KAATSU vs. no-KAATSU] x sets [1 vs. 2 vs. 3 vs. 4 vs. 5] x repetitions [1-4 vs 5-8 vs 9-12 vs. 13-16 vs 17-20]) were used to analyze the EMG and MMG amplitude and MPF data during the isometric exercises. When appropriate, post-hoc analyses were performed using Bonferroni corrections. All data were expressed as means \pm SE in the text, figures, and tables. An alpha of 0.05 was used to determine statistical significance.

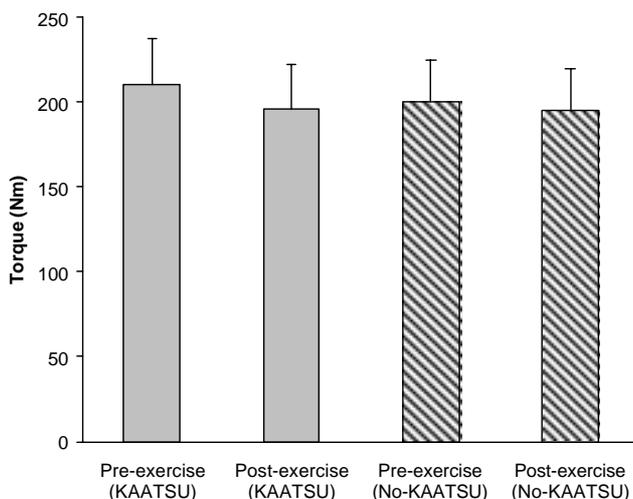


Figure 2. Pre- and post-exercise maximal voluntary contraction (MVC) torque for the KAATSU (shaded) and no-KAATSU (hatched) sessions. Values are means \pm SE.

The data were analyzed using SPSS 12.0 for Windows (SPSS Inc., Chicago, IL).

RESULTS

Isometric Strength

For MVC torque, there was no significant time x session interaction ($p=0.38$) and no significant main effect for either time ($p=0.06$) or session ($p=0.51$) (Figure 2). In addition, no significant difference was observed in pre-exercise MVC values for the KAATSU and no-KAATSU ($p=0.38$) sessions.

Percent Voluntary Activation

There was no significant time x session interaction ($p=0.57$) or significant main effect for time ($p=0.57$) or session ($p=0.36$) (Figure 3).

Surface Electromyography

Figure 4 shows the EMG amplitude and MPF values for the pre- and post-exercise isometric MVCs with and without KAATSU. There were no significant interactions ($p=0.41$ and 0.48), and no significant main effect for time ($p=0.39$ and 0.18) or session ($p=0.56$ and 1.00) for either EMG amplitude or EMG MPF, respectively (Figure 4).

Figure 5 shows the average normalized EMG amplitude (%MVC) values for sets 1-5 plotted across the isometric exercise repetitions with (A) and without (B) KAATSU. There was no significant three-way interaction for session x sets x repetitions ($p=0.44$), no significant two-way interactions for session x sets ($p=0.56$), session x repetitions ($p=0.11$), or sets x repetitions ($p=0.19$), and no significant main effect for session ($p=1.00$) or sets ($p=0.78$), but there was a significant main effect for repetitions ($p<$

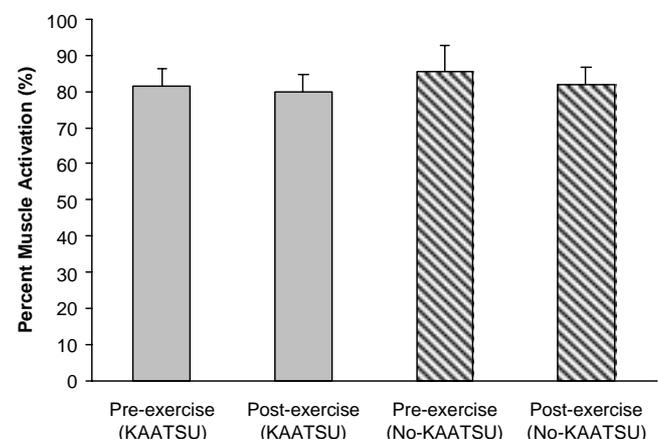


Figure 3. Pre- and post-exercise percent muscle activation (% VA) for the KAATSU (shaded) and no-KAATSU (hatched) sessions. Values are means \pm SE.

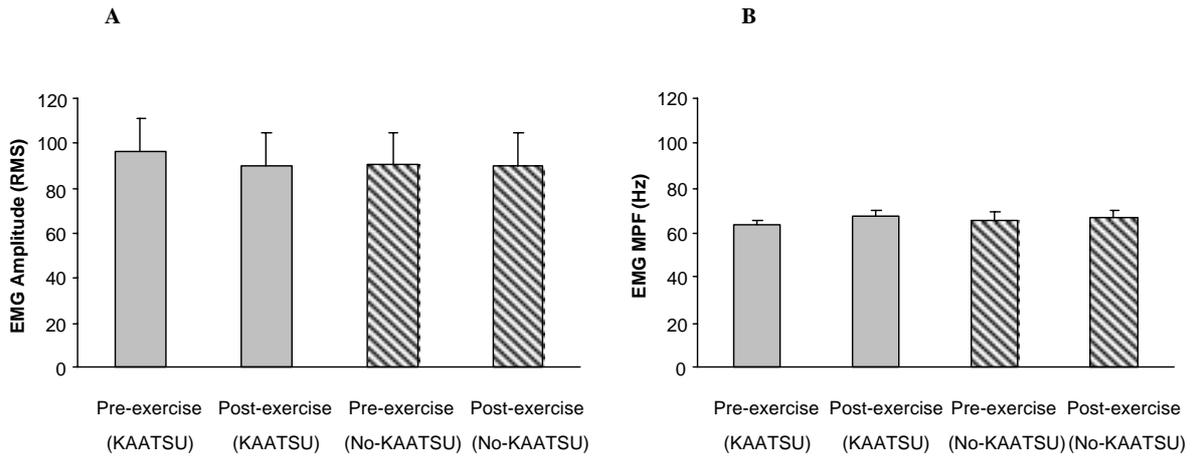


Figure 4. Pre- and post-exercise A. normalized EMG amplitude (% MVC) and B. normalized EMG MPF (% MVC) during the isometric MVCs for the KAATSU (shaded) and no-KAATSU (hatched) sessions. Values are means \pm SE.

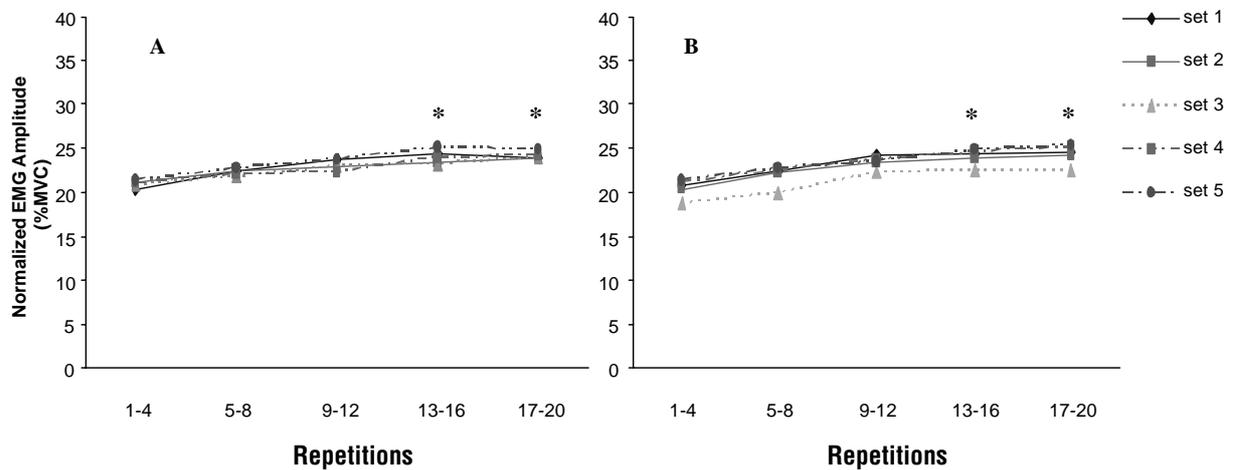


Figure 5. Normalized EMG amplitude (%MVC) during the isometric exercise repetitions for the A. KAATSU B. no-KAATSU sessions. Values are means \pm SE.

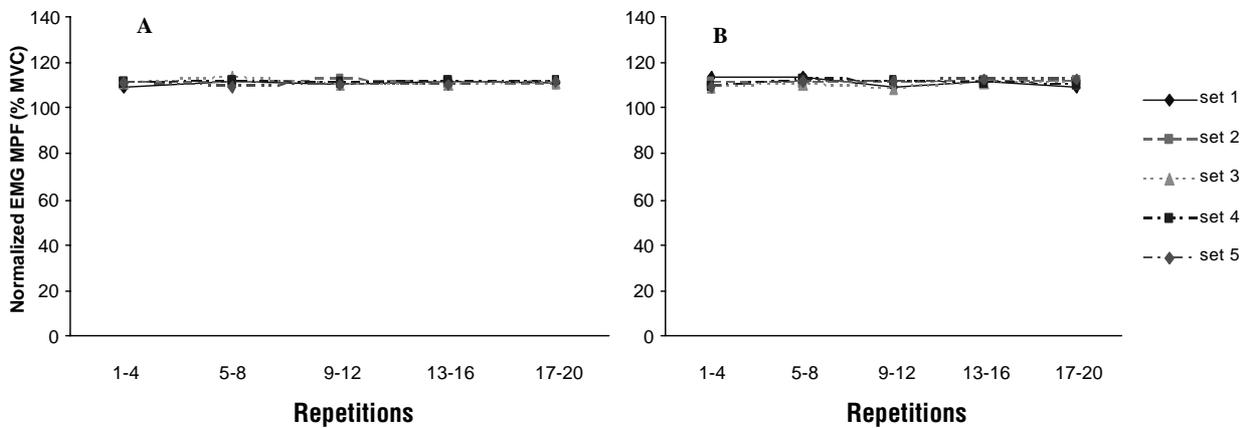


Figure 6. Normalized EMG frequency (%MVC) during the isometric exercise repetitions for the A. KAATSU B. no-KAATSU sessions. Values are means \pm SE.

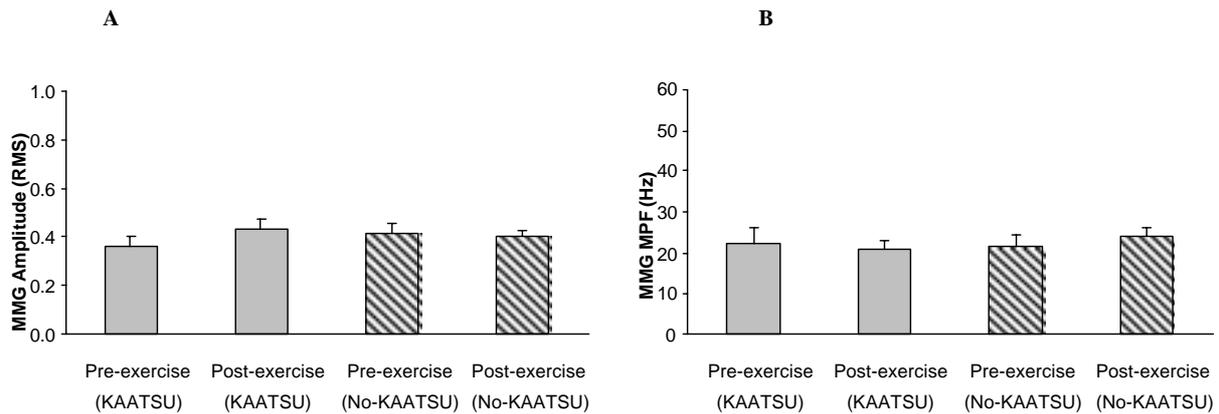


Figure 7. Pre- and post-exercise A. normalized MMG amplitude (% MVC) and B. normalized MMG MPF (% MVC) during the isometric MVCs for the KAATSU (shaded) and no-KAATSU (hatched) sessions. Values are means \pm SE.

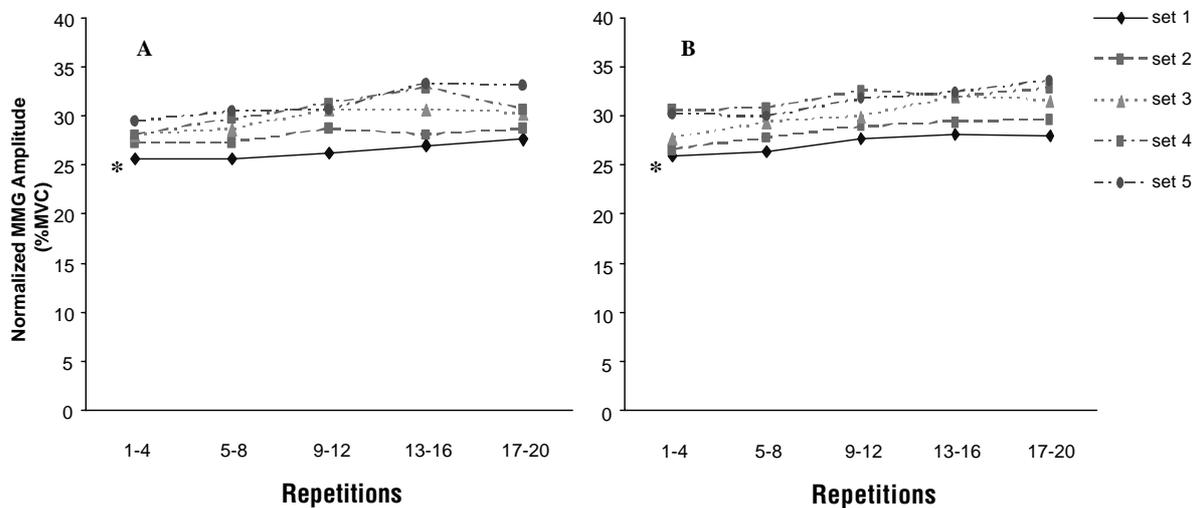


Figure 8. Normalized MMG amplitude (%MVC) during the isometric exercise repetitions for the A. KAATSU B. no-KAATSU sessions. Values are means \pm SE.

0.001). EMG amplitude increased from repetitions 1-4 to 5-8 to 9-12, but there was no difference between repetitions 13-16 and 17-20 for sets 1-5 for both the KAATSU and no-KAATSU sessions (Figure 5).

Figure 6 displays the average normalized EMG MPF values for sets 1-5 plotted across the isometric exercise repetitions with (A) and without (B) KAATSU. There was no significant three-way interaction for session \times sets \times repetitions ($p = 0.22$), no significant two-way interactions for session \times sets ($p = 0.58$), or session \times repetitions ($p = 0.84$), and no significant main effect for session ($p = 0.82$), sets ($p = 0.78$), or repetitions ($p = 0.40$), but there was a significant two-way interaction for sets \times repetitions ($p = 0.01$) (Figure 6). The follow-up analyses (collapsed across session) indicated main effect decreases in EMG MPF for set 1 ($p = 0.05$) and increases for set 5 ($p = 0.03$) across the repetitions,

however, the Bonferroni-corrected pairwise comparisons did not detect specific differences ($p > 0.05$) between individual repetitions. Likewise, there were main effect decreases in EMG MPF from set 1 to set 5 for repetitions 5-8 ($p = 0.01$), however, the Bonferroni-corrected pairwise comparisons did not detect specific differences ($p > 0.05$). There were no other differences ($p > 0.05$) noted among the follow-up analyses for EMG MPF.

Surface Mechanomyography

Figure 7 shows the MMG amplitude and MPF values for the pre- and post-exercise isometric MVCs with (shaded) and without KAATSU (hatched). There were no significant interactions ($p = 0.11$ and 0.38), and no significant main effects for time ($p = 0.35$ and 0.92) or session ($p = 0.65$ and 0.60) for either MMG amplitude or MMG MPF, respectively (Figure 7).

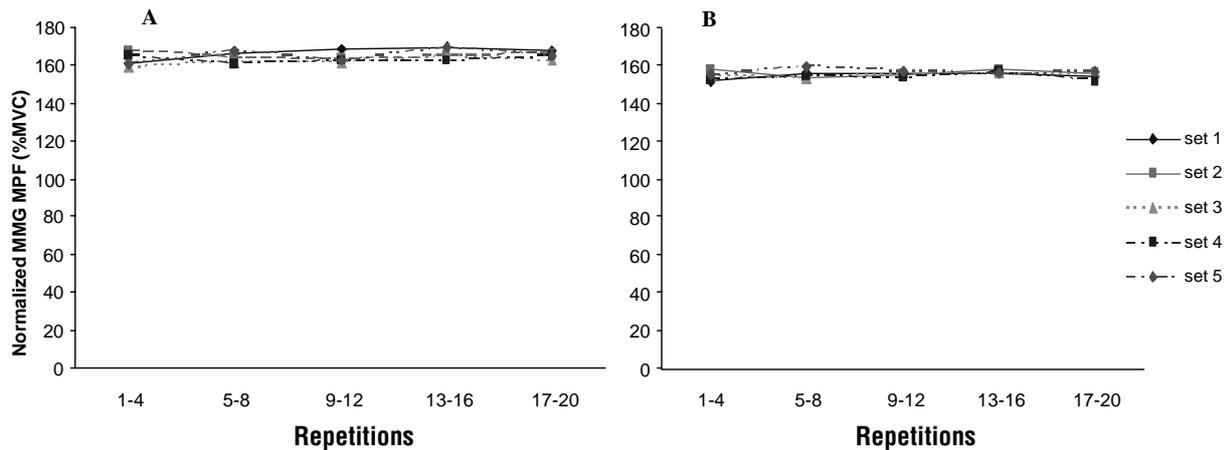


Figure 9. Normalized MMG frequency (%MVC) during the isometric exercise repetitions for the A. KAATSU B. no-KAATSU sessions. Values are means \pm SE.

Figure 8 shows the average normalized MMG amplitude (%MVC) values for sets 1-5 plotted across the isometric exercise repetitions with (A) and without (B) KAATSU. There was no significant three-way interaction for session \times sets \times repetitions ($p=0.46$), no significant two-way interactions for session \times sets ($p=0.96$), session \times repetitions ($p=0.95$), or sets \times repetitions ($p=0.89$), and no significant main effect for session ($p=0.85$) or repetitions ($p=0.18$), but there was a significant main effect for sets ($p<0.001$). MMG amplitude increased from set 1 to 2, but there was no difference between sets 2, 3, 4, and 5 for both the KAATSU and no-KAATSU sessions (Figure 8).

Figure 9 displays the average normalized MMG MPF values for sets 1-5 plotted across the isometric exercise repetitions with (A) and without (B) KAATSU. There was no significant three-way interaction for session \times sets \times repetitions ($p=0.92$); no significant two-way interactions for session \times sets ($p=0.66$), session \times repetitions ($p=0.95$), or sets \times repetitions ($p=0.63$); and there were no significant main effects for session ($p=0.97$), sets ($p=0.30$), or repetitions ($p=0.24$) (Figure 9).

DISCUSSION

The primary findings of the present study indicated that low intensity (20% 1-RM) intermittent isometric exercise either alone or in combination with moderate vascular restriction did not affect MVC torque, %VA, EMG or MMG amplitude or MPF from pre- to post-exercise. During the isometric exercises, there were increases in EMG and MMG amplitude, but EMG MPF increased and decreased, and there were no changes in MMG MPF. In addition, qualitative perceptions of this experiment indicated that the participants felt that they could continue exercising and did not feel fatigued following the isometric exercises. Overall, these results suggested

that the 5 sets of 20 isometric exercise repetitions at 20% of MVC did not elicit an appreciable fatigue affect with or without KAATSU. It is possible that the neuromuscular or metabolic demands of these exercises may not be suitable for KAATSU training.

There was a 7% reduction in MVC torque after the KAATSU trial and 2% reduction in MVC torque without KAATSU, which suggested a trend toward a fatigue-induced decrease in force production as a result of KAATSU, however, these decreases were not significant ($P=0.06$). Since long periods of vascular restriction would theoretically reduce the oxygen supply to skeletal muscles, slow-twitch muscle fibers may have been unable to contribute to isometric force production during the post-exercise MVC trials with KAATSU, because slow-twitch fibers rely heavily on oxidative phosphorylation. Therefore, the nonsignificant 7% decrease in MVC torque during the KAATSU trial may have been due to a reduced ability of slow-twitch fiber contributions to force production, compared to the 2% reduction in MVC torque without KAATSU. Consequently, this hypothesis is consistent with the lack of change in %VA, EMG, or MMG amplitude from pre- to post-exercise, which indicated that the slow-twitch fibers were still being recruited, but unable to contribute to force production. Overall, this explanation is predicated on the imposed metabolic demands of KAATSU, rather than the central or peripheral manifestations of neuromuscular of fatigue.

Yasuda et al. (2006) investigated EMG responses during multi-joint exercises with and without KAATSU. The participants performed dynamic bench press exercises [30% of one repetition maximum (1-RM)] with the cuffs at the most proximal position of the upper arm during the KAATSU session. EMG was recorded from the triceps brachii and the pectoralis major. Normalized integrated EMG (iEMG) increased

gradually during 4 sets of dynamic exercise at 30% 1-RM and the magnitude of the EMG in both the triceps brachii and the pectoralis major were significantly higher during the KAATSU session. Normalized iEMG was also used to determine the mean exercise intensity for the sets. The exercise intensity for the first set was the same for both the control and KAATSU session, but the intensity of exercise was higher in the KAATSU session during the fourth set. Krogh-Lund et al. (1993) demonstrated that EMG amplitude increased across time during sustained, fatiguing isometric exercise (at 40% and 10% of MVC), but EMG median frequency decreased across time, and a higher intensity of sustained isometric exercise resulted in a greater decrease in EMG median frequency. Similarly, Weir et al. (2000) also demonstrated that EMG amplitude increased across time during submaximal voluntary contractions of the right tibialis anterior (at 50% of MVC). The previous findings were consistent with the well-established relationships among EMG amplitude, EMG center frequency, and fatigue during submaximal muscle actions (Basmajian and De Luca, 1985). EMG amplitude generally increases during submaximal fatiguing tasks due to the recruitment of additional motor units to replace those that fail to maintain force production (Krogh-Lund, 1993; Weir et al., 2000). EMG center frequency generally decreases during fatigue, perhaps due to changes in the shapes of the action potentials and/or decreases in muscle action potential conduction velocity (Basmajian and De Luca, 1985; Hermens et al., 1992). However, there were no changes in EMG amplitude or MPF from pre- to post-exercise in the present study. The fact that EMG amplitude increased across the repetitions was similar to previous findings (Beck et al., 2004; Krogh-Lund, 1993; Weir et al., 2000), but the increases occurred for both the KAATSU and no-KAATSU conditions, which indicated that the isometric exercise demands were not enhanced by KAATSU. EMG MPF in the present study exhibited sporadic decreases, which were somewhat consistent with Krogh-Lund et al. (1993), again, however, the patterns for EMG MPF during the isometric exercises were the same with and without KAATSU. These findings suggested that the fatigue was not sufficient to elicit a post-exercise response, and the fatigue that was present during the isometric exercises was not enhanced by the KAATSU restriction. It is possible that the intermittent isometric loading and unloading between 0% and 20% MVC that occurred in this study might not have created a metabolic demand comparable to the constant concentric and eccentric tension experienced during dynamic muscle actions at the same relative intensity.

To our knowledge, no previous study has examined the MMG responses to KAATSU-related

interventions. However, previous studies (Goldenberg et al., 1991; Orizio et al., 1989; Rodriguez et al., 1993) have shown that MMG amplitude increases during low-level sustained, fatiguing isometric exercise. In addition, Perry-Rana et al. (2002) reported muscle-specific decreases in MMG amplitude during 50 consecutive maximal, concentric isokinetic leg extensions. MMG amplitude decreased less for the vastus lateralis (VL) and vastus medialis (VM) than the rectus femoris (RF). The authors suggested that a higher number of fast-twitch fibers in the RF may have caused the greater decrease in MMG amplitude. Beck et al. (2004) also demonstrated a linear decrease for both MMG amplitude and MPF during fatiguing isokinetic muscle actions of the biceps brachii. Neither MMG amplitude or frequency were affected from pre- to post-exercise, but MMG amplitude increased from the first set to the second set during the isometric exercises. This increase in MMG amplitude may be explained by an increase in motor unit recruitment, but this pattern did not continue for the last three sets. In addition, there were no changes in MMG MPF during the isometric exercises in the present study. Although not confirmed, MMG MPF may qualitatively reflect the global firing rate of the motor units contributing to the MMG signal (Beck et al., 2005). Therefore, it is possible that the isometric exercise task did not result in any substantial changes in motor unit firing rates.

In conclusion, the results of the present study suggest that 5 sets of 20 intermittent isometric muscle actions at 20% MVC might not elicit the same neuromuscular or metabolic demands as dynamic muscle actions of the same relative intensity. Based on our findings, future studies should use either dynamic or isometric exercise with higher cuff pressures, higher contraction intensities, and/or longer sustained contraction durations in order to investigate the effects of KAATSU blood restriction on neuromuscular fatigue.

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