2016-03-01

The Effect of Whole Body Vibration on Exercise-Induced Muscle Damage and Delayed-Onset Muscle Soreness

Ryan Darin Magoffin
Brigham Young University

The Effect of Whole Body Vibration on Exercise-Induced Muscle Damage and Delayed-Onset Muscle Soreness

Ryan Darin Magoffin

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

J. Brent Feland, Chair
Robert D. Hyldahl
Allen C. Parcell

Department of Exercise Sciences

Brigham Young University

March 2016

ABSTRACT

The Effect of Whole Body Vibration on Exercise-Induced Muscle Damage
and Delayed-Onset Muscle Soreness

Ryan Darin Magoffin
Department of Exercise Sciences, BYU
Master of Science

Current scientific evidence suggests that when whole body vibration (WBV) is used as a warm-up prior to performing eccentric exercise, delayed-onset muscle soreness (DOMS) is mitigated and strength loss recovers faster. These benefits were observed primarily in nonresistance-trained individuals. The aim of this study was to determine if WBV could mitigate soreness and expedite strength recovery for resistance-trained individuals when used as a warm-up prior to eccentric exercise. Thirty resistance-trained males completed 300 maximal eccentric contractions of the quadriceps after warming up with (WBV) or without (CON) WBV. Both CON and WBV experienced significant isometric (27.8% and 30.5%, respectively) and dynamic (52.2% and 47.1%, respectively) strength loss immediately postexercise. Isometric strength was significantly depressed after 24 hours in the CON group (9.36% $p < 0.01$), but not in the WBV group (5.8% $p = 0.1$). Isometric strength was significantly depressed after 48 hours in the CON group (7.18% $p < 0.05$), but not in the WBV group (4.02% $p = 0.25$). Dynamic strength was significantly decreased in both the CON and WBV groups both at 24 hours (19.1% $p < 0.001$, and 16.1% $p < 0.001$, respectively), 48 hours (18.5% $p < 0.01$, and 14.5% $p < 0.03$), and 1 week postexercise (9.3% $p = 0.03$, and 3.5%, respectively). Pain as measured by visual analog scale (VAS) was significant in both CON and WBV groups at 24 and 48 hours postexercise, but the WBV experienced significantly less soreness than the CON group after 24 hours (28 mm vs. 46 mm $p < 0.01$ respectively), and 48 hours (38 mm vs. 50 mm $p < 0.01$). Pain as measured by pain pressure threshold (PPT) increased significantly in both groups after 24 and 48 hours, but there was no difference in severity of perceived soreness. The use of WBV as a warm-up may mitigate DOMS but does not appear to expedite the recovery of strength in the days following eccentric exercise in resistance-trained individuals.

Keywords: DOMS, strength loss, Power Plate

ACKNOWLEDGMENTS

I want to thank those people who have helped and encouraged me along my way as I have pursued this master's degree. To all the professors, fellow graduate students, and undergrad research assistants, I offer up my gratitude. This project could not have been completed without their consistent help. I also owe a huge thanks to my sweet wife, Maritza. Her constant encouragement and immense patience with me have been tremendous.

TABLE OF CONTENTS

List of Tables

List of Figures

INTRODUCTION

Exercise-induced muscle damage (EIMD) is a common occurrence when individuals begin a new training program or perform unaccustomed physical activity. The soreness and decrease in functionality of the damaged muscle, which can last for several days, suggests that changes in the muscle have occurred. Indirect characteristics of muscle damage include: the decreased ability of the muscle to produce force (1, 3), changes in electromyogram (EMG) readings (27, 28), various levels of soreness (3), acute inflammation and swelling (33), stiffness of the muscle and joints (14, 33, 55, 57), increased creatine kinase (CK) levels in the blood (3), and changes in magnetic resonance image (MRI) intensity (9, 12, 41). Many of these characteristics are expressed less severely in individuals who participate in a regular exercise program, although soreness can still be present with novel exercise in trained or untrained people (43). Evidence that damage has occurred in the muscle can be determined by examining the muscle tissue in question. Some of these observations include: changes in immunohistological staining intensity of the structural skeletal proteins desmin (60) and dystrophin (37), increased satellite cell activation (57), disruption of the z-lines (8), increased expression of the Xin protein (44), extracellular matrix disruption (53), and inflammatory cell infiltration into the damaged muscle fibers (5, 40, 60).

Various treatments and modalities have been used to mitigate soreness and speed up the restoration of muscle function, such as cryotherapy (18, 52), massage (22, 29), ultrasound (49), NSAIDs (35), and immobilization (61). The research determining the effectiveness of these various treatments has produced conflicting results, calling into question the frequent prescription of these strategies as a means to reduce symptoms and enhance the repair process of damaged muscle.

A recent strategy that is purported to attenuate the symptoms of muscle damage is whole body vibration (WBV). Some have suggested that WBV stimulates greater recruitment of motor units and muscle spindles to elicit greater activation of the musculature (39, 42). Its reported benefits include increases in power (6), force production (7), vertical jump height (16, 17), total muscular work (2), and flexibility (16) in trained and athletic populations. In contrast, untrained individuals have seen decreases in force production following WBV training (20, 21). WBV has been shown to have either no effect (58) or a detrimental effect (4) when used as a postexercise treatment strategy for restoring strength of the muscle following a damaging bout of exercise. In contrast, Aminian-Far et al. reported that WBV, as part of a warm-up prior to eccentric exercise, reduced soreness, serum creatine kinase levels, and a loss of force-producing capabilities in the days following the exercise bout (1). These results suggest that WBV may reduce symptoms of muscle damage, although the damage protocol used was relatively small (60 eccentric contractions) and performed in untrained subjects.

It is currently unknown why WBV may attenuate soreness. One theory is that WBV leads to greater synchronicity of the motor units, thereby more evenly distributing the load during exercise (1). Evidence for motor unit synchronicity is provided by Christensen et al. (13) who demonstrated increased force output with no change or depressed sEMG amplitude. Because there have been differences reported between trained (7) and untrained (21) individuals in response to WBV, vibration training cannot be prescribed as a means of decreasing or preventing muscle soreness and damage in trained populations. Further research in this area will help determine if WBV can reduce soreness and muscle damage in trained populations (4). Therefore, we have tested the effectiveness of using WBV as a means to prevent muscle soreness and damage prior to performing maximal eccentric exercise in a resistance-trained population.

Purpose Statement

The purpose of this study was to determine what effect WBV, when used as a warm-up, has on indirect markers of muscle damage, including muscle strength, subjective ratings of soreness, total muscular work, thigh circumference, knee range of motion, and sEMG before and after eccentric exercise of the quadriceps in recreationally strength-trained subjects.

Hypothesis

We hypothesized that the WBV group would experience less soreness, attenuated increases in thigh circumference, smaller decreases in force production and sEMG amplitude, increased relative work done, and smaller decreases in range of motion compared to the CON group.

METHODS

Experimental Approach to the Problem

This study explored the effects of using whole body vibration (WBV) as a warm-up to attenuate knee-extensor muscle damage following a maximal eccentric exercise bout. Subjects were assigned randomly to either the experimental group or the control group, and performed 300 maximal eccentric contractions of the knee extensors. The experimental group received whole body vibration (WBV) just prior to the exercise session while the control group did the same exercise without WBV (CON). The independent variable was treatment (WBV) or no treatment (CON), and dependent variables included soreness, sEMG, isometric and isokinetic strength, total work done, active knee flexion range of motion, thigh circumference, and pressure sensitivity as measured by an algometer.

Subjects

Thirty college-aged males (age: 22.7 ±2.9 years; body mass: 82.35 ± 11.3 kg; stature: 180.6 ± 5.6 cm) who regularly participated in recreational resistance training (defined for this study as continuously for 6 months with at least twice per week working the legs) were recruited to participate in this study. Subject number was determined by performing a sample size analysis in the software program G*Power 3.1.9.2 (Franz Faul, University of Kiel, Germany). With an estimated effect size of .71 (based on EMG data) (27) and power set at 0.8, we estimated a minimum total subject number of n = 26.

To qualify, subjects must have had no recent history of injury in the past six months to the lower extremities. During the course of this study, each subject agreed not to participate in any treatment designed to alleviate the symptoms of muscle damage that they may have experienced, including massage, stretching, use of medications or any abnormal physical activity. Subjects also agreed to avoid strenuous activity 48 hours prior to and throughout the 1-week follow-up period of this study. We received human subject approval from the university Institutional Review Board (IRB) prior to beginning the study, and all subjects gave their written informed consent.

Pre-Exercise Testing

Subjects for the study were screened to ensure they were injury-free for the past six months in the lower extremities and had been resistance training at least twice a week for the past six months. Those subjects who qualified read and signed an IRB approved informed consent form. Each subject received a detailed explanation from the researchers of the exercise and testing procedures. Researchers discussed in detail the procedures of the study, including any risks associated with performing a high volume of exercise. At least 48 hours prior to baseline

testing, subjects were familiarized with the maximal voluntary isometric contraction (MVIC) protocol by coming in for three consecutive days and undergoing five MVICs each day to improve learning of the task and stabilize performance during testing of the MVIC with sEMG (25). Subjects familiarized themselves with positioning on the vibration machine for the warm-up protocol. All subjects agreed to refrain from strenuous physical activity for 48 hours prior to the first visit and through the duration of this study (1 week).

Baseline measurements of soreness (VAS and algometer), ROM of knee joint flexion, and thigh circumference were taken. The subject then warmed-up on a cycle ergometer for 5 minutes at 70 watts before using the Biodex System 4 Pro (Shirley, NY, USA) dynamometer chair to test maximal isokinetic and isometric strength of the quadriceps and maximal activation of the vastus lateralis and vastus medialis using sEMG. This constituted visit 1, which took place at least 48 hours prior to visit 2. Visits 3 (24 hours postexercise), 4 (48 hours postexercise), and 5 (1 week postexercise) consisted of the same testing protocol as visit 1. We measured soreness, ROM and thigh circumference at the beginning of visit 2 to confirm the baseline measures obtained in visit 1.

Experimental Warm-Up

For visit 2, subjects assigned to the experimental group stood on the whole body vibration platform for 5 bouts of 60 seconds (40 Hz and amplitude setting on “high”) on the Power Plate Pro5 (Northbrook, IL, USA) separated by 30 seconds of active rest (casual walking) as a warm-up for the exercise to follow. The control group performed the same warm-up protocol, only the vibration unit was not active.

Damaging Exercise Protocol

Following warm-up, the subjects were seated and secured by chest, waist, and leg straps in the Biodex dynamometer chair and began the eccentric exercise protocol. The exercise bout included 30 sets of 10 maximal, voluntary, eccentric contractions of the right knee extensors. The speed of the eccentric contraction was 120 degrees/second. Resistance exercise volume (300 repetitions) was selected based on previous research (4) showing that this volume was sufficient to cause damage to the knee extensors in trained subjects. After 100, 200, and 300 repetitions, respectively, maximal isometric strength and sEMG were measured. Isokinetic strength and sEMG also were measured after 300 repetitions.

Soreness

A Visual Analog Scale (VAS), consisting of a 100 mm line with ends "no pain at all" (0 mm) and "worst pain imaginable" (100 mm), was used for subjective rating of muscle soreness. The subjects rated perceived soreness by performing two single leg squats lowering their body to sit in a chair so that their knees and hips reached 90 degrees flexion in the seated position (31). The subjects then rated their perceived soreness by placing a single vertical line through the VAS, which has been shown to be a reliable measure that soreness is present (32).

Pressure pain threshold (PPT) was measured by the J-Tech Commander Echo Algometer (Midvale, UT, USA) which has also been shown to be a reliable method of measurement for soreness (34). PPT was measured at three sites (vastus medialis, vastus lateralis, and rectus femoris). The electrode placement sites were the measurement sites on the vastus medialis and vastus lateralis. Measurement of the rectus femoris was taken 2 inches proximal the most distal visible point of the rectus femoris. PPT recordings were done in a seated position in the hip and

knee joint at approximately a 90-degree angle. Assessment of soreness occurred at the beginning of each visit.

Range of Motion

Active range of motion of knee flexion was measured using a goniometer. The subjects lay prone on an examining table and actively flexed the knee as far as possible. Measurement was obtained at peak flexion by measuring the angle of fibula with the midline of the femur as described by Norkin and White (45) and used by Dabbs et al. (19).

Thigh Circumference

Thigh circumference was measured with a cloth measuring tape and measurements were taken from the point that is 40% of the distance measured from the base of the patella to the anterior superior iliac spine (same point as the PPT). Subjects were in the long-sitting position on an examining table with relaxed quadriceps (1).

Maximal Strength

Familiarization of the MVIC and isokinetic contraction protocols on the Biodex took place before visit 1. For baseline strength testing on visit 1, subjects' legs were prepared for sEMG (see sEMG measures for details). Subjects warmed-up by cycling for 5 minutes on a cycle ergometer at 70 watts, after which they sat in the Biodex and were secured by chest, waist, and leg straps. The subjects performed a maximal isokinetic concentric strength test at 60 degrees/ second for three repetitions. After three minutes of rest, the subjects performed three MVICs lasting 5 seconds each with the knee joint flexed at a 60-degree angle on the Biodex dynamometer**.** Baseline maximal isometric and isokinetic strength assessments took place at least 48 hours prior to exercise, immediately postexercise, 24 and 48 hours postexercise, and 1 week postexercise. Maximal torque for each contraction type was determined by finding the peak

torque production during the three repetitions of each respective test. Additional maximal isometric strength measurements were obtained after 100, 200, and 300 repetitions during the damaging exercise protocol.

Surface Electromyography (sEMG) Measures

Following the bicycle warm-up and before strength testing, sEMG electrodes were placed on the vastus lateralis (VL) and vastus medialis (VM) of the involved leg. Before attaching electrodes the skin was shaved, abraded with sandpaper, and cleaned with an alcohol preparation pad to reduce skin impedance. Electrode placement on the VL was at 40% of the distance from the base of the patella to the anterior superior iliac crest, in line with the longitudinal axis of the muscle. Placement of the second electrode was on the distal quarter of the VM. Outlines of the electrodes were traced with permanent marker to ensure consistent placement of electrodes on subsequent testing days.

Surface electromyography (sEMG) data were collected at 1000 Hz via Delsys Bagnoli Desktop EMG (Natick, MA, USA). The Delsys electrode contains two 99.9% pure silver bars that are 10 mm in length and spaced 10 mm apart. The analog EMG data were filtered using standard band-pass real-time processing with cutoffs of 20 and 450 Hz. The common mode rejection ratio is > 80 dB with a gain of 1000.

Amplitudes of the sEMG data were smoothed using the root mean square (RMS) method and a 20-ms moving window. The sEMG amplitude was normalized to the RMS value of the resting sEMG recorded prior to each strength test. Peak sEMG was computed from the sEMG signals during a time interval of 3 seconds (isometric) and 0.5 seconds (isokinetic) centered at the time instant of the maximal force for each contraction type. Peak amplitude was found using Delsys EMGworks Software 4.0 (Natick, MA, USA).

Total Work and Work Rate Decline

Total work done was calculated by determining intercept and slope of decline of the working sets.

Statistical Analyses

Since we were unsure of the form of the treatment effect over time, we analyzed the data using a cell means model with repeated measurements. The dependent variable was the difference of the strength measurement taken at least 24 hours prior to the treatment being administered, and the strength measurements taken at the four postexercise times: (1) immediately posttreatment, (2) 24 hours posttreatment, (3) 48 hours posttreatment, and (4) 1 week posttreatment.

Thus, we had six cell means to estimate, 2 treatments times, and 4 measurements posttreatment. Since multiple measurements were taken of each subject, we needed to account for both within- and between-subject variance to most accurately estimate uncertainty.

Such a formulation was well suited to using a Bayesian approach. In the Bayesian framework, the model consists of the scaled product of the likelihood of the data given the parameters and prior probability densities for each of the parameters (11, 23). Current practice to analyze such a model is to implement some form of Markov chain Monte Carlo (MCMC) procedure to produce samples from the posterior distributions of interest (24, 51). We used the program JAGS (48) to generate the samples from the posterior distributions using MCMC (38). The sampling chains were then moved to the program R (The R Foundation, Vienna, Austria) for further analyses (54). Treatment differences were determined using 95% credible intervals on the posterior distributions of the $t\mathbf{i}$.

RESULTS

Muscular Strength

There is evidence that WBV had a positive effect on the recovery of maximal isometric strength (see Figure 1). There was no difference between the control and treatment groups at baseline and both groups significantly decreased in strength from baseline at 100 repetitions (18.5% and 16%, respectively), 200 repetitions (29.1% and 30.4%, respectively), and immediately postexercise (27.8% and 30.5%, respectively). Within-group analysis showed the control group significantly decreased in strength from baseline by 9.36% ($p < 0.01$) and 7.18% ($p < 0.05$) at 24 and 48 hours, respectively. However, within the WBV group, strength decreases from baseline at both 24 and 48 hours (5.8% $p = 0.1$, and 4.02% $p = 0.25$, respectively) were not found to be statistically significant. There were no significant differences between groups at any time point.

Dynamic strength decreased significantly from baseline in both control and vibration groups immediately postexercise by 52.2% ($p < 0.001$) and 47.1% ($p < 0.001$), respectively (see Figure 2). The control group experienced decrements in strength from baseline of 19.1% ($p < 0.001$) at 24 hours, 18.5% ($p < 0.001$) at 48 hours, and 9.3% ($p = 0.03$) after 1 week. The vibration group experienced decrements in strength from baseline by 16.1% ($p < 0.001$) at 24 hours, 14.5% ($p = 0.002$) at 48 hours, and recovered to within 3.5% ($p = 0.4$) after 1 week. There were no significant differences between groups at any time point.

Soreness as Measured by VAS

While both groups experienced significant increases in soreness from baseline at 24 and 48 hours postexercise, the treatment group experienced significantly less perceived soreness than the control group at 24 hours (p-value < 0.01) and 48 hours (p-value < 0.01) (see Figure 2). The

control group increased in soreness to 46 mm and 50 mm at the respective time points. The treatment group increased in soreness to 28 mm and 38 mm at the respective time points. The treatment group's perceived soreness was significantly less than that of the control group at both 24 hours ($p < 0.01$), and at 48 hours ($p < 0.01$). Both groups returned to near baseline levels 1 week postexercise.

Soreness as Measured by PPT

The control group increased in soreness at both 24 hours ($p < 0.001$) and 48 hours ($p < 0.001$) and returned to baseline after 1 week. The vibration group experienced increased soreness at both 24 hours ($p < 0.001$) and 48 hours ($p = 0.02$) and returned to baseline after 1 week. The groups did not differ from each other at any time point (see Figure 3).

Total Work and Work Rate Decline

There was no difference found in beginning work output ($p = 0.77$) or work rate decline ($p = 0.64$) relative to the treatments, thus total work was similar between groups.

Thigh Circumference and Knee Range of Motion

There was no significant difference in thigh circumference at any point within or between groups (see Table 1). There were no significant differences between groups for range of motion (ROM). There were significant decreases in ROM at 24 and 48 hours for both groups (see Table 1).

Surface Electromyography (sEMG)

Significant differences in sEMG values were not observed over time in either group for the vastus lateralis, nor were significant differences found between groups (see Figure 4). The sEMG values of the vastus medialis significantly declined after 100 and 200 repetitions in the control group ($p < 0.01$ and $p < 0.05$, respectively). Differences were not observed at any other

time point in the control group (see Figure 5). There were no significant differences in sEMG values at any time point for the vibration group, nor any difference found between groups at any time point.

DISCUSSION

Prior research suggests that WBV can attenuate soreness and the loss of strength that is usually associated with eccentric exercise in untrained subjects (1). Our study investigated if similar results would be found in resistance-trained subjects using a more intense muscle damaging protocol. Many of the existing performance enhancement studies have utilized trained subjects or athletes, so a study designed to determine the potential effects of WBV within the context of muscle soreness seemed warranted with this population.

Our results show that vibration decreased perceived soreness using the VAS but not the PPT scores. The VAS scores significantly increased in both groups at 24 and 48 hours post exercise, and were accompanied by a loss of active-knee range of motion in both groups. However, VAS scores at both 24 and 48 hours significantly differed between groups, with the vibration group experiencing significantly lower levels of perceived soreness compared to the control group. When soreness was measured by PPT, the pounds of pressure required to elicit soreness decreased similarly for both the WBV and CON groups. This measurement was taken from one particular spot on each of the three superficial quadriceps muscles. Subjectively, several subjects commented that they were very sensitive to the touch, just not in the areas we designated to be tested. This may account for the observation that there was no difference between groups when measuring PPT. Since delayed-onset muscle soreness can manifest in a large generalized area, testing multiple sites over the same muscle would probably help the validity of the PPT measurement. When measuring with the VAS, the subjects were actively

moving the muscle through a ROM, whereas there was no active lengthening of the muscle when measured using PPT. This could have contributed to the discrepancy between the results of the two methods as well.

Our results indicate that WBV expedited the recovery of isometric strength after the damaging protocol and supports the previous work of Aminian-Far et al. (1). It has been suggested that strength loss is an indirect measure of muscle damage (4, 30). Our subjects were required to perform 300 maximal eccentric contractions of the quadriceps muscle group to elicit measureable muscle damage. This volume (300 repetitions) has been shown to elicit significant strength loss and an increase in soreness for resistance-trained individuals (4) and is similar to other studies which have investigated a variety of variables associated with muscle damage (5, 31). In our study, both groups fatigued as the exercise bout progressed, but only the control group showed significant isometric strength loss at 24 and 48 hours postexercise (9.36% and 7.18%, respectively). Strength loss in the vibration group was insignificant at both 24 and 48 hours (5.8% and 4.02%, respectively). Although it appears that WBV contributed to the faster recovery of strength in the treatment group, there was no significant difference found between the treatment and control groups.

The isokinetic strength decreases at 24 hours, 48 hours, and 1 week postexercise were more severe than the isometric strength losses seen at the same time points. Tufano et al. also reported a decline in isometric strength compared to dynamic strength when measuring the quadriceps in the days following eccentric exercise. They suggested that a possible training effect of the isometric testing protocol could be partially responsible for this observation (56). Close et al. reported that concentric and eccentric strength recover at varying rates following a

damaging exercise bout (15). These studies combined with our results suggest that isometric, eccentric, and dynamic strength recover at different rates.

Three hundred maximal eccentric quadriceps contractions have been shown to elicit up to a 24% decrease in maximal torque for up to 24 hours in resistance-trained individuals (4). Our results do not support such a drastic decrease in isometric torque-producing capabilities. Nevertheless, we did report decreased MVIC torque production of 9.36% in the control group while the vibration group experienced only a 5.8% decrease in maximal torque production. Our strength and sEMG data seem to show less damage than that of Barnes et al. when using resistance-trained subjects (4). This discrepancy may be explained by the speed of the eccentric contractions required in our exercise protocol. Our subjects performed 300 maximal eccentric contractions of the knee extensors at a speed of 120 degrees/second. Barnes et al. prescribed a 30 degrees/second contraction speed in their study using the same number of repetitions. This much slower contraction speed of the Barnes study means those subjects spent a longer time in eccentric contraction. Our subjects' comparatively shorter amount of time under tension may explain the lower magnitude of strength loss we observed.

Why WBV may help mitigate strength loss and soreness induced by exercise is unknown. One theory is that WBV can enhance gamma activation and muscle spindle sensitivity, which would lead to higher motor-unit recruitment (10, 50). A resultant lower firing threshold of motor units (36) has been hypothesized to reduce the stress placed on individual muscle fibers by recruiting more motor units, which spreads the contractile stress across a larger number of muscle fibers and lowers the individual stress each fiber experiences (7). If this in fact happens, we would expect to see an increased sEMG signal transmitted during a maximal contraction,

however, following exposure to WBV, acute increases in strength and power have been seen in resistance-trained individuals, while sEMG amplitude remained unchanged (25).

We looked at sEMG measures of the vastus lateralis and vastus medialis hoping to observe any neurological changes WBV may have caused. If any neurological changes were evident between groups during the exercise bout, we could theorize how WBV may protect against strength loss and soreness. Thus, sEMG and maximal isometric voluntary contractions (MVIC) were performed following each block of 100 repetitions of the eccentric protocol. We observed that peak sEMG values for the vastus lateralis did not change significantly after 100, 200, or 300 repetitions in either group. Whereas the strength measures significantly decreased in both the treatment and control groups after 100 repetitions (15.98% and 18.58%, respectively), 200 repetitions (30.35% and 29.06%, respectively), and immediately postexercise (30.45% and 27.79%, respectively). This is consistent with other data showing decreased efficiency (decreased torque output with no change in sEMG measures) in motor unit recruitment at the onset of fatigue (13).

For the vastus medialis, the control group exhibited a significant decrease in sEMG amplitude after 100 and 200 repetitions when measuring sEMG, while the vibration group showed a similar trend, but it was not statistically significant. The sEMG measurements immediately postexercise were not significantly different from baseline in either group.

Strength loss without a subsequent loss of motor unit recruitment was seen in both the vastus lateralis and vastus medialis muscles in the treatment group, and the vastus lateralis of the control group. This is consistent with the work of Hamlin and Quigley who reported an increased MVIC sEMG/torque ratio immediately after performing 20 minutes of eccentric stair stepping (26). Why our control group's vastus medialis sEMG readings decreased through the exercise

protocol is unknown. It is possible that our MVIC test angle (60 degrees) affected the performance of the vastus medialis since prior research has shown 70–90 degrees to be optimal for vastus medialis sEMG (46).

In the days following the exercise bout (24 hours, 48 hours, and 1 week), no differences in peak sEMG in either muscle or group were observed when compared with baseline measurements. This is in contrast to Plattner et al. who reported a significant decrease in peak sEMG amplitude for a maximal voluntary contraction of the biceps brachii muscle in the days following a bout of muscle damaging exercise (47). However, the Plattner et al. study used nonresistance-trained subjects, making them more susceptible to muscle damage than resistance-trained individuals. The protective qualities of the repeated bout effect in resistance-trained individuals (43) may also have come into play with our subjects to protect them from the significant damage typically seen in those who participate in high-volume eccentric exercise. Furthermore, the larger muscle mass of the combined quadriceps also may have added a protective effect as compared to the smaller biceps brachii.

Our sEMG measurement had two possible limitations. First, we had to replace the electrodes after each block of 100 repetitions because the adhesive was ineffective due to increased perspiration of the subjects. To decrease variability in electrode replacement we outlined the electrode with marker to ensure it was replaced as close as possible to the previous placement, but measurement error has been reported as high as 16% for within- or between-day sEMG recording for a maximal contraction (59). Thus, electrode positioning and change in skin moisture may have introduced sEMG measurement error. Second, our ability to detect a relationship between sEMG and strength could have been due to timing. Previous research suggests that WBV can positively influence power and force up to 10 minutes after WBV

stimulus in athletic populations (7). By the time we measured MVIC and sEMG after 100 repetitions approximately 15 minutes had passed since the subject had received vibration. If a relationship between sEMG and strength occurred, we did not detect it with our tests, possibly because the effect had dissipated by the time the first 100 repetitions were completed.

Total work done over the first 100 repetitions was not significantly different between groups, nor was the rate of decline in total work output different between groups. Based on previous research showing that WBV can cause acute increases in strength in resistance-trained individuals (6, 7) and increased sEMG amplitude, (7) we expected the WBV group to have started at a higher work output and for total work done to be higher than the CON group, but this was not the case. We did not test sEMG or strength immediately after administration of WBV, so we cannot confirm or refute the previous research showing increases in motor unit activation or strength.

PRACTICAL APPLICATIONS

This study supports the use of WBV as a warm-up strategy prior to exercise to aid in the attenuation of soreness. The VAS results are consistent with the idea that a possible protective effect against muscle soreness may result from the use of WBV as part of a warm-up prior to performing high volume eccentric exercise in resistance-trained individuals.

We recognize several limitations to our study. First, the high volume eccentric exercise protocol we chose to use is not typical in a competent resistance-training program. Second, the control group warmed up by static squatting on a vibration platform instead of a more typical dynamic warm-up. Future research ought to use typical training exercises (i.e., squats, lunges) and training volumes to judge the practical use of WBV as a DOMS-preventing warm-up. Third, alternate WBV frequency, amplitudes, and time of exposure may be effective at preventing

strength loss and DOMS, however we only looked at 40 Hz with “high” amplitude (approximately 4mm). Future research should use variations of these variables.

REFERENCES

1. Aminian-Far A, Hadian MR, Olyaei G, Talebian S, and Bakhtiary AH. Whole-body vibration and the prevention and treatment of delayed-onset muscle soreness. *Journal of athletic training* 46: 43-49, 2011.

2. Avelar NC, Costa SJ, da Fonseca SF, Tossige-Gomes R, Gripp FJ, Coimbra CC, and Lacerda AC. The effects of passive warm-up vs. whole-body vibration on high-intensity performance during sprint cycle exercise. *Journal of strength and conditioning research / National Strength & Conditioning Association* 26: 2997-3003, 2012.

3. Bakhtiary AH, Safavi-Farokhi Z, and Aminian-Far A. Influence of vibration on delayed onset of muscle soreness following eccentric exercise. *British journal of sports medicine* 41: 145-148, 2007.

4. Barnes MJ, Perry BG, Mundel T, and Cochrane DJ. The effects of vibration therapy on muscle force loss following eccentrically induced muscle damage. *European journal of applied physiology* 112: 1189-1194, 2012.

5. Beaton LJ, Tarnopolsky MA, and Phillips SM. Contraction-induced muscle damage in humans following calcium channel blocker administration. *The Journal of physiology* 544: 849-859, 2002.

6. Bosco C, Cardinale M, and Tsarpela O. Influence of vibration on mechanical power and electromyogram activity in human arm flexor muscles. *European journal of applied physiology and occupational physiology* 79: 306-311, 1999.

7. Bosco C, Colli R, Introini E, Cardinale M, Tsarpela O, Madella A, Tihanyi J, and Viru A. Adaptive responses of human skeletal muscle to vibration exposure. *Clinical physiology* 19: 183-187, 1999.

8. Brown LM and Hill L. Some observations on variations in filament overlap in tetanized muscle fibres and fibres stretched during a tetanus, detected in the electron microscope after rapid fixation. *Journal of muscle research and cell motility* 12: 171-182, 1991.

9. Cagnie B, Elliott JM, O'Leary S, D'Hooge R, Dickx N, and Danneels LA. Muscle functional MRI as an imaging tool to evaluate muscle activity. *The Journal of orthopaedic and sports physical therapy* 41: 896-903, 2011.

10. Cardinale M and Bosco C. The use of vibration as an exercise intervention. *Exercise and sport sciences reviews* 31: 3-7, 2003.

11. Carlin BP and Louis TA. *Bayes and empirical Bayes methods for data analysis.* Boca Raton: Chapman & Hall/CRC, 2000.

12. Cermak NM, Noseworthy MD, Bourgeois JM, Tarnopolsky MA, and Gibala MJ. Diffusion tensor MRI to assess skeletal muscle disruption following eccentric exercise. *Muscle & nerve* 46: 42-50, 2012.

13. Christensen H, Sogaard K, Jensen BR, Finsen L, and Sjogaard G. Intramuscular and surface EMG power spectrum from dynamic and static contractions. *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology* 5: 27-36, 1995.

14. Clarkson PM and Hubal MJ. Exercise-induced muscle damage in humans. *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists* 81: S52-69, 2002.

15. Close GL, Ashton T, Cable T, Doran D, Noyes C, McArdle F, and MacLaren DP. Effects of dietary carbohydrate on delayed onset muscle soreness and reactive oxygen species after contraction induced muscle damage. *British journal of sports medicine* 39: 948-953, 2005.

16. Cochrane DJ and Stannard SR. Acute whole body vibration training increases vertical jump and flexibility performance in elite female field hockey players. *British journal of sports medicine* 39: 860-865, 2005.

17. Cormie P, Deane RS, Triplett NT, and McBride JM. Acute effects of whole-body vibration on muscle activity, strength, and power. *Journal of strength and conditioning research / National Strength & Conditioning Association* 20: 257-261, 2006.

18. Crystal NJ, Townson DH, Cook SB, and LaRoche DP. Effect of cryotherapy on muscle recovery and inflammation following a bout of damaging exercise. *European journal of applied physiology* 113: 2577-2586, 2013.

19. Dabbs NC, Black CD, and Garner J. Whole-body vibration while squatting and delayed-onset muscle soreness in women. *Journal of athletic training* 50: 1233-1239, 2015.

20. de Ruiter CJ, Jones DA, Sargeant AJ, and de Haan A. Temperature effect on the rates of isometric force development and relaxation in the fresh and fatigued human adductor pollicis muscle. *Experimental physiology* 84: 1137-1150, 1999.

21. Erskine J, Smillie I, Leiper J, Ball D, and Cardinale M. Neuromuscular and hormonal responses to a single session of whole body vibration exercise in healthy young men. *Clinical physiology and functional imaging* 27: 242-248, 2007.

22. Farr T, Nottle C, Nosaka K, and Sacco P. The effects of therapeutic massage on delayed onset muscle soreness and muscle function following downhill walking. *Journal of science and medicine in sport / Sports Medicine Australia* 5: 297-306, 2002.

23. Gelman A. *Bayesian data analysis.* Boca Raton, Fla.: Chapman & Hall/CRC, 2004.

24. Gilks WR, Richardson S, and Spiegelhalter DJ. *Markov chain Monte Carlo in practice.* Boca Raton, Fla.: Chapman & Hall, 1998.

25. Green LA, Parro JJ, and Gabriel DA. Quantifying the familiarization period for maximal resistive exercise. *Applied physiology, nutrition, and metabolism = Physiologie appliquee, nutrition et metabolisme* 39: 275-281, 2014.

26. Hamlin MJ and Quigley BM. Quadriceps concentric and eccentric exercise 2: differences in muscle strength, fatigue and EMG activity in eccentrically-exercised sore and non-sore muscles. *Journal of science and medicine in sport / Sports Medicine Australia* 4: 104-115, 2001.

27. Hedayatpour N, Arendt-Nielsen L, and Falla D. Facilitation of quadriceps activation is impaired following eccentric exercise. *Scandinavian journal of medicine & science in sports* 24: 355-362, 2014.

28. Hedayatpour N, Falla D, Arendt-Nielsen L, and Farina D. Effect of delayed-onset muscle soreness on muscle recovery after a fatiguing isometric contraction. *Scandanavian journal of medicine & science in sports* 20: 145-153, 2010.

29. Hilbert JE, Sforzo GA, and Swensen T. The effects of massage on delayed onset muscle soreness. *British journal of sports medicine* 37: 72-75, 2003.

30. Hody S, Rogister B, Leprince P, Laglaine T, and Croisier JL. The susceptibility of the knee extensors to eccentric exercise-induced muscle damage is not affected by leg dominance but by exercise order. *Clinical physiology and functional imaging* 33: 373-380, 2013.

31. Hyldahl RD, Olson T, Welling T, Groscost L, and Parcell AC. Satellite cell activity is differentially affected by contraction mode in human muscle following a work-matched bout of exercise. *Frontiers in physiology* 5: 485, 2014.

32. Jensen MP, and Karoly, P. Self-report scales and procedures for assessing pain in adults, in: *Handbook of Pain*. DC Turk, Melzack, R., ed. New York: Guilford Press, 2001, pp 135-151.

33. Kanda K, Sugama K, Hayashida H, Sakuma J, Kawakami Y, Miura S, Yoshioka H, Mori Y, and Suzuki K. Eccentric exercise-induced delayed-onset muscle soreness and changes in markers of muscle damage and inflammation. *Exercise immunology review* 19: 72-85, 2013.

34. Kinser AM, Sands WA, and Stone MH. Reliability and validity of a pressure algometer. *Journal of strength and conditioning research / National Strength & Conditioning Association* 23: 312-314, 2009.

35. Kraemer WJ, Joseph MF, Volek JS, Hoffman JR, Ratamess NA, Newton RU, Fragala MS, French DN, Rubin MA, Scheett TP, McGuigan MR, Thomas GA, Gomez AL, Hakkinen K, and Maresh CM. Endogenous opioid peptide responses to opioid and anti-inflammatory medications following eccentric exercise-induced muscle damage. *Peptides* 31: 88-93, 2010.

36. Lau WY and Nosaka K. Effect of vibration treatment on symptoms associated with eccentric exercise-induced muscle damage. *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists* 90: 648-657, 2011.

37. Lovering RM and De Deyne PG. Contractile function, sarcolemma integrity, and the loss of dystrophin after skeletal muscle eccentric contraction-induced injury. *American journal of physiology cell physiology* 286: C230-238, 2004.

38. Lunn DJ, Thomas, A., Best, N., and Spiegelhalter D. WinBUGS-a Bayesian modelling framework: concepts, structure and extensibility. *Statistics and computing*: 325-327, 2000.

39. Luo J, McNamara B, and Moran K. The use of vibration training to enhance muscle strength and power. *Sports medicine* 35: 23-41, 2005.

40. Malm C and Yu JG. Exercise-induced muscle damage and inflammation: re-evaluation by proteomics. *Histochemistry and cell biology* 138: 89-99, 2012.

41. Mendiguchia J, Arcos AL, Garrues MA, Myer GD, Yanci J, and Idoate F. The use of MRI to evaluate posterior thigh muscle activity and damage during nordic hamstring exercise. *Journal of strength and conditioning research / National Strength & Conditioning Association* 27: 3426-3435, 2013.

42. Mester J, Kleinoder H, and Yue Z. Vibration training: benefits and risks. *Journal of biomechanics* 39: 1056-1065, 2006.

43. Newton MJ, Morgan GT, Sacco P, Chapman DW, and Nosaka K. Comparison of responses to strenuous eccentric exercise of the elbow flexors between resistance-trained and untrained men. *Journal of strength and conditioning research / National Strength & Conditioning Association* 22: 597-607, 2008.

44. Nilsson MI, Nissar AA, Al-Sajee D, Tarnopolsky MA, Parise G, Lach B, Furst DO, van der Ven PF, Kley RA, and Hawke TJ. Xin is a marker of skeletal muscle damage severity in myopathies. *The American journal of pathology* 183: 1703-1709, 2013.

45. Norkin CC and White DJ. *Measurement of joint motion : a guide to goniometry.* Philadelphia: F.A. Davis, 2009.

46. Pincivero DM, Salfetnikov Y, Campy RM, and Coelho AJ. Angle- and gender-specific quadriceps femoris muscle recruitment and knee extensor torque. *Journal of biomechanics* 37: 1689-1697, 2004.

47. Plattner K, Baumeister J, Lamberts RP, and Lambert MI. Dissociation in changes in EMG activation during maximal isometric and submaximal low force dynamic contractions after exercise-induced muscle damage. *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology* 21: 542-550, 2011.

48. Plummer MC. JAGS: A Program for Analysis of Bayesian Graphical Models Using Gibbs Sampling. Presented at 3rd International Workshop on Distributed Statistical Computing, Vienna, Austria, March 20-22, 2003.

49. Rantanen J, Thorsson O, Wollmer P, Hurme T, and Kalimo H. Effects of therapeutic ultrasound on the regeneration of skeletal myofibers after experimental muscle injury. *The American journal of sports medicine* 27: 54-59, 1999.

50. Rehn B, Lidstrom J, Skoglund J, and Lindstrom B. Effects on leg muscular performance from whole-body vibration exercise: a systematic review. *Scandinavian journal of medicine & science in sports* 17: 2-11, 2007.

51. Robert CP and Casella G. *Monte Carlo statistical methods.* New York: Springer, 2004.

52. Sellwood KL, Brukner P, Williams D, Nicol A, and Hinman R. Ice-water immersion and delayed-onset muscle soreness: a randomised controlled trial. *British journal of sports medicine* 41: 392-397, 2007.

53. Stauber WT, Clarkson PM, Fritz VK, and Evans WJ. Extracellular matrix disruption and pain after eccentric muscle action. *Journal of applied physiology* 69: 868-874, 1990.

54. Team RDC. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing, 2010.

55. Tee JC, Bosch AN, and Lambert MI. Metabolic consequences of exercise-induced muscle damage. *Sports medicine* 37: 827-836, 2007.

56. Tufano JJ, Brown LE, Coburn JW, Tsang KK, Cazas VL, and LaPorta JW. Effect of aerobic recovery intensity on delayed-onset muscle soreness and strength. *Journal of strength and conditioning research / National Strength & Conditioning Association* 26: 2777-2782, 2012.

57. van de Vyver M and Myburgh KH. Cytokine and satellite cell responses to muscle damage: interpretation and possible confounding factors in human studies. *Journal of muscle research and cell motility* 33: 177-185, 2012.

58. Wheeler AA and Jacobson BH. Effect of whole-body vibration on delayed onset muscular soreness, flexibility, and power. *Journal of strength and conditioning research / National Strength & Conditioning Association* 27: 2527-2532, 2013.

59. Yang JF and Winter DA. Electromyography reliability in maximal and submaximal isometric contractions. *Archives of physical medicine and rehabilitation* 64: 417-420, 1983.

60. Yu JG, Malm C, and Thornell LE. Eccentric contractions leading to DOMS do not cause loss of desmin nor fibre necrosis in human muscle. *Histochemistry and cell biology* 118: 29-34, 2002.

61. Zainuddin Z, Hope P, Newton M, Sacco P, and Nosaka K. Effects of partial immobilization after eccentric exercise on recovery from muscle damage. *Journal of athletic training* 40: 197-202, 2005.

Table 1 Measures for thigh circumference (cm) and active knee range of motion (degrees).

Variable and Group	Pre	24 Hours	48 Hours	1 Week
Thigh Circumference, cm				
Control	51.3 ± 4.7	51.4 ± 4.7	51.4 ± 4.7	51.3 ± 4.7
Treatment	55.8 ± 4.6	55.9 ± 4.6	56 ± 4.6	55.8 ± 4.6
Range of Motion, degrees				
Control	132.3 ± 7.4	*127.9 ± 7.6	**127.8 ± 11.1	132.4 ± 9.4
Treatment	135.2 ± 4.5	*131 ± 6	*129.5 ± 6.2	134.8 ± 6.2

*Denotes significant difference from pre value ($p < 0.001$).

**Denotes significant difference from pre value ($p < 0.02$).

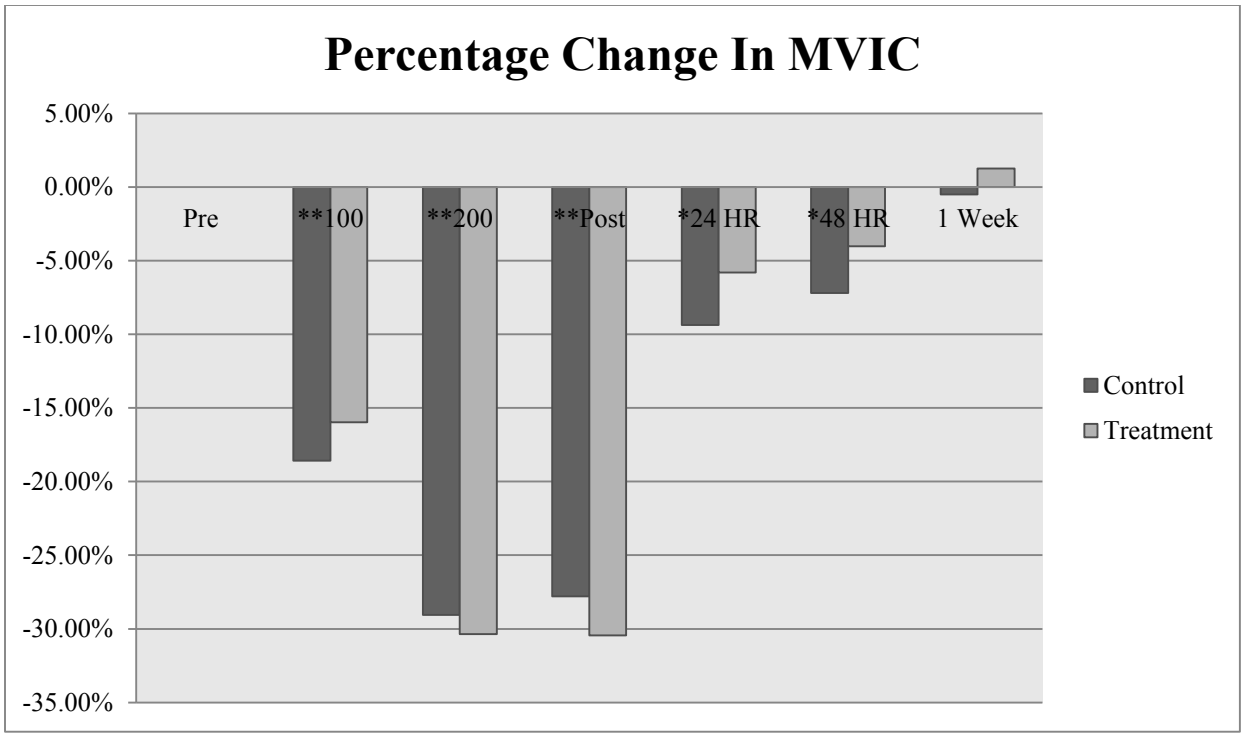

Figure 1 Percent Changes in Maximal Voluntary Isometric Contraction

**Denotes both groups significantly different from zero.

*Denotes only control group significantly different from zero.

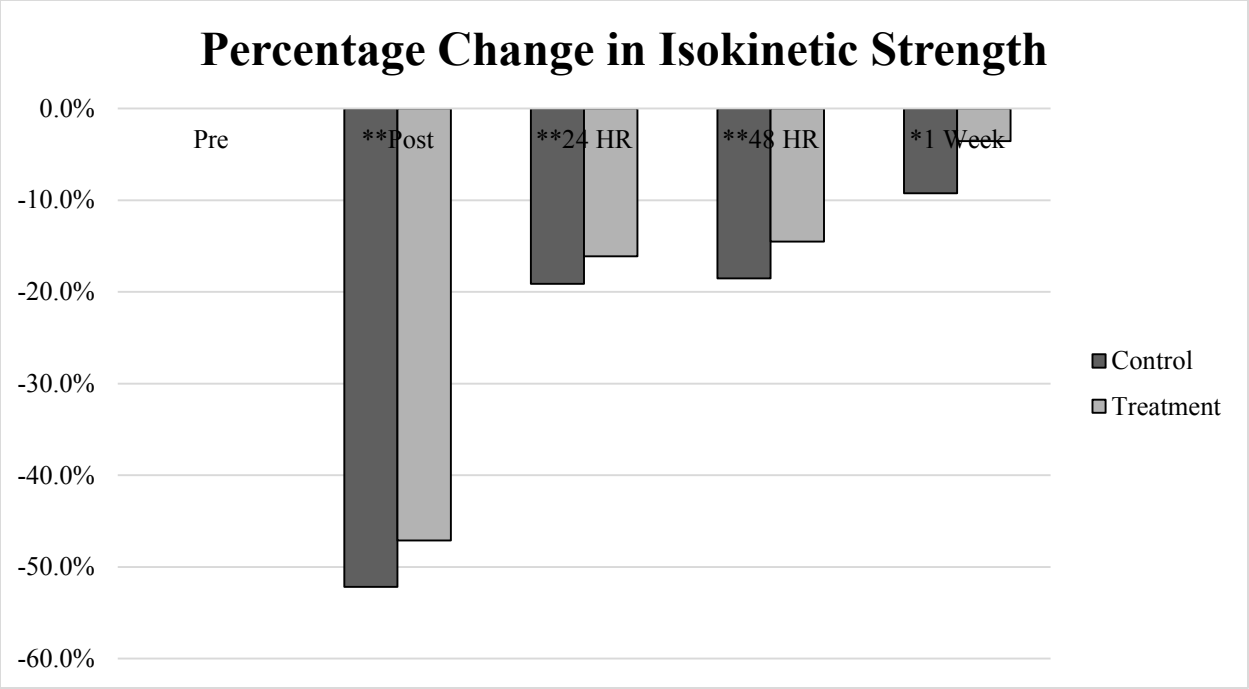

Figure 2 Percentage Changes in Isokinetic Strength.

**Denotes both groups significantly different from zero.

*Denotes only control group significantly different from zero.

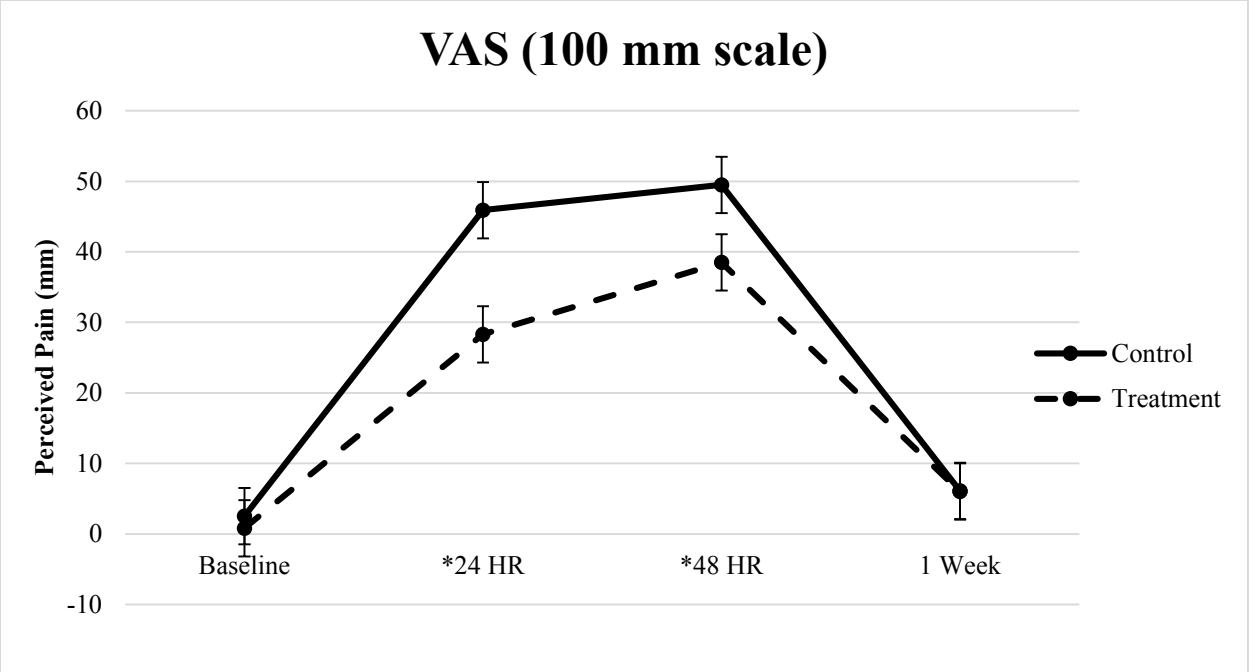

Figure 3 Changes in Soreness as Measured on a Visual Analog Scale (VAS)

*Denotes a significant difference from baseline for both control and treatment groups and a significant difference between groups.

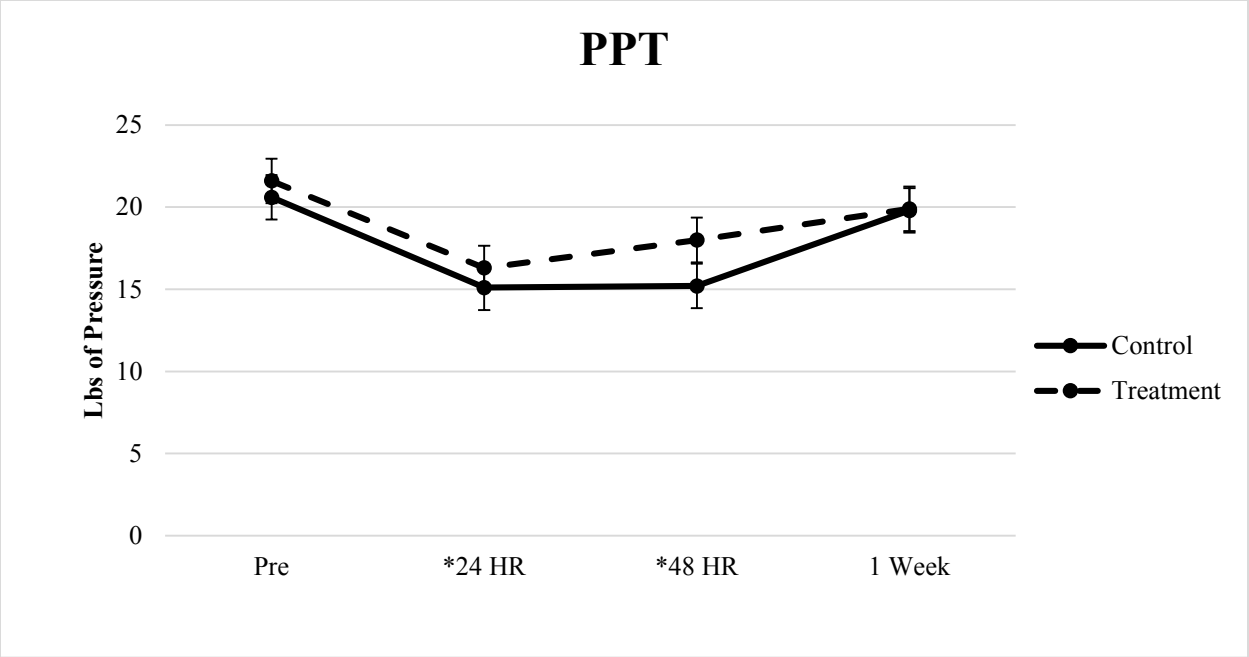

Figure 4 Changes in Pressure Pain Threshold (PPT)

Measured in lbs of pressure before exercise, 24 and 48 hours, and 1 week postexercise.

*Denotes a significant difference from baseline for both control and treatment groups.

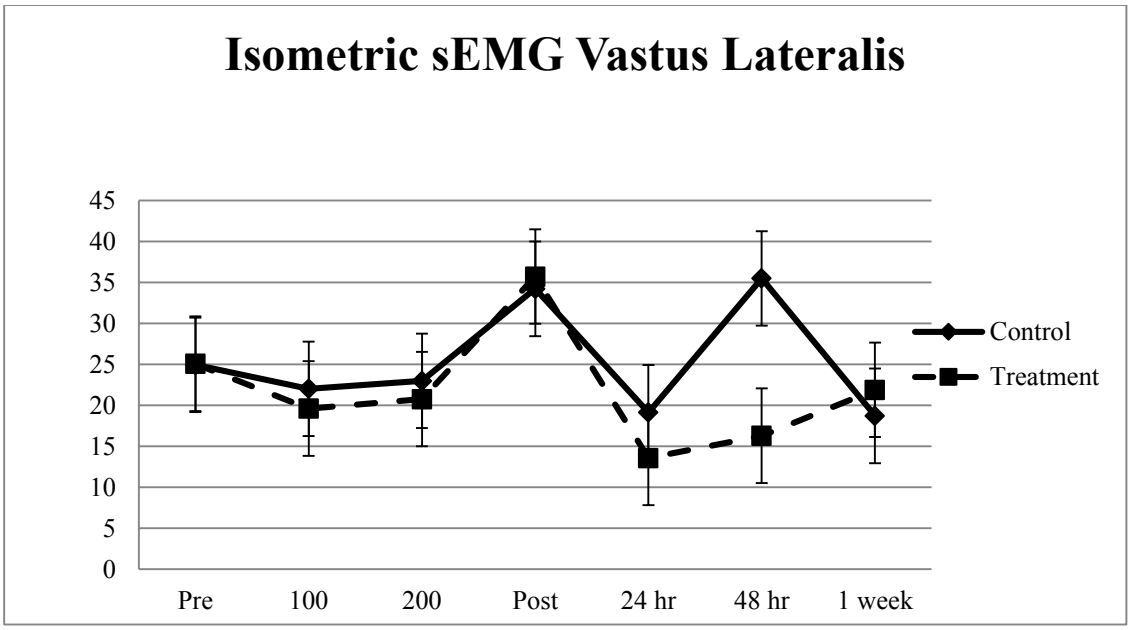

Figure 5 Normalized sEMG Values from the Vastus Lateralis

Recorded before exercise, after 100 and 200 repetitions, postexercise, 24 and 48 hours, and 1 week postexercise.

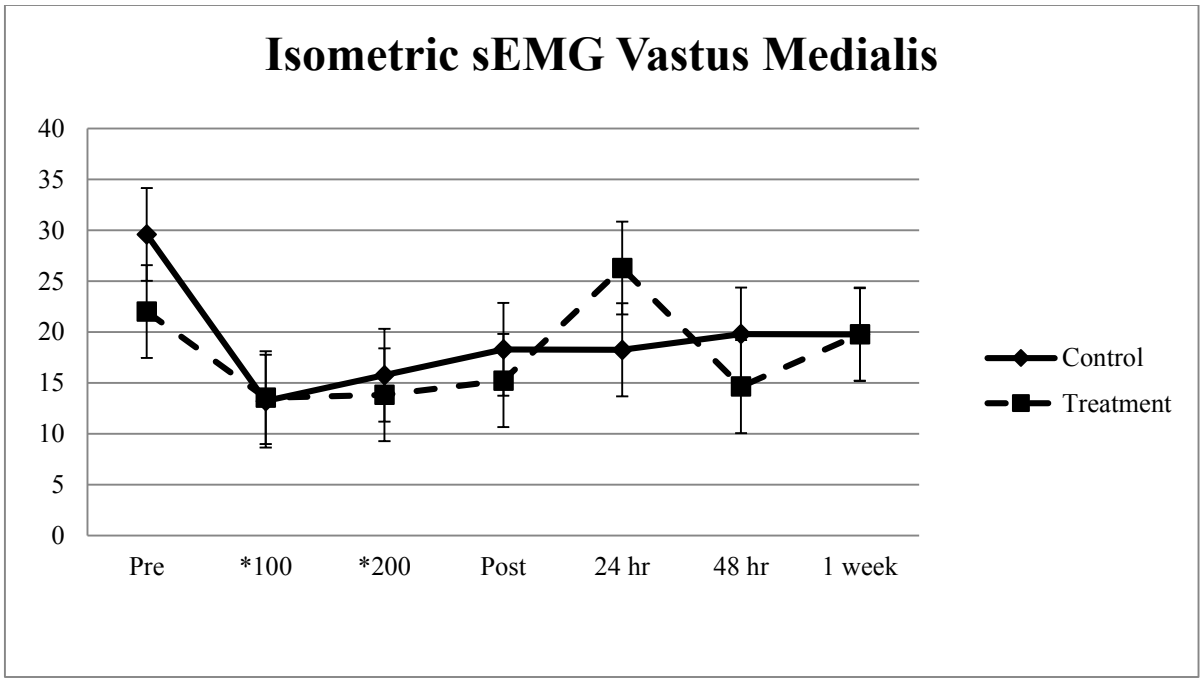

Figure 6 Normalized sEMG Values from the Vastus Medialis

Recorded before exercise, after 100 and 200 repetitions, postexercise, 24 and 48 hours, and 1 week postexercise.

*Denotes a significant difference from baseline in the control group only.