Final Progress Report

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Biomechanical Effects of Industrial Eccentric Exertions

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List of Terms and Abbreviations

Magnetic resonance imaging (MRI)

Maximum voluntary contraction (MVC)

Stiffness (*k*),

Damping constant (c)

Region of interest (ROI

Confidence Interval (CI)

Visual Analog Scale (VAS)

Analysis of variance (ANOVA)

Abstract

The mechanical and magnetic resonance imaging (MRI) changes following eccentric and concentric exertions were studied. Prolonged mechanical and physiological changes in the upper extremity following short-term simulated power hand tool use were also investigated.

Prior work has shown that changes in mechanical parameters and MRI parameters occur following submaximal eccentric activity but it was unclear whether similar changes occurred following submaximal concentric activity. This study compared mechanical response parameters and MRI relaxation parameters following submaximal concentric or eccentric exertions.

This single site, randomized study investigated *in-vivo* changes in human upper limb dynamic mechanical properties following exposure to short term repetitive submaximal eccentric or concentric exertions. Eighteen subjects were assigned to either an eccentric or concentric group and exercised for 30 minutes at 50% of isometric forearm maximum voluntary contraction. Changes in strength, symptom intensity, MRI T_2 relaxation measurements, which are indicative of edema, and dynamic mechanical parameters (stiffness, effective mass, and damping) were ascertained prior to exercise, one hour after, and 24 hours later.

Strength decreased following exercise ($P < 0.01$), however only the eccentric exercise group exhibited a reduction in mechanical stiffness (55%, $P < 0.01$) and damping (31%, $P < 0.05$), and an increase (17%, $P < 0.05$) in MRI T_2 relaxation time.

The changes in mechanical parameters and MRI findings following repetitive submaximal eccentric activity could negatively impact the ability of the arm to react to rapid forceful loading during repetitive industrial work activities and may result in increased strain on the upper limb. Similar changes were not observed following concentric exercise.

In-vivo changes in upper limb dynamic mechanical properties and MRI parameters following short term power hand tool operation were also investigated. Previous studies have found reduction in mechanical properties following short term power tool usage at long buildup times. This study advances that work by having participants operate a simulated pistol grip power hand tool and evaluating changes in mechanical properties, strength, discomfort level and MRI prior to tool operation and daily for three days after tool operation.

Twenty four participants were randomly assigned to operate a simulated power hand tool for either a high reaction force of 123 N (peak torque = 8 Nm, build-up time = 250 ms) or at a low reaction force of 5 N (peak torque = 2 Nm, build-up time = 50 ms). Subjects operated the tool for 60 minutes at the rate of six times per minute. A reduction in stiffness (27%, $p<0.05$) was observed 24 hours after tool operation for the high force group and this change persisted (26%, $p<0.05$) up to 72 hours after tool operation. Similar changes were not observed for the low force group. No changes were observed in mass moment of inertia, damping, isometric strength and damping for either group ($p>0.05$). There was a signal

intensity increase (12%, CI = 19%, 5.06%) in the supinator muscle MR images for both groups 24 hours after tool operation but only the high force group remained elevated (10%,CI = 13.7%, 0.06%) 72 hours after tool operation.

Persistent short term changes in mechanical and MRI parameters at high force levels could indicate increased strain on the upper limb and may negatively affect ability to react during rapid forceful loading of the upper limb.

Significant Findings

Changes in both mechanical and MRI findings were observed following short duration submaximal eccentric activity. The decrease in mechanical properties and a subsequent increase in edema suggest that short duration submaximal activity has a negative short-term effect on extremities that are eccentrically exercised. Reductions in strength, mechanical stiffness and damping of the forearm following eccentric contractions are associated with an increase in mechanical strain during loading tasks such as tool operation. Further studies are needed to characterize the significance of these changes and their relationship to musculoskeletal disorders frequently observed in the workplace.

Sustained changes in both mechanical and MRI parameters were observed following short duration power hand tool use. A decrease in mechanical properties and a subsequent increase in edema persisted 72 hours after tool operation for the high force group only. .It is plausible that the physical demands associated with torque producing power tool operation have an adverse effect on the musculoskeletal tissues of the upper extremity, which affect mechanical properties and result in localized edema, similar to effects sometimes seen following muscle lengthening exertions. The reduction in mechanical properties and increase in edema following tool operation can be viewed as potential precursors to the development of musculoskeletal disorders.

Translation of Findings

This study employed a less fatiguing protocol to represent the level of exertion found in occupational settings. Rarely during the course of normal work activities do employees persistently work at their maximum or until exhaustion occurs. Our subjects worked at a moderate level for a relatively short duration, at a level similar to that sustained in the workplace for many more hours. Because we observed mechanical parameter changes following moderate eccentric exercise for a short duration, it may be possible to observe similar changes after longer durations, as are common in the workplace. These observed mechanical changes may be indicative of mechanical strain.

In previous work (Sesto et al., 2006), we evaluated the mechanical parameters of industrial assembly workers. All workers also underwent a physical examination, MRI scan, and symptom survey. The mechanical response parameters for workers with reported forearm symptoms were 46-74% less than parameters for the asymptomatic group. In another study of industrial power hand tool operation (Lin et al., 2001), less mechanical stiffness was associated with greater force and displacement, and consequent external stresses from physical loading of the arm. Increased stresses on the body can lead to increased risk of injury (NRC/IOM, 2001); thus these findings further support the relationship between injury and a reduction in mechanical parameters.

Eccentric exertions frequently occur in the workplace, such as during power hand tool use, and have been rarely studied in this context. Reduction in mechanical properties is associated with greater forces and displacements when operating industrial power hand tools and consequently increased external stress from physical loading of the arm (Lin, Radwin et al. 2001; Lin, Radwin et al. 2003). Increased stresses on the body can also increase the risk of an injury (National Research Council Institute of Medicine 2001). This reduction in capacity could potentially have adverse long-term effects on operator safety, particularly for large level exertions that are frequent and forceful. It is anticipated that this research will lead to an improved understanding of the relationship between tool properties and upper limb disorders as well as better power hand tool selection and design.

Outcomes/ Relevance/ Impact

This study investigated the changes in upper limb dynamic mechanical response parameters for subjects randomly assigned to either 30 minutes of repetitive submaximal eccentric muscle activity or repetitive submaximal concentric activity. Measured parameters included stiffness, damping, and effective mass for forearm rotation. The eccentric exercise group decreased 17% in static strength whereas the concentric exercise group decreased 10% at one hour post-exercise. Decreases in mechanical stiffness and damping were only observed in subjects in the eccentric exercise group. These findings concur with our earlier study where a reduction in mechanical parameters was observed after eccentric but not isometric exercise (Sesto et al., 2004). At the time, it was unclear if the differences between the eccentric and isometric exercise groups were a result of the eccentric contractions or the dynamic nature of the exertion. Because changes in mechanical response parameters were not observed with the concentric exercise group in this study, we conclude that changes of this type occur only following eccentric activity.

There was no statistically significant decrease in the forearm supination strength levels following simulated power hand tool operation. Fatigue therefore cannot explain the reduction in stiffness. It was suggested that mechanical stiffness of muscle is dependent on the actin-myosin binding of the muscle sarcomeres (Linari, Dobbie et al. 1998) . Since eccentric exertions are sometimes related to damage to the actin-myosin contractile machinery this damage may be reflected as a reduction in mechanical stiffness. Consequently greater damage at high torque and longer buildup times might result in a greater drop in mechanical stiffness. This observation alone does not infer that sarcomere damage necessarily occurred in the current study. Furthermore if these changes did occur, no functional deficits (i.e. static strength) were observed and consequently these changes are not necessarily related to injury.

Eccentric exercise has also been attributed to motor recruitment changes. Prasartwurth et al. (2005) examined voluntary activation following eccentric exercise using motor nerve and motor cortex stimulation. They found impairment of voluntary activation to peripheral nerve stimulation but not motor cortical stimulation which eliminated an activation deficit at the motor cortex or spinal level. It is therefore plausible that the reduction in stiffness observed in the current study could be explained by possible mechanical damage to the contractile elements or reduced neural drive. Future research should address these effects.

The measurement of stiffness in the current study is similar to a dynamic strength test. No change in isometric strength was observed following tool operation, however a statistically significant reduction in the mechanical stiffness was observed following tool operation. It is reported that measures of static and dynamic strength often do not correlate (Baker, Wilson et al. 1994). Similar outcomes were observed in the current study.

This research can ultimately lead to better ergonomic interventions through quantitative power hand tool design guidelines and work practices based on understanding the damaging effects of exposure to specific levels of reaction force, build-up time and repetition, as well as providing new outcome measures for epidemiological studies

Scientific Report

Mechanical and Magnetic Resonance Imaging Changes Following Eccentric or Concentric Exertions

Background

Workplace exertions can result in muscle contractions that shorten muscles (concentric), lengthen muscles (eccentric), or involve no change in muscle length (isometric). The use of torque-producing power hand tools, such as screwdrivers and nutrunners, may generate eccentric contractions when rapidly rising forces exceed the tool operator's capacity to react (Armstrong et al., 1999; Oh et al., 1997; Oh & Radwin, 1998). Mechanical factors corresponding to eccentric contractions, such as high levels of force and velocity, have been attributed to the initiation and early stages of contraction-induced microinjury in muscles during repetitive loading (Armstrong et al., 1995). If the external forces from these types of power hand tools exceed the tolerance of the muscle's passive and active contractile structures, damage could result, particularly to forearm muscles.

Intense eccentric exercise is often associated with muscle weakness and soreness 24 to 48 hours following activity (Clarkson et al., 1992; Cleak & Eston, 1992; Friden et al., 1983). Unaccustomed eccentric contractions cause more severe skeletal muscle injuries than unaccustomed isometric or concentric contractions, often resulting in disruptions of the muscle myofibrillar structure (Faulkner et al., 1993; Lieber et al., 1991). This disruption may negatively affect the muscle's mechanical response parameters (e.g. stiffness, effective mass and damping). For example, Leger and Milner (2000) reported a significant decrease in stiffness in male subjects following maximal eccentric exercise.

Specific Aims

The mechanical response properties of muscles and tendons are functionally important because they counteract the effects of applied loads. Changes in these mechanical properties affect the muscle's ability to react to rapid forceful loading and result in increased muscle strain. Both mechanical and magnetic resonance imaging (MRI) changes have been documented in skeletal muscles following eccentric activity at intensities similar to those found in the workplace (Nosaka & Newton, 2002; Sesto et al., 2004; Sesto et al., 2005a). Sesto et al. (2005a) reported a 41% decrease in mechanical stiffness after 24 hours and a 28% increase in the MRI T2 parameter 72 hours after short duration submaximal eccentric activity at levels similar to those occurring in the workplace. Shellock et al. (1991) reported a statistically significant increase in T2 relaxation time 24 hours after eccentric, but not concentric, exercises. Common workplace exertions such as reaches and lifts involve concentric muscle contractions, however it is unknown if similar changes in mechanical response parameters and MRI findings occur following these activities. The current study was designed to compare mechanical response parameters and MRI changes following submaximal concentric or eccentric exertions. We hypothesized greater changes in mechanical response parameters and the MRI T2 relaxation parameter following eccentric exertions.

Procedures and Methodology

Participants

This randomized, single-blinded trial evaluated changes in mechanical parameters and MRI T_2 relaxation following either concentric or eccentric activity. Twenty-one healthy volunteers were recruited from a mid-western college university campus; of these, eighteen subjects met the inclusion criteria and were considered eligible (Figure 1). All participants reported that they were free of symptoms and existing injuries in the dominant upper extremity. The dominant arm was used for all testing. Informed consent was obtained in accordance with the University of Wisconsin guidelines for the protection of human subjects.

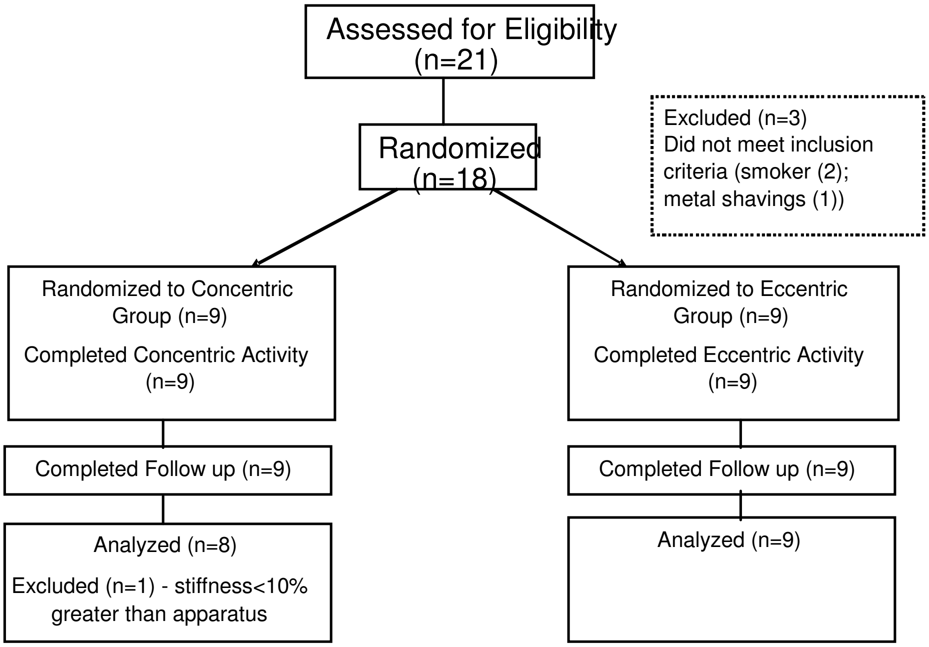


Figure 1. Randomized Controlled Trial Flow Diagram

All subjects completed a self–administered general health status and symptom questionnaire immediately prior to testing. The questionnaire queried upper extremity activities and demographic information such as gender, age, weight, stature, and hand dominance. Inclusion criteria included no existing upper extremity symptoms, limitations, or current injury; willingness to refrain from weight training activities or intensive recreational sports involving the upper extremities for at least one week prior to the experiment and for the duration of the study; ability to undergo a MRI; and ability to complete upper extremity exercise for 30 minutes. Subjects who occupationally used power hand tools were excluded from the study. All subjects also completed a screening questionnaire prior to magnetic resonance imaging to exclude those with braces or a history of orbital metal fragments, those who worked with metal shavings without appropriate eye protection, and those with embedded metal. Pregnant subjects were also excluded.

Experimental Design

Subjects were randomly assigned to perform a bout of either eccentric or concentric exertions; their knowledge of exercise status was controlled to the extent possible. The researcher reading the MR images was also blinded to exercise condition. Differences in stiffness, effective mass, damping, and self-reported discomfort levels were measured before, 1 hour, and 24 hours following repetitive submaximal exertion. All participants also underwent an MRI before exercise, and 1 hour and 24 hours after exercise. Mechanical parameter assessment was performed after strength testing, following a five-minute rest period, and prior to the MRI. The testing methods were completed in the same sequence for each session and for each subject.

Strength Measurement

Each subject was seated with the shoulder, forearm, and wrist placed in a neutral position and the elbow flexed to 90°. The upper arm was stabilized against the body with a strap to prevent substitution or unwanted movement. Strength testing was performed using a Biodex™ (Biodex Medical Systems, Shirley, NY) measurement system and a custom forearm rotation accessory. Maximum voluntary contraction (MVC) of the forearm supinator muscles was measured isometrically as the subject supinated the dominant forearm, applying torque to the handle. The power-head maintained zero velocity during the isometric strength test, so force could be developed without any significant change in muscle length.

Two five-second MVCs, separated by a one minute rest between exertions, were performed prior to exercise, 1 hour after exercise, and 24 hours later. The second to fourth seconds were averaged for each MVC exertion. The average of the two MVC exertions was used for analyses. MVC data were always collected prior to mechanical parameter testing on the free vibration apparatus. A five-minute rest period was provided following strength assessment and prior to mechanical parameter testing. The handle torque was digitized and sampled using a DAQCard-6024E data acquisition board (National Instruments Corporation, Austin, TX) for a sampling rate of 50 samples per second.

Exercise Protocol

The Biodex™ apparatus was also used for the exercise protocol. The dominant forearms of the eccentric exercise subjects were started in a neutral position and then pronated to 90°. The dominant forearms of the concentric exercise subjects were first pronated to 90° and then supinated to the neutral position. In both groups, the elbow was flexed at 90° while the upper arm was stabilized against the body with a strap to prevent substitution or unwanted movement.

The handle rotation velocity on the Biodex apparatus was set at 30°/s. This velocity allowed subjects to control the generated torque throughout the set range of motion. Subjects in both exercise groups exerted 50% MVC for a total of 30 minutes with a 1 minute rest break after each 5 minute interval. Continuous visual feedback of torque output was presented so subjects could maintain the desired exertion level. Most subjects were able to maintain the desired torque, although some had difficulty during the last 1-2 minutes of the exercise protocol. Data sampling was 1000 samples per second using a National Instruments DAQCard-6024E data acquisition card.

Subjects rated their pain intensity immediately before, 1 hour later, and 24 hours after the bout of exercise using a visual analog scale ranging from “0=no pain” to “10=most pain”.

Upper Limb Mechanical Response Parameters

Subjects were tested on an apparatus designed to measure upper limb mechanical response parameters, stiffness, viscous damping, and effective mass during active exertion. The upper extremity is characterized as a single degree of freedom dynamic mechanical system (Lin et al., 2001, 2003a, 2003b, 2003c). A harmonic sinusoidal rotation is transmitted to the forearm though a 4 cm diameter handle. When grasped by the subject, the handle aligns the forearm axis of rotation with the axis of rotation of the apparatus. The upper arm is stabilized against the body with a strap to prevent substitution or unwanted movement. Subjects were instructed to grasp the handle as hard as they could to inhibit oscillatory motion.

The stiffness, effective mass and damping responses were determined for the combined apparatus as well as the subject. The variations in these mechanical responses were defined by calculating the change in oscillation frequency and the decay in displacement amplitude. The resulting mechanical parameters (stiffness, effective mass, and damping) for the hand-arm system were measured from the change in the system response imposed by the hand-arm.

The equation of motion describing the free vibration response of this system is

$$J\ddot{\theta} + c\dot{\theta} + k\theta = 0 \qquad (1)$$

where *J* = mass moment of inertia, *c* = damping constant, *k* = stiffness, ϑ = angular displacement. When the subject externally loads the apparatus handle, the sum of the contributions of the apparatus, applied mass and the operator define the physical characteristics of the combined system. The relationship between the moment of inertia of the effective mass and the resultant frequency is described in equation 2. The relationship between the moment of inertia of the effective mass and damping ratio is represented in equation 3 (Lin et al, 2001).

$$J_{mass} = k\frac{1}{\omega_n^{2}} - (J_0 + J_{subject}) \qquad (2)$$

$$J_{mass} = c\left(\frac{1}{2\omega_n\zeta}\right) + \text{constant} \qquad (3)$$

The torsional stiffness (*k*), is the resulting slope of the line of frequency as a function of apparatus mass in the form of Equation 2. The moment of inertia was calculated in prior studies, using an earlier version of the apparatus and the intercept from equation 2 (Lin, et al. 2001, 2003a, 2003b, 20003c; Sesto et al. 2004, 2005a, 2005b, 2006). The moment of inertia of the effective mass is now calculated using the conservation of momentum principle. The angular velocities before and after the zero position is crossed during the first cycle of oscillation of the handle are measured over a period of 10 milliseconds. The moment of inertia of the device and the applied mass is known and the moment of inertia of the effective mass for the human subject is calculated using the following equation:

$$J_{device+mass}\,\omega_1 = (J_{device+mass} + J_{subject})\,\omega_2 \qquad (4)$$

The damping constant (c) is calculated by:

$$c = 2\varsigma\sqrt{kJ} \qquad (5)$$

where, ζ = damping factor, measured from the oscillations of the apparatus.

Handle displacement was measured using an Allen Bradley angle encoder (Rockwell Automation, Milwaukee, WI) sampled at 1000 samples/sec. The inertial mass of the system can be varied by changing the location of two masses with respect to the centre of rotation. The free vibration oscillation frequency of the apparatus ranged from 3.64 to 4.12 Hz and the period of oscillation ranged from 4 seconds to 17 seconds depending upon the inertia of the apparatus and the human operator.

Magnetic Resonance Imaging

The MRI examination was conducted on an Artoscan 0.17 T extremity scanner (GE

Healthcare, Milwaukee, WI). The T_2-weighted images of both exercised and non-exercised muscles were examined visually and numerically. Scan parameters for this experiment were set at 2050 ms TR, echo times of 18ms, 80 ms and 120ms, 16 cm FOV and 196 x 196 resolution.

Central regions were selected in the corresponding active and inactive muscles for slices where visual differences were noted. Special care was taken to avoid inclusion of subcutaneous fat, fascia, blood vessels, or bone structures. Elevation of T_2 relaxation time occurs with edema and displays a higher intensity in T_2-weighted images. T_2 relaxation times were determined by fitting the region of interest (ROI) data from each echo to an exponential curve with MR Vision software (Mr Vision, Inc. Boston, MA).

Data Analysis

Data were analyzed for differences between exercise groups and for differences prior to exercise, 1 hour later, and 24 hours after exercise. A mixed-effects, repeated-measures analysis of variance was used to evaluate statistical significance of the mechanical and MRI variables. All confidence intervals are reported at 95%.

Results

Baseline

Subjects were enrolled between October 2004 and May 2005. A total of eighteen subjects were randomized to either the eccentric or concentric group. All subjects completed the exercise protocol, although one subject was excluded because her level of stiffness was not 10% greater than the apparatus stiffness. The data were analyzed with and without this subject and the results were unaffected. The results reported are for the remaining 17 subjects (nine males and eight females). Baseline demographic data did not differ between the two groups (Table 1).

Table 1 – Demographic Information

	Concentric (n=8)	*Eccentric (n=9)*	*P Value*
Age – mean (SD), years	*27 (5)*	*29 (7)*	*.52*
Gender			
Men	*4*	*5*	*.82*
Women	*4*	*4*	
Race			
White	*6*	*4*	*.31*
African American	*2*	*1*	
Hispanic	*0*	*2*	
Asian	*1*	*2*	
BMI – mean (SD)	*24 (2.5)*	*23 (1.1)*	*.59*
Hand Dominance			
Right	*7*	*9*	*.27*
Left	*1*	*0*	
Participation in Recreational Sports			
Yes	*6*	*5*	*.40*
No	*2*	*4*	
Participation in Weight Lifting			
Yes	*5*	*3*	*.23*
No	*3*	*6*	

Prior to exercise, no differences were observed between subjects in the eccentric and concentric groups for forearm supination static strength, mechanical stiffness, effective mass, viscous damping, symptom intensity, or MRI T_2 relaxation times (Table 2). No adverse events or side effects occurred.

Strength

The average static forearm supination strength was reduced following exercise ($p< 0.01$). After 1 hour, the eccentric exercise group decreased 16% (mean = 6.83Nm; CI = -27.9%, -3.9%) while the concentric exercise group decreased 10% (mean = 7.73Nm; CI = -27.6%, 30.7%). After 24 hours, subjects in both groups recovered within 2% of their baseline strength level (eccentric group: mean = 8.25; CI = -10.2%, 8.1% and concentric group: mean = 8.68; CI = -60.6%, 138.1%).

Mechanical Response Parameters

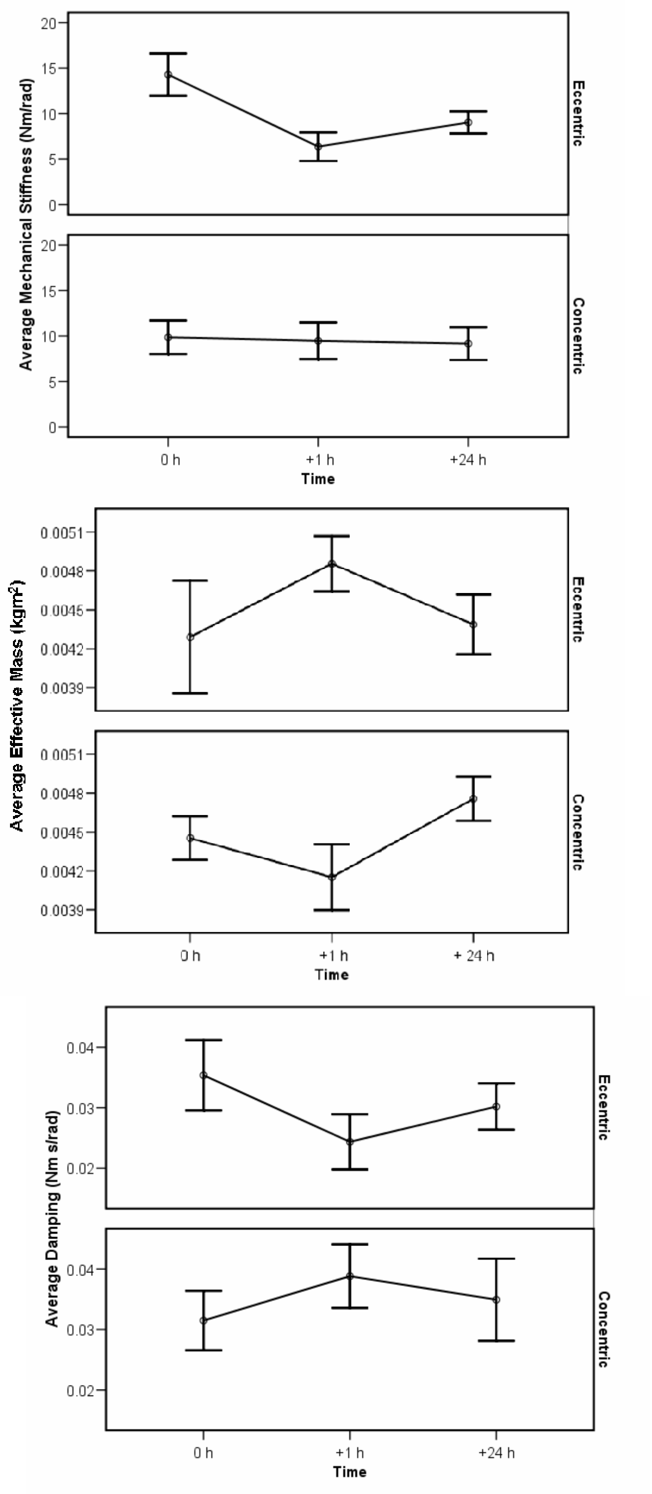
Mechanical stiffness, measured before, 1 hour after, and 24 hours after exercise is shown in Figure 2a. Average mechanical stiffness was reduced following exercise ($p<0.01$). After 1 hour, the eccentric exercise group decreased 55% (CI = -75.5%, -39.5%) while the concentric exercise group decreased 4% (CI = -34.3%, 24.1%). After 24 hours, mechanical stiffness for the eccentric exercise group remained 37% less than before exercise (CI = -53.2%, 0.3%) and stiffness in the concentric group remained 7% decreased (CI = -55.4%, 66.5%).

Table 2 – Baseline Strength, Mechanical Parameters, Symptom Intensity and MRI T_2 Relaxation Time

	Concentric (n=8)	*Eccentric (n=9)*	*P Value*
Strength (MVC)	*8.56 (4.78)*	*8.18 (3.93)*	*.86*
Mechanical Parameters – mean (SD)			
Stiffness (Nm/rad)	*9.9 (5.2)*	*14.3 (6.9)*	*.16*
Effective Mass	*.0043 (.0005)*	*.0044 (.0013)*	*.74*
Damping	*.031 (.014)*	*.035 (.017)*	*.62*
Symptom Intensity (VAS)	*0*	*0*	
MRI (T_2 Relaxation Time) - mean (SD)			
Supinator	*51.38 (3.43)*	*50.20 (2.16)*	*.40*
Flexor	*49.76 (4.82)*	*48.38 (3.55)*	*.51*

Figure 2b illustrates effective mass measured before, 1 hour later, and 24 hours after exercise. There was a significant association between average effective mass and exercise type ($p< 0.01$). After 1 hour, the eccentric exercise group increased 13% (CI = -1.7% to 40.6%), while the concentric exercise group decreased 7% (CI = -17.9%, 4.1%). After 24 hours, effective mass returned to within 2% of baseline (CI = -26.1%, 51.0%) for the eccentric exercise group, and increased 7% from baseline (CI = -1.7%, 16.3%) for the concentric group.

There was a significant association between average viscous damping and exercise type ($p< 0.01$), as illustrated in Figure 2c. After 1 hour, the eccentric exercise group decreased 31% (CI = -47.3%, -12.5%) and remained 15% decreased (CI = -35.2%, 23.6%) at 24 hours. The concentric exercise group increased 23% (CI = 3.6%, 51.8%) after 1 hour and remained 11% increased (CI = -32.3%, 40.2%) after 24 hours.



Figures 2a to c: Mechanical Stiffness, Effective Mass and Damping (Mean/SE):

Pain Intensity

All subjects reported a pain intensity of 0 at baseline. Average pain levels increased after exercise for both groups of subjects ($p<0.05$). After 1 hour, the eccentric exercise group reported an average intensity of 1.9 (CI = 0.2, 3.6), and intensity remained elevated at 1.6 after 24 hours (CI = 0.1, 3.1). The concentric exercise group reported an average intensity of 1.4 (CI = 0.6, 2.7) 1 hour after exercise and an average of 0.5 (CI = -0.2, 1.2) 24 hours after exercise.

Magnetic Resonance Imaging

Figure 3 shows MR T_2 images for exercised arms. An increase in the T_2 relaxation time was noted after exercise ($p<0.05$) (Figure 4). After 1 hour, the eccentric group exhibited a 6% average increase (CI = -3.3%, 15.1%) and the concentric group had a 2% increase (CI = -5.3%, 9.5%). After 24 hours, the eccentric group showed an average 17% increase (CI = 6.1%, 27.7%) and the concentric group had a 6% increase (CI = -6.6%, 18.5%) from baseline.

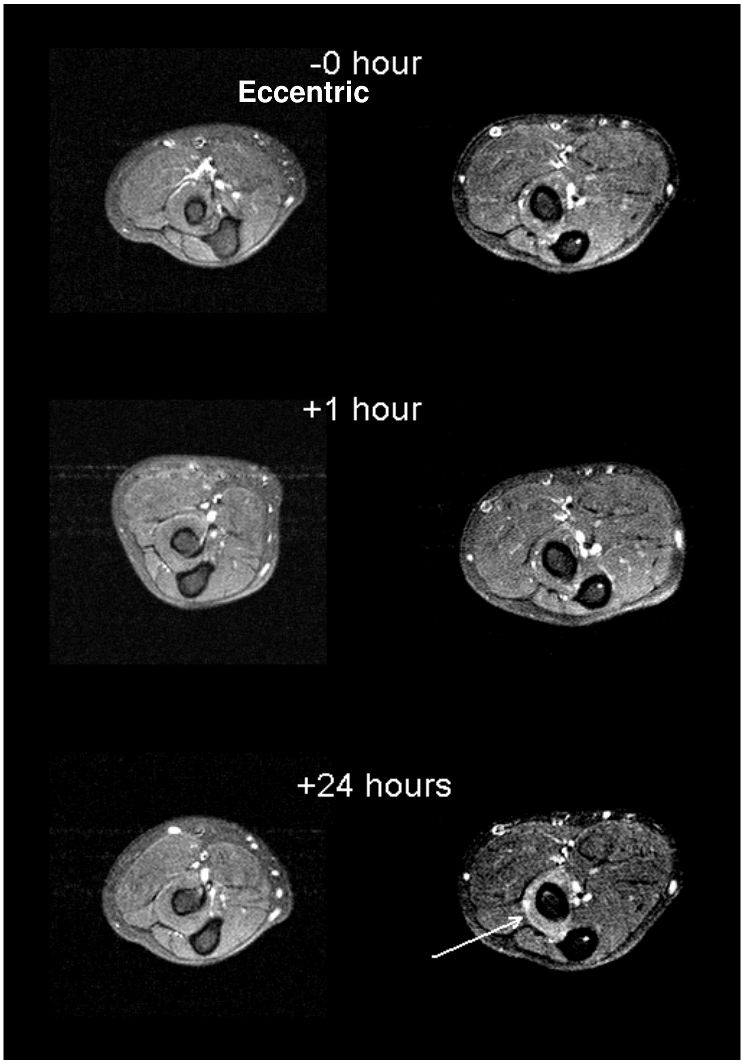


Figure 3: MR T_2 Forearm Image: Before, 1 h After, and 24 h After Exercise. T_2 enhancement is clearly evident and localized to the supinator muscle in the study obtained 24 hours after eccentric exercise study (arrow).

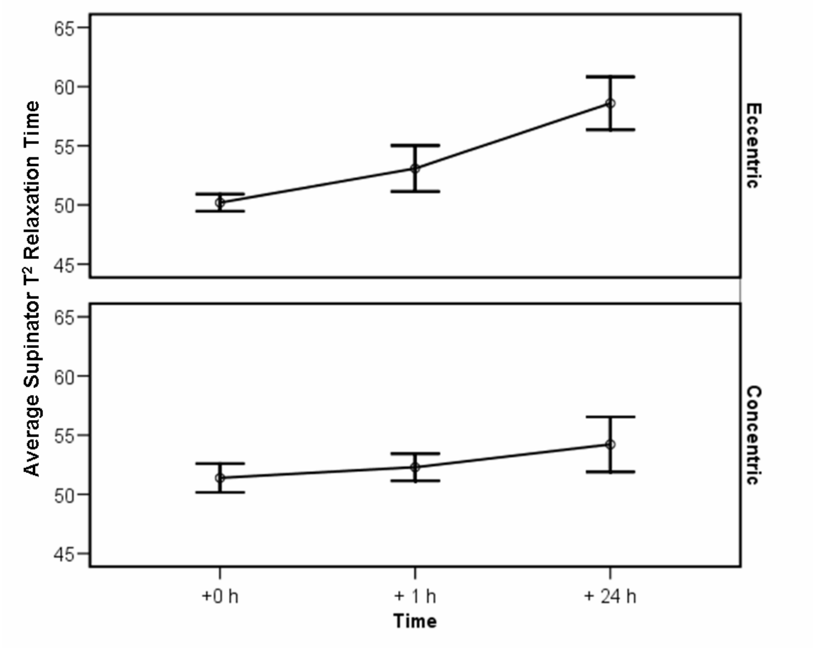


Figure 4: SupinatorT_2 Relation Time (Mean/SE): Before, 1 h After, and 24 h After Exercise.

Discussion

This study investigated the changes in upper limb dynamic mechanical response parameters for subjects randomly assigned to either 30 minutes of repetitive submaximal eccentric muscle activity or repetitive submaximal concentric activity. Measured parameters included stiffness, damping, and effective mass for forearm rotation. The eccentric exercise group decreased 17% in static strength whereas the concentric exercise group decreased 10% at one hour post-exercise. Decreases in mechanical stiffness and damping were only observed in subjects in the eccentric exercise group. These findings concur with our earlier study where a reduction in mechanical parameters was observed after eccentric but not isometric exercise (Sesto et al., 2004). At the time, it was unclear if the differences between the eccentric and isometric exercise groups were a result of the eccentric contractions or the dynamic nature of the exertion. Because changes in mechanical response parameters were not observed with the concentric exercise group in this study, we conclude that changes of this type occur only following eccentric activity.

Only a minimal increase in supinator T_2 relaxation time was observed for the eccentric (6%) and concentric groups (2%) one hour after exercise. This result was not unexpected since increases in T_2 relaxation time do not typically occur immediately after activity. After 24 hours, the eccentric exercise group had a 16% increase from baseline, while the concentric exercise group had a 6% increase. It is not known if this was the peak T_2 relaxation time because subjects were not followed beyond 24 hours.

It does not appear that fatigue alone can explain the initial decrease in mechanical properties. Both exercise groups experienced some fatigue after exercise, but only the eccentric exercise group showed a decrease in mechanical stiffness and damping 1 hour post-exercise. It is interesting that isometric strength for both exercise groups recovered to within 2% of baseline by 24 hours, but the eccentric group still exhibited a 37% reduction in mechanical stiffness and a 15 % reduction in damping at that point. If the mechanical changes were solely due to strength loss or fatigue, then recovery in mechanical response parameters should parallel strength recovery.

These findings are consistent with observations that tissue disruption and muscle injury occur frequently during high levels of eccentric activity and are often associated with muscle weakness and soreness occurring 24-48 hours following activity (Clarkson et al., 1992; Ebbeling & Clarkson, 1990; Friden et al., 1983). It is plausible that the muscle's contractile machinery may be damaged, resulting in a decrease in mechanical response parameters and a subsequent increase in edema, as measured by MRI T_2 enhancement. Fatigue occurring in the absence of obvious structural damage would not be expected to cause an increase in the T_2 relaxation time. These findings are important because lower level eccentric exertions may be of sufficient intensity to produce damage that influences future musculoskeletal disorders. Further biomechanical research on eccentric exertion levels similar to those encountered during occupational activities should test this hypothesis.

This study employed a less fatiguing protocol to represent the level of exertion found in occupational settings. Rarely during the course of normal work activities do employees persistently work at their maximum or until exhaustion occurs. Our subjects worked at a moderate level for a relatively short duration, at a level similar to that sustained in the workplace for many more hours. Because we observed mechanical parameter changes following moderate eccentric exercise for a short duration, it may be possible to observe similar changes after longer durations, as are common in the workplace. These observed mechanical changes may be indicative of mechanical strain.

In previous work (Sesto et al., 2006), we evaluated the mechanical parameters of industrial assembly workers. All workers also underwent a physical examination, MRI scan, and symptom survey. The mechanical response parameters for workers with reported forearm symptoms were 46-74% less than parameters for the asymptomatic group. In another study of industrial power hand tool operation (Lin et al., 2001), less mechanical stiffness was associated with greater force and displacement, and consequent external stresses from physical loading of the arm. Increased stresses on the body can lead to increased risk of injury (NRC/IOM, 2001); thus these findings further support the relationship between injury and a reduction in mechanical parameters.

Conclusions

Changes in both mechanical and MRI findings were observed following short duration submaximal eccentric activity. The decrease in mechanical properties and a subsequent increase in edema suggest that short duration submaximal activity has a negative short-term effect on extremities that are eccentrically exercised. Reductions in strength, mechanical stiffness and damping of the forearm following eccentric contractions are associated with an increase in mechanical strain during loading tasks such as tool operation. Further studies are needed to characterize the significance of these changes and their relationship to musculoskeletal disorders frequently observed in the workplace.

Prolonged mechanical and physiological changes in the upper extremity following short-term simulated power hand tool use

Background

Power hand tool use in industrial work may involve repetitive eccentric (muscle lengthening) exertions when rapidly rising tool-generated forces exceed the tool operator's capacity to react (Oh, Radwin et al. 1997; Oh and Radwin 1998; Armstrong, Bir et al. 1999). Armstrong et al. (1995) suggested that several mechanical factors corresponding to eccentric contractions, such as high levels of force and velocity, contribute to the initiation and early stages of contraction induced micro-injury in muscles during repetitive skeletal muscle loading. If the external forces from power hand tools exceed internal tolerance limits of the muscle's passive and active contractile structures, damage could result, particularly in the muscles of the forearm that oppose rapidly rising tool-generated forces. The current study aims to test that theory.

Intense eccentric exercise is often associated with muscle weakness and soreness that develops 24 to 48 hours following that activity (Friden, Sjostrom et al. 1983; Clarkson, Nosaka et al. 1992; Cleak and Eston 1992). Unaccustomed eccentric contractions cause more severe skeletal muscle injuries than unaccustomed isometric or concentric contractions, often resulting in disruptions of the muscle myofibrillar structure (Lieber, Woodburn et al. 1991; Faulkner, Brooks et al. 1993). This disruption may negatively affect the muscle's mechanical response parameters. For example, Leger and Milner (2000) reported a statistically significant decrease in stiffness following maximal eccentric exercise in male subjects.

Lin et al. (2001) developed a single degree of freedom mass-spring-damper mechanical model to understand the response of the hand and arm to mechanical shock in nutrunner operation. The dynamic mechanical properties of the upper limb (stiffness, effective mass and damping) are important for quantifying function since they mechanically characterize the response to counteract applied loads. A decrease in these parameters represents reduced ability to react to external force perturbations resulting in increased limb motion and greater dynamic forces acting against the hand and arm when an impulsive force is encountered. (Lin, Radwin et al. 2001).

Specific Aims

Previous studies in our lab found that mechanical properties (stiffness, effective inertial mass and damping) and MRI of muscle inflammation (edema) changed following short-term eccentric exercise at submaximal intensities (Sesto, Radwin et al. 2004; Sesto, Radwin et al. 2005). Sesto et al. (2005) also found that mechanical responses immediately decreased following short duration power tool use for power tools with a long torque build-up time (250 ms). Sesto (2006) found reduced mechanical properties in symptomatic workers and edema has been associated with muscle injury (Shellock, Fukunaga et al. 1991; Evans, Haller et al. 1998).

The current study advances that work by having participants operate a simulated pistol grip power hand tool and daily evaluating mechanical responses, MRI, symptoms and isometric strength together for three days following tool use. An additional motivation for conducting this experiment was to investigate if power tool operation has a related effect on MRI findings of the forearm, similar to that observed for maximal controlled eccentric exertions previously reported (Shellock, Fukunaga et al. 1991)

The dynamic mechanical properties (stiffness, effective inertial mass and damping), subjective discomfort, isometric strength, and MRI of the forearm were investigated following simulated power hand tool use. The overall hypothesis was that participants experience greater changes in mechanical response parameters and MRI for high reaction forces (high torque and long build-up time) than for lower reaction forces (low torque and short build-up time) and that changes precipitate or persist over the course of several days following exposure.

Procedures and Methodology

Participants

A total of 24 volunteers participated in the experiment. Participants were healthy young college students (mean age = 23.6 years, SD = 3.3) recruited from the university campus. All volunteers were right hand dominant and inexperienced power hand tool operators. The dominant right arm was used for all testing.

All participants completed a self–administered general health status and symptom questionnaire immediately prior to testing. The questionnaire included information about demographics such as age, weight, stature, upper extremity injuries, power hand tool usage and hand dominance. Those reporting upper extremity symptoms, a history of injury or occupational use of power hand tools, or contraindications to MR imaging were excluded from testing. Participants were asked to refrain from exercise or recreational sports for three days prior to participation in the experiment and for the duration of the experiment. All participants received a detailed explanation of the study prior to obtaining informed consent. The protocol and consent forms used were approved by the University of Wisconsin-Madison internal review board.

Experimental Design

Participants were randomly assigned to operate a simulated pistol grip power tool set either at a high reaction force of 123 N (peak torque = 8 Nm and build up time = 250 ms) or a low reaction force of 5 N (peak torque = 2 Nm and build up time = 50 ms) on a vertical work surface. The power tool used was a modified Dewalt DW959 (DeWALT Industrial Tool Co, Baltimore MD) drill which was connected to a computer-controlled power supply, RKW-1500 (Kepco Inc., Flushing NY) .An electronic torque transducer, SWS-50 (Transducer Techniques, Temecula, CA) monitored the torque output at the spindle. The height of the power hand tool handle was fixed at 109 cm which was equivalent to the 50 percentile male standing elbow height based on the 1988 US Army Anthropometric survey (Gordon, Bradtmiller et al. 1989).

Upper Limb Mechanical Response Parameters

The apparatus used for measuring mechanical properties was similar to Lin et al.(2001) except the current study used translational springs instead of a torsional spring (figure 5). The apparatus inertia was changed by moving two cylindrical masses from the center of rotation of the device. This reduced the setup time and has made the system portable.

The shoulder, forearm and wrist were positioned in a neutral position with the elbow flexed at 90°. The upper arm was stabilized against the body using a Velcro strap. The participants were instructed to grip the handle of the apparatus as hard as possible and inhibit the oscillations by trying to maintain the handle in its neutral position.

When a human operator resists the apparatus oscillatory motion by grasping the handle, the frequency and damping of oscillation is changed. The equation of motion that describes the free vibration response of this system is:

$$J\ddot{\theta} + c\dot{\theta} + k\theta = 0 . \qquad (1)$$

where *J* = mass moment of inertia, *c* = damping constant, *k* = stiffness, ϑ = angular displacement. When the human subject externally loads the handle, the contributions of the apparatus, applied mass and the operator define the physical characteristics of the combined system. The relationship between the moment of inertia of the effective mass and the resultant frequency is described in equation 2. The relationship between the moment of inertia of the effective mass and damping ratio is represented in equation 3 (Lin et al, 2001).

$$J_{mass} = k\frac{1}{\omega_n^{\ 2}} - (J_0 + J_{subject}) \qquad (2)$$

$$J_{mass} = c(\frac{1}{2\omega_n\zeta}) + \text{constant} \qquad (3)$$

The torsional stiffness (*k*) is the linear slope of frequency as a function of mass in the form of equation 2. In previous studies (Lin, Radwin et al. 2001; Lin, Radwin et al. 2003; Lin, Radwin et al. 2003; Lin, Radwin et al. 2003; Sesto, Radwin et al. 2004; Sesto, Radwin et al. 2005; Sesto, Radwin et al. 2005; Sesto, Radwin et al. 2006) the moment of inertia was calculated using intercept from equation 2. The moment of inertia of the effective mass in the current study is calculated using the conservation of momentum principle. The angular velocities before and after the zero position is crossed during the first cycle of oscillation of the handle are measured over a period of 10 milliseconds. The moment of inertia of the device and the applied mass is known and using the following equation the moment of inertia of the effective mass for the human subject is calculated.

$$J_{device+mass}\,\omega_1 = (J_{device+mass} + J_{subject})\,\omega_2 \tag{4}$$

The damping constant (c) is calculated using the following equation.

$$c = 2\varsigma\sqrt{kJ} \tag{5}$$

where, ζ = damping factor, measured from the oscillations of the apparatus.

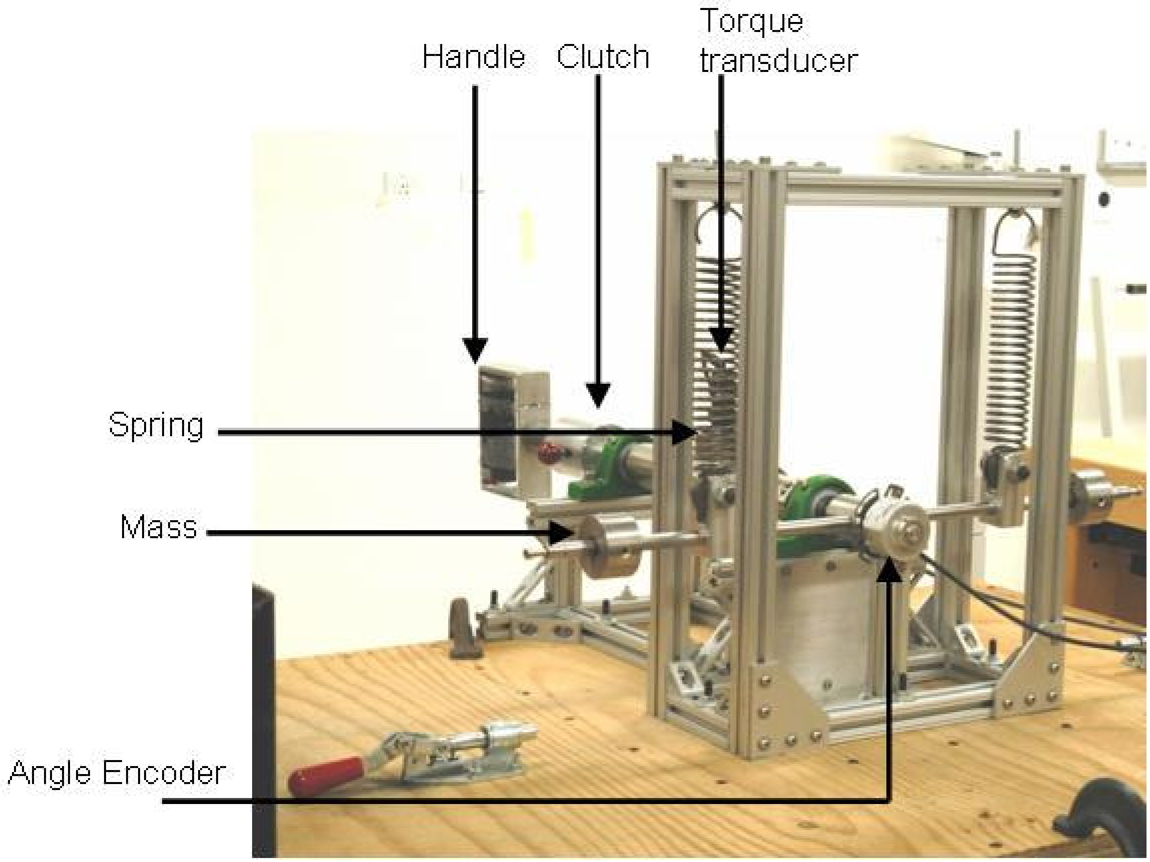


Figure 5: Apparatus for measurement of mechanical properties

Handle rotation was measured using an Allen Bradley Encoder 844B-Z405-D1024 (Rockwell Automation, Milwaukee, WI) angle encoder sampled at 1000 samples/sec. The free vibration oscillation frequency ranged from 3.64 to 4.12 Hz and the period of oscillation ranged from 4 seconds to 17 seconds depending upon the inertia of the apparatus and the human operator.

Strength Measurement

A Biodex® (Biodex Medical Systems, Shirley, NY) apparatus was used for isometric strength testing. The shoulder, forearm and wrist were positioned in a neutral position with the elbow flexed at 90°. The upper arm was stabilized against the body using a Velcro strap. Two forearm supinator isometric maximum voluntary contractions (MVC) were performed for five-seconds with a one minute rest between exertions. The five second exertion was averaged between the first and the fourth second and the average of the two MVC measurements was used for analyses.

Magnetic Resonance Imaging

The MRI examination was conducted using an Artoscan 0.17 T extremity scanner (GE Healthcare, Milwaukee, WI). Scan parameters for this experiment were 2050 ms TR, 34 ms TE, 75ms TI, 16 cm FOV, 196 x 196 resolution. Elevation of T_2 relaxation time occurs with edema and displays a higher intensity (brighter) in the image. The STIR-weighted images of the exercised muscles as well as non-exercising muscles were examined visually. Based on visual inspection regions of interest were selected in the supinator and flexor muscles. MR Vision software (Mr Vision, Inc. Boston, MA) was used to select the regions of interest. The signal intensity was measured for the regions of interest and the ratio of supinator signal intensity to flexor signal intensity was used to look for differences in the high and low force group. The observer analyzing the MR images was blinded to the treatments. Special care was taken to avoid inclusion of subcutaneous fat, fascia, blood vessels, or bone structures.

Procedure and Data Analysis

The tool was run at a rate of 6 times per minute for 60 minutes to simulate power hand tool usage in manufacturing. A clock was used to pace the subjects and a two minute rest break was given after 30 minutes of use.

Mechanical parameters, isometric strength and symptoms were measured prior to power tool use, immediately following use, and daily for 3 days. Participants underwent MR imaging of the forearm before power tool activity, on day one, and on day three following power tool use. A visual analog scale was used for assessing localized forearm discomfort ranging from 0-10 (0 corresponding to “no pain”, and 10 corresponding to “most pain”).

Repeated measures analysis of variance (ANOVA) was used to test the statistical significance of the main effect of high force power tool operation and low force power tool operation on the mechanical parameters, isometric strength and symptoms. Multivariate test results are reported here. All confidence intervals are reported at 95%.

Results

A reduction in stiffness was observed (figure 6) following tool operation ($F(3,20) = 7.05$, $p<0.05$). Stiffness was 27% less (CI = -14.5%,-39.81%) than pre-operation levels for the high force group 24 hours after operation, 21% less (CI = -3.93%, -39.32%) 48 hours after operation, and 26% (CI = -9.25%, -42.11%) less 72 hours after operation for the high force group. Stiffness for the low force group was 5.38% higher (CI = 16.54%, -5.78%) than pre tool operation level 24 hours after tool operation, 3.18% less (CI = 12.04%, -18.39%) 48 hours after tool operation, and 9.65% less (CI = 4.02 %, -23.32%) 72 hours after tool operation.

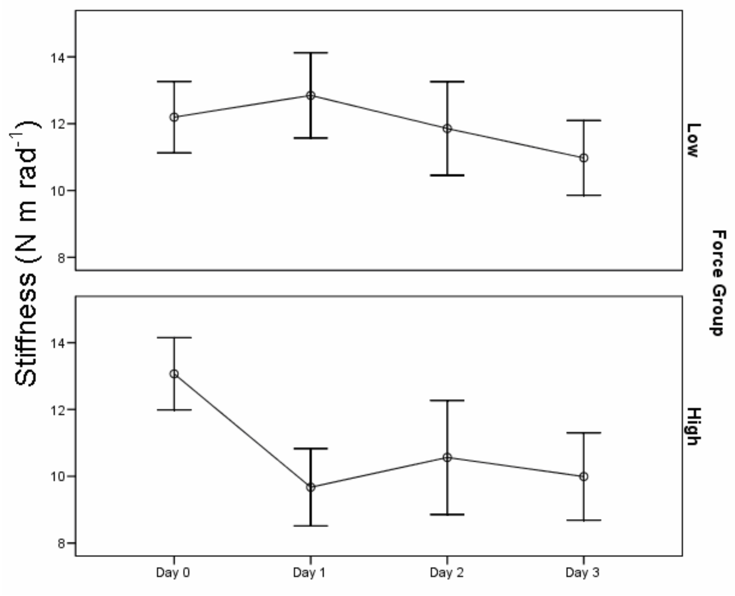


Figure 6: Stiffness (Mean and SE) for low force and high force group

No statistically significant changes in effective mass (F(3,20) = 0.634, p>0.05) and damping (F(3,20) = 0.493, p>0.05) were observed from day to day following power tool use for either group (See figures 7 and 8).

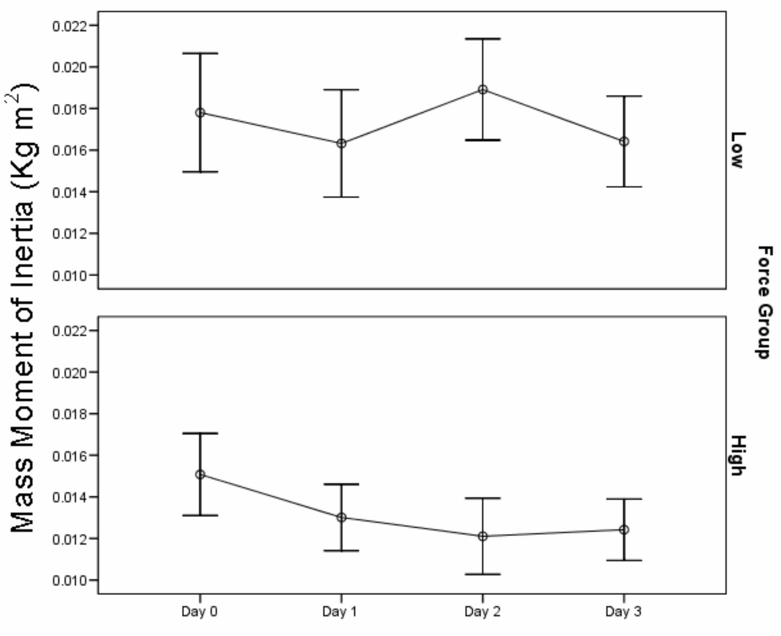


Figure 7: Mass moment of inertia (Mean and SE) for low force and high force group

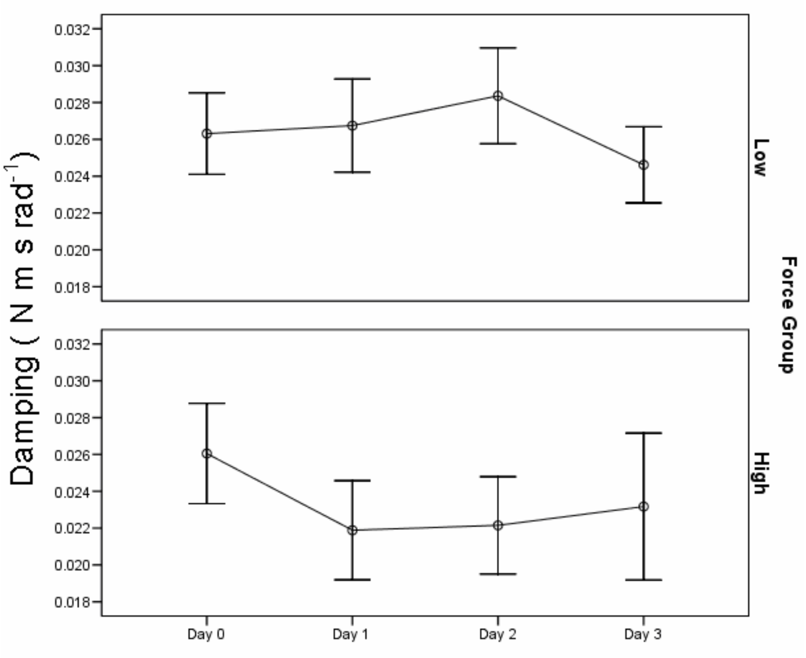


Figure 8: Damping (Mean and SE) for low force and high force group

No statistically significant (F(3,20) = 0.491, *p>0.05*) change in average static forearm static supination strength or symptom intensity (F(3,20) = 2.627, p > 0.05) was observed following power tool use for either group.

There was a statistically significant association between MRI flexor supinator intensity ratio and tool use (F(2,21 = 6.178, p<0.05) (figure 9). A13.08% (CI = 22.13%, 4.02%) increase was observed in the flexor supinator intensity ratio for the high force group after 24 hours and a 9.79% (CI = 20.57%, -0.98%) increase in the flexor supinator intensity ratio was observed after 72 hours (figure 10). A 10.99 % (CI = 22.7%, -0.72%) increase in the supinator flexor intensity ratio was observed for the low force group, after 24 hours and a 3.97% (CI = 13.64%, -5.71%) increase was observed after 72 hours.

Discussion

There was no statistically significant decrease in the forearm supination strength levels following simulated power hand tool operation. Fatigue therefore cannot explain the reduction in stiffness. It was suggested that mechanical stiffness of muscle is dependent on the actin-myosin binding of the muscle sarcomeres (Linari, Dobbie et al. 1998) . Since eccentric exertions are sometimes related to damage to the actin-myosin contractile machinery this damage may be reflected as a reduction in mechanical stiffness. Consequently greater damage at high torque and longer buildup times might result in a greater drop in mechanical stiffness. This observation alone does not infer that sarcomere damage necessarily occurred in the current study. Furthermore if these changes did occur, no functional deficits (i.e. static strength) were observed and consequently these changes are not necessarily related to injury.

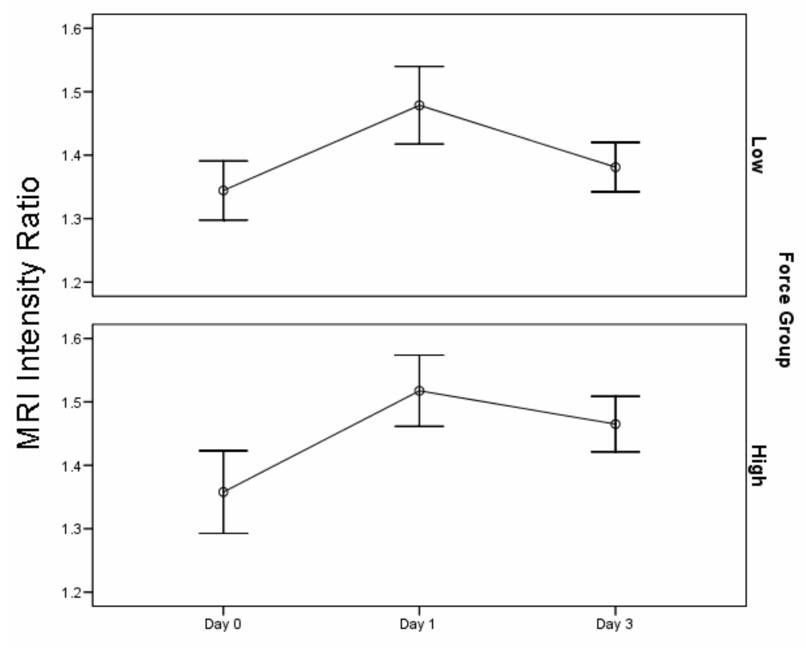


Figure 9: Supinator flexor intensity (Mean and SE) ratio for low force and high force group

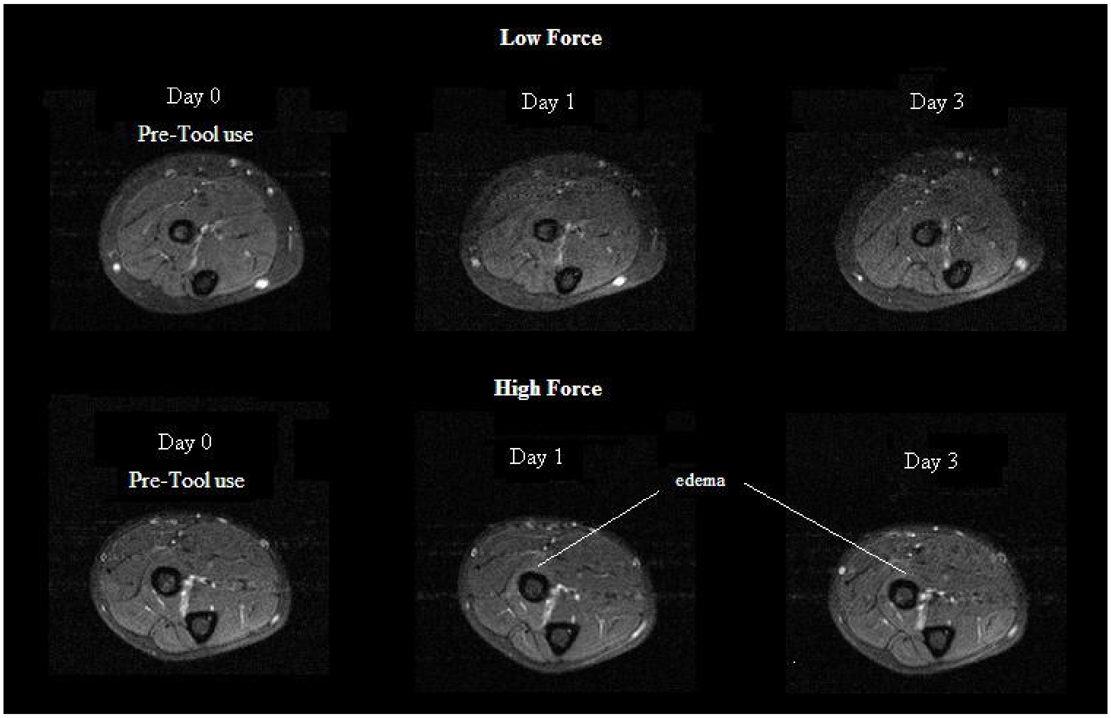


Figure 10: MR images of a subject each from the low and high force group (Day 0, Day 1and Day 3)

Eccentric exercise has also been attributed to motor recruitment changes. Prasartwurth et al. (2005) examined voluntary activation following eccentric exercise using motor nerve and motor cortex stimulation. They found impairment of voluntary activation to peripheral nerve stimulation but not motor cortical stimulation which eliminated an activation deficit at the motor cortex or spinal level. It is therefore plausible that the reduction in stiffness observed in the current study could be explained by possible mechanical damage to the contractile elements or reduced neural drive. Future research should address these effects.

The measurement of stiffness in the current study is similar to a dynamic strength test. No change in isometric strength was observed following tool operation, however a statistically significant reduction in the mechanical stiffness was observed following tool operation. It is reported that measures of static and dynamic strength often do not correlate (Baker, Wilson et al. 1994). Similar outcomes were observed in the current study.

In previous studies (Sesto, Radwin et al. 2004; Sesto, Radwin et al. 2006) subjects were monitored for only 24 hours post exercise. In the current study, subjects were monitored up to 72 hours post tool operation. Subjects in the high force group maintained a 27% statistically significant decrease in mechanical stiffness even 72 hours post tool operation, while the low force group did not show any statistically significant changes in stiffness.

Edema is often accompanied following intense eccentric exercise (Shellock, Fukunaga et al. 1991; Foley, Jayaraman et al. 1999). The mechanism of edema is not well understood but is associated with increased permeability of the blood vessels in response to inflammation following muscle damage. This results in an increase in the interstitial fluid. Edema has also been observed at less than maximal intensity exercise levels (Nosaka and Newton 2002; Sesto, Radwin et al. 2005). Presence of edema in the muscles causes the signal intensity of the MR image to increase in those areas. A statistically significant change in the signal intensity in the current study was observed for both the groups 24 hours after tool operation. The high force group continued to show an increase in the supinator signal intensity 72 hours after tool operation.

The findings of this study concur with the study performed by Sesto et al.(2005) who found a similar reduction in mechanical stiffness following power hand tool operation. Sesto used male participants while the current study included both male and female participants. In the current study, a statistically significant change in effective mass was not observed whereas Sesto et al. (2005b) observed a difference. The effective inertial mass has been interpreted as a possible measure of the quantity of muscle that is recruited during the specific activity (Sesto, Radwin et al. 2005). It is likely that the baseline effective mass in the current study experienced a floor effect and it was not possible to detect changes in the effective mass. Neither study had a statistically significant change in damping. The baseline level of damping observed was very small so it is possible that the apparatus was not sufficiently sensitive to detect these changes.

The apparatus used by Sesto differed from the apparatus used in the current study where translational springs were used instead of torsional springs and the oscillation frequency range varied from 3.64 Hz to

4.12 Hz instead of 3 to 5 Hz. A wider frequency range would be more suitable for measurement of mechanical parameters due to less pronounced noise effects.

Leger and Milner (2000) exercised the wrist extensors of subjects until fatigue and found a reduction in mechanical stiffness which was defined as ratio of change in mean torque divided by change in mean position. The protocol that was used in the current study did not fatigue the participants but a reduction in mechanical parameters was still observed. The level of exertion used in the current protocol was thought to better simulate the conditions in an assembly plant. The reduction in mechanical parameters following such sub-maximal exertions is significant as it can affect the way reactive forces are countered while operating power hand tools.

Lin et al.(2001) reported that laboratory subjects exerted an average of 56.6% of their static MVC during power screwdriver use which is similar to the level subjects worked at in this study. Eccentric exertions frequently occur in the workplace, such as during power hand tool use, and have been rarely studied in this context. Reduction in mechanical properties is associated with greater forces and displacements when operating industrial power hand tools and consequently increased external stress from physical loading of the arm (Lin, Radwin et al. 2001; Lin, Radwin et al. 2003). Increased stresses on the body can also increase the risk of an injury (National Research Council Institute of Medicine 2001). This reduction in capacity could potentially have adverse long-term effects on operator safety, particularly for large level exertions that are frequent and forceful. It is anticipated that this research will lead to an improved understanding of the relationship between tool properties and upper limb disorders as well as better power hand tool selection and design.

Conclusions

Sustained changes in both mechanical and MRI parameters were observed following short duration power hand tool use. A decrease in mechanical properties and a subsequent increase in edema persisted 72 hours after tool operation for the high force group only. .It is plausible that the physical demands associated with torque producing power tool operation have an adverse effect on the musculoskeletal tissues of the upper extremity, which affect mechanical properties and result in localized edema, similar to effects sometimes seen following muscle lengthening exertions. The reduction in mechanical properties and increase in edema following tool operation can be viewed as potential precursors to the development of musculoskeletal disorders.

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Chourasia, A. O., Sesto, M. E., Block, W. F., Radwin, R. G., Prolonged mechanical and physiological changes in the upper extremity following short-term simulated power hand tool use, *Ergonomics*, In Press

Sesto, M. E., Chourasia, A. O., Block, W. F., and Radwin, R. G., Mechanical and magnetic resonance imaging changes following eccentric or concentric exertions, *Clinical Biomechanics*, In Press.

Conference Presentations and Proceedings

Chourasia, A.O., Sesto, M.E., Jung, Y., Howery, R.S., Radwin, R.G., “Comparison of Biomechanical and Anatomical Effects following Eccentric and Concentric Exertions,” Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting, Orlando, FL, 2005.

Radwin, R.G., Chourasia, A.O., Sesto, M.E., Upper limb mechanical changes following simulated repetitive power tool use. 16th World Congress of the International Ergonomics Association Meeting, Maastricht, The Netherlands, July, 2006.