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Anatomical and mechanical changes following repetitive eccentric exertions

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Abstract

Background. Submaximal eccentric exertions occur occupationally when rapidly rising tool-generated forces exceed the operator's capacity to react against them. The purpose of this study was to investigate the effects of short duration repetitive submaximal eccentric forearm exertions at levels comparable to industrial power hand tool use on dynamic mechanical properties (stiffness, effective mass and damping) and on forearm edema.

Methods. This study investigated changes following short term repetitive submaximal eccentric exertions comparable to occupational levels. Eight male participants exercised eccentrically for 30 min at 50% of isometric maximum voluntary contraction forearm supination in a posture and loading similar to power hand tool use in the workplace. Dynamic mechanical properties (stiffness, effective mass and damping) of the upper limb were measured before, immediately following, and daily for three days after the activity. An MRI scan to assess edema was also performed for five of the participants before, on day one and day three following the activity.

Findings. Mechanical stiffness decreased 51% ($P < 0.05$) and effective mass decreased 43% ($P = 0.052$) immediately following eccentric exercise. Average isometric strength also decreased 42% immediately following exercise ($P < 0.01$) and pain persisted for two days. The recovery of static strength however was not correlated with changes in mechanical stiffness ($r = 0.56$) or effective mass ($r = 0.30$). The exercised arms had a 360% increase ($P < 0.01$) in supinator–extensor T_2 relaxation time difference, a quantifiable measure of edema, one day after exercise while the non-exercised arms had no significant changes.

Interpretation. Changes in both T_2 relaxation time, indicative of edema, and forearm mechanical properties, were observed following short duration submaximal repetitive exercise. If similar changes in dynamic mechanical properties of the upper extremity occur following repetitive submaximal eccentric activity in the workplace, they could negatively impact the ability of the arm to react to rapid forceful loading during repetitive industrial work activities and increase mechanical loading of the upper limb.

Keywords: Mechanical properties; Stiffness; Forearm; Submaximal eccentric exertions; Magnetic resonance imaging; Hand tool

1. Introduction

Power hand tool use has been considered a risk factor for upper extremity musculoskeletal disorders (MSD) because of the associated repetitive motions, forceful exertions, vibration, and posture stress (Armstrong et al., 1993; Keyserling et al., 1993; Muggleton et al., 1999; NIOSH, 1997). Rotation of the forearm (supination/pronation) accompanies pistol grip power tool use and several studies have reported relationships between forceful and repetitive movements and development of forearm musculoskeletal disorders (Haahr and Anderson, 2003; MacFarlane et al., 2000; NRC/IOM, 2001).

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Eccentric exertions (muscle lengthening contractions) often accompany power screwdriver use when rapidly rising tool-generated forces exceed the tool operator's capacity to react against them (Armstrong et al., 1999; Oh et al., 1997; Oh and Radwin, 1998). It is well documented that injury occurs during intense eccentric exercise and is often associated with muscle weakness and soreness that develops 24–48 h following that activity (Clarkson et al., 1992; Cleak and Eston, 1992; Friden et al., 1983).

Both mechanical and anatomical changes have been described in skeletal muscle following intense eccentric activity (Armstrong, 1990; Evans et al., 1998; Foley et al., 1999; Friden and Lieber, 1992). One anatomical change observed following eccentric exercise is an increase in muscle water content or edema (Evans et al., 1998; Foley et al., 1999; Shellock and Fleckenstein, 2000).

Mechanical properties of muscle and tendon are functionally important since they counteract the effects of applied loads. Changes in mechanical properties following eccentric exertions may affect a muscle's ability to react to rapid forceful loading, resulting in increased strain in the muscle.

The human tool operator has been modeled as a single-degree of freedom second order system mechanical system consisting of an element for stiffness, effective mass and viscous damping (Lin et al., 2001, 2003a,b,c). An apparatus delivers an external perturbation to the hand through a handle resulting in oscillations that the person actively attempts to stop. Since the apparatus has known mechanical stiffness, damping and effective mass, any change in the system response when the hand is coupled to the handle is attributed to the person. The mechanical elements are therefore identified from the handle displacement by calculating the frequency changes of the externally loaded system in oscillation.

This apparatus was used for model parameter identification by Lin et al. (2001), and the correlation between measured and predicted frequency was 0.9. Good test–retest reliability was found with controls demonstrating less than a 5% difference in mechanical stiffness 24 h later (Sesto, 2003). The apparatus was employed in the current study to investigate the mechanical changes in muscle following repetitive submaximal eccentric loading.

Magnetic resonance imaging (MRI) is sensitive to acute and chronic variations in muscle water content or edema (Fleckenstein and Shellock, 1991). An increase in the T_2 relaxation time correlates with an increase in edema and has been observed following muscle strain and delayed onset muscle soreness (Fleckenstein et al., 1989; Shellock and Fleckenstein, 2000). The T_2 relaxation time has also been used to assess edema in muscle following eccentric exertions. Time to peak T_2 relaxation time varies, but increases have been observed 48 h after submaximal eccentric activity (Evans et al., 1998).

The level of exertion considered in most previous eccentric exertion studies are rarely observed occupationally or in daily living activities, making it difficult to extend their outcomes to these activities. Recently, several investigations have considered changes following submaximal eccentric muscle activity at exertion levels comparable in occupational settings (Nosaka and Newton, 2002; Sesto, 2003). Maximal eccentric exercise has been compared to submaximal eccentric exercise levels at 50% of isometric maximum voluntary contraction (MVC) and a similar magnitude of initial muscle injury has been reported although secondary damage was less in the submaximal group (Nosaka and Newton, 2002). Reductions in mechanical stiffness (41%) and effective mass (40%) were reported following short duration eccentric activity at 50% of isometric MVC but there were no change in these properties for the isometrically exercised group (Sesto, 2003).

The purpose of the current study was to investigate the effects of short duration repetitive submaximal eccentric exertions at levels comparable to industrial power hand tool use on dynamic mechanical properties (stiffness, effective mass and damping) and on forearm edema. It was hypothesized that changes in anatomical (edema) and mechanical properties of stiffness, damping and effective mass occur in muscles repeatedly exposed to submaximal eccentric exertions at levels typically encountered occupationally. Anatomical measures using magnetic resonance T_2 relaxation time and dynamic mechanical properties were measured before, immediately after and daily for three days following submaximal eccentric exertions.

2. Methods

2.1. Protocol

Eight healthy right-handed male volunteers were recruited as subjects (mean age = 26.4 years, SD = 5.92 years). The study was limited to males due to strength requirements for the test apparatus in the particular posture used. Informed consent was obtained in accordance with the University of Wisconsin guidelines for the protection of human subjects. A general health status questionnaire was administered to all subjects immediately prior to testing. Subjects were excluded if they reported upper extremity symptoms or regularly participating (greater than one time per week) in an upper extremity weight lifting program in the previous 6 months. The dominant arm was used for all testing. Subjects reported not participating in occupational activities (e.g. power tool use) in which they had experienced prolonged or intense eccentric contractions of the upper extremity.

A self report symptom questionnaire was also administered which included questions about upper extremity symptoms (numbness, pain, tingling, aching, etc.), and localized discomfort. A visual analog scale ranging from 0 to 10 (0 corresponding to "no pain", and 10 corresponding to the "most pain") was used to measure pain intensity. The checklist and visual analog scale were administered prior to exercise, immediately following exercise, and then daily for three days. Subjects were instructed to avoid activities including weight lifting, cardiovascular exercise or recreational sports for the week prior to and the week of the experiment. No subject reported using ice or anti-inflammatory medication during the study.

All subjects completed 30 min of submaximal repetitive eccentric exercise with the dominant arm. Strength, forearm edema, symptoms and mechanical property measurements were completed immediately before a bout of exercise, immediately following and daily for three days. Given that a submaximal exercise protocol was used, it was anticipated that changes in these properties would be detected within three days following exercise, although peak changes may not be observed during this timeframe. Imaging was performed on a 1.5 T GE CVi scanner (General Electric Medical Systems, Waukesha, WI, USA) before exercise, and on days one and three following exercise for five of the subjects.

2.2. Strength assessment procedure

The shoulder, forearm and wrist were positioned in a neutral position and the elbow was flexed to 90°, with the subject seated. The upper arm was stabilized against the body by a strap to prevent substitution or unwanted movement. Strength testing was performed using the Biodex™ (Biodex Medical Systems, Shirley, NY, USA) strength measurement system. Maximum voluntary contraction of the forearm supinator muscles was measured isometrically. Two 5 s MVC, separated by a 1 min rest between exertions were performed prior to exercise, immediately following exercise, and 24 h later. The second to fourth seconds were averaged for each MVC exertion. The average of the two MVC exertions was used for the analyses. MVC data were always collected prior to mechanical testing on the free vibration apparatus.

A custom forearm rotation accessory was attached to the Biodex™ power-head. The subject supinated the dominant forearm, applying torque to the handle. The power-head maintained zero velocity during the isometric strength test, so force can be developed without any significant change in muscle length. The handle torque was digitized and sampled using a Lab-PC+ data acquisition board (National Instruments Corporation, Austin, TX, USA) with a sampling rate of 100 samples per second.

2.3. Exercise protocol

The Biodex™ apparatus was also used for the exercise protocol. The shoulder, forearm and wrist were in a neutral position with the elbow flexed at 90°. The upper arm was stabilized against the body by a strap to prevent substitution or unwanted movement. Subjects repeated 50% MVC exertions for a total of 30 min of exercise with a 1 min rest break after every 5 min of exercise. Visual feedback of torque output was continuously presented to the subject so that they could maintain the desired exertion level. The exercise consisted of a 3 s contraction followed by a 3 s rest. The starting position of the forearm was neutral and then pronated to 90° with the elbow flexed at 90°. The handle rotation velocity was controlled for 30°/s. This velocity allowed subjects to control the torque generated throughout the set range of motion. Subjects were seated with their upper arm stabilized against the body by a strap to prevent substitution or unwanted movement. Following exercise, subjects were given 3 min rest prior to assessing strength and testing on the free vibration apparatus to minimize any effects from fatigue.

2.4. Mechanical measurements

Forearm mechanical properties were tested prior to exercise, immediately following exercise and daily for three days. The apparatus had adjustable inertial mass that can be varied to achieve different free-vibration rotation frequencies of the hand and forearm as a damped sinusoid near 4 Hz. A 4 cm diameter handle that aligned the forearm axis of rotation with the axis of rotation of the free vibration and positioned the wrist in neutral was used for the current study. This minimized substitution by muscles other than those specifically tested. The upper arm was stabilized against the body by a strap to prevent substitution or unwanted movement.

Subjects were instructed to grasp the handle as hard as they could in order to inhibit oscillations. When the handle was released to vibrate freely, it produced a damped sinusoid oscillation for 2.5 s. Handle displacement was measured using a rotational variable differential transformer (RVDT). The data acquisition sampling rate was 1000 samples per second. The input loading of the hand was a damped sinusoid with a rise time (220–330 ms) consistent with impulsive forces found in power hand tools (Oh et al., 1997; Oh and Radwin, 1998).

The stiffness, effective mass and damping parameters were determined for the combined apparatus and human subject. The variations in these mechanical properties were defined by calculating the change in oscillation frequency and the decay in displacement amplitude. The resulting stiffness, effective mass and damping for the hand–arm system was measured from the change in the system response imposed by the hand–arm.

The equation of motion that describes the free vibration response of this system (J = mass moment of inertia, c = damping constant, k = stiffness) is:

$$J\ddot{\theta} + c\dot{\theta} + k\theta = 0 \tag{1}$$

When the human subject externally loads the 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 mass moment of inertia of the effective mass and the resultant frequency for the apparatus and the hand–arm is shown in Eq. (2) and the relationship between the mass moment of inertia and damping ratio is shown in Eq. (3) (Lin et al., 2001).

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

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

The torsional stiffness (k), is the resulting slope of plotting the frequency for several applied apparatus masses in the form of Eq. (2), and the intercept is the combined effective mass for the apparatus and the subject. The torsional damping constant (c) is the resulting slope of plotting the frequency and the damping ratio for several applied masses using Eq. (3). Based on these parameters, the equivalent stiffness, mass and damping constant for the forearm can be extracted. A detailed description is provided in Lin et al. (2001).

2.5. Forearm circumference and symptom measurements

Forearm circumference was measured to assess edema. Circumference measurements were made 2.5 cm distal to the lateral epicondyle. The location was marked on the skin for reproducibility of measurement. During measurement the arm was placed in a relaxed, supported position. Measurements were collected prior to exercise, immediately following exercise and daily for three days.

Localized discomfort was assessed using a visual analog scale, ranging from 0 to 10, (0 defined as "no pain" and 10 defined as "most pain"). Muscle soreness was assessed before exercise, immediately following and daily for three days.

2.6. Magnetic resonance imaging

Three of the subjects were scanned prior to the other five to develop an MR protocol that would provide an adequate signal to noise ratio, resolution, artifact suppression, and T2 sensitivity in a total exam time of 25 min. As these scans did not use a consistent protocol, comparative results over the three days of scanning were not computed.

Five subjects were imaged in a prone position with both arms extended above their head, resting in a quadrature head coil for an increased signal to noise ratio (SNR). Axial slices with a 7 mm thickness and separated by a 3 mm gap were obtained beginning at the radial head in the elbow joint and extending distally 20 cm using the following parameters: fast spin–echo pulse sequence, 26 cm field of view (FOV), 256×256 imaging matrix, 4 s repetition time (TR), superior and inferior flow suppression, and fat suppression. Echo times for the proton density, moderate T_2, and heavily weighted T_2 images were 15, 75, and 105 ms, respectively. Fat suppression was achieved through radio-frequency saturation of fat signal based on the different resonance frequencies between fat and water (220 Hz with 1.5 T magnets). Unfortunately, air–tissue interfaces in the imaged subject can create magnetic field inhomogeneity within the imaged volume that distort the theoretical resonant frequency. These variations can lead to unintentional water suppression instead of fat suppression. A saline bag was placed between the arms to reduce air–tissue interfaces and improve magnetic field inhomogeneity when uneven fat suppression across the imaged volume was detected.

Images of the arm muscles that performed the exercise protocol as well as the muscles of the non-exercising arm were examined visually. Regions of interest were selected in the center of the corresponding active and inactive muscles for slices where visual differences were detected. Special care was taken to avoid inclusion of subcutaneous fat, fascia, blood vessels, or bone structures. T_2 relaxation times were determined for these regions of interest by fitting the region of interest (ROI) data from each echo to an exponential curve with MR Vision software (Mr Vision, Inc., Boston, MA).

3. Data analysis

Repeated measures analysis of variance (ANOVA) was used to investigate the effect of exercise on mechanical and anatomical measures over time. Square root transformation of the mechanical variables was used due to moderate skewness observed in some of the post-exercise mechanical values. Post hoc analysis was done using the Bonferroni multiple pair-wise comparison method.

4. Results

4.1. Strength and symptoms

Forearm supination static strength, measured before, immediately after, and daily for three days following

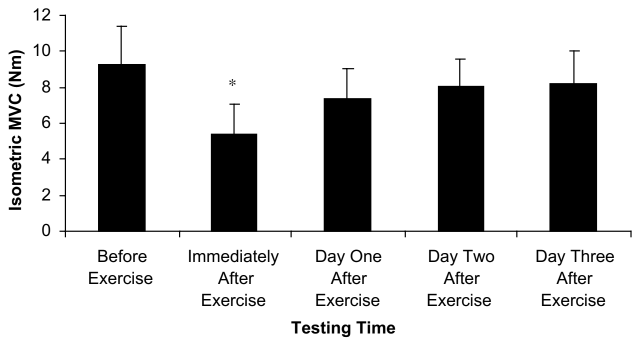

Fig. 1. Supinator MVC (mean and SD) before exercise, immediately after exercise and daily for three days. *Significantly different than before exercise.

exercise, is shown in Fig. 1. Static forearm supinator MVC was significantly less following exercise ($P < 0.01$). A 42% loss of static strength was observed in the exercised muscles immediately after exercise ($P < 0.01$). No other change in static strength occurred following exercise and static strength returned to within 10% by day three ($P > 0.05$).

Pain levels, (using a 0–10 analog visual scale), measured before, immediately following, and for three days after exercise, is shown in Fig. 2. Pain was reported as 0 at baseline. Immediately following exercise, an increase was reported, with an average pain level of 4.1 (SD = 2.08) ($P < 0.01$). Pain improved, but remained at 1.97 (SD = 1.21) two days after exercise, which was significantly greater than before exercise ($P < 0.05$).

4.2. Dynamic mechanical properties

Upper limb mechanical properties measured before, immediately after, and daily for three days following exercise, are shown in Figs. 3–5. Significant decreases in mechanical stiffness ($P < 0.01$) and effective mass ($P < 0.05$) were observed following submaximal eccentric exercise. A 51% decrease in mechanical stiffness oc-

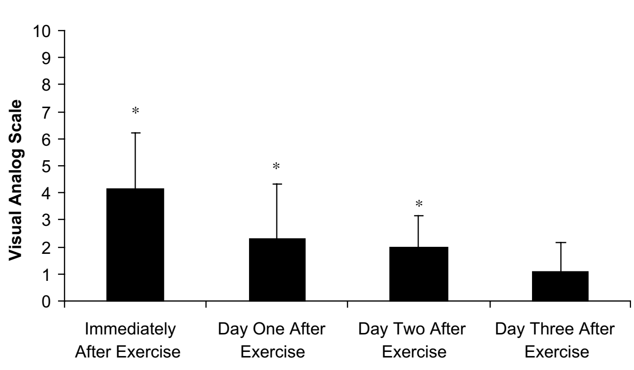

Fig. 2. Visual analog scale (mean and SD) immediately after exercise and daily for three days. *Significantly different than before exercise.

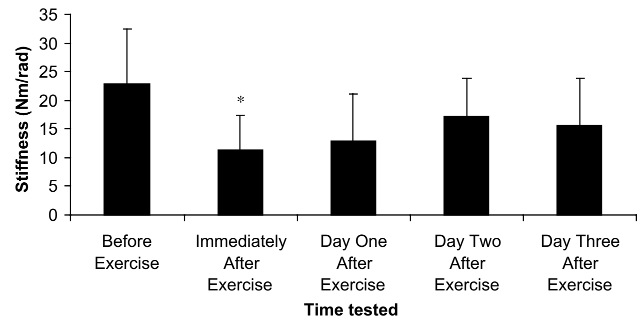

Fig. 3. Mechanical stiffness (mean and SD) before exercise, immediately after exercise and daily for three days. *Significantly different than before exercise.

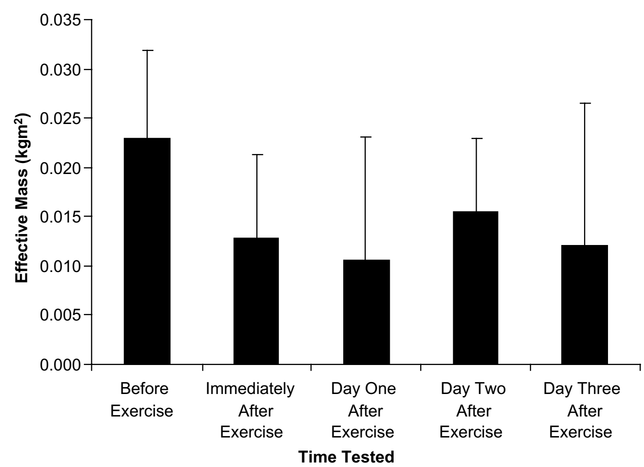

Fig. 4. Effective mass (mean and SD) before exercise, immediately after exercise and daily for three days.

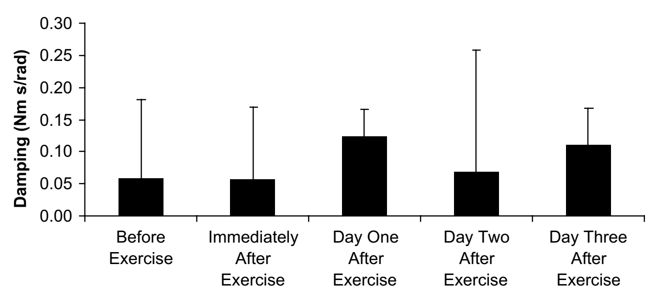

Fig. 5. Damping constant (mean and SD) before exercise, immediately after exercise and daily for three days.

curred immediately after exercise ($P < 0.05$). No other post hoc significant changes in mechanical stiffness were observed ($P > 0.05$). No significant differences were observed in effective mass with post hoc pair-wise comparisons although the percent decrease in effective mass from pre-exercise to immediately following exercise was 43% ($P = 0.052$). The changes in mechanical stiffness ($r = 0.56$) and effective mass ($r = 0.30$) were not correlated with changes in static strength.

A significant change in damping was not observed following submaximal eccentric exercise ($P > 0.05$). Before exercise the average damping constant was 0.059 Nm s/rad and increased to 0.111 Nm s/rad after 72 h.

4.3. Magnetic resonance imaging

Supinator enhancement was observed in the exercised arm MRI scan (Fig. 6). The exercised arms had a 23% larger supinator T_2 relaxation time than the non-exercised arms one day after exercise ($P < 0.01$) and a 28% larger T_2 relaxation time three days following exercise than before exercise but this difference was not significant ($P > 0.05$).

The supinator–extensor T_2 difference was also evaluated and the exercised arms had 360% ($P < 0.01$) more supinator–extensor T_2 enhancement one day following exercise than the non-exercised arms which had less than a 10% change ($P > 0.05$) (Fig. 7). A significant increase was not observed in the supinator–extensor T_2 difference three days following exercise even though the percent increase in the supinator–extensor T_2 difference from pre-exercise to three days following exercise (457%) was larger than the increase one day after exercise.

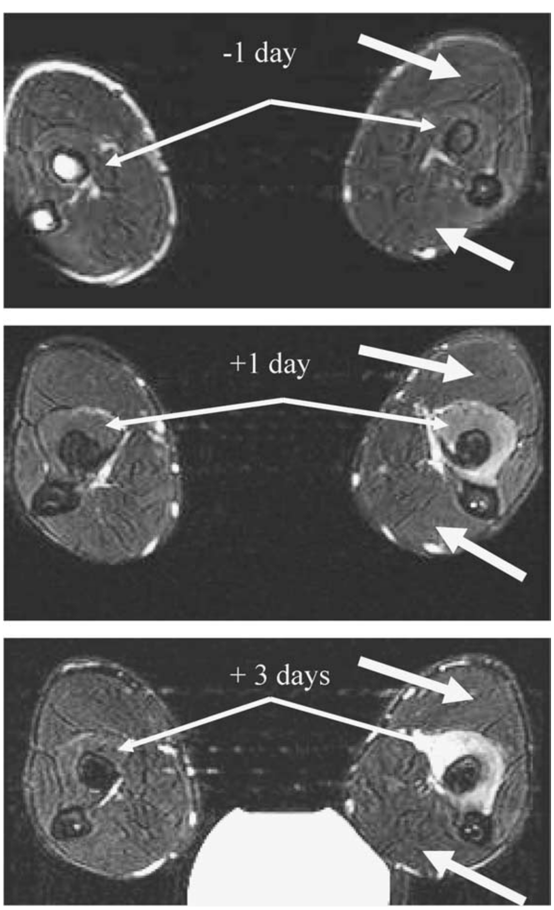

Fig. 6. MR T_2 forearm image, before exercise, day one and day three after exercise (extensor and flexor muscle groups—large arrow; supinator muscle—small arrow).

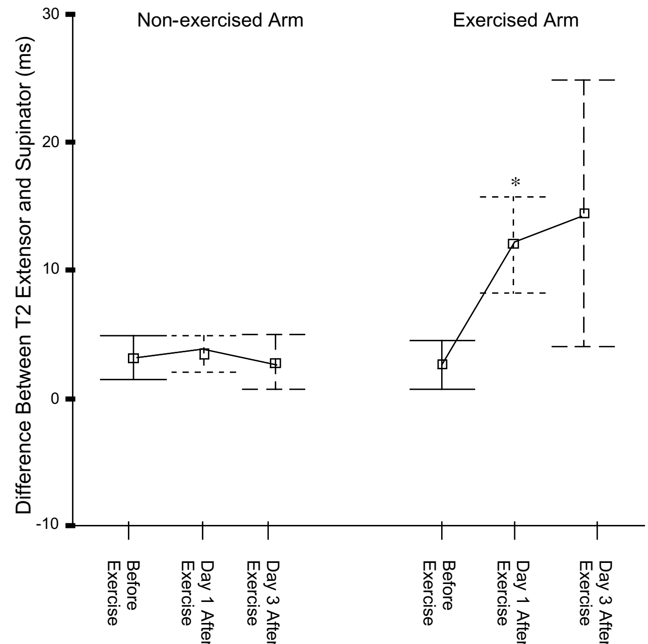

Fig. 7. T_2 parameter for supinator–extensor mean difference (±1 SD error bars) before exercise, day one and day three after exercise for exercised and non-exercised arms. *Significantly different than before exercise.

5. Discussion

The purpose of this study was to investigate the effects of short duration repetitive submaximal eccentric exertions at levels comparable to industrial power hand tool use on dynamic mechanical properties (stiffness, effective mass and damping) and forearm edema. A decrease in mechanical stiffness and effective mass and a subsequent increase in MRI T_2 relaxation constant were observed after 30 min of submaximal eccentric activity.

The changes in mechanical stiffness ($r = 0.56$) and effective mass ($r = 0.30$) were not correlated with changes in static strength which indicated that mechanical changes likely did not occur solely due to strength changes. Previous studies have reported ultrastructural abnormalities within muscle including structural and ultrastructural myofiber damage following eccentric contractions (Lieber et al., 1991; Faulkner et al., 1993; Friden and Lieber, 1998). Damage to the contractile machinery may result in less contributing parallel mechanical spring elements during stretching which may play a role in the reduction in muscle stiffness observed following eccentric activity.

The underlying physiological mechanism behind the effective mass decrease observed in this study is not known. Clearly, there is no overall reduction in the mass of the arm. One plausible explanation is that effective mass reflects the quantity of muscle that is recruited during the specific activity. Possible damage to the contractile machinery may result in less muscle fibers actively contributing which results in a decrease in effective mass. No change in viscous damping was observed. This may be due to the minimal level of damping that was observed.

It was assumed that all subjects exerted at maximal voluntary contraction levels during all strength test and upper limb mechanical test procedures, however this was not verified. Surface electromyography (EMG) was not possible due to the deep location of the supinator muscle. Although we could not verify maximal voluntary contraction, controls in an earlier study had good test–retest reliability (<5%) which indicates that subjects were working at their maximal levels (Sesto, 2003).

All participants had an increase in supinator T_2 relaxation time day one after exercise. On day three, T_2 relaxation time for several subjects started returning to baseline following exercise while others remained elevated, which explains the large variance in T_2 relaxation time on day three (Fig. 7). It is anticipated that those subjects who did not have an improvement in T_2 relaxation time on day three would eventually improve later if scanned. It is unknown if this was the peak for T_2 relaxation time since subjects were not followed after three days.

It is plausible that the muscle's contractile machinery may be damaged resulting in a decrease in mechanical properties 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. This finding is important because lower level eccentric exertions may be of sufficient intensity to produce damage that is a precursor to the development of clinical musculoskeletal disorders. Further biomechanical research is necessary to test this hypothesis using eccentric levels similar to those encountered during occupational activities.

A reduction in mechanical properties following short duration eccentric activity at 50% of isometric MVC but no change in these properties for an isometrically exercised group was observed (Sesto, 2003). Although exercised muscles were not evaluated by MRI in this earlier experiment, it is important to note that in the current study enhancement was not observed in muscles in the exercised arm that did not undergo eccentric activity. It appears that the enhancement was specific to the supinator muscle that was exercised eccentrically.

The forearm muscle groups had an average 2% increase in forearm circumference following exercise ($P > 0.05$). A significant increase in circumference has been reported in studies where larger muscle groups such as the biceps have undergone maximal eccentric exercise (Nosaka and Newton, 2002). Our results may not be surprising given the submaximal level of activity and the relative size of the forearm muscle group. The measured increase in edema from the MRI scans was apparently too small to make a difference in circumference.

Pain levels remained significantly elevated until day two following exercise ($P < 0.05$). Since subjects were only followed for three days after exercise the peak in pain levels may have been missed although subjects exercised at 50% isometric MVC demonstrated a peak in symptoms one to two days after exercise (Nosaka and Newton, 2002).

The findings in the current study concur with the observations of Leger and Milner (2000), who noted a reduction in mechanical stiffness, defined as the ratio of change in mean torque divided by the change in mean position of the wrist extensors following strenuous exercise. No measurements of inertial mass and damping were made. Leger and Milner (2000) had subjects exercise until they could no longer move a weight in a controlled continuous manner. The authors described the exercise protocol as being designed to exhaustively exercise the wrist extensor muscles. In the current study, subjects exercised for a total of 30 min with a 1 min rest break every 5 min at an exertion level of 50% isometric MVC. Even though the level of exertion in the current study was less than that employed by Leger and Milner (2000), a significant decrease in mechanical stiffness immediately after exercise was still observed. This observation may be significant given that industrial employees frequently work at this level. To our knowledge, this finding has not been noted previously. A less fatiguing protocol was chosen in the current study to more closely simulate occupational work activities. Rarely during the course of occupational activities do employees persistently work at a maximum exertion level or until exhaustion. 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. This intensity of activity level is likely to be sustained in the work place for many more hours.

Eccentric exertions frequently occur in the workplace, such as during power hand tool use, and have been rarely studied in this context. Less mechanical stiffness and effective mass were associated with greater forces and displacements when operating industrial power hand tools and consequently increased external stress from physical loading of the arm (Lin et al., 2001, 2003c). Increased stresses on the body can also increase the risk of an injury (NRC/IOM, 2001).

Based on the reduction in stiffness and effective mass observed following eccentric activity in the current study for an operator using a pistol grip tool on a vertical surface, Lin's model predicts that the tool displacement would increase by more than 37% with a target torque of 7 Nm and a soft joint. This reduction in capacity could potentially have adverse long-term effects on operator safety, particularly for large level exertions that are frequent and forceful.

6. Conclusions

Changes in both mechanical and anatomical properties were observed following short duration submaximal eccentric activity. The combination of these findings, a decrease in mechanical properties and a subsequent increase in edema, suggest that short duration submaximal activity may have a negative short-term effect on an extremity that is eccentrically exercised. It is plausible that the physical demands associated with torque producing power tool operation have a detrimental impact on the musculoskeletal tissues of the upper extremity, which in turn can affect mechanical properties and resulting edema, similar to what is seen following eccentric exercise in muscle anatomy. The consequence of these changes may be greater handle displacement during power tool operation and therefore possible increased tissue loads and strains. Further studies are needed to characterize the significance of these changes and their relationship to human musculoskeletal disorders frequently observed in the workplace.

Acknowledgments

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