Upper limb mechanical changes following short duration repetitive eccentric exertions

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Abstract

Background. Power hand tool use is considered a risk factor for upper extremity musculoskeletal disorders. It is unclear if submaximal eccentric activity inherent to power tool use adversely affects the mechanical properties of muscle.

Methods. This study investigated in vivo changes in human upper limb dynamic mechanical properties following exposure to short-term repetitive submaximal eccentric exertions that are similar to operating an industrial power hand tool. Eighteen subjects (12 males and 6 females) were assigned to one of three exercise groups (isometric, eccentric or control) and exercised 10 min for 60 repetitions at 50% of isometric forearm supination maximum voluntary contraction. Supination strength and dynamic mechanical properties (stiffness, effective mass, and damping) of forearm rotation, modeled as a single-degree-of-freedom system during maximal exertion, were ascertained prior to exercise, immediately following exercise and 24 h later.

Findings. Strength decreased for the isometric (17%) (P<0.05) and eccentric (34%) (P<0.01) groups following exercise. Only the eccentric exercise group had a reduction in mechanical stiffness (53%) (P<0.01) and effective mass (58%) (P<0.05). The other groups had no changes in mechanical properties.

Interpretation. The change in mechanical properties 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 indicate mechanical strain on the upper limb.

Keywords: Mechanical properties; Stiffness; Forearm; Submaximal eccentric exertions

1. Introduction

More than 700,000 workers annually sustain injuries due to overexertion or repetitive motion with sufficient severity to result in lost time from work (BLS, 2002). Upper extremity work-related musculoskeletal disorders (MSD) include nerve entrapment syndromes, tenosynovitis, tendinitis, peritendinitis, and nonspecific muscle and tenderness (NIOSH, 1997). The majority of reported MSD in the upper extremity region are nonspecific and lack a well-defined clinical diagnosis (NRC/IOM, 2001). Although incidence is frequent, the actual prevalence of these disorders and syndromes is not precisely known since many disorders are difficult to classify in epidemiologic studies (NIOSH, 1997; NRC/IOM, 2001).

Power hand tool use has been considered a risk factor for upper extremity 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; Myers and Trent, 1988). Rotation of the forearm (supination/pronation) accompanies pistol grip power hand 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).

Power hand tool use in industrial work sometimes involves eccentric exertions (Armstrong et al., 1999; Oh and Radwin, 1998) when rapidly rising tool-generated forces exceed the tool operator's capacity. Changes in mechanical properties following eccentric exertions may affect a muscle's ability to react to rapid forceful loading, resulting in increased strain of the muscle. 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 microinjury in muscles during repetitive skeletal muscle loading. If the external forces from power hand tools exceed 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.

It is well documented that mild 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; Ebbeling and Clarkson, 1990; Friden et al., 1983). Adverse effects include onset of muscle soreness, greater strength decrements than isometric or concentric exertions, and possibly greater risk for musculoskeletal injury (Komi and Rusko, 1974; Lieber et al., 1991; Lieber and Friden, 1999).

Both mechanical and biochemical changes have been described in skeletal muscle following intense eccentric activity (Armstrong, 1990; Cannon and St. Pierre, 1998; Friden and Lieber, 1992). An increase in passive muscle stiffness has also been reported following eccentric exercise (Chleboun et al., 1998; Cleak and Eston, 1992; Howell et al., 1993). Although the majority of these studies have examined physiological and anatomical changes, several recent studies have investigated changes following submaximal eccentric muscle activity (Evans et al., 1998; Nosaka and Newton, 2002).

What is less clear is whether submaximal eccentric activity inherent to power tool use affects the muscle in the same manner as more intense eccentric exercise. Lin et al. (2001) reported subjects exerted an average of 56.6% of their static MVC (maximum voluntary contraction) during power screwdriver use which is similar to submaximal exercise levels in which physiologic changes such as a reduction in isometric strength and range of motion and an increase in plasma creatine kinase were observed (Nosaka and Newton, 2002).

The dynamic mechanical properties of muscle and tendon (stiffness, effective mass and damping) are important for function since they counteract the effects of applied loads. Quantification of muscle stiffness has predominantly involved the evaluation of resting joint angle and the amount of force required to move a joint through its complete range while the muscle is passive (Clarkson et al., 1992; Howell et al., 1993). A less often studied component of mechanical stiffness is associated with active muscle force, which is becoming increasingly recognized as important in the normal control of posture and movement (Kearney and Hunter, 1990; Leger and Milner, 2000; Milner and Cloutier, 1998; Milner et al., 1995). Damping is important for postural maintenance control when reacting to external perturbations (de Vlugt et al., 2002; Milner and Cloutier, 1998) and an increase in muscle tension has been found to affect muscle damping in the lower extremity (Wachter et al., 1996). It is plausible that the ability of the muscle to dampen an applied perturbation will be negatively affected following exposure to high velocity eccentric activity. The dynamic effective mass reflects the quantity of muscle that is involved in the muscle contraction. Possible impairment of muscle contractile properties may result in fewer muscle fibers carrying load which results in a decrease in effective mass. It is therefore hypothesized that a decrease in mechanical stiffness and other mechanical properties consistent with reduced muscle involvement will occur in muscles repeatedly exposed to repetitive submaximal eccentric exertions.

Our laboratory has developed an instrument to quantify dynamic mechanical properties of active muscle (Lin et al., 2001). The apparatus delivers an external perturbation to the limb through a handle. The mechanical stiffness, damping and effective mass elements are determined from free vibration displacement by calculating the frequency changes of the externally loaded system. Since the mechanical characteristics of the apparatus do not significantly change with loading, any change in the system mechanical elements is attributed to the person coupled to the handle. The apparatus has been used for dynamic mechanical model parameter identification by Lin et al. (2001). This apparatus was employed in the current study to investigate the mechanical changes in muscle following repetitive submaximal eccentric loading, similar to operating industrial power hand tools.

2. Methods

2.1. Subjects

Eighteen volunteers were tested (mean age = 27.3 years, SD = 3.74 years), including 12 males and 6 females. All participants were right hand dominant and self-reported that they were free of symptoms and injuries in the dominant upper extremity. The dominant arm was used for all testing. Subjects were instructed to avoid participating in upper extremity weight training.
activities for at least 72 h prior to the experiment and for the duration of the study. Informed consent was obtained in accordance with the University of Wisconsin guidelines for the protection of human subjects.

A short questionnaire was administered prior to testing. The questionnaire included questions about demographics such as gender, age, weight, stature, and hand dominance. A visual analog scale ranging from 0 to 10 (0 corresponding to "no pain", and 10 corresponding to the "most pain") was also used. The same visual analog scale was completed by subjects prior to exercise, immediately following exercise and 24 h after exercise.

2.2. Experimental design

Subjects were stratified by gender and then randomly assigned to one of three treatments: (1) six subjects performed isometric exercise, (2) six subjects performed eccentric exercise, and (3) six subjects were control subjects who performed no exercise. Each group was limited to four males and two females. Subjects were tested on the free vibration apparatus described previously (Lin et al., 2001) to measure mechanical stiffness, damping, and effective mass properties of muscles immediately prior to a bout of exercise, immediately following exercise and 24 h later.

2.3. Strength assessment

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 a Biodex® (Biodex Medical Systems, Shirley, NY, USA) strength measurement system. Maximum voluntary contraction of the forearm supinator muscles was measured isometrically. Two 5-s maximum voluntary contractions (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. 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.

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 Hz.

2.4. 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 in both exercise groups exerted 50% MVC for a total of 10 min with a 1 min rest break after 5 min. A total of 60 repetitions were completed. Visual feedback of torque output was continuously presented to the subject so that they could maintain the desired exertion level. The majority of subjects were able to maintain the desired torque, although some of the subjects had difficulty during the last 1–2 min of the exercise protocol. The exercise consisted of a 3-s contraction followed by a 3-s rest. The forearm position for the isometric exercise group was a neutral position with the elbow flexed at 90°. The starting position of the forearm for the eccentric exercise group was neutral and then pronated to 90° with the elbow flexed at 90°. Subjects in the eccentric exercise group were exercised at a handle rotation velocity of 30°/s. This velocity allowed subjects to control the torque generated throughout the set range of motion. Subjects were seated with their torso and arm stabilized to prevent substitution by other muscle groups. The subjects in the control group were strength tested in the same manner as the other groups but rested during the 10 min exercise session. Subjects were asked to rate perceptions of muscle soreness using a visual analog scale, from 0 to 10, with 0 defined as "no pain" and 10 defined as "the most pain."

2.5. Mechanical property measurements

The apparatus consisted of a mechanical system containing a known stiffness, negligible viscous damping, and inertial mass that can be varied to achieve different free-vibration responses (Lin et al., 2001, 2003) (Fig. 1). Free vibration of the system produced a hand and forearm damped rotational vibration at a frequency of 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. The data acquisition sampling rate was 1000 Hz. 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 of the system 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

\[
\ddot{\theta} + \dot{c}\theta + k\theta = 0
\]  

(1)

When the human subject externally loads the free vibration apparatus, 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 free vibration 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).

\[
J_{\text{mass}} = k \frac{1}{\omega_n^2} - (J_h + J_{\text{subject}})
\]  

(2)

\[
J_{\text{mass}} = c \left( \frac{1}{2\omega_n} \right) + \text{constant}
\]  

(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 more detailed explanation is provided in Lin et al., 2001.

2.6. Data analysis

Data were analyzed for differences between exercise groups as well as prior, immediately following, and 24 h after exercise. A mixed effects repeated measures analysis of variance was used for evaluating statistical significance of the mechanical and physiological variables. Post hoc analysis was done using the Bonferroni multiple pairwise comparison method.

3. Results

Forearm supination static strength, measured before, immediately following, and 24 h after exercise, is shown in Fig. 2. No differences were observed between any of the groups prior to exercise \((P>0.05)\). Following exercise, average static forearm supination strength was significantly less for the two exercise groups \((P<0.01)\), but not for the control group. The isometric exercise group had a 17% decrease in static strength \((P<0.05)\) and the eccentric exercise group had a 34% decrease in static strength \((P<0.01)\) immediately following exercise. No change in average strength was observed for any of the groups between initial testing and 24 h after exercise \((P>0.05)\).

Mechanical stiffness, measured before, immediately following, and 24 h after exercise, is shown in Fig. 3. No differences were observed between any of the groups prior to exercise \((P>0.05)\). A significant reduction in average mechanical stiffness was observed following exercise for the eccentric exercise group \((P<0.01)\) but
not for the isometric or control groups. The eccentric exercise group had a 53% decrease in average mechanical stiffness ($P < 0.05$) immediately following exercise. No differences in average mechanical stiffness were observed for the isometric and control groups before exercise and immediately following exercise ($P > 0.05$). No change in average mechanical stiffness was observed for any of the groups between initial testing and 24 h after exercise ($P > 0.05$).
Symptoms (0–10 visual analog scale) were reported as 0 at baseline for all groups. No change in average symptom intensity was observed before and immediately after exercise ($P > 0.05$). An increase in average symptom intensity was observed 24 h following exercise for the eccentric group ($P < 0.05$) but not for the isometric or control groups ($P > 0.05$). After 24 h, average symptom intensity was 2.3 (SE = 0.58) for the eccentric group and was 1.2 (SE = 0.49) for the isometric group. The control group continued to report no symptoms.

4. Discussion

The purpose of this study was to investigate the changes in upper limb dynamic mechanical properties following repetitive submaximal eccentric muscle activity. These properties include mechanical stiffness, damping, and effective mass for active forearm supination in a mid-range position. Subjects in both the isometric and eccentric exercise groups had less static strength immediately following 10 min of exercise while changes in mechanical properties were only observed in subjects following eccentric exercise.

A logical question is, was the decrease in mechanical stiffness and effective mass due primarily to fatigue or strength loss? It does not appear that fatigue alone can explain the initial decrease in mechanical properties since both exercise groups potentially experienced some fatigue immediately after exercise, but only the eccentric exercise group had a decrease in mechanical properties immediately after exercise. Strength loss following eccentric exercise was considerably greater than for isometric exercise, which may partially explain why there was no change in mechanical properties following isometric exercise. These findings however do not explain why after 24 h the eccentric group strength returned within 10%, and the isometric group recovered within 5%, while the eccentric group still had $41\%$ less mechanical stiffness and $40\%$ less effective mass. If the mechanical changes were solely due to strength loss or fatigue then recovery in mechanical properties should parallel strength recovery.

Several factors may have contributed to the non-significant post hoc findings including the large variability in mechanical properties following exercise, the small sample size (six subjects in each exercise group), and the smaller mechanical properties of females. For females, the average mechanical stiffness prior to testing was only $7\%$ larger than the stiffness for the free vibration apparatus resulting in a floor effect that may limit the measurable decrease in mechanical properties following exercise.

Previous studies have observed ultrastructural abnormalities within muscle including damage to contractile units 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 spring elements during stretching which may play a role in the reduction in muscle stiffness observed following eccentric exercise. Another question raised is, why does effective mass decrease following submaximal eccentric exercise? Clearly, there was not an overall reduction of the inertial mass of the arm. One plausible explanation is that the dynamic effective mass reflects the quantity of muscle that is involved in the muscle contraction. Possible damage to the contractile machinery may result in less muscle fibers actively contributing which results in a decrease in effective mass.

The findings in our study concur with the findings by Leger and Milner (2000), who also observed a reduction in mechanical stiffness of the wrist extensors following strenuous exercise. Stiffness in their study was defined as the ratio of change in mean torque divided by the change in mean position. 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. An average strength deficit of $24.5\%$ was observed 24 h later. In our study, subjects exercised for a total of 10 min with a 1-min rest break after 5 min. A total of 60 repetitions were completed. The average strength deficit 24 h after exercise for the eccentric group was $14\%$. Even though the exercise protocol used in this study was not as fatiguing as the one used by Leger and Milner (2000), a significant decrease in mechanical stiffness immediately after exercise was still observed.

A less fatiguing protocol than the one used by Leger and Milner (2000) was chosen in the current study to more closely represent occupational activities which are common in industrial and manufacturing environments. Rarely during the course of work activities do employees persistently work at a maximum or until exhaustion. Subjects worked at a moderate level for a relatively short duration. This type of activity level is likely to be sustained in the work place for many more hours. It is anticipated that since mechanical parameter changes were observed following moderate eccentric exercise for a short duration, it may be possible to observe similar changes following eccentric work activity for longer durations, as is common in the workplace. The mechanical changes observed may be indicative of possible mechanical strain.

Lin et al. (2003) have shown that less mechanical stiffness results in greater forces acting against the hands and greater hand displacement during nutrunner use. Applying the reduced mechanical properties demonstrated following eccentric activity to the average mechanical properties for an operator using a pistol grip
tool on a vertical surface, Lin's model predicted that tool displacement would increase by more than 40% during operation of a pistol grip torque reaction power tool with a target torque of 7 Nm and a soft joint. This reduction in capacity may have adverse long-term effects on operator safety, particularly for large exertions that are frequent and forceful.

5. Conclusions

The practical consequences of mechanical stiffness and effective mass reductions following eccentric exertions include less capacity to react against rapidly-building torque reaction forces encountered when operating power hand tools such as nutrunners (Lin et al., 2001). Lin et al. (2003) have shown that less mechanical stiffness results in greater forces acting against the hands during nutrunner use. This reduction in capacity and increased force may have adverse long-term effects on operator safety, particularly for large level exertions that are frequent and forceful and beyond those used in the current study.

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References


