*Ergonomics*
Vol. 52, No. 1, January 2009, 15–24

Taylor & Francis
Taylor & Francis Group

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

Amrish O. Chourasia, Mary E. Sesto, Walter F. Block and Robert G. Radwin*

*Department of Biomedical Engineering, University of Wisconsin, 1550 Engineering Drive, Madison, WI 53706, USA*

This study investigated *in-vivo* changes in upper limb dynamic mechanical properties and magnetic resonance imaging (MRI) parameters following short-term power hand tool operation. Previous studies have found reduction in mechanical properties following short-term power tool usage at long build-up 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 3 d after tool operation. Twenty-four participants were randomly assigned to operate a simulated power hand tool for either a high peak reaction force of 123 N (peak torque = 8 Nm, build-up time = 250 ms) or at a low peak reaction force of 5 N (peak torque = 2 Nm, build-up time = 50 ms). Subjects operated the tool for 60 min at the rate of six times per min. A reduction in stiffness (27%, $p < 0.05$) was observed 24 h after tool operation for the high force group and this change persisted (26%, $p < 0.05$) up to 72 h 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 MRI for both groups 24 h after tool operation but only the high force group remained elevated (10%, CI 13.7%, 0.06%) 72 h 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. 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.

**Keywords:** power hand tool; mechanical parameters; eccentric exertions; oedema

## 1. Introduction

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 (Radwin *et al.* 1987, Oh *et al.* 1997, Oh and Radwin 1998, Armstrong *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 might 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 h following that activity (Friden *et al.* 1983, Clarkson *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 *et al.* 1991, Faulkner *et al.* 1993). This disruption may negatively affect the muscle's mechanical response properties. 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 nut runner operation. The dynamic mechanical properties of the upper limb (stiffness, effective inertial mass and damping) are important for quantifying function since they mechanically characterise 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

*Corresponding author. Email: radwin@engr.wisc.edu

ISSN 0014-0139 print/ISSN 1366-5847 online

DOI: 10.1080/00140130802480877
http://www.informaworld.com

arm when an impulsive force is encountered. (Lin *et al.* 2001).

Previous studies in the authors' laboratory found that mechanical properties (stiffness, effective inertial mass and damping) and magnetic resonance imaging (MRI) of muscle inflammation (oedema) changed following short-term eccentric exercise at submaximal intensities (Sesto *et al.* 2004, 2005a). Sesto *et al.* (2005b) 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 *et al.* (2006) found reduced mechanical properties in symptomatic workers and oedema has been associated with muscle injury (Shellock *et al.* 1991, Evans *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 3 d 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 *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 greater changes are observed 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.

## 2. Methods

### 2.1. Participants

A total of 24 volunteers participated in the experiment. Participants were healthy young college students (mean age 23.6 (SD 3.3) years) 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 experience and hand dominance. Those reporting upper extremity symptoms, a history of injury or occupational use of power hand tools or contra-indications to MRI were excluded from testing. Participants were asked to refrain from exercise or recreational sports for 3 d 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.

### 2.2. Experimental design

Participants were randomly assigned to operate a simulated pistol grip power tool set either at a high peak reaction force of 123 N (peak torque = 8 Nm and build-up time = 250 ms, torque build-up rate = 32 Nm/s) or a low peak reaction force of 5 N (peak torque = 2 Nm and build-up time = 50 ms, torque build-up rate = 40 Nm/s) on a vertical work surface. The reaction forces were calculated using the method proposed by Lin *et al.* (2001). The power tool used was a modified pistol grip Dewalt DW959 (DeWalt Industrial Tool Co., Baltimore, MD, USA) drill, which was connected to a computer-controlled power supply, RKW-1500 (Kepco Inc., Flushing, NY, USA). An electronic torque transducer, SWS-50 (Transducer Techniques, Temecula, CA, USA) 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 50th percentile male standing elbow height based on the 1988 US Army Anthropometric survey (Gordon *et al.* 1989). The fixed handle height was used to simulate tightening a fixed threaded fastener in the workplace. The 50th percentile elbow height was chosen in order to accommodate the most subjects.

### 2.3. Upper limb mechanical response parameters

The method used for measuring mechanical properties was similar to Lin *et al.* (2001), except the current study used an apparatus incorporating translational springs instead of a torsional spring (Figure 1). The handle inertia was changed by moving two cylindrical masses from the centre of rotation of the device. This reduced the set-up time from the Lin *et al.* (2001) apparatus and has made the system portable.

Participants were seated on an adjustable-height chair with back support (Biodex Medical Systems, Shirley, NY, USA). The shoulder, forearm and wrist were positioned in a neutral position with the elbow flexed at 90°. The upper arm was stabilised 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 oscillations by grasping the handle, the frequency and

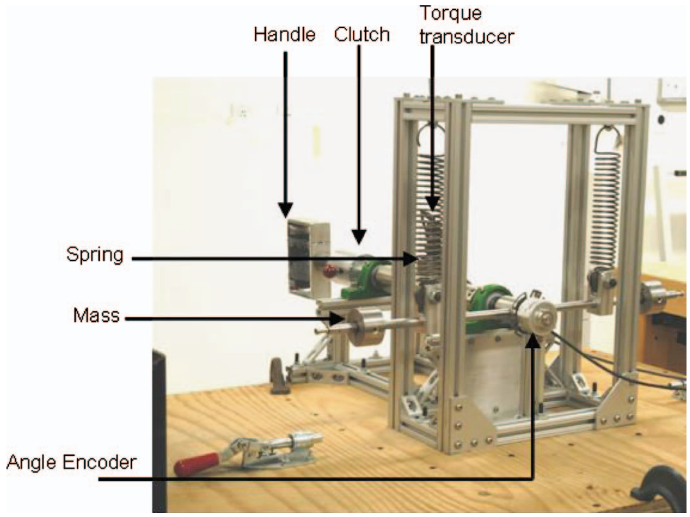


Figure 1. Apparatus for measurement of mechanical properties.

damping of oscillation is changed. The equation of motion that describes the free vibration response of this system is:

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

where, $J =$ mass moment of inertia, $c =$ damping constant, $k =$ stiffness, $\theta =$ 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 mass moment of inertia of the effective mass and the resultant frequency is described in Equation (2). The relationship between the mass moment of inertia of the effective mass and damping ratio is represented in Equation (3) (Lin *et al.* 2001).

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

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

where, $\omega_{\mathrm{n}} =$ natural frequency of oscillation, $\zeta =$ damping factor, measured from oscillations of the apparatus.

Three masses were used to calculate the stiffness. 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 *et al.* 2001, 2003a,b,c, Sesto *et al.* 2004, 2005a,b, 2006), the mass moment of inertia was calculated using intercept from Equation (2). The mass 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 ms. The mass moment of inertia of the device and the applied mass is known and, using the following equation, the mass moment of inertia of the effective mass for the human subject is calculated.

$$J_{deivice+mass}\omega_1 = (J_{device+mass} + J_{subject})\omega_2 \quad (4)$$

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

$$c = 2\zeta\sqrt{kJ} \quad (5)$$

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

### 2.4. *Strength measurement*

A Biodex™ (Biodex Medical Systems) apparatus was used for isometric strength testing (Chaffin 1975). Participants were seated on a height-adjustable chair with back support. The shoulder, forearm and wrist were positioned in a neutral position with the elbow flexed at 90°. The upper arm was stabilised against the body using a Velcro strap. The response to tool reaction forces involves co-contraction of pronator, supinator and other muscle groups. The supinator is the eccentrically exercised muscle, making it the object of possible changes; hence, only supination strength was measured. Two forearm supinator isometric maximum voluntary contractions (MVC) were performed for 5 s with a 1-min rest between exertions. The 5-s exertion was averaged between the first and the fourth second and the average of the two MVC measurements was used for analyses.

### 2.5. *Magnetic resonance imaging*

The MRI examination was conducted using an Artoscan 0.17 T extremity scanner (GE Healthcare, Waukesha, WI, USA). Scan parameters for this experiment were 2050 ms repetition time (TR), 34 ms echo time (TE), 75 ms inversion time (TI), 16 cm field of view (FOV), 196 × 196 resolution. Elevation of $T_2$ relaxation time occurs with oedema and displays a higher intensity (brighter) in the image. Generally, inversion recovery or fat-suppressed $T_2$ weighted sequences are used to assess for muscle oedema. For both sequences, oedema will have higher signal intensity than normal muscle. (Napier *et al.* 2006).

The short T, inversion recovery (STIR)-weighted images of the eccentrically exercised muscles as well as non-eccentrically exercised muscles were examined visually. Based on visual inspection, regions of interest were selected in the supinator (eccentrically exercised) and flexor (non-eccentrically exercised) muscles. MR Vision software (MR vision Inc., Boston, MA, USA) 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 analysing the MRI was blinded to the treatments. Special care was taken to avoid inclusion of subcutaneous fat, fascia, blood vessels, tendons or bone structures.

### 2.6. *Procedure*

The power hand tool was used at a rate of six times per min for 60 min to simulate occupational usage. A clock was used to pace the subjects and a 2-min rest break was given after 30 min of use.

Mechanical response parameters, isometric strength and symptoms were assessed prior to power tool use, immediately following use and daily for 3 d. Participants underwent MRI of the forearm before power hand tool activity, on day one and on day three following power tool use. A visual analogue scale was used for assessing localised forearm discomfort ranging from 0–10 (0 corresponding to 'no pain' and 10 corresponding to 'most pain').

### 2.7. *Data analysis*

Repeated measures ANOVA was used to investigate the significance of the main effect of high force power tool operation and low force power tool operation on mechanical response parameters, isometric strength and symptoms. Multivariate test results are reported here. All CI are reported at 95%.

## 3. Results

A reduction in mechanical stiffness was observed (Figure 2) following power hand tool operation ($F(3,20) = 7.05$, $p < 0.05$). Stiffness was 27% less (CI −14.5%, −39.81%) than before power hand tool use 24 h after operation, 21% less (CI −3.93%, −39.32%) 48 h after operation and 26% less (CI −9.25%, −42.11%) 72 h after operation for the high force group. Stiffness was 5.38% greater (CI 16.54%, −5.78%) than before power hand tool use 24 h after operation, 3.18% less (CI 12.04%, −18.39%) 48 h after tool operation, and 9.65% less (CI 4.02%, −23.32%) 72 h after operation for the low 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 3 and 4).

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 hand tool use for either group.

There was a statistically significant association between MRI flexor supinator intensity ratio and power hand tool use ($F(2,21 = 6.178$, $p < 0.05$) (Figure 5). A 13.08% (CI 22.13%, 4.02%) increase was observed in the flexor supinator intensity ratio after 24 h and a 9.79% (CI 20.57%, −0.98%) increase in the flexor supinator intensity ratio was observed after 72 h (Figure 6) for the high force group. A 10.99% (CI 22.7%, −0.72%) increase in the supinator flexor intensity ratio was observed after 24 h and a 3.97% (CI 13.64%, −5.71%) increase was observed after 72 h for the low force group.

## 4. Discussion

Strength changes were regarded as an indicator of muscle injury following intense eccentric exercise (Warren *et al.* 1999). The current study involves less

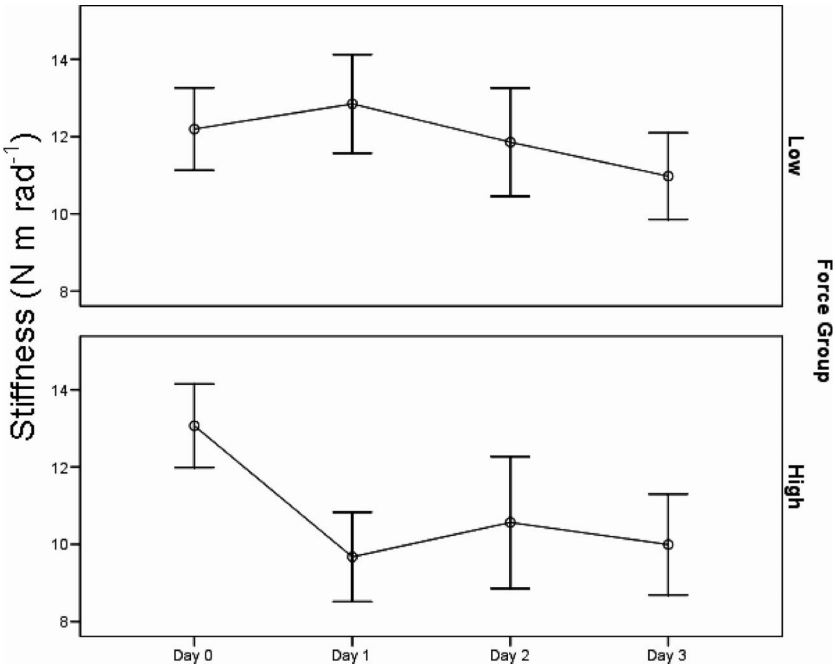


Figure 2. Stiffness (mean and SE) for low force and high force group.

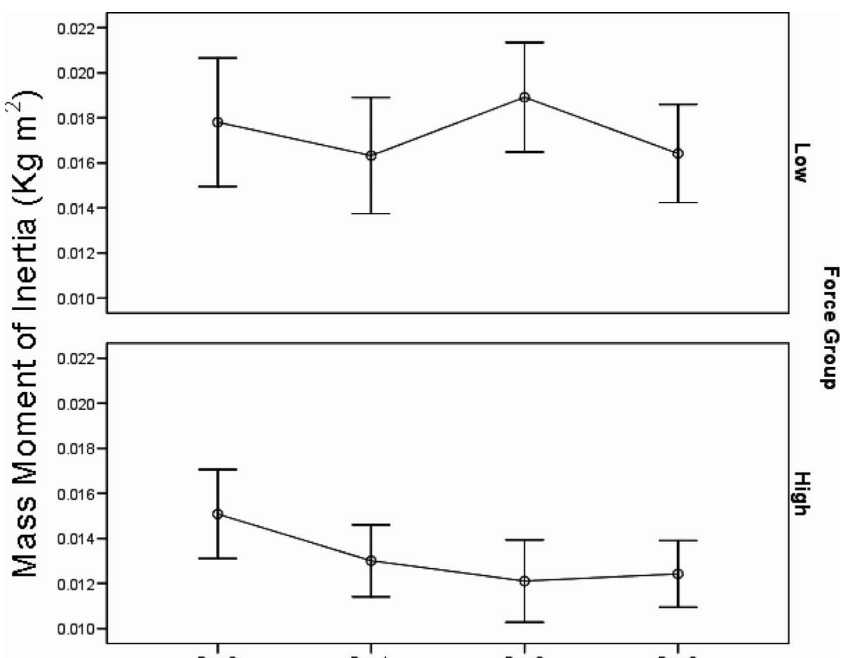


Figure 3. Mass moment of inertia (mean and SE) for low force and high force group.

intense eccentric exercise than previous research, similar to occupational power hand tool operation. There was no statistically significant decrease in the forearm supination strength levels following simulated power hand tool use, even though a significant reduction in mechanical stiffness was observed for the high force group. This may suggest absence of muscle injury.

Mechanical stiffness of muscle is dependent on the actin–myosin binding of the muscle sarcomeres

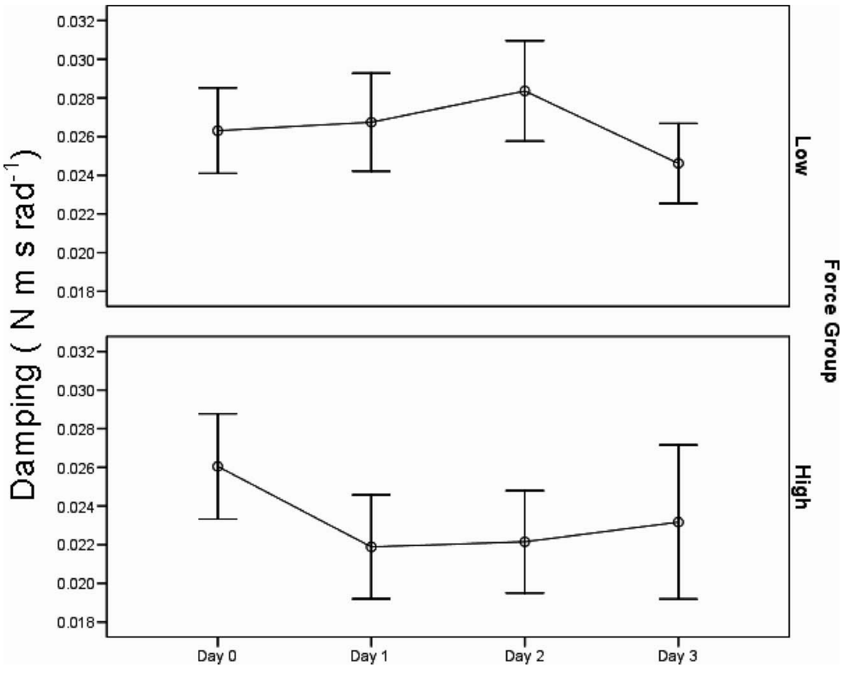


Figure 4. Damping (mean and SE) for low force and high force group.

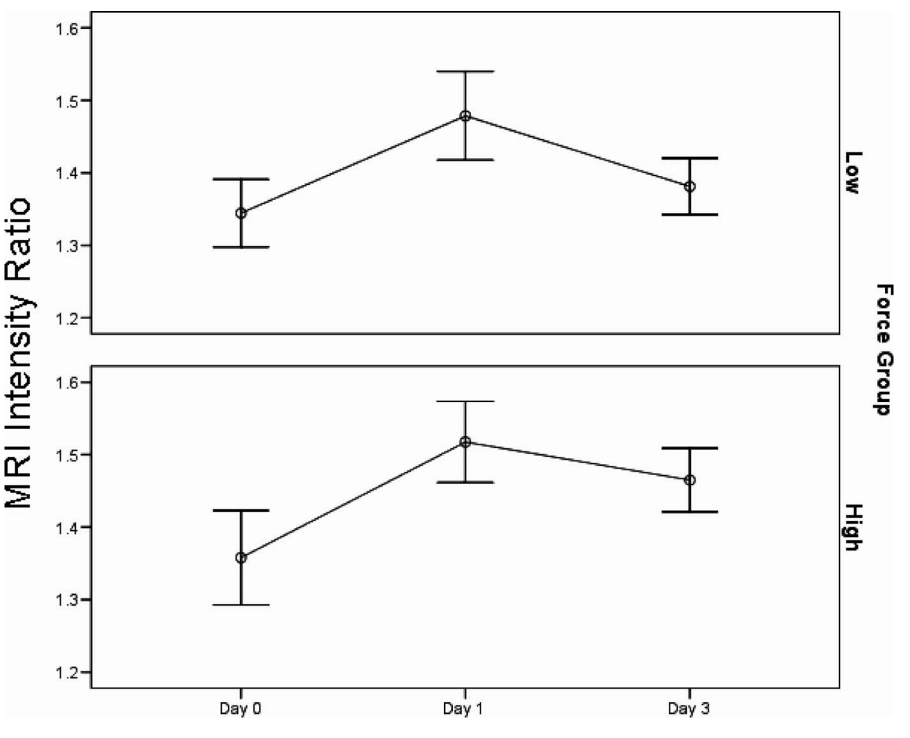


Figure 5. Supinator flexor intensity (mean and SE) ratio for low force and high force group. MRI = magnetic resonance imaging.

(Linari *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 build-up times might result in a greater drop in mechanical

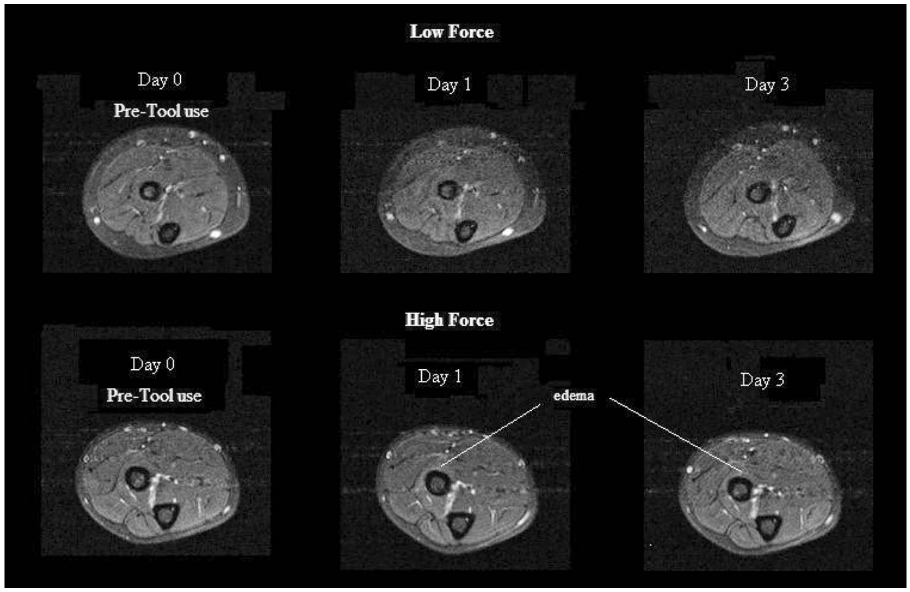


Figure 6. Magnetic resonance images of a subject each from the low and high force group (day 0, day 1 and day 3).

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.

The muscles primarily involved in the pronation and supination of the forearm are the biceps, pronator, pronator teres and the supinator. Compensatory mechanisms could mask any changes in the supination MVC following power tool operation. The supinator is the eccentrically exercised muscle during power tool operation and the experimenters sought to minimise the contribution of the biceps muscle by stabilising the upper arm against the body using a Velcro strap. The measurement of stiffness is done by means of a dynamic contraction, in which supination and pronation of the forearm alternate rapidly. In both measurements the contribution of the biceps is minimised. The measurement of stiffness in the current study is analogous to a dynamic strength test. Baker *et al.* (1994) reported that measures of strength and speed strength for dynamic and isometric strength performance may correlate significantly but the relationship does not suggest generality of muscle function.

One possible explanation for the observed reduction in mechanical stiffness is localised muscle fatigue (Chaffin 1973). Fatigue is any exercise-induced reduction in the force generation capacity of the muscle (Gandevia 2001). The causes for fatigue could be central or peripheral. Endoh *et al.* (2005) reported that, in a sustained MVC exertion, central and peripheral fatigue progressed faster in maximally eccentrically exercised muscle than in non-exercised muscle and the reduction in voluntary activation persisted up to 4 d following eccentric exercise. Deschenes *et al.* (2000) found impaired neuromuscular efficiency (torque/integrated electromyography) up to 10 d following maximal eccentric exercise while other symptoms of damage (creatine kinase (CK), soreness, plasma interleukin –I$\beta$) showed changes up to 7 d post exercise. Prasartwuth *et al.* (2005) had subjects eccentrically exercise elbow flexors till MVC dropped by 40%. They concluded that changes in force-generating capacity after eccentric exercise altered neural drive to the elbow flexor muscles during submaximal contractions. The slope in near-linear relation between force and electromyography (EMG) (Chaffin *et al.* 1980) was reduced immediately after eccentric exercise, so that almost 90% of maximal voluntary EMG was needed to generate a 50% MVC.

Muscle soreness often appears many hours after eccentric exercise and is widely used for muscle function evaluation. Soreness was used as a muscle function evaluation tool in 33 of 52 human studies reviewed by Warren *et al.* (1999). Clarkson and Hubal (2002) reported that exercise that does not produce profound muscle damage, such as downhill running or isokinetic eccentric knee extension, produced soreness values of 4 or 5 on a scale on 1 to 10 (1 = no soreness, 10 = very sore), while maximal eccentric contractions of the elbow flexors produced soreness values of 7 to 8. No soreness was observed before and after power hand tool usage in the current study for either the low force or high force group.

The exercise protocol used in the current study simulated the conditions of power tool use such as in an assembly plant. The protocol was not designed to exercise subjects until the point of exhaustion or until a certain reduction in isometric strength was achieved. The participants did not report any localised forearm soreness at any point during the study. The exercise protocol used and the absence of significant changes in the supination MVC and in the soreness ratings suggest that fatigue was not a critical factor affecting the MVC and stiffness in this study.

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 altered neural drive. Future research should address these effects.

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

Oedema is often experienced following intense eccentric exercise (Shellock *et al.* 1991, Foley *et al.* 1999). The mechanism of oedema 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. Oedema has also been observed at less than maximal intensity exercise levels (Nosaka and Newton 2002, Sesto *et al.* 2005a). Presence of oedema in the muscles causes the signal intensity of the MRI to increase in those areas. A statistically significant change in the signal intensity in the current study was observed for both the groups 24 h after tool operation. The high force group continued to show an increase in the supinator signal intensity 72 h after tool operation.

The findings of the present study concur with the study performed by Sesto *et al.* (2005b), 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 *et al.* 2005a). 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) had subjects exercise wrist extensors until exhaustion 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 exhaust the participants but a reduction in mechanical properties was still observed. The level of exertion used in the current protocol was thought to better simulate occupational conditions. The reduction in mechanical properties following such submaximal exertions is noteworthy 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 intensity that subjects worked at in this study. Eccentric exertions frequently occur in the workplace, such as in 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 *et al.* 2001, 2003c). 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.

## 5. Conclusion

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 oedema persisted 72 h 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 localised oedema, similar to effects sometimes seen following muscle-lengthening exertions. The reduction in mechanical properties and increase in oedema following tool operation can be viewed as potential precursors to the development of musculoskeletal disorders.

**Acknowledgements**

This article is dedicated in honour of Professor Don B. Chaffin. Many of the methods and principles used in this research were pioneered by Don Chaffin. Thank you for your inspiration, mentorship and guidance. This research was partially supported by the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention Grant R01OH07793-02 and The National Institutes of Health, NCRR K12 Roadmap Grant 8K12RR023268-02.

## References

Armstrong, R.B., Warren, G.L., and Lowe, D.A., 1995. Mechanisms in the initiation of contraction-induced skeletal muscle injury. *In: Repetitive motion disorders of the upper extremity*. Rosemont, IL: American Academy of Orthopaedic Surgeons.

Armstrong, T., *et al*., 1999. Muscle responses to simulated torque reactions of hand-held power tools. *Ergonomics*, 42 (1), 146–159.

Baker, D., Wilson, G., and Carlyon, B., 1994. Generality versus specificity – a comparison of dynamic and isometric measures of strength and speed-strength. *European Journal of Applied Physiology and Occupational Physiology*, 68 (4), 350–355.

Chaffin, D.B., 1973. Localized muscle fatigue-definition and measurement. *Journal of Occupational Medicine*, 15, 346–354.

Chaffin, D.B., 1975. Ergonomics guide for the assessment of human static strength. *American Industrial Hygiene Association Journal*, 36, 505–511.

Chaffin, D.B., Lee, M., and Freivalds, A., 1980. Muscle strength assessment from EMG analysis. *Medicine and Science in Sports and Exercise*, 12, 205–211.

Clarkson, P.M. and Hubal, M.J., 2002. Exercise-induced muscle damage in humans. *American Journal of Physical Medicine & Rehabilitation*, 81 (11), S52–S69.

Clarkson, P.M., Nosaka, K., and Braun, B., 1992. Muscle function after exercise-induced muscle damage and rapid adaptation. *Medicine and Science in Sports and Exercise*, 24 (5), 512–520.

Cleak, M.J. and Eston, R.G., 1992. Muscle soreness, swelling, stiffness and strength loss after intense eccentric exercise. *British Journal of Sports Medicine*, 26 (4), 267–272.

Deschenes, M.R., *et al*., 2000. Neuromuscular disturbance outlasts other symptoms of exercise-induced muscle damage. *Journal of the Neurological Sciences*, 174 (2), 92–99.

Endoh, T., *et al*., 2005. Effects of muscle damage induced by eccentric exercise on muscle fatigue. *Medicine and Science in Sports and Exercise*, 37 (7), 1151–1156.

Evans, G.F.F., *et al*., 1998. Submaximal delayed-onset muscle soreness: correlations between MR imaging findings and clinical measures. *Radiology*, 208 (3), 815–820.

Faulkner, J.A., Brooks, S.V., and Opiteck, J.A., 1993. Injury to skeletal muscle fibers during contractions: conditions of occurrence and prevention. *Physical Therapy*, 73 (12), 911–921.

Foley, J.M., *et al*., 1999. MR measurements of muscle damage and adaptation after eccentric exercise. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, 87 (6), 2311–2318.

Friden, J., Sjostrom, M., and Ekblom, B., 1983. Myofibrillar damage following intense eccentric exercise in man. *International Journal of Sports Medicine*, 4 (3), 170–176.

Gandevia, S.C., 2001. Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews*, 81 (4), 1725–1789.

Gordon, C.C., *et al*., 1989, 1987–1988. *Anthropometric survey of U.S. army personnel: Methods and summary statistics*. Natick, MA: US Army Natick Research, Development and Engineering Center.

Leger, A.B. and Milner, T.E., 2000. Passive and active wrist joint stiffness following eccentric exercise. *European Journal of Applied Physiology*, 82 (5–6), 472–479.

Lieber, R.L., Woodburn, T.M., and Friden, J., 1991. Muscle damage induced by eccentric contractions of 25% strain. *Journal of Applied Physiology*, 70 (6), 2498–2507.

Lin, J.H., Radwin, R.G., and Richard, T.G., 2001. Dynamic biomechanical model of the hand and arm in pistol grip power hand tool usage. *Ergonomics*, 44 (3), 295–312.

Lin, J.H., *et al*., 2003a. Forces associated with pneumatic power screwdriver operation: statics and dynamics. *Ergonomics*, 46 (12), 1161–1177.

Lin, J.H., Radwin, R.G., and Richard, T.G., 2003b. A single-degree-of-freedom dynamic model predicts the range of human responses to impulsive forces produced by power hand tools. *Journal of Biomechanics*, 36, 1845–1852.

Lin, J.H., Radwin, R.G., and Richard, T.G., 2003c. Handle dynamics predictions for selected power hand tool applications. *Human Factors*, 45 (4), 645–656.

Linari, M., *et al*., 1998. The stiffness of skeletal muscle in isometric contraction and rigor: the fraction of myosin heads bound to actin. *Biophysical Journal*, 74 (5), 2459–2473.

Napier, N., Shortt, C., and Eustace, S., 2006. Muscle edema: classification, mechanisms, and interpretation. *Seminars in Musculoskeletal Radiology*, 10 (4), 258–267.

National Research Council Institute of Medicine, 2001. *Musculoskeletal disorders and the workplace: Low back and upper extremities*. Panel on Musculoskeletal Disorders and the Workplace Commission on Behavioral and Social Sciences and Education. Washington: National Academy Press.

Nosaka, K. and Newton, M., 2002. Difference in the magnitude of muscle damage between maximal and submaximal eccentric loading. *Journal of Strength and Conditioning Research*, 16 (2), 202–208.

Oh, S.A. and Radwin, R.G., 1998. The influence of target torque and torque build-up time on physical stress in right angle nut runner operation. *Ergonomics*, 41 (2), 188–206.

Oh, S.A., Radwin, R.G., and Fronczak, F.J., 1997. A dynamic mechanical model for hand force in right angle nut runner operation. *Human Factors*, 39 (3), 497–506.

Prasartwuth, O., Taylor, J.L., and Gandevia, S.C., 2005. Maximal force, voluntary activation and muscle soreness after eccentric damage to human elbow flexor muscles. *Journal of Physiology-London*, 567, 337–348.

Radwin, R.G., Armstrong, T.J., and Chaffin, D.B., 1987. Power hand tool vibration effects on grip exertions. *Ergonomics*, 30, 833–855.

Sesto, M.E., *et al*., 2004. Upper limb mechanical changes following short duration repetitive eccentric exertions. *Clinical Biomechanics (Bristol, Avon)*, 19 (9), 921–928.

Sesto, M.E., *et al*., 2005a. Anatomical and mechanical changes following repetitive eccentric exertions. *Clinical Biomechanics (Bristol, Avon)*, 20 (1), 41–49.

Sesto, M.E., Radwin, R.G., and Richard, T.G., 2005b. Short-term changes in upper extremity dynamic mechanical response parameters following power hand tool use. *Ergonomics*, 48 (7), 807–820.

Sesto, M.E., *et al*., 2006. Upper limb dynamic responses to impulsive forces for selected assembly workers. *Journal of Occupational and Environmental Hygiene*, 3 (2), 72–79.

Shellock, F.G., *et al*., 1991. Exertional muscle injury: evaluation of concentric versus eccentric actions with serial MR imaging. *Radiology*, 179 (3), 659–664.

Warren, G.L., Lowe, D.A., and Armstrong, R.B., 1999. Measurement tools used in the study of eccentric contraction-induced injury. *Sports Medicine*, 27 (1), 43–59.