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Short-term changes in upper extremity dynamic mechanical response parameters following power hand tool use

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Dynamic mechanical response parameters (stiffness, damping and effective mass), physiological properties (strength and swelling) and symptoms of the upper limb were measured before power tool operation, immediately following and 24 h after power tool operation. Tool factors, including peak torque (3 Nm and 9 Nm) and torque build-up time (50 ms and 250 ms), were controlled in a full factorial design. Twenty-nine inexperienced power hand tool users were randomly assigned to one of four conditions and operated a pistol grip nutrunner four times per min for 1 h in the laboratory. Isometric strength decreased immediately following tool use (15%) ($p < 0.01$) and 24 h later (9%) ($p < 0.05$). Mechanical parameters of stiffness ($p < 0.05$) and effective mass ($p < 0.05$) were affected by build-up time. An average decrease in stiffness (43%) and effective mass (57%) of the upper limb was observed immediately following pistol grip nutrunner operation for the long (250 ms) build-up time. A previously developed biomechanical model was used to estimate handle force and displacement associated with the tool factors in the experiment. The conditions associated with the greatest predicted handle force and displacement had the greatest decrease in mechanical stiffness and effective mass, and the greatest increase in localized discomfort.

Keywords: Mechanical responses; Stiffness; Forearm; Power tool

1. Introduction

Power hand tool use has been considered a risk factor for upper extremity musculoskeletal disorders because of the associated repetitive motions, forceful exertions, vibration and posture stress (Myers and Trent 1988, Armstrong *et al.* 1993, Keyserling *et al.* 1993, Muggleton *et al.* 1999). Rotation of the forearm (supination/pronation)

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accompanies pistol grip power hand tool use and several studies have reported relationships between forceful and repetitive movements and development of forearm musculoskeletal disorders (Marfarlane *et al.* 2000, National Research Council/Institute of Medicine 2001, Haahr and Andersen 2003).

Power hand tool use in industrial work may involve eccentric exertions (Oh *et al.* 1997, Oh and Radwin 1998, Armstrong *et al.* 1999) when rapidly rising tool-generated forces exceed the tool operator's capacity to keep the tool stationary. 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 a power hand tool 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.

Research has demonstrated that when all other factors are similar, power hand tool handle displacement and reaction forces are greater for nutrunners with high peak torques (HPTs) and soft joints, than for low peak torques (LPTs) and hard joints (Oh *et al.* 1997, Oh and Radwin 1998). Oh and Radwin (1998) observed that handle displacement was 7.88 cm for a nutrunner with a peak torque of 55 Nm compared to 3.71 cm for a nutrunner with a peak torque of 25 Nm. A 256% increase in eccentric work was observed with a 900 ms build-up compared to a 35 ms build-up.

Lin *et al.* (2001) reported that subjects exerted an average of 56.6% of their static maximum voluntary contraction (MVC) during power screwdriver use, which is similar in magnitude to eccentric motions and exertions that have been related to anatomical (Sesto *et al.* 2005) and mechanical (Nosaka and Newton 2002, Sesto *et al.* 2004) effects on muscle. Anatomical changes, including oedema in muscle following eccentric exertions, have been measured with magnetic resonance imaging using T_2 relaxation time constant (Shellock *et al.* 1991, Evans *et al.* 1998, Foley *et al.* 1999, Sesto *et al.* 2005). Sesto *et al.* (2005) reported that the average supinator T_2 relaxation time constant following submaximal eccentric exercise of these muscles for five volunteers increased 22% ($p < 0.05$) 24 h after exercise. These effects were not observed for the unexercised muscles. Evans *et al.* (1998) also reported the appearance of muscle oedema accompanying submaximal eccentric exertions.

The current experiment was conducted to evaluate the effect of actual operation of power hand tools, by varying torque and torque build-up time, on mechanical response parameters of forearm muscle, including stiffness, damping and effective mass and physiological measures, including localized pain, discomfort and swelling. An important motivation for conducting this experiment was to investigate if power tool eccentric exertions associated with power hand tool operation had an effect on mechanical and physiological properties of the forearm, similar to that observed for controlled eccentric exertions previously reported.

This laboratory has developed an instrument to quantify dynamic mechanical properties during active muscle exertions (Lin *et al.* 2001, 2003a,b,c). 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. This apparatus has been used for model parameter identification previously by Lin *et al.* (2001) and the correlation between measured and predicted frequency was 0.9.

The dynamic mechanical properties of the upper limb (stiffness, effective mass and damping) are important for function since they counteract the effects of applied loads. Quantification of 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, Milner *et al.* 1995, Milner and Cloutier 1998, Leger and Milner 2000). Damping is important for postural maintenance control when reacting to external perturbations (Milner and Cloutier 1998, de Vlugt *et al.* 2002) and an increase in muscle tension has been found to affect 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 fibres carrying load, which results in a decrease in effective mass.

Recently, several investigations have considered changes following submaximal eccentric muscle activity at exertion levels comparable to occupational settings (Nosaka and Newton 2002, Sesto *et al.* 2004, 2005). Nosaka and Newton (2002) compared maximal eccentric exercise to submaximal eccentric exercise levels at 50% of isometric MVC and reported a similar magnitude of initial muscle injury, although secondary damage was less in the submaximal group. Sesto *et al.* (2004) reported a 41% reduction in mechanical stiffness and 40% reduction in effective mass following short duration eccentric activity at 50% of isometric MVC but no change in these responses for the isometrically exercised group. For industrial participants, Sesto (2003) reported that symptomatic workers had a markedly less mechanical stiffness (46%), damping (74%) and effective mass (59%) than asymptomatic workers.

The consequence of the observed mechanical parameter changes is an increase in the displacement response of the operator's hand when reacting against tool-generated forces, which may result in increased strain of the muscles (Lin *et al.* 2003a,b,c). This can negatively affect a worker's ability to operate power hand tools and limit their capacity to use them. Increased stresses on the body can also increase the risk of an injury (National Research Council/Institute of Medicine, 2001).

Differences in the mechanical response parameters of the right forearm associated with repetitive use of power hand tools, before, immediately after and 24 h following tool use were investigated. It was hypothesized that subjects would experience a greater change in mechanical stiffness, viscous damping and effective mass of the upper limb following operation of higher peak torque power hand tools than subjects operating power hand tools with lower peak torque output. Similarly, it was hypothesized that subjects operating nutrunners with longer torque build-up times would experience a greater change in upper limb mechanical responses than those operating tools with a shorter build-up time.

2. Methods

2.1. Subjects

Twenty-nine healthy male volunteers were recruited as participants (mean age 24.45 (SD 6.59) years). The study was limited to males due to strength requirements for the test apparatus. 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 age, weight, stature and hand dominance. A visual analogue scale ranging from 0–10 (0 corresponded to 'no pain' and 10 corresponded to the 'most pain') was also used. The same visual analogue scale was completed by subjects prior to tool use, immediately following tool use and 24 h after tool use.

2.2. Experimental design

The design of this experiment was a mixed 2 x 2 x 3 (peak torque x torque build-up time x test time) full factorial design. Mechanical and physiological variables were measured before tool use, immediately following tool use and 24 h later. The fixed independent variables were nutrunner peak torque (9 Nm or 3 Nm) and torque build-up time (250 ms or 50 ms). The levels of these variables were representative of those observed in automotive assembly. Nutrunner peak target torque was evaluated for 65 workstations at an automobile assembly plant that used power hand tools, and the average peak torque was 6.84 (SD 4.86) Nm. These data were used to define tool parameters of peak torque and build-up time.

Subjects were randomly assigned to one condition, with a minimum of seven subjects for each condition. Subjects operated an industrial pistol grip nutrunner set either at a HPT (9 Nm) or a LPT (3 Nm), and either a long build-up time (LBT) (250 ms) or a short build-up time (SBT) (50 ms) on a vertical work surface. All subjects were inexperienced tool operators. A SIOUX pistol grip nutrunner was used in this experiment. Nutrunner weight was 4.2 kg with a free running speed of 500 rpm and a target torque of either 3 Nm or 9 Nm. The same tool was used for both high and low torque conditions and this was achieved by use of different springs.

Mechanical and physiological variables were measured before tool use, immediately following tool use and 24 h later. Mechanical measures included upper limb stiffness, damping and effective mass. Physiologic measures included forearm circumference measurement and isometric MVC. Sesto (2003) found good test–retest reliability with controls demonstrating less than a 5% difference in mechanical stiffness 24 h later.

2.3. Nutrunner operation

The nutrunner was operated using a custom threaded fastener joint simulator. Stacked Bellville washers were used to achieve the SBTs and LBTs. A SBT was defined as less than 50 ms and a LBT was defined as more than 250 ms. A torque transducer attached to the nutrunner was used prior to testing to quantify actual peak torque and torque build-up time for each condition.

The power hand tool was operated for 60 min at a rate of four times per min, which typified the duty cycle for power tool operation on an automobile assembly line. A clock was used to pace the subjects and a break of 1 min was given after every 10 min of tool operation. The subjects were positioned so the shoulder, forearm and wrist were in a neutral position and the elbow was flexed at a 90° angle.

2.4. 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^{TM} strength measurement system (Biodex Medical Systems, Shirley, NY, USA). MVC of the forearm supinator muscles was measured isometrically. Two 5 s MVCs, separated by a 1 min rest between exertions were performed before tool use, immediately following tool use 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 power tool use, subjects were given several minutes 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^{TM} 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 could 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/s.

2.5. Forearm circumference

Forearm circumference was measured in order to assess oedema in the muscles involved during tool operation. 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 before tool use, immediately following tool use and 24 h later.

2.6. Upper limb mechanical responses

An apparatus was used consisting of a freely vibrating rotating 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, 2003a,b,c). When the system was set to free vibration it produced a damped sinusoidal 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 apparatus was grasped by the subject. 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 oscillated for 2.5 s. The loading of the hand was a damped sinusoid with a rise time (220 to 330 ms) consistent with impulsive forces found in power hand tools (Oh *et al*. 1997, Oh and Radwin 1998). Handle displacement was measured using a rotational variable differential transformer. The data acquisition sampling rate was 1000 samples per s.

The stiffness, effective mass and damping responses were determined for the combined apparatus and human subject. The variations in these mechanical responses were defined by calculating the change in oscillation frequency and the decay in displacement amplitude (Lin *et al*. 2001, 2003a,b,c). The resulting stiffness, effective mass and damping for the hand-arm system were measured from the change in the system response imposed by the hand – arm.

The dynamic hand tool model from Lin *et al*. (2001, 2003a,b,c) was used to predict handle displacement and handle force using the tool characteristics (i.e. tool dimensions and weight, free running speed) of the SIOUX pistol grip nutrunner that was operated on a vertical surface with a peak torque of either 3 Nm or 9 Nm, and either a SBT (50 ms) or LBT (250 ms) (table 1). The handle responses were predicted for a male having 95th percentile stiffness.

Data were analysed using ANOVA to investigate the significance of the main and interaction effects of peak torque and joint type on mechanical and physiologic measures over time. Mauchly's Test of Sphericity was significant ($p < 0.05$) for forearm circumference and symptom intensity so a multivariate ANOVA was used to evaluate statistical significance. Logarithmic transformation of the mechanical and physiologic variables was performed due to skewness observed in some of the post-tool operation values. *Post hoc* analysis was done using the Bonferroni multiple pair-wise comparison method.

3. Results

Forearm supination static strength, measured before, immediately following and 24 h after tool use, is shown in figure 1. No statistically significant strength differences were observed between any of the groups prior to tool use ($p > 0.05$). Isometric strength decreased following tool use ($p < 0.001$). *Post hoc* analysis showed that a 15% ($p < 0.01$) decrease in average static strength occurred immediately following tool use and a 9% ($p < 0.05$) strength decrease remained 24 h later.

Upper limb mechanical response parameters (stiffness, effective mass and damping) before tool use, immediately following and 24 h later are shown in figures 2 to 4. Statistically significant differences were observed between the LBT and SBT groups for stiffness ($p < 0.05$) and effective mass ($p < 0.05$). The LBT group had a 43% decrease ($p < 0.01$) in average mechanical stiffness and 57% decrease ($p < 0.05$) in effective mass immediately following tool use. The ANOVA results for isometric strength, mechanical stiffness and effective mass are summarized in table 2. No statistically significant differences were observed between any of the groups prior to tool use ($p > 0.05$). The changes in mechanical stiffness (r = 0.089) and effective mass (r = −0.09) were not correlated with changes in static strength.

No statistically significant changes in the average damping constant were observed following exercise for any of the groups ($p > 0.05$). The overall average damping constant before exercise was 0.118 Nm s/rad (SD 0.109) (rad = $360/2\pi°$).

Table 1. Predicted handle force and handle displacement for 95th percentile male

	Handle force (N)	Handle displacement (mm)
High peak torque/Long build-up time (250 ms)	82.48	49.15
Low peak torque/Long build-up time (50 ms)	29.14	13.22
High peak torque/Short build-up time (250 ms)	22.87	5.64
Low peak torque/Short build-up time (50 ms)	1.93	0.24

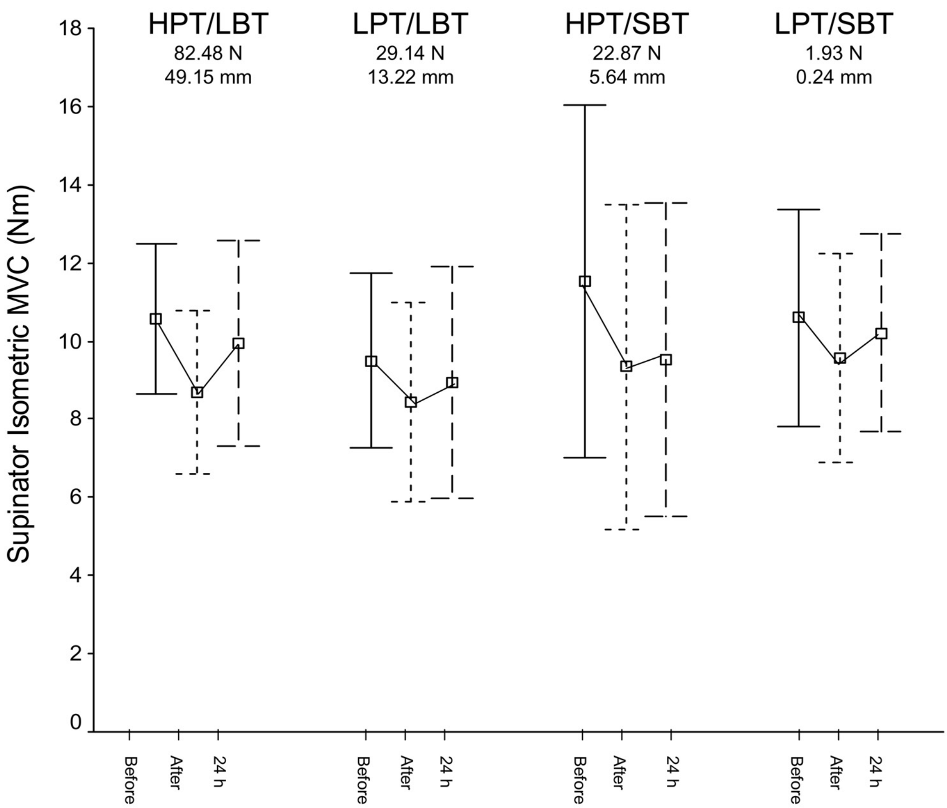

Figure 1. Supinator maximum voluntary contraction (MVC) (mean and SD) before tool use, immediately after tool use and 24 h later. HPT = High peak torque; LPT = low peak torque; LBT = long build-up time; SBT = short build-up time.

Multivariate ANOVA was used to assess change in forearm circumference since Mauchly's Test of Sphericity was significant ($p < 0.05$). Forearm circumference increased following tool operation ($p < 0.05$) for all groups, but less than a 2% change in circumference was observed.

Symptom intensity (0 – 10 visual analogue scale) increased following tool operation ($p < 0.001$) (figure 5). All groups were asymptomatic at baseline. Mauchly's Test of Sphericity was significant ($p < 0.05$) so multivariate ANOVA was used to assess change in symptoms. Average symptom intensity increased from 0 to 1.61 (SD 1.90) ($p < 0.01$) immediately following tool use and remained at 0.690 (SD 1.2) ($p < 0.01$) 24 h later.

Lin's dynamic power hand tool operator model (Lin *et al.* 2001, 2003a,b,c) predicted that handle displacement and handle force for the 95th percentile male was greatest for the LBT (250 ms) (figures 6 and 7). The LBT and HPT had the greatest predicted handle force (82.48 N) and handle displacement (49.15 mm). The greatest decrease in stiffness (50%) was observed following power tool use for the LBT and HPT condition. The LBT and LPT had the next greatest predicted handle force (29.14 N) and handle displacement (13.22 mm). A 35% decrease in stiffness was observed following power tool use for that condition.

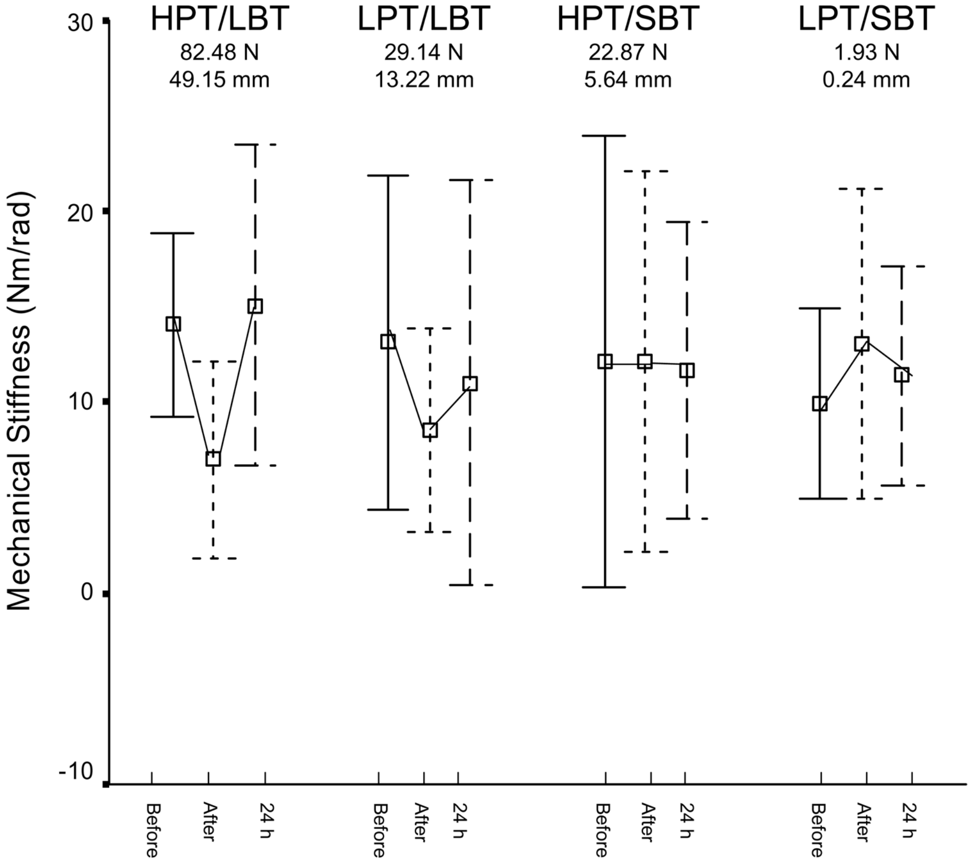

Figure 2. Mechanical stiffness (mean and SD) before tool use, immediately after tool use and 24 h later. rad = $360/(2\pi)^{\circ}$; HPT = high peak torque; LPT = low peak torque; LBT = long build-up time; SBT = short build-up time.

4. Discussion

The study found that an average decrease in mechanical stiffness (43%) and effective mass (57%) was observed immediately following pistol grip nutrunner operation for the LBT (250 ms) for both HPT (9 Nm) and LPT (3 Nm) groups. These finding also concur with earlier findings for college males who had a decrease in mechanical stiffness (51%) and effective mass (43%) following submaximal eccentric exertions (Sesto *et al.* 2005). The current study involved relatively short-term use of power nutrunners by a small group of inexperienced operators. Sesto (2003) observed that symptomatic industrial workers had less mechanical stiffness (46%) and effective mass (59%) than asymptomatic industrial workers. It is not known if the short-term effects observed in the current study are due to similar causes as the industrial worker study.

All groups had less static strength following power tool use, whilst only the LBT groups had less mechanical stiffness and effective mass. The SBT groups had either no change or an increase in mechanical response parameters immediately after tool use. The changes in mechanical stiffness and effective mass were not correlated with changes in

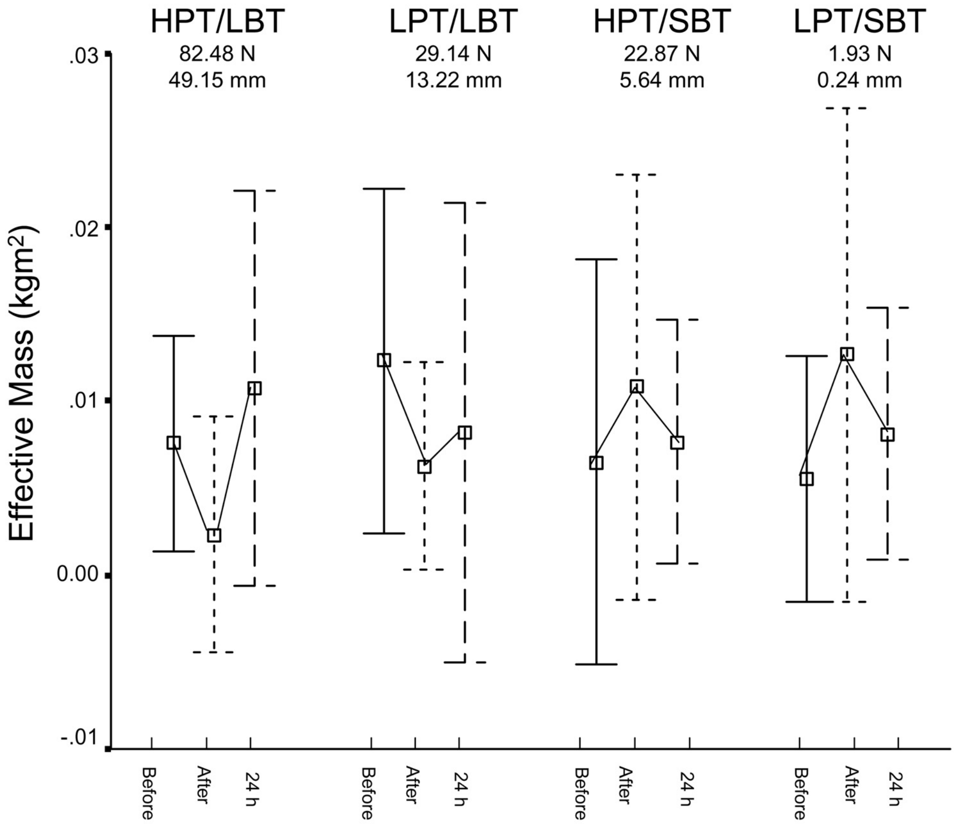

Figure 3. Effective mass (mean and SD) before tool use, immediately after tool use and 24 h later. HPT = High peak torque; LPT = low peak torque; LBT = long build-up time; SBT = short build-up time.

static strength, which indicated that mechanical changes likely did not occur solely due to strength changes or fatigue.

Although power hand tools were operated for a short period of time, it is plausible that the muscle's contractile machinery may have been sub-clinically damaged in the inexperienced operators participating in the study, resulting in a decrease in mechanical response parameters. Previous studies have reported ultrastructural abnormalities within muscle including structural and ultrastructural myofibre damage following eccentric contractions (Lieber *et al*. 1991; Faulkner *et al*. 1993; Friden and Lieber 1998), although these studies involved more intense contraction levels than those associated with power hand tool use. Damage to the contractile machinery may result in less contributing parallel mechanical spring elements, which may play a role in the reduction in muscle stiffness and effective mass observed following power tool use.

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 (National Research Council/Institute of Medicine 2001). If the reduction in mechanical stiffness and effective mass were

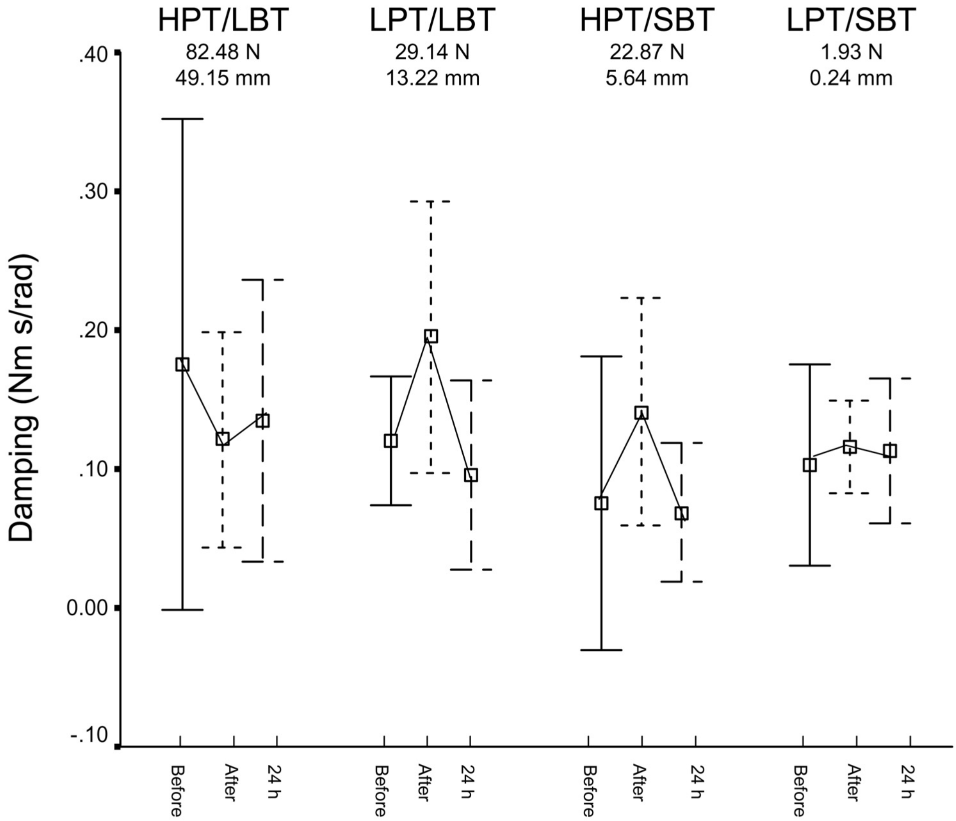

Figure 4. Damping (mean and SD) before tool use, immediately after tool use and 24 h later. rad = $360/(2\pi)^{\circ}$; HPT = high peak torque; LPT = low peak torque; LBT = long build-up time; SBT = short build-up time.

Table 2. ANOVA summary for maximum voluntary contraction (MVC) and mechanical responses (stiffness and effective mass)

		MVC		Stiffness		Effective mass	
Effect	d.f.	MS	F	MS	F	MS	F
Time	2	0.221	13.365†	0.011	1.511	0.0006	0.062
Time x Torque	2	0.0230	1.389	0.007	0.886	0.004	0.423
Time x Build-up	2	0.0037	0.226	0.030	3.920*	0.031	3.208*
Time x Torque x Build-up	2	0.0148	0.892	0.003	0.449	0.0041	0.428
Error	50	0.0166		0.008		0.0096	

d.f. = degrees of freedom; MS = mean squares; F = f statistics; $*p < 0.05$; $\dagger p < 0.01$.

attributed to low level eccentric exertions accompanying power tool use of sufficient intensity to produce damage, it may be a precursor to the development of disorders.

Symptom intensity increased from 0 to 1.61 (SD 1.90) immediately following tool use and remained at 0.690 (SD 1.2) 24 h later. It is notable that the LBT groups, which had

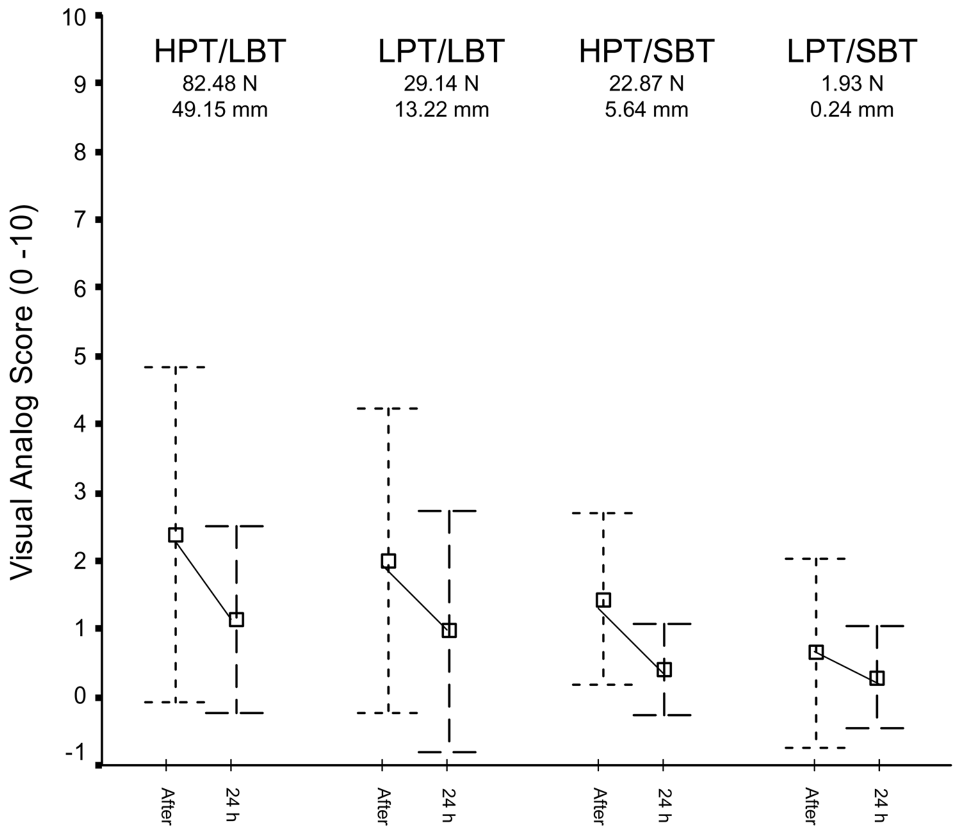

Figure 5. Visual analogue scale (mean and SD) immediately after tool use and 24 h later. HPT = High peak torque; LPT = low peak torque; LBT = long build-up time; SBT = short build-up time.

the greatest decrease in mechanical response parameters, also had the greatest increase in symptoms.

The hypothesis that LBT was associated with reduced mechanical response parameters than SBT was supported. HPT, *per se*, was not associated with these changes. This outcome is partially explained by the mechanical model of the human tool operator developed by Lin *et al.* (2001). The tool parameter values of peak torque (3 Nm and 9 Nm) and build-up time (50 ms and 250 ms) were entered into Lin's model and the predicted handle force and displacement values were determined for the 95th percentile male stiffness. The subjects assigned the greatest predicted handle force and displacement, the LBT groups, had the largest decreases in mechanical stiffness and effective mass. They also had the largest increase in symptom intensity. The HPT/LBT group had the largest predicted handle force and displacement, 82.48 N and 49.15 mm respectively, which correlated with the greatest decrease (50%) in mechanical stiffness (figures 6 and 7). The LPT/LBT group had the next largest predicted handle force (29.14 N) and predicted handle displacement (13.22 mm) and a 35% decrease in stiffness following power tool use. Therefore, larger predicted handle forces and displacements were correlated with increased symptoms and decreased mechanical stiffness and effective mass.

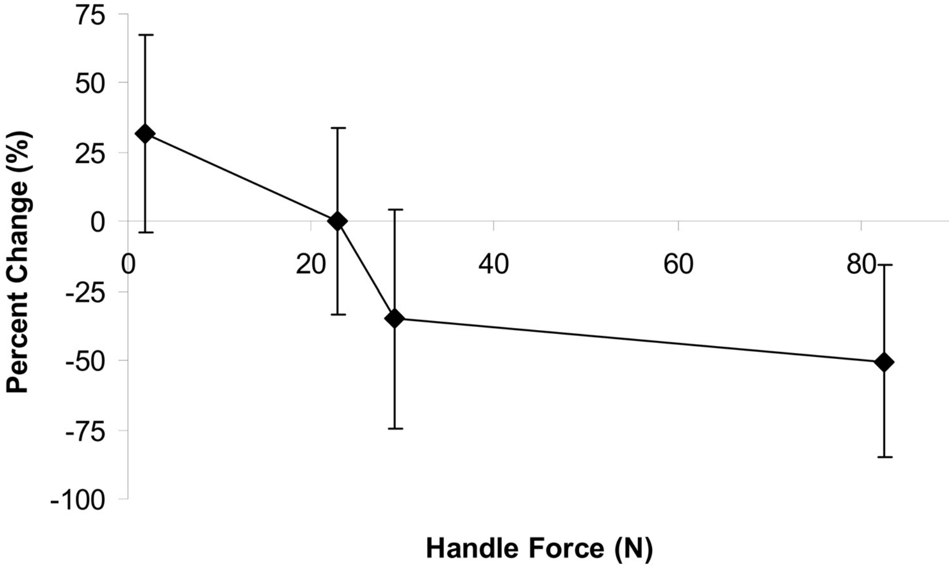

Figure 6. Percent change in stiffness from before tool use to immediately following tool use for predicted handle force (N) (mean and SD).

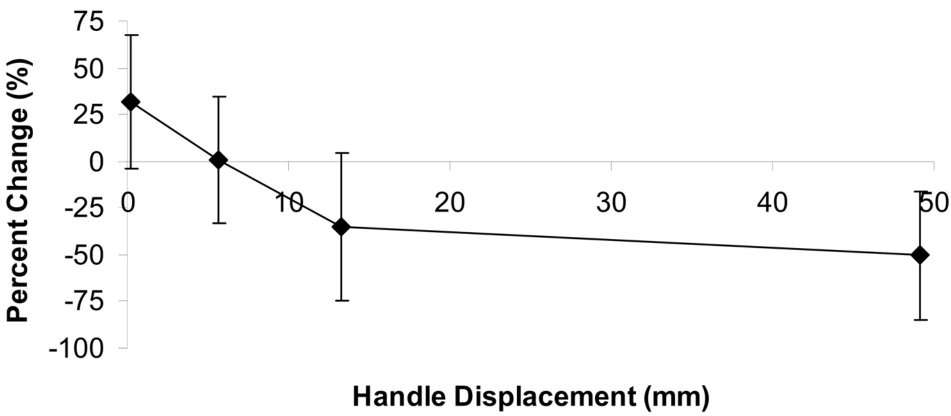

Figure 7. Percent change in stiffness from before tool use to immediately following tool use for predicted handle displacement (mm) (mean and SD).

A limitation of this study was that subjects were inexperienced tool operators. It is not known if similar mechanical differences are observed in experienced tool users operating tools under similar conditions in an occupational setting. The majority of subjects recovered to their initial mechanical response parameters 24 h after tool use, which indicated that the decrease in mechanical response parameters was only short term, although this may be due in part to operating a power tool for just a short duration (60 min). The effect of longer tool use is not known.

Another limitation of this study is the small sample size. Subjects were randomly assigned to groups but three of the four participants with the greatest isometric MVC were by chance assigned to the HPT/SBT group, which had the greatest isometric MVC (11.5 Nm). Therefore a 16% difference exists between the pre-exercise group with the greatest isometric MVC and the group with the lowest isometric MVC, which may be a result of the small number of subjects in each group.

In summary, this research leads to a better understanding of power hand tool conditions that are potentially damaging. It is anticipated that short-term outcomes measured in this study may lead to long-term disorders.

5. Conclusions

Changes in mechanical response parameters were observed for inexperienced power hand tool users following short duration tool operation. An average decrease in stiffness (43%) and effective mass (57%) immediately followed pistol grip nutrunner operation for the long torque build-up time (250 ms) using either the HPT (9 Nm) or LPT (3 Nm) tools. The groups with the greatest predicted handle forces and displacements had the largest decrease in mechanical stiffness immediately after tool use but recovery occurred in 24 h. If this short-term reduction in capacity occurred in the workplace it can increase exposure to forces and may lead to long-term effects.

Acknowledgements

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