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Upper Limb Dynamic Responses to Impulsive Forces for Selected Assembly Workers

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This study evaluated the upper limb, dynamic, mechanical response parameters for 14 male assembly workers recruited from selected jobs based on power tool use. It was hypothesized that the type of power tool operation would affect stiffness, effective mass, and damping of the upper extremity; and workers with symptoms and positive physical examination findings would have different mechanical responses than asymptomatic workers without physical examination findings. Participants included operators who regularly used torque reaction power hand tools, such as nutrunners and screwdrivers, and nontorque reaction power hand tools, such as riveters. The mechanical parameters of the upper limb were characterized from the loading response of an apparatus having known dynamic properties while worker grasps an oscillating handle in free vibration. In addition, all workers underwent a physical examination, magnetic resonance imaging, and completed a symptom survey. Workers were categorized as controls or cases based on reported forearm symptoms and physical exam findings. A total of seven workers were categorized as cases and had less average mechanical stiffness (46%, $p < 0.01$), damping (74%, $p < 0.01$), and effective mass (59%, $p < 0.05$) than the seven workers categorized as controls. Magnetic resonance imaging (MRI) findings suggestive of muscle edema were observed for two workers classified as cases and who regularly used torque reaction power tools. No MRI enhancement was observed in the seven subjects who did not regularly use torque reaction power tools. The ergonomic consequences of less stiffness, effective mass, and damping in symptomatic workers may include reduced capacity to react against rapidly building torque reaction forces encountered when operating power hand tools.

Keywords forearm, magnetic resonance imaging, mechanical model, power tool use, stiffness, work-related musculoskeletal disorders

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Eccentric exertions (muscle lengthening contractions) can occur in industrial work, particularly with power hand tools (e.g., nutrunners) when rapidly rising tool-generated forces exceed the tool operator's capacity to react against them.(1−3) Torque-producing power hand tool operators initially overcome the tool reaction force with an isometric or concentric (muscle shortening) exertion, but as the tool force rapidly increases, the operator may be overcome by the tool, which would result in upper limb motion in opposition to muscle contraction. Conversely, non-torque-producing power hand tools (e.g., riveters) involve operator exertions but do not require the operator to react against rapidly building forces. Lin et al.(4) reported 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 mechanical(5,6) and anatomical(7) effects on muscle. Prior research has reported that the severity of injury is greatest following eccentric exertions than isometric or concentric exertions.(8,9)

Dynamic mechanical properties of stiffness, effective mass, and damping are related to a muscle's capacity to react to rapid forceful loading, resulting in increased strain of the muscle. These properties are important for function since they counteract the effects of applied loads.(10−14) Quantification of muscle and tendon stiffness in the clinical world 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.(10,11) Mechanical stiffness associated with active muscle force in biomechanics is important in the normal control of posture and movement.(10−13) 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. Damping is important for postural maintenance control when reacting to external perturbations, and an increase in muscle tension has been found to affect muscle damping in the lower extremity.[12,14,15] Damping also dissipates energy of the system.

Anatomical changes, including edema in muscles following eccentric exertions, have been measured with magnetic resonance imaging (MRI) using T_2 weighting, which is related to muscle water concentrations.[7,16–20] Sesto et al.[7] reported that the average supinator T_2 relaxation time following submaximal eccentric exercise of these muscles for five volunteers increased 22% ($p < 0.05$) 24 hours after exercise. These effects were not observed for the nonexercised muscles. Evans et al.[16] also reported the appearance of muscle edema accompanying submaximal eccentric exertions.

Our laboratory has developed an instrument to quantify dynamic mechanical properties of the upper limb.[4,21–23] The 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 properties (stiffness, damping, and effective mass), any change in the system response can be attributed to the person coupled to the handle. This apparatus was employed in the current study to investigate the mechanical properties of the upper extremity of assembly workers.

It is unknown whether long-term power tool use affects the muscle in the same manner as submaximal eccentric exercise. Research to date has investigated anatomical and mechanical changes in individuals exposed to varying intensities of short duration eccentric exercise.[5–7,11,16,18] However, none of these studies involved experienced industrial power hand tool operators. It is therefore not known whether similar findings occur in workers who are periodically exposed to regular eccentric activity through power hand tool use over longer durations in the workplace. It is plausible that the physical demands associated with torque-producing power hand tool operation have a detrimental impact on the musculoskeletal tissue in the forearm and hand, which in turn can affect mechanical responses similar to what occurs following eccentric exercise. Workers with upper extremity symptoms and physical examination findings may have sustained tissue injury that could also affect the mechanical responses.

This experiment investigated dynamic mechanical responses to impulsive forces for experienced industrial workers. Employees were recruited from selected jobs that required use of power hand tools. They were stratified on power hand tool use, torque reaction (TR) power hand tool users, and nontorque reaction (NTR) power hand tool users. Participants completed a self-reported symptom questionnaire and underwent a physical examination of the upper extremities. Employees were classified as case or control based on physical examination findings and reported symptoms. It was hypothesized that TR power hand tool users had different upper limb mechanical responses than NTR power hand tool users, and employees who were cases had different upper limb mechanical responses than employees who were controls.

METHODS

Subjects

A total of 21 employees from a U.S. appliance manufacturer volunteered for the experiment. A self-report, general health status and symptom questionnaire was administered to all subjects immediately prior to testing. Four subjects reporting pre-existing medical confounders (e.g., thyroid problems, rheumatoid arthritis, upper extremity surgeries) were excluded. All subjects underwent a standard screening exam by an MRI technologist prior to imaging. Subjects reporting a history of orbital metal fragments, working with metal shavings without appropriate eye protection, or history of embedded metal were excluded due to contraindications for MR imaging. Three subjects were excluded due to inability to undergo or complete MRI. A total of 14 employees participated in the experiment.

All subjects were healthy right-handed male workers recruited from jobs based on the use of impulsive force generating power tools. The average age was 37.5 years (standard deviation [SD] = 9.73) and the age range was 22 to 52 years. The employees worked for their current employer an average of 12.9 (SD = 8.83) years, with a range of 3 to 29 years. The average time employees worked in their current position was 5.51 years (SD = 8.07), with a range of 0.1 to 24 years. Informed consent was obtained in accordance with the University of Wisconsin guidelines for the protection of human subjects.

Power Hand Tool Activity

Subjects were recruited from jobs that differed in tasks and the type of power hand tool used but had similar hand activity levels. Jobs were classified as those involving regular use of TR pistol grip power screwdrivers or jobs that contained similar intensity hand work but used NTR pistol grip tools. Hand activity levels (HAL) were analyzed for all identified jobs using the American Conference of Governmental Industrial Hygienists (ACGIH®) threshold limit value (TLV®)[24] to compare intensities of hand work. The scale ranges from 0 to 10 (0 corresponds to hands idle most of the time, no regular exertions; and 10 corresponds to rapid steady motion or continuous exertion, difficulty keeping up). The NTR power hand tool use group had an average HAL of 4.0 (SD = 0.77), and the TR power hand tool use group had an average HAL of 4.4 (SD = 0.53).

Symptom Questionnaire

A self-report symptom questionnaire adapted from the National Institute for Occupational Safety and Health (NIOSH, 1993) was administered and included questions about upper extremity symptoms (numbness, pain, tingling, aching), the type of work performed, and past medical history (diabetes, arthritis, thyroid disease, ruptured cervical disk, and renal failure). Subjects were also questioned about time frame for symptoms, frequency, and pattern of occurrence. The questionnaire also included questions about demographics, including gender, age, handedness, and job classification.

Physical Examination

All subjects underwent a physical examination conducted by a qualified physical therapist that was blinded to job, tool use, and other study outcomes. The examination focused on the upper limbs, shoulder, and neck, which included general range of motion, strength assessment, and provocative tests (i.e., Speed's and Phalen's tests), to exclude individuals with potentially confounding conditions (e.g., carpal tunnel syndrome). A similar examination protocol has been used in previous research with industrial participants.[25]

Experimental Design

Subjects were classified by power hand tool use (torque reaction versus nontorque reaction power tool) and symptom questionnaire and physical examination results (case versus control). Based on power hand tool use, seven subjects were classified as torque reaction power hand tool operators and seven subjects were classified as nontorque reaction power hand tool operators. Subjects were classified as a case or control based on physical examination findings and reported symptoms. Subjects had to have both positive physical exam findings and report pain and discomfort in the forearm area to be considered a case. If only one variable was positive (physical examination or symptoms), the subjects were considered a control. Symptoms had to occur at least monthly, with at least moderate intensity, and had to occur in the forearm to be positive. Pain with either supinator resistance or tenderness over the lateral forearm area was required for positive physical exam findings.

Subjects were tested on the apparatus described previously[4] to measure mechanical stiffness, damping, and effective mass properties, and they also underwent an MRI.

Strength Assessment

Strength testing was performed using a Biodex strength measurement system (Biodex Medical Systems, Inc., Shirley, N.Y.). The subject was seated and the shoulder, forearm, and wrist were in a neutral position and the elbow was flexed 90°. The upper arm was stabilized against the body by a strap to prevent substitution or unwanted movement. The MVC of the forearm supinator muscles was measured isometrically. Two 5-sec MVCs, separated by a 1-min rest between exertions were performed. The second to fourth seconds were averaged for each MVC exertion. The average of the two MVC exertions was used. MVC data were always collected prior to mechanical testing on the mechanical apparatus. Following strength testing, subjects were given 3 min rest prior to testing on the mechanical 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, Austin, Texas) with a sampling rate of 100 samples/sec.

Dynamic Response Parameter Measurements

The apparatus used for measuring subject mechanical properties contained a 4 cm diameter handle that was grasped in the hand with a neutral wrist posture and oriented so that it aligned the forearm axis of rotation with the axis of rotation of a freely vibrating mechanical system. This position isolated the forearm pronator and supinator muscles and minimized substitution by other muscles. The upper arm was stabilized against the body by a strap to prevent substitution or unwanted movements.

The free vibration mechanical system contained a fixed stiffness (k_0), negligible viscous damping, and an inertial mass (J_0) that was varied to achieve different free-vibration oscillation responses at various frequencies[4,21–23] (Figure 1). The apparatus spring was preloaded and released to set the

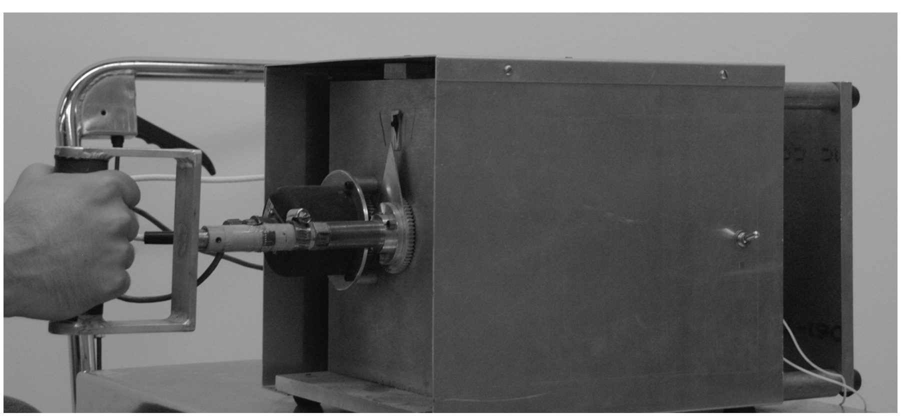

FIGURE 1. The dynamic mechanical property test apparatus consists of a torsional spring and mass system. An angle transducer measures handle rotation. Dynamic parameters (stiffness, effective mass, and damping) of the subjects are determined by the change in its free vibration response of the known system when the handle is grasped.

system into free vibration. When released, the apparatus produced a damped sinusoid oscillation at a frequency of 4 Hz with a rise time (220 to 330 millisec), which was consistent with impulsive forces found in industrial power hand tools.[26,27] The oscillation decayed in 2.5 sec. Handle rotation displacement was measured using a rotational variable differential transformer. The data acquisition sampling rate was 1000 Hz.

When the subject externally loads the apparatus by grasping the handle, the sum of the contributions of the apparatus and the operator define the physical characteristics of the combined mechanical system. Subjects were instructed to grasp the handle as hard as they could to inhibit oscillations. The dynamic mechanical parameters that describe the subject's influence on the apparatus when a subject opposes free vibration (k_{subject}, J_{subject}, c_{subject}) were identified by measuring the resulting rotational displacement response, $\theta\ (t)$. The variations between the observed mechanical response and the known mechanical system response were used to identify the subject's mechanical parameters by calculating the changes in oscillation frequency (Hz) and the displacement decay amplitude (peak to peak angle). The responses were recorded for three different inertial masses.

The equation of motion that describes the angular displacement $\theta\ (t)$ of a freely vibrating single degree of freedom mechanical system is a function of its dynamic mechanical properties (J = mass moment of inertia, c = damping constant, k = stiffness) such that:

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

The natural frequency of the system ω_n is:

$$\omega_n = \sqrt{\frac{k}{J}} \quad \textbf{(2)}$$

The damping ratio of the system ζ is:

$$\zeta = \frac{c}{2J\omega n} \quad \textbf{(3)}$$

The relationship between the mass moment of inertia of the effective mass J_{mass}, resulting from loading the apparatus inertial mass J_0 by the subject's inertial mass, J_{subject}, and the natural frequency ω_n is given in Eq. 4. The relationship between the mass moment of inertia of the effective mass J_{mass}, the natural frequency ω_n and damping ratio ζ is provided in Eq. 5.[4]

$$J_{\text{mass}} = k\frac{1}{\omega_n^2} - (J_0 + J_{\text{subject}}) \quad \textbf{(4)}$$

$$J_{\text{mass}} = c\left(\frac{1}{2\omega_n\zeta}\right) + \text{constant} \quad \textbf{(5)}$$

The torsional stiffness when the subject loads the apparatus (k), is therefore obtained from the linear regression slope of the oscillation frequency for the various applied masses plotted against the effective mass J_{mass} in the form of Eq. 4. The inertial mass ($J_0 + J_{\text{subject}}$) is the intercept. The torsional damping constant when the subject loads the apparatus (c) is the resulting linear regression slope of the oscillation frequency plotted against the damping ratio for the various applied masses using Eq. 5. Based on these parameters, the equivalent stiffness, mass and damping constant for the subject can be estimated. A more detailed description is provided in Lin et al.[4]

This apparatus has been used for model parameter identification previously by Lin et al.[4] and the correlation between measured and predicted frequency was 0.9. Sesto et al.[5] found good test-retest reliability with controls demonstrating less than a 5% difference 24 hours later.

Magnetic Resonance Imaging

Muscle edema was assessed using T_2-weighted MRI because it is highly sensitive to the accumulation of fluid that accompanies muscle injury.[17,20] Imaging was performed on a 1.5 T GE CVi scanner (General Electric, Waukesha, Wisc.). Subjects were scanned in a supine position with each arm imaged separately. A four-channel phased array coil configured as an arm wrap was used for an increased signal to noise ratio (SNR). Axial slices with a 7 mm thickness and separated by a 3-mm gap were obtained 3 cm proximal to the radial head in the elbow joint and extending distally 20 cm using the following parameters: fast spin-echo pulse sequence, 26 cm FOV, 256×256 imaging matrix, 4 sec repetition time (TR), superior and inferior spatial saturation, and fat suppression. Echo times for the proton density, moderate T_2, and heavily-weighted T_2-weighted images were 15, 45, 75, and 105 millisec, respectively.

A musculoskeletal radiologist blinded to subject job categorization and symptoms reviewed all scans and identified via visual inspection scans in which supinator enhancement existed.

Statistical Analysis

The data were analyzed for differences between subjects classified as cases or controls, as well as differences between TR and NTR power tool use in this cross-sectional study. A univariate analysis of variance was used for evaluating statistical significance of the mechanical and physiological variables. Only the dominant side was analyzed. The mechanical response data were also analyzed for differences between the industrial workers and college students from an earlier study who had performed eccentric exertions. A univariate analysis of variance was also used for evaluating statistical significance of the mechanical variables.

RESULTS

A total of 14 employees participated in the experiment. Based on the symptom questionnaire and physical examination findings, a total of seven subjects were categorized as cases and seven subjects were categorized as controls. Four cases were NTR power tool uses and three cases were TR power tool users. Three controls were NTR power tool users and four controls were TR power tool users. No difference in age was observed for power tools groups (TR versus NTR) or case-control groups ($p > 0.05$). There was also no difference

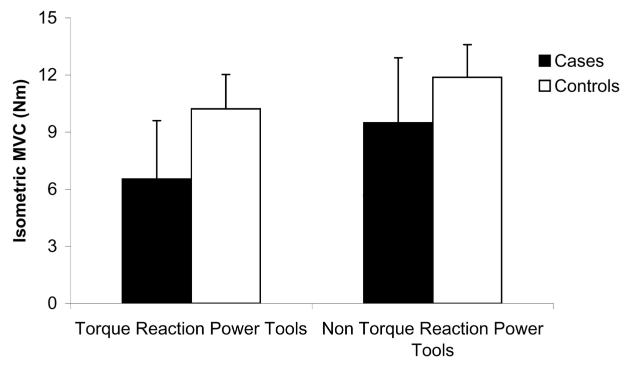

FIGURE 2. Isometric MVC (mean and SD) for case and control groups in the torque reaction and nontorque reaction tool groups

in length of time in current job for power tool groups ($p = 0.06$) or case-control groups ($p > 0.05$). The average time in the current job was 17 (SD = 25.26) months for TR power tool users and 115 (SD = 118.44) months for NTR power tool users.

The isometric supinator MVC for symptom status and tool use is plotted in Figure 2. No differences in isometric MVC between groups for either symptom status ($p = 0.06$) or type of tool use were observed ($p = 0.14$). Isometric MVC was 24% less for the symptomatic than asymptomatic group and 18% less for TR than NTR tool user group.

Dynamic response parameters (stiffness, effective mass, and damping) by case-control status and tool use are shown in Figures 3 to 5. Significant differences were observed between the case and control groups for stiffness ($p < 0.05$), damping ($p < 0.01$), and effective mass ($p < 0.05$). All mechanical response parameters for the case group were less than the control group. The case workers had 46% less stiffness, 59% less effective mass, and 74% less damping than the control group. No differences in mechanical responses were observed for the effect of power tool type (TR and

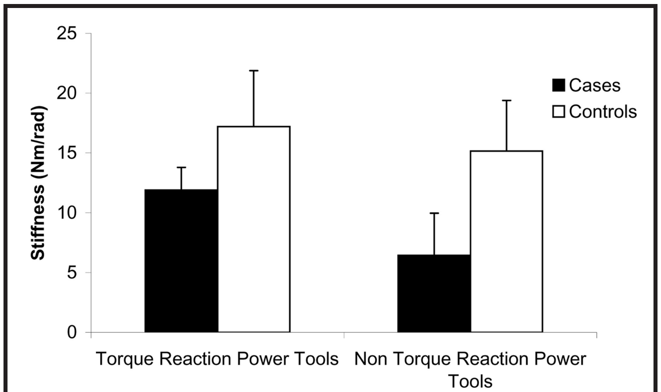

FIGURE 3. Mechanical stiffness of the upper limb (mean and SD) for case and control groups in the torque reaction and nontorque reaction tool groups

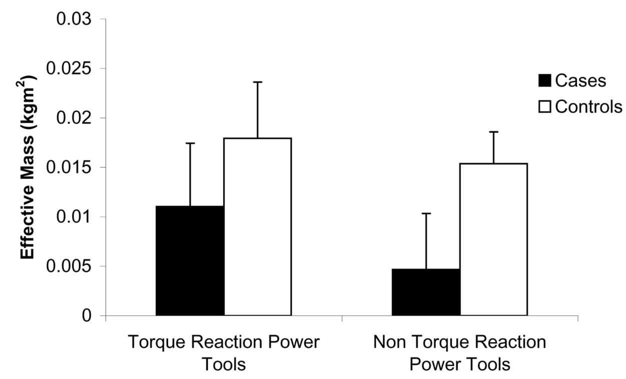

FIGURE 4. Effective mass of the upper limb (mean and SD) for case and control groups in the torque reaction and nontorque reaction tool groups

NTR) (<0.05). Mechanical stiffness ($r = .22$), effective mass ($r = .35$), and damping ($r = .26$) were not correlated with static strength.

Two of 14 MRI scans were identified by a blinded musculoskeletal radiologist as having supinator enhancement in the dominant arms. Axial slices of the forearm from the two individuals with enhancement are shown in Figure 6A; axial slices from two individuals without enhancement are shown in Figure 6B. Inspecting the slice visually, the two darkened areas are the bones of the forearm and the supinator muscle is located around the superior bone, the radius. With increased edema, the supinator muscle appears brighter in the T_2 weighted image and is referred to as being enhanced. The two individuals with enhancements were TR power hand tool users, and both were cases.

Average isometric supinator MVC for the subjects who demonstrated MRI T_2 enhancement of the supinator muscle and who were TR power tool users was 53% less than the nonenhanced TR power tool users ($p < 0.05$). The TR power tool users who did not demonstrate T_2 enhancement had an average isometric supinator MVC of 10.22 Nm (SD = 1.81),

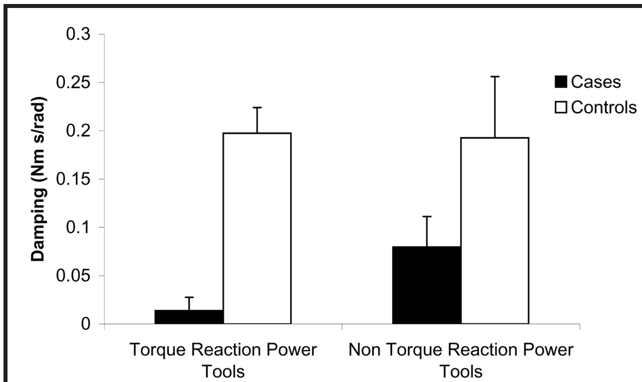

FIGURE 5. Damping of the upper limb (mean and SD) for case and control groups in the torque reaction and nontorque reaction tool groups

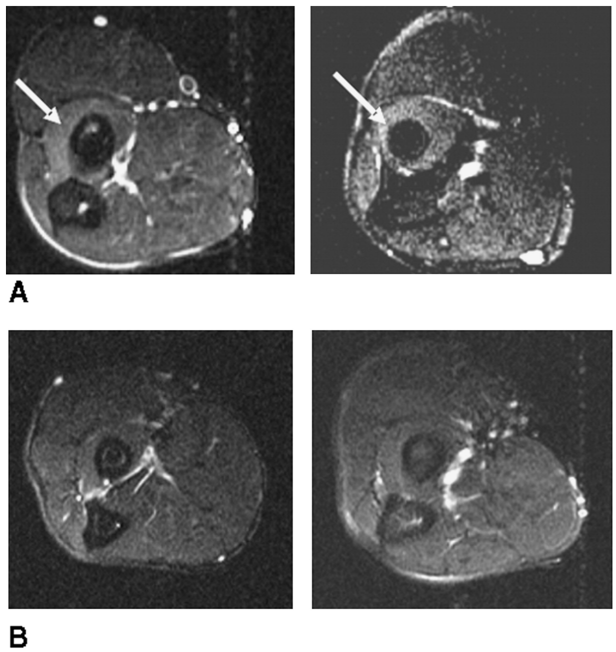

FIGURE 6. (A) MRI T2 weighted image shows enhancement (indicated by lighter area shown by arrow) in the supinator region in the dominant forearm for two symptomatic workers who use TR tools. (B) MRI T2 weighted image does not show enhancement in the supinator region of the dominant forearm for two asymptomatic workers who use TR tools.

whereas the TR power tool users experiencing T_2 enhancement had an average isometric supinator MVC of 4.76 Nm (SD = 0.23). No statistically significant differences in mechanical response parameters were observed between the TR power tool users who did or did not experience T_2 enhancement ($p > 0.05$).

The mechanical response parameters of the industrial workers were compared with those of college males who previously performed submaximal eccentric exertions in the laboratory at a similar magnitude and velocity to industrial power hand tools.[7] Prior to exercise, the college males had greater stiffness (62%) and effective mass (70%) than the case group ($p < 0.05$) in the current study, but they were not different from the control group. The control group had 68% greater damping than the college students ($p < 0.05$), but there was no difference in damping between college students and the case group. A difference in strength was not observed between the college students and industrial participants ($p > 0.05$).

DISCUSSION

This study investigated dynamic response parameters for workers who regularly used industrial power hand tools. It was hypothesized that the type of power tool operation would affect dynamic response properties of the upper extremity. It was also hypothesized that workers with symptoms and positive physical examination findings (cases) would have different dynamic response parameters than asymptomatic workers without physical examination findings (controls).

Average isometric MVC was 24% less for the case group than the control group, but this difference was not statistically significant possibly due to the great variability among subjects and the small sample size. The case group had markedly less mechanical stiffness (46%), damping (74%), and effective mass (59%) than the control group.

These findings concur with short-term effects from repetitive eccentric exertions in our previous study where college males who performed submaximal eccentric exertions in the laboratory at a similar magnitude and velocity to industrial power hand tools had significantly less mechanical stiffness (51%) and effective mass (48%) following eccentric exercise.[7] Prior to exercise, the college males had greater stiffness (62%) and effective mass (70%) than the case group ($p < 0.05$) in the current study, but they were not different from the control group. Conversely, the control group had greater damping than the case group (74%) and college students prior to exercise (68%), but there was no difference in damping between college students and case workers. A difference in strength was not observed between the college students and industrial participants ($p > 0.05$).

Differences were not observed in dynamic response parameters or isometric MVC between TR power tool and NTR power tool users. This may be due to the small sample size or relatively small differences in repetition and exertion between both power hand tool user groups. The NTR power tool use group had an average HAL of 4.0 (SD = 0.77) and the TR power tool use group had an average HAL of 4.4 (SD = 0.53). These differences may not have been sufficient to contribute to differences in the mechanical parameters or isometric MVC.

A notable finding was that a difference in dynamic response properties was observed between case and control groups, whereas strength differences were not observed. It did not appear that the differences in mechanical parameters between case and control groups were due to strength since the mechanical response of stiffness ($r = .22$), effective mass ($r = .35$), and damping ($r = .26$) were not correlated with static strength. This finding was also observed in a prior experiment where subjects in both isometric and eccentric exercise groups had less static strength immediately following exercise, whereas changes in mechanical properties were observed only in the subjects performing eccentric exercise.[5]

Another distinction between our earlier studies involving asymptomatic college participants was that an effect on damping was not observed.[5,7] This finding was observed only for the control group having larger damping than the case group and college participants.

Previous studies have observed ultrastructural abnormalities within muscle following eccentric contractions.[8,9,28] Damage to contractile machinery may result in fewer contributing parallel mechanical spring elements during loading, which may play a role in the reduction in muscle mechanical properties observed in symptomatic workers with physical examination findings. Furthermore, these reductions in mechanical properties could result in greater handle force and displacement during tool operation, which may in turn cause an increased strain on the tissue.[23] The actual pathophysiological mechanisms are not yet known; however, the results of the current study may provide new insight into the complex mechanisms involved in the injury process.

Two of 14 MRI scans had T_2 supinator enhancement, which is highly sensitive for muscle edema. This finding concurs with others that have used MRI to measure edema following eccentric muscle activity.[17,19] Both individuals with supinator enhancement were TR power hand tool users, and both were members of the case group.

The present study demonstrated that for a small sample of assemblers, the case group had less mechanical stiffness, damping, and effective mass than the control group. It is not known whether the mechanical properties observed in the case group were present prior to development of symptoms or if this is a consequence of injury or repetitive activity. This study leads to the hypothesis that the physical demands associated with torque producing power tool operation and other types of exertions associated with work activities have a detrimental impact on the musculoskeletal tissues of the upper extremity, which in turn can affect mechanical responses and muscle anatomy.

The ergonomic consequences of less stiffness, effective mass, and damping in symptomatic workers may include less capacity to react against rapidly building torque reaction forces encountered when operating power hand tools, such as nutrunners.[4,21–23] Lin et al.[23] have shown that less mechanical stiffness resulted in greater forces acting against the hands and greater hand displacement during nutrunner use. Applying the reduced mechanical response parameters from the case group in the current study to the average mechanical responses for an operator using a pistol grip tool on a vertical surface, Lin's model predicted that the tool displacement would increase by more than 100%, and that the resulting reaction force would increase by 8% 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 and increased force may have adverse long-term effects on operator safety, particularly for large level exertions that are frequent and forceful.

CONCLUSION

Industrial employees with upper limb symptoms and positive physical examination findings, regardless of tool use, had less dynamic response parameters of the corresponding upper limb than controls. The cases had 46% less mechanical stiffness, 74% less damping, and 59% less effective mass than the control group. Two subjects in the tool use group who were also cases had T_2 weighted MRI enhancement and muscle edema. No subjects in the non-tool-use group had MRI changes in the dominant arm. The decreased mechanical response properties observed in case group subjects may result in greater power hand tool handle reaction forces and displacements during tool operation with resulting increased stress on the upper limb.

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REFERENCES

1. **Armstrong, T., C. Bir, J. Foulke, B. Martin, L. Finsen, and G. Sjogaard:** Muscle response to simulated torque reations of hand-held power tools. *Ergonomics 42*:146–159 (1999).
2. **Oh, S.A., R.G. Radwin, and F.J. Fronczak:** A dynamic mechanical model for hand force in right angle nutrunner operation. *Hum. Factors 39*:497–506 (1997).
3. **Oh, S.A., and R.G. Radwin:** The influence of target torque build up time on physical stress in right angle nutrunner operation. *Ergonomics 41*:88–206 (1998).
4. **Lin, J.L., R.G. Radwin, and T.G. Richard:** Dynamic biomechanical model of the hand and arm in pistol grip power handtool usage. *Ergonomics 44*:295–312 (2001).
5. **Sesto, M.E., R.G. Radwin, T.M. Best, and T.G. Richard:** Upper limb mechanical changes following short duration repetitive eccentric exertions. *Clin. Biomech. 19*:921–928 (2004).
6. **Nosaka, K., and M. Newton:** Difference in the magnitude of muscle damage between maximal and submaximal eccentric loading. *J. Strength Condition. Res. 16*:202–208 (2002).
7. **Sesto, M.E., R.G. Radwin, W.F. Block, and T.M. Best:** Anatomical and mechanical changes following repetitive eccentric exertions. *Clin. Biomech. 20*:41–49 (2005).
8. **Lieber, R.L., T. McKee-Woodburn, and J. Friden:** Muscle damage induced by eccentric contractions of 25% strain. *J. Appl. Physiol. 70*:2498–2507 (1991).
9. **Faulkner, J.A., S.V. Brooks, and J.A. Opiteck:** Injury to skeletal muscle fibers during contractions: Conditions of occurrence and prevention. *Phys. Ther. 73*:911–921 (1993).
10. **Kearney R.E., and I.W. Hunter:** System identification of human joint dynamics. *Biomed. Eng. 18*:55–87 (1990).
11. **Leger, A.B., and T.E. Milner:** Passive and active wrist joint stiffness following eccentric exercise. *Eur. J. Appl. Physiol. 82*:472–479 (2000).
12. **Milner, T.E., and C. Cloutier:** Damping of the wrist joint during voluntary movement. *Exp. Brain Res. 122*:309–317 (1998).
13. **Milner, T.E., C. Cloutier, A.B. Leger, and D.W. Franklin:** Inability to maximally activate muscles during co-contraction and the effects of joint stiffness. *Exp. Brain Res. 107*:293–305 (1995).
14. **de Vlugt, E., A.C. Schouten, and F.C. van der Helm:** Adaptation of reflexive feedback during arm posture to different environments. *Biol. Cybern. 87*:10–26 (2002).
15. **Wachter, K.C., H.E. Kaeser, H. Guhring, T.M. Ettlin, P. Mennet, and W. Muller:** Muscle damping measured with a modified pendulum test in patients with fibromyalgia, lumbago, and cervical syndrome. *Spine 21*:2137–2142 (1996).
16. **Evans, G.F., R.G. Haller, P.S. Wyrick, R.W. Parkey, and J.L. Fleckenstein:** Submaximal delayed onset muscle soreness: Correlations between MRI findings and clinical measures. *Radiol. 208*:815–820 (1998).
17. **Fleckenstein, J.L., P.T. Weatherall, R.W. Parkey, J.A. Payne, R.M. Peshock:** Sports-related muscle injuries: Evaluation with MR imaging. *Radiol. 172*:793–798 (1989).

18. **Foley, J.M., R.C. Jayaraman, B.M. Prior, J.M. Pivarnik, and R.A. Meyer:** MR measurements of muscle damage and adaptation after eccentric exercise. *J. Appl. Physiol. 87*:2311–2318 (1999).
19. **Shellock, F.G., and J.L. Fleckenstein:** Muscle physiology and pathophysiology: Magnetic resonance imaging evaluation. *Semin. Musculoskelet. Radiology 4*:459–479 (2000).
20. **Shellock, F.G., T. Fukunaga, J.H. Mink, and V.R. Edgerton:** Exertional muscle injury: Evaluation of concentric versus eccentric actions with serial MR imaging. *Radiology 179*:659–664 (1991).
21. **Lin, J.L., R.G. Radwin, and T.G. Richard:** A single-degree-of-freedom dynamic model predicts the range of human responses to impulsive forces produced by power hand tools. *J. Biomechan. 36*:1845–1852 (2003).
22. **Lin, J.L., R.G. Radwin, F.J. Fronczk, and T.G. Richard:** Forces associated with pneumatic power screwdriver operation: Statics and dynamics. *Ergonomics 46*:1161–1177 (2003).
23. **Lin, J.L., R.G. Radwin, and T.G. Richard:** Handle dynamics predictions for selected power hand tool applications. *Hum. Factors 45*:645–656 (2003).
24. **American Conference of Governmental Industrial Hygienists (ACGIH®):** *Hand Activity Threshold Limit Value*. Cincinnati, Ohio: ACGIH, 2001.
25. **Sesto, M.E., R.G. Radwin, and F. Salvi:** Functional deficits in carpal tunnel syndrome. *Am. J. Ind. Med. 44*:133–140 (2003).
26. **Oh, S.A., R.G. Radwin, and F.J. Fronczak:** A dynamic mechanical model for hand force in right angle nutrunner operation. *Hum. Factors 39*:497–506 (1997).
27. **Oh, S.A., and R.G. Radwin:** The influence of target torque build up time on physical stress in right angle nutrunner operation. *Ergonomics 41*:188–206 (1998).
28. **Friden, J., and R.L. Lieber:** Segmental muscle fiber lesions after repetitive eccentric contractions. *Cell Tissue Res. 293*:165–171 (1998).