Upper Limb Dynamic Mechanical and Anatomical Properties Among Assembly Operators

Sesto M.E.
Radwin R.G.
Block W.F.
Best T.M.

University of Wisconsin
Madison, WI

This study investigated upper limb mechanical and anatomical properties in assembly workers. Fourteen male assembly workers were recruited from selected jobs including power hand tool users and non-power hand tool users. Active dynamic mechanical properties of the upper extremity were measured using a free vibration apparatus. All workers underwent a physical examination, magnetic resonance imaging and completed a symptom survey. Employees were categorized as asymptomatic versus symptomatic based on reported forearm symptoms and physical exam findings. Symptomatic individuals had 46% less mechanical stiffness and a 59% less mass moment of inertia of the forearm than the asymptomatic group. Workers were stratified based on power tool use and two of the seven subjects who regularly used power nutrunners demonstrated MRI T_2 enhancement, which is indicative of muscle edema. T_2 MRI enhancement was not demonstrated in the seven subjects who did not regularly use power nutrunners.

INTRODUCTION

Industrial power hand tool use is considered a risk factor for work-related musculoskeletal disorders (MSD) because of the repetitive and forceful exertions associated with their use (Armstrong, et al., 1986; Kattel and Fernandez, 1998; Meagher, 1987; Muggleton, et al. 1999). Rotating spindle power hand tools such as nutrunners are commonly used in industries such as automobile assembly, electronics, and appliance manufacturing. VanBergeijk (1987) estimated that 75% of the work force in an automotive assembly plant uses power hand tools. Studies have shown that operating these tools often involves forceful eccentric exertions of the forearm (Oh and Radwin 1997, Oh et al., 1997, Oh and Radwin 1998; Armstrong et al., 1999). Typically, the operator initially overcomes tool generated forces using a concentric exertion, but as the tool force rapidly raises the operator may be overcome by the tool, resulting in upper limb motion in opposition to muscle contraction, producing eccentric muscle exertions.

Changes in muscle tissue following submaximal eccentric exercise have been quantified using magnetic resonance imaging (MRI) (Evans et al., 1998, Foley et al., 1999, Sesto 2002). These were detected as increases in the MR relaxation constant T_2, resulting from edema present in muscle and anatomic distortion. Although not necessarily indicative of muscle injury, other investigators have reported edema accompanying muscle injury (Evans et al., 1998, Foley et al., 1999).

The research to date has investigated mechanical and physiological changes in individuals exposed to varying intensities of short duration eccentric activity. Sesto (2002) found that college males demonstrated a decrease in mechanical stiffness (51%) and inertial mass (48%) following short duration repetitive submaximal eccentric activity. Concurrently, an increase in MRI T_2 enhancement (22%) was observed.

But, none of these studies involved experienced industrial power hand tool operators. It is therefore not known if similar findings occur in workers who are periodically exposed to regular eccentric activity over longer durations in the workplace.

The ergonomic consequences of stiffness and mass moment inertia reductions in symptomatic workers may include decreased ability to control and react against rapidly-building torque reaction forces used when operating power hand tools such as nutrunners (Lin, et al., 2001). This reduction in capacity may have adverse long-term effects on operator safety, particularly for power tools that require large level exertions that are frequent and forceful. Reduced stiffness and inertial mass may also be associated with increased mechanical strain during loading tasks, such as tool operation.

This experiment investigated biomechanical and anatomical properties in industrial workers. Employees were recruited from selected jobs and were stratified on power hand tool usage. It was hypothesized that symptomatic workers demonstrate different mechanical properties and MRI findings than asymptomatic workers.

METHODS

A total of 14 employee volunteers from a US appliance manufacturer participated in the experiment.

Subjects reporting preexisting medical confounders (e.g. thyroid problems, rheumatoid arthritis, upper extremity surgeries) were excluded from testing. The average age was 37.5 years (SD=9.73) and the age range 22-52 years. The employees worked an average of 12.9 (SD=8.83) years with a range of 3-29 years for their current employer. 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. Industrial subjects were healthy right-handed male workers recruited from jobs based on the use of impulsive force generating power tools. A total of seven subjects were power hand tool operators and seven subjects were not.

Informed consent was obtained in accordance with the University of Wisconsin guidelines for the protection of human subjects. A self–reported general health status and symptom questionnaire was administered to all subjects immediately prior to testing.

All subjects underwent a detailed screening exam by an MRI technologist prior to magnetic resonance imaging. Subjects reporting a history of orbital metal fragments, working with metal shavings without appropriate eye protection, or history of embedded metal were excluded.

Hand activity levels were analyzed for all identified jobs using the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (2002) in order to compare intensities of hand work. The scale ranges from 0 to 10. Subjects were recruited from jobs that differed in power hand tool use but had similar hand activity levels (HAL). The non-tool use group had an average HAL of 4.0 (SD=0.77) and the tool use group had an average HAL of 4.4 (SD=0.53).

All subjects completed a symptom questionnaire adapted from NIOSH (1993), which contained questions about symptoms in the upper extremities, the type of work performed, and past medical history (i.e. diabetes, arthritis, thyroid disease, ruptured cervical disk, and renal failure). The questionnaire also included questions about demographics such as gender, age, handedness, and job classification. The questionnaire inquired about upper extremity symptoms such as numbness, pain, tingling, aching, etc.

All subjects underwent a physical examination of the upper limbs, shoulder and neck, which included general range of motion and strength assessment and provocative tests (i.e. Speed's and Phalen's tests). The examination was conducted by a licensed physical therapist with more than fourteen years of experience.

A Biodex™ (Shirley, NY) apparatus was used for isometric strength testing. The shoulder, forearm and wrist were positioned in a neutral position with the elbow flexed at 90°. Two forearm supinator isometric maximum voluntary contractions (MVC) of five-second duration were performed with a one minute rest between exertions.

Subjects were tested on an apparatus designed for measuring mechanical properties of muscles, stiffness, viscous damping and mass moment of inertia. The apparatus was previously developed for measuring the mechanical properties of the forearm by considering it as a single degree of freedom mechanical system (Lin et al., 2001). All subjects had a minimum of a 60-minute rest period following work and testing on the free vibration apparatus.

Muscle edema was assessed through MRI T_2-weighting because it is highly sensitive to the accumulation of fluid that accompanies muscle injury. Imaging was performed on a 1.5 T GE CVi scanner (General Electric Medical Systems, Waukesha, WI). Subjects were imaged in a supine position with each arm imaged separately. An arm wrap coil, which is a 4 phased array coil, was used for an increased signal to noise ratio (SNR).

A musculoskeletal radiologist blinded to subject job categorization reviewed all MRI scans and identified via visual inspection scans in which supinator enhancement existed. Regions of interest (ROI) were selected where visual differences were detected. T_2 relaxation times were determined for these regions of interest by fitting the ROI data from each echo to an exponential curve with MR Vision Software (MR Vision, Inc. Boston, Massachusetts).

The data were analyzed for differences in mechanical and physiological variables based on reported symptoms and physical exam findings. Subjects were categorized as positive symptoms and physical exam findings +(PE/SXS) or negative symptoms and physical exam findings –(PE/SXS). To be symptomatic, subjects needed to have both positive physical exam findings and report symptoms in the forearm area. If only one was positive (physical exam or symptoms), the subjects were considered –(PE/SXS). For symptoms to be defined as positive, they needed to occur at least monthly, with at least moderate intensity, and pain located in the forearm. Either pain with supinator resistance or tenderness over the lateral forearm area was required for positive physical exam findings.

RESULTS

The +(PE/SXS) subjects had an average mechanical stiffness of 8.78Nm/rad (SD=3.98) and demonstrated 46% less stiffness ($F(1,11)=10.327$, $p<.01$) than the – (PE/SXS) group, which had an average stiffness of 16.33Nm/rad (SD=4.26).

The +(PE/SXS) group had an average mass moment of inertia of 0.007 kgm^2 (SD=0.006), which was 59% less ($F(1,11)=6.715$, $p=<.05$) than the –(PE/SXS) group which had an average mass moment of inertia of 0.017kgm^2 (SD=0.005).

The damping ratio had less than an 8% difference between the +(PE/SXS) and the –(PE/SXS) groups. The –(PE/SXS) group had a damping ratio of 0.049 (SD=0.036) and the +(PE/SXS) group had a damping ratio of 0.053 (SD=0.014).

Two of 14 MRI scans were identified by a musculoskeletal radiologist as having "likely" supinator enhancement, and two arms were identified with "slight" enhancement. The likely supinator enhancement was identified in dominant arms whereas slight enhancement was identified in non-dominant arms. Both individuals identified with likely enhancement in the dominant arm were power hand tool users, and both reported having symptoms in the forearm in the past year. The remaining non-enhanced power tool users reported no symptoms in the forearm.

It is interesting to note that the average isometric supinator MVC for the MRI enhanced power tool group was 53% less than the non-enhanced power tool users ($F(1,4)=16.015$, $p<.05$). The non-enhanced MRI power tool group had an average isometric supinator MVC of 10.22Nm (SD=1.81) while the enhanced MRI power tool group had an average isometric supinator MVC of 4.76Nm (SD=0.23).

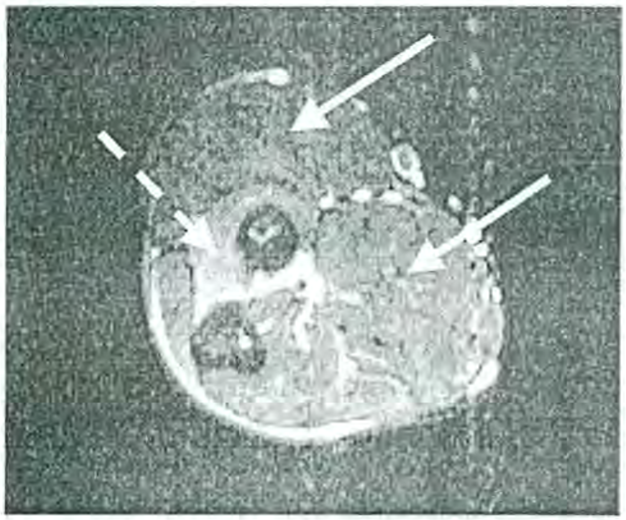

Figure 1 – Supinator Enhancement Dominant Arm (dashed arrow – supinator muscle, solid arrows – flexor and extensor muscles)

DISCUSSION

Symptomatic individuals demonstrated less supinator mechanical stiffness (46%) and mass moment of inertia (59%) than non-symptomatic subjects. This finding concurs with our earlier findings in which college males completing submaximal eccentric exertions demonstrated a significant decrease in mechanical stiffness (51%) and inertial mass (48%) following repetitive submaximal eccentric activity (Sesto 2002).

The difference in damping ratio between the symptomatic and non-symptomatic subjects was less than 8%, which is considered insignificant in magnitude.

Data was not analyzed for differences between power tool and non-power tool use groups because several workers reported working in power tool use jobs but did not regularly operate power hand tools. Therefore, it was felt that accurate classification of power tool versus non-power tool groups had not been achieved.

It is interesting to note that although the tool use group demonstrated greater mechanical parameters, regardless of tool use status symptomatic individuals demonstrated decreased mechanical properties as compared to non-symptomatic individuals.

The present study established that for a small group of assemblers, symptomatic individuals demonstrated notably less mechanical stiffness and mass moment of inertia than asymptomatic individuals. It is not known whether the decreased mechanical properties in the symptomatic group were present prior to development of symptoms or if this is a consequence of injury.

CONCLUSION

Biomechanical differences were observed between the forearm of power tool users and non-power tool users. Individuals in the power tool users group demonstrated a larger mechanical stiffness (47%) and mass moment of inertia (83%) than the non-power tool users group. Individuals with symptoms, regardless of tool use, demonstrated decreased stiffness. The symptomatic users demonstrated 46% less mechanical stiffness and 59% less mass moment of inertia than the asymptomatic group. MR imaging was used to evaluate muscles in the forearm. Two of the subjects in the tool use group demonstrated T_2 enhancement. No subjects in the non-tool use group demonstrated enhancement in the dominant arm. The two subjects that demonstrated T_2 enhancement also demonstrated less mechanical stiffness and mass moment of inertia than the tool users without enhancement, but this difference was not statistically significant.

ACKNOWLEDGEMENTS

This research was partially supported by a Grant from the University of Michigan Center for Occupational Health and Safety Engineering and the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

REFERENCES

American Conference of Governmental Industrial Hygienists (2001). *Hand Activity Threshold Limit Value.*

Armstrong, T.J., Radwin, R.G., Hansen, D.J. and Kennedy,K.W. (1986). Repetitive trauma disorders: job evaluation and design. *Human Factors*, 28(3):325-36.

Evans, G. F., Haller, R.G., Wyrick, P.S., Parkey, R.W. and Fleckenstein, J.L. (1998). Submaximal delayed onset muscle soreness: correlations between MRI findngs and clinical measures, *Radiology* 208(3), 815-820.

Foley, J. M., Jayaraman, R.C., Prior, B.M., Pivarnik, J.M. and Meyer, R.A. (1999). MR measurements of muscle damage and adaptation after eccentric exercise. *J of Applied Physiology* 87(6), 2311-2318.

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

Meagher, S.W. (1987). Tool design for prevention of hand and wrist injuries. *Journal of Hand Surgery*, 12:2, 855-857.

Muggleton, J. M., Allen, R. and Chappell, P.H. (1999). Hand and arm injuries associated with repetitive manual work in industry: a review of disorders, risk factors and preventive measures. *Ergonomics* 42(5), 714-739.

Oh, S. A. and., Radwin, R.G. and Fronczak, F.J. (1997). A Dynamic Mechanical Model for Hand Force in Right Angle Nutrunner Operation. *Human Factors*, 39(3), 497-506.

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

Sesto (2002). Biomechanical and physiological changes following submaximal eccentric activity. Doctoral dissertation, University of Wisconsin.

VanBergeijk, E. (1987). Selection of power tools and mechanical assists for control of occupational hand and wrist injuries. In ACGIH (Ed.) *Ergonomic Interventions to Prevent Musculoskeletal Injuries in Industry*. Chelsea, MI.: Lewis Publishers.