Handle Dynamics Predictions for Selected Power Hand Tool Applications

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This study uses a previously developed single-degree-of-freedom mechanical model to predict the power hand tool operator handle kinematic response to impulsive reaction forces (Lin, 2001). The model considers the human operator as a lumped parameter passive mechanical system, consisting of stiffness, mass moment of inertia, and viscous damping elements. Six power nutrunners were operated by 9 volunteers (3 men, 6 women) in the laboratory, and corresponding handle kinematics were compared against model predictions. A full-factorial experiment considered torque buildup time and work location. Normalized forearm flexor EMG was measured to quantify muscle exertions and used to proportionally adjust the stiffness parameter. The measured handle displacement for actual tool operation strongly correlated to the model predictions (R = .98) for all handle configurations. The overall model prediction error was 3% for predicting tool handle responses to impulsive reaction forces for various tool and workstation parameters. This model should make it possible for designers to identify conditions that minimize the torque reaction experienced by power hand tool operators.

INTRODUCTION

A 1983 survey of hand tool related injuries in the United States (Meyers & Trent, 1988) showed that of 129 399 cases, 22% were associated with powered hand tools. Recent data indicate that injuries associated with hand tools accounted for 4.5% (74 830) of the total recorded work-related injury cases in the United States (Bureau of Labor Statistics, 2002). Among them, power hand tools accounted for 23.8% (17 852) of the cases, which involved being "struck by" or "struck against" and "overexertion."

Nutrunners are power hand tools that are widely used for securing threaded fasteners in manufacturing and assembly operations, such as in the automotive, mechanical equipment, and electronics industries. Radwin, VanBergeijk, and Armstrong (1989) conducted a study using electromyography (EMG) as an index of muscle effort during pneumatic shut-off nutrunner operation. They found that the EMG activity during threaded fastener torque buildup was affected by tool torque output and torque buildup time. EMG activity during torque buildup was more than three times greater than it was during preparation and shutoff.

Oh and Radwin (1998) observed that the operator initially overcomes the tool reaction force with a concentric muscle exertion. As the force rapidly rises, however, the tool eventually overcomes the operator, causing the motion in opposition to muscle contraction, resulting in an eccentric muscle exertion. This torque reaction effect on muscle length is demonstrated in Figure 1. During an eccentric, or lengthening, contraction the muscle acts like a spring, producing proportionally more force as it lengthens because of passive properties of the muscle.

Force in eccentric contractions is generally greater than in isometric or concentric contractions (Griffin, 1987; Walmsley, Pearson, & Stymiest, 1986). Furthermore, the physiological cost, as well as perceived exertion, is often less

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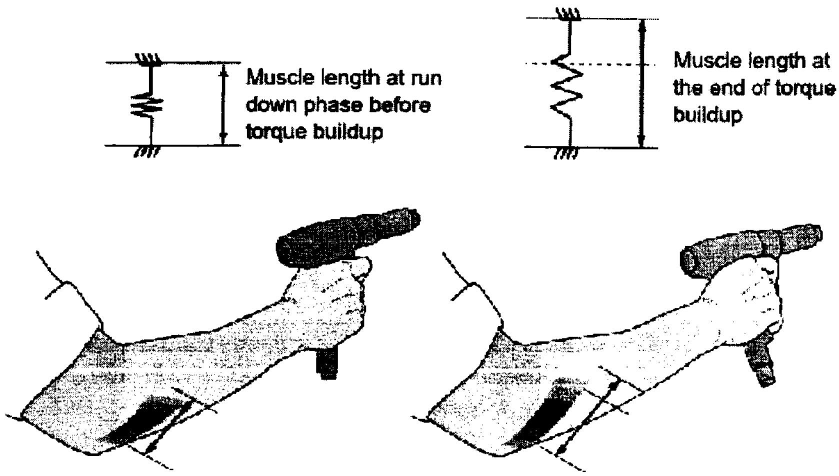

Figure 1. Muscle reaction to power hand tool torque buildup. The springs at the top represent the muscles below. Left panel: the run down phase before torque buildup. Right panel: end of the torque buildup phase.

for eccentric contractions as compared with other types at similar intensities (Henriksson, Knuttgen, & Bonde-Peterson, 1972; Pandolf, 1977; Rasch, 1974; Stauber, 1989). Repeated eccentric contractions may therefore have negative consequences, including muscle soreness (Dolezal, Potteiger, Jacobsen, & Benedict, 2000; Komi & Buskirk 1972; Talag, 1973) and muscle damage (Boppart et al., 1999; Brown, Child, Day, & Donnelly, 1997; Clarkson & Sayers, 1999; Dolezal et al., 2000). The magnitude of an eccentric exertion is proportional to the magnitude of the tool handle force, velocity, and displacement. Armstrong, Warren, and Lowe (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 for repetitive skeletal muscle loading.

Psychophysical experiments (Freivalds & Eklund, 1993; Kihlberg, Kjellberg, & Lindbeck, 1993; Kihlberg, Lindbeck, & Kjellberg, 1994) have shown that power hand tool handle displacement response to the torque reaction force is highly correlated with subjective ratings of discomfort. Kihlberg, Kjellberg, and Lindbeck (1995) tested four right-angle nutrunners with target torque levels of 50 and 75 Nm. They concluded that to be accepted by 90% of the operators, the tools should produce handle displacement responses less than 3 cm.

Biomechanical models of the human hand and arm were developed in order to better understand the effects of continuous periodic vibration produced by power hand tools (Fritz, 1991; Louda & Lukas, 1977; Reynolds, 1977; Reynolds & Soedel, 1972; Wood, Suggs, & Abrams, 1978). Those models considered the human operator as combinations of passive springs, masses, and dampers. These empirical models, however, were not applicable to nutrunners or screwdrivers because the mechanical elements were calculated for continuous vibration input in the range of 20 to 2000 Hz, which is much greater than those encountered for impulsive reaction forces in these power hand tools.

Lindqvist (1993) suggested that a simple mass-spring mechanical system might be sufficient to describe the handle response to impulsive reaction forces encountered in nutrunner operation but did not identify specific parameters for these elements. Lin, Radwin, and Richard (2001) considered a similar model of the human operator for pistol-grip power hand tool operation using a dynamic mechanical analog. The operator was represented as a single-degree-of-freedom mechanical system in order to predict the kinematic and kinetic response of the handle (motion and force) when an impulsive reaction force was encountered in threaded fastener power hand tool operation. A brief description of the model is provided here.

The model represents the human operator as a dynamic system consisting of a linear spring, a mass, and a viscous damper (Figure 2). Instead of modeling for individual contributing muscles, it combines the loading of the muscles and joints into lumped mechanical elements without considering the directions of the loads. The mechanical properties M_s, k_s, and c_s are assumed to be passive and invariant for an individual, a given posture, and a given tool orientation. The effective mass, M_s, would represent the total contributions of the standing operator coupled to the tool through the hands. The effective spring stiffness and damping represent the gross effect of the operator acting against the handle, which includes contributions from the entire body and

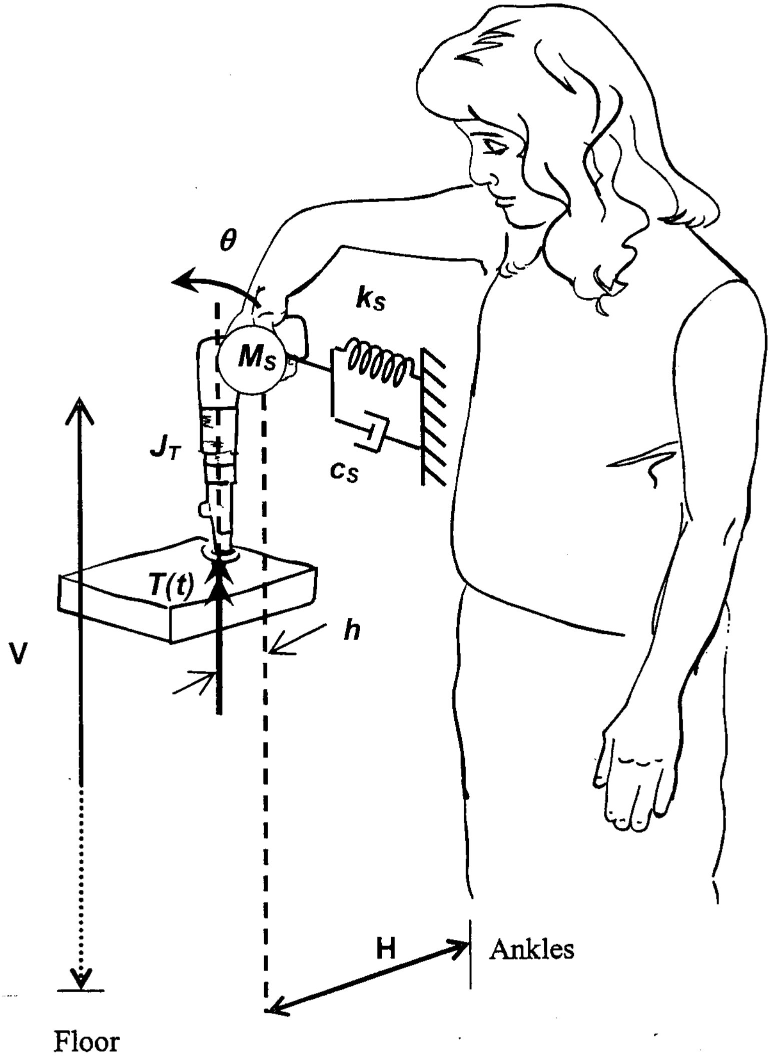

Figure 2. A pistol-grip pneumatic hand tool with a normal operator grip. The mechanical parameters are defined as follows: M_s = the total effective mass of the operator's arm, hand, and a portion of the upper body lumped at the distance h from the center of rotation of the tool spindle or line of action of the tool torque, $T(t)$; J_T = the rotational mass moment of inertia of the tool about the spindle; h = location of the center of pressure of the operator's hand on the tool handle; k_s = the effective stiffness of the operator's arm, hand, and a portion of the upper body; c_s = the effective damping of the operator's arm, hand, and a portion of the upper body; $T(t)$ = the tool torque that is transmitted to the operator in a typical mechanical fastening operation; = the rotation of the tool and hand about the tool spindle axis; H = horizontal distance between the floor and the handgrip; V = vertical distance between the ankles and the handgrip.

nonspecific muscle groups. A system identification method utilizing free oscillation was used to measure these mechanical parameters for various work locations for three common tool shapes: pistol grip, right angle, and in line. This method measured the influence of the operators' mechanical elements on the system dynamic response (oscillation frequency and damping ratio) of a known mechanical system. The mechanical parameters were then extracted analytically (Lin et al., 2001).

When the mechanical parameters for an operator are known, the dynamic response (angular displacement and force) when the operator encounters an impulsive reaction force from a power tool can be estimated. A torsional, dynamic equilibrium equation can be written about the tool spindle axis. The following differential equation results in terms of the tool rotation θ:

$$(J_T + M_s h^2)\frac{d^2\theta}{dt^2} + c_s h^2 \frac{d\theta}{dt} + k_s h^2\theta = T(t), \quad (1)$$

in which $T(t)$ is the tool torque, M_s, c_s, and k_s are the operator mechanical parameters, J_T is the mass moment of inertia of the tool about its spindle, and h is the distance between the hand and the tool spindle.

This second-order differential equation can be solved numerically using finite difference techniques and a discrete time step variation of the tool torque, $T(t)$. The result will be a description of the time variation of the tool rotation, $\theta(t)$:

$$\theta_{i+1} = \left\{ \frac{1}{\frac{M_s h^2 + J_T}{(\Delta t)^2} + \frac{c_s h^2}{2\Delta t}} \right\} \left[\left\{ \frac{2(M_s h^2 + J_T)}{(\Delta t)^2} - k_s h^2 \right\} \theta_i + \left\{ \frac{c_s h^2}{2\Delta t} \; \frac{2(M_s h^2 + J_T)}{(\Delta t)^2} \right\} \theta_{i-1} + T_i \right], \quad (2)$$

in which i is the iteration step, Δt is the time step, and T_i is the tool torque.

With the rotational response of the tool predicted, the motion of the handle can be defined as $h\theta(t)$. The force $F(t)$ delivered to the handle can be approximated by

$$c_s h \frac{d\theta}{dt} + k_s h\theta = F(t). \quad (3)$$

Lin et al. (2001) tested 25 participants, and the mechanical parameter values for a maximal voluntary exertion were ascertained while varying tool location using a pistol grip tool on a vertical surface. The stiffness, mass moment of inertia, and damping constants were found to be affected by work location (Lin et al.). The spring stiffness and mass moment of inertia changed by 20.6% and 44.5%, respectively, with vertical location and 23.6% and 41.2%, respectively, with horizontal location. Using the same concept, the single-degree-of-freedom mechanical model was further applied to broader tool operations that included three common tool shapes used in the industry – pistol grip, right-angle, and in-line handles used on a horizontal surface – and the corresponding mechanical parameters were obtained (Lin, 2001).

The model (Lin et al., 2001) estimated the tool handle displacement with a high correlation (.88) for 5 participants when they operated an actual power hand tool. However, the model underestimated the resulting displacement by 27%. It was anticipated that this might be because tool operators do not normally use maximum exertion levels during actual tool operation. Because the mechanical model parameters were estimated for maximum exertion levels rather than for the actual exertions, the current study uses normalized EMG as an index of exertion to assess the level of effort. It was hypothesized that adjusting the mechanical stiffness parameter according to exertion level would result in better model predictions.

This paper aims to investigate model predictions for a range of tool operations and shapes to which the dynamic human operator model can be applied. The goal is to validate the passive dynamic model (Lin, 2001) by comparing predictions of handle kinematic responses against actual tool responses measured for various tool operations and conditions.

METHODS

Apparatus

Six tools (Figure 3) were used, and their mechanical properties were measured prior to the experiment. The tools' centers of gravity (COGs) were determined using the free-suspension method (Radwin & Haney, 1996). Each tool was suspended by a line twice from two different orientations. Two plumb lines were drawn on the tool, and the intersection of the lines was the location of the COG. The mass moment of inertia I for in-line tools was estimated by assuming a uniform cylinder rotating about its long spindle using the equation

$$I = \frac{1}{2} MR^2, \tag{4}$$

in which M is the tool mass and R is the handle radius. The mass moment of inertia for pistol-grip and right-angle tools was determined using the oscillation method. Pistol-grip tools were suspended in a manner similar to a simple pendulum. The friction was assumed to be negligible. The COG of the tool provided restoring force when it was set into oscillation. The equilibrium equation for the pendulum system is

$$Wr\sin\varphi = -I\ddot{\varphi}, \tag{5}$$

in which W is the tool weight, r is the distance between COG and the suspension, φ is the angular displacement, $\ddot{\varphi}$ is the angular acceleration, and I is the mass moment of inertia. For small oscillations, $\sin\varphi$ can be approximated as φ. The natural frequency (ω_n) of the system is a function of its mass moment of inertia about the supporting points:

$$\omega_n = \sqrt{\frac{Wr}{I}}. \tag{6}$$

The mass moment of inertia about the tool spindle can be found by applying the parallel axis theorem twice.

The bifilar pendulum method was employed for right-angle tools. Two strings supported the tool at an equal distance from the center of gravity of the tool. The tool was set into oscillation, and the period of 10 cycles was measured. For small oscillations, the natural frequency can be described as

$$\omega_n = \frac{H}{2}\sqrt{\frac{W}{dI}}, \tag{7}$$

in which H is the distance between the two strings and d is the length of the strings.

Torque output of the tools was measured using a full bridge strain gauge torque cell. The spindle free running speed was measured using an AMETEX digital tachometer Model 1726. The measured specifications of all the tools are listed in Table 1.

Tool motion during operation was recorded in three dimensions using a Northern Digital OptoTRAK 3020 motion analysis system. One infrared marker was attached at the end of the tool handle to track the handle movement. Another marker was located on a threaded fastener joint simulator base (ITD Automation) to monitor the fastener during torque buildup. The tracking error was less than 0.45 mm for this setup. Data acquisition was controlled using OptoTRAK software and a microcomputer with a 500 samples/s sampling rate.

Torque buildup time is dependent on joint hardness. A hard joint has a rapid buildup time, whereas a soft joint has a long buildup time. Two types of torque buildup times (hard and soft joints) were simulated on the joint simulator by changing the number of Belleville spring washers (Figure 4). These conditions are summarized in

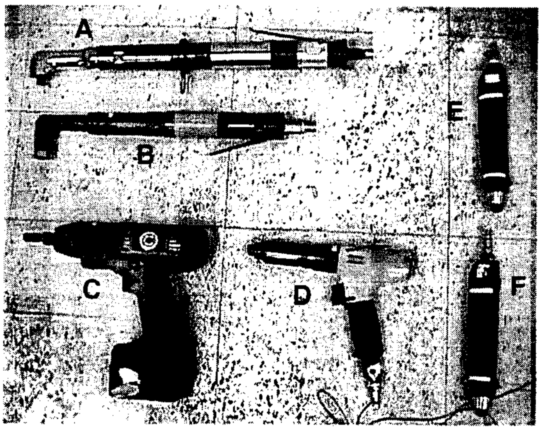

Figure 3. Tools used in the current experiment.

TABLE 1: Specifications of the Six Tools Used in the Experiment

Tool	Shape	Power Source	Free Running Speed (rpm)	Moment of Inertia about Spindle (kg m^2)	Target Torque (Nm)
A	Right angle	Air	366	0.1932	21.2
B	Right angle	Air	713	0.1219	6.5
C	Pistol grip	Battery	593	0.0439	4.2
D	Pistol grip	Air	714	0.0052	7.2
E	In line	Air	825	0.0107	2.1
F	In line	Air	495	0.0107	3.6

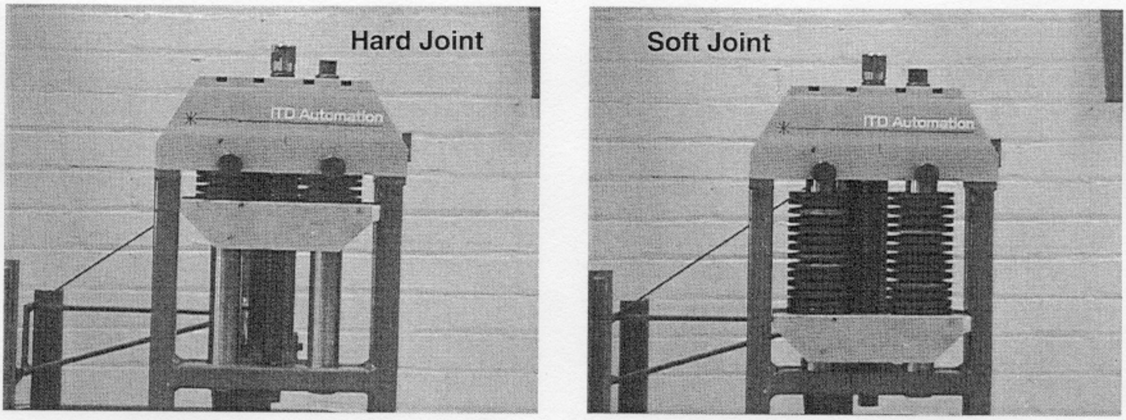

Figure 4. Joint simulator illustrating different joint types. Mechanical joint stiffness is controlled by the number of Belleville washers.

Table 2. Vertical reach distances were changed using a height-adjustable platform. Horizontal reaches were controlled by instructing the operator to stand over different targets located on the floor.

A set of bipolar Ag–AgCl surface electrodes measured EMG activity during tool operation. Rather than palpating a specific muscle, the electrodes were affixed over the forearm extensors as a group according to Basmajian and Blumenstein (1989). These muscles were selected based on function and accessibility. EMG signals were measured differentially with respect to a reference ground electrode, which was attached near the superficial lateral epicondyle. Root-mean-squared (RMS) EMG signals were sampled using a National Instruments Lab PC+ data acquisition board. A handle with a diameter of 4.3 cm,

TABLE 2: Test Target Conditions Simulated Using the Joint Simulator for All Tools Tested

	Joint Rate (Nm/°)		Buildup Time (ms)	
Tool	Hard Joint[a]	Soft Joint[a]	Hard Joint[a]	Soft Joint[a]
A	0.51	0.053	88	448
B	0.11	0.029	25	161
C	0.1	0.02	15	46
D	0.12	0.028	36	160
E	0.027	0.017	23	106
F	0.08	0.025	24	91

[a]As shown in Figure 4.

similar to the tool handles, was used for the purpose of exerting maximum voluntary contractions (MVCs).

Experimental Procedures

EMG signals were first measured during an MVC exertion corresponding to the respective tool operation (Table 3) before each experimental condition (two work locations and four tool configurations). Participants were asked to exert force against a handle for 5 s with maximum effort in the manner and posture in which that tool is operated. The average of the EMG signal was taken for the middle 3 s.

Every participant practiced operating each tool for 1 min. Participants held the tool using the posture and location assigned by the experimenter. The participant waited for a verbal signal before starting to run the tool. A subset of 9 of the 25 participants in the previous experiment (Lin, 2001) was recalled for the current experiment, and the mechanical parameters previously measured for each participant were used for model predictions. Three men and 6 women participated in the current experiment. Informed consent was obtained prior to the experimental trials.

Experimental Design and Analysis

The experiment was a repeated-measures 4 × 2 × 2 × 2 full-factorial design for tool and surface (pistol grip on a vertical surface, pistol grip on a horizontal surface, right angle on a horizontal surface, and in line on a horizontal surface), target torque (low and high levels corresponding to individual tool shapes), torque buildup time (hard and soft joints), and work location (near and far). Work locations were selected for each tool and surface condition based on locations where the greatest and least mean stiffness were measured in Lin (2001). These work locations are summarized in Table 4. Three replicates were made for each condition, giving a total of 96 trials per participant. The trials were presented to the participant in a random order. Each trial took less than 5 s. Volunteers were tested in two sessions on two different days, each session lasting about 1 hr. Rest breaks were provided after every six trials.

Because the model predicts operator kinematic response (handle displacement) during torque buildup, it was necessary to identify the start and end of torque buildup for each trial. A typical threaded fastener joint simulator displacement, as measured on the OptoTRAK, is shown in Figure 5. The tool shutoff was identified as the instance when the joint simulator base stopped moving. The starting point was identified when the speed of the base motion began to change and by verifying the start of buildup based on a set buildup time for each tool (Table 2). Handle displacement during the identified torque buildup was then determined.

The average RMS EMG 50 ms prior to torque buildup (preset level) was normalized to MVC in order to allow us to assess the relative muscle exertion level for each trial. The muscle was assumed to maintain constant stiffness into the torque buildup reaction during the post-rundown phase and torque shutoff (Armstrong et al., 1999; Radwin et al., 1989).

The handle displacement θ for power hand tool operation at each working location and for each of the 9 participants was estimated using Equation 2 for individual k_s, M_s, and c_s. The measured mechanical parameters can be found in Lin (2001). The torque output of the tools under study was a function of time, $T(t)$, and

TABLE 3: Maximal Voluntary Contraction Directions

Tool Configuration	Exertion Performed
Pistol grip/horizontal	Forearm medial rotation
Pistol grip/vertical	Wrist supination
Right angle/horizontal	Pulling
In line/horizontal	Wrist extension

TABLE 4: Work Location Assignations for Each Tool Configuration in the Experiment

Tool Configuration (Handle/Surface)	Location[a] (cm), Horizontal/Vertical	
	Near	Far
Pistol grip/horizontal	30/140	60/80
Pistol grip/vertical	30/142[b]	60/55
Right angle/horizontal	30/140	60/80
In line/horizontal	30/90	90/90

[a]Measured from the ankles.
[b]Second-highest stiffness posture was used because of the limitation of setup for the joint simulator.

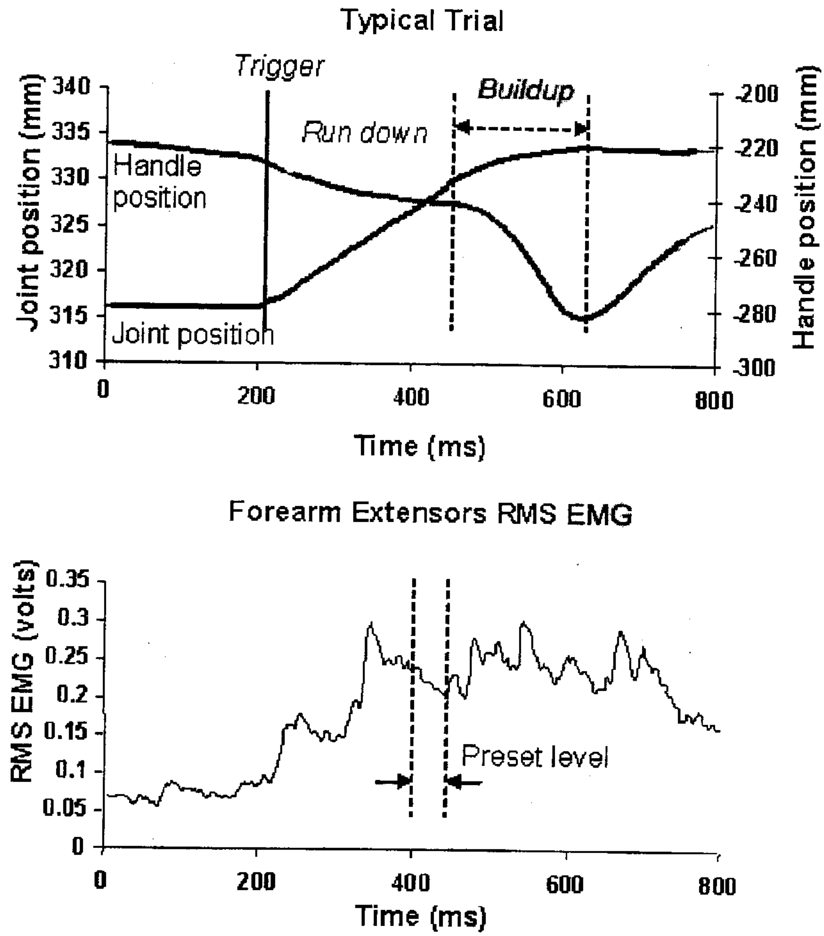

Figure 5. A typical trial. Top: joint simulator position and handle position. Bottom: RMS EMG recording.

can be approximated using the following equation (Lin, 2001):

$$T(t) = T_{\max} - T_{\max} e^{\frac{T_{\max} S}{\theta_s T_{\max}} t}, \tag{8}$$

in which T_{max} is the tool maximum torque output, θ_s is the angular displacement of the spindle rotation, and S is the spindle free running speed.

The handle force F was estimated by solving Equation 3. A computer program was written to calculate the displacement and force responses using Equations 2 and 3. The time step Δt in Equation 2 was set to 1 ms, and initial conditions were $\theta_{-1} = 0$ and $\theta_0 = 0$. Linear regression between the model-predicted handle displacement (independent variable) and measured handle displacement (dependent variable) was performed using the software package SPSS. The slope of the resulting regression between the measured and predicted variables was used to estimate the model prediction error, and the coefficient of determination R^2 between the two variables was also determined.

RESULTS

The mean peak handle displacement was 6.63 mm (SD = 6.86) for the hard joint and 35.28 mm (SD = 34.81) for the soft joint. The mean peak handle displacement when tools were used at the near work location was 19.18 mm (SD = 25.77), and at the far location it was 22.10 mm (SD = 31.35). For right-angle tools used on soft joint only, the mean peak handle displacement at the near work location was

59.11 mm (*SD* = 30.81), and at the far location it was 79.02 mm (*SD* = 43.32).

Participants exerted an average of 56.6% (*SD* = 16%) of MVC prior to torque buildup for all trials. The average was 59.9% (*SD* = 13%) for right-angle tools, 54.9% (*SD* = 17%) for pistol grip tools, and 57.1% (*SD* = 18%) for in-line tools. The mean normalized EMG for the two in-line tools was 55.3% (*SD* = 18%) when used on the hard joint and 58.9% (*SD* = 18%) on the soft joint.

When the model stiffness parameter for each operator was adjusted by the normalized EMG during maximum voluntary exertion, the results showed that the model overpredicted actual handle displacement by only 3%. Without the EMG correction, the model overpredicted actual displacement by an average of 10%. Handle displacement for actual tool operation was strongly correlated with the model estimates, $F(1, 23) = 543.8$, $R = .98$, for all experimental conditions (Figure 6). Regression analyses of the measured versus the predicted displacements showed that the slope was 1.07 ($R = .99$) for right-angle tools, 0.86 ($R = .99$) for pistol grip tools, and 0.95 ($R = .63$) for in-line tools.

The tool operator mechanical model was also used to estimate tool handle kinematics during torque buildup. The resultant handle displacement for using right-angle Tool B, having buildup times ranging from 35 (hard) to 1000 (soft) ms, was calculated using Equations 2 and 8 and is plotted in Figure 7. Corresponding hand force is plotted in Figure 8. Under the simulated conditions, the peak force and displacement occurred when the buildup time was 107 ms for Participant A (male with greatest operator stiffness parameter), whereas the peak responses occurred when the buildup time was 214 ms for Participant B (female with smallest operator stiffness parameter).

DISCUSSION

It is well known that as the stiffness of a linear spring increases, the corresponding displacement decreases (Hooke's law). When work locations associated with different operator stiffness levels (Lin, 2001) were tested (Table 4), the results confirmed that the mean handle displacement was greater for the far locations (22.10 mm), where less stiffness was observed, than for the near locations (19.18 mm), where the stiffness was greater.

The effect of joint hardness was consistent with previous observations (Freivalds & Eklund, 1993; Lin et al., 2001; Oh & Radwin, 1997). The current experiment tested two different torque buildup times for each tool and showed that hard joints resulted in less displacement than did soft joints. This was verified in the

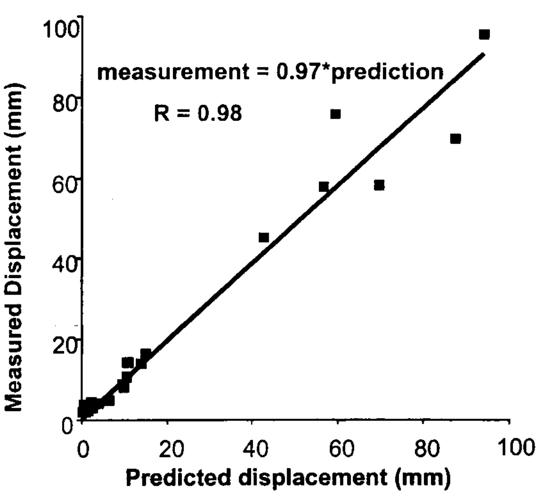

Figure 6. Regression analysis using measured handle displacement as the dependent variable and predicted displacement as the independent variable. Each point represents the average of 27 trials (9 participants × 3 replicates) for one experimental condition.

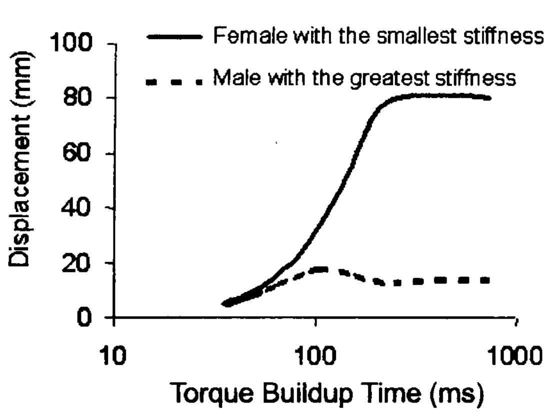

Figure 7. Model prediction for handle displacement when using a right-angle nutrunner on a horizontal surface for different torque buildup times. Specifications of Tool B were used in the model. Model parameters were measured in Lin (2001).

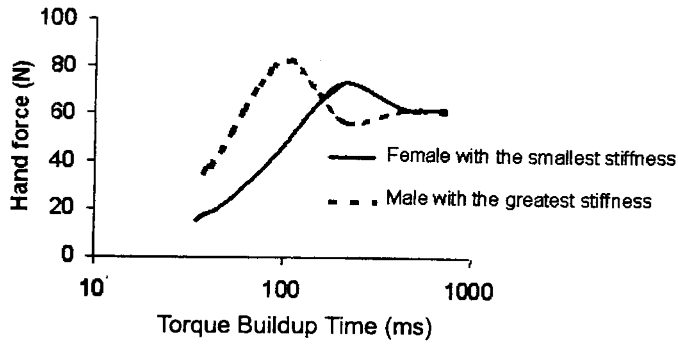

Figure 8. Model prediction for hand force when using a right-angle nutrunner on a horizontal surface for different torque buildup times. Specifications of Tool B were used in the model. Model parameters were measured in Lin (2001).

current study, in which the mean handle displacement was 35.28 mm for soft joints but only 6.63 mm for hard joints. The torque buildup time is dependent on threaded fastener joint hardness and, hence, on the frequency characteristics of the torque input signal.

When a single-degree-of-freedom model oscillates at its resonant frequency, peak displacement and force will be observed (Figures 7 and 8). This is consistent with previous observations by Dagalakis, Muehlhouse, Wakamiya, and Yang (1987), who analyzed the response spectrum of human arm and elbow. For the right-angle tool simulated in Figures 7 and 8, the resonant frequency was 4.7 Hz for Participant B and 9.3 Hz for Participant A. Therefore, operating a tool at the resonant frequency can be avoided by modifying the buildup time by adjusting the tool speed.

In a previous experiment (Lin et al., 2001), the single-degree-of-freedom biomechanical model predicted actual handle displacement for a pistol-grip tool with a correlation coefficient of .88. However, the model underestimated displacement by an average of 27%. It was concluded that the error may be attributable to the fact that the participants did not use maximum exertions when operating tools, as the model assumes. The results in the current study, showing an average exertion of 56% of MVC during tool operation, confirmed this hypothesis. The exertion level was similar to the observations in a previous study conducted by Armstrong et al. (1999). They found that when participants used in-line tools, the average normalized flexor EMG was about 39%. Furthermore, the exertion level varied as the torque buildup times varied.

The current results also showed that the normalized flexor muscles' EMG activity prior to torque buildup was greater when tools were used on a soft joint than when used on a hard joint. Armstrong et al. (1999) suggested that the tool operators were "bracing" for the torque reaction by stiffening up their muscles. Therefore the stiffness parameter adjusted according to normalized EMG should reflect the actual muscle contraction level during tool operation better than using full stiffness measured in a free-vibration experiment. The error was reduced to 3% and the correlation increased to .998, as compared with the previous experiment (Lin et al., 2001). Normalized EMG can therefore be used as a scaling factor in order to account for individual differences in muscle contraction during hand tool operation.

Spring stiffness is considered the most significant factor among the three mechanical elements that contribute to the behavior of muscle contraction at low frequencies (<10 Hz; Kearney, Stein, & Parmeswaran, 1997; Sinkjær & Hayashi, 1989). Stiffness has been found to be proportional to the force of contraction (Zahalak & Heyman, 1979). Cannon and Zahalak (1982) concluded that for small-amplitude perturbation at the human forearm, stiffness increases as the level of contraction represented by EMG increases. Subsequent researchers have used EMG to estimate hand (Tsuji & Kaneko, 1996) and arm (Osu & Gomi, 1999) mechanical stiffness.

For the current experimental setup, right-angle tools showed the greatest stability during torque reaction, and their handles moved in a single horizontal plane. Because of the nature of the equipment setup, in which in-line tools were suspended at the air hose and could not be perfectly balanced, it was observed that in-line tools allowed more degrees of freedom of handle movement. This resulted in translational movements in addition to pure rotation along the spindle for some instances. Failure to extract the net rotational displacement from the combined displacement also may have contributed to the error observed in the results.

Several additional possible sources of error were considered in the design of the current study. Some studies have observed that muscle stiffness may change after long periods of exercise (Avela & Komi, 1998b; McHugh et al., 1999). Leger and Milner (2000) found that wrist stiffness for maximal range of motion decreased after participants eccentrically exercised using submaximal loads at the wrist for 25 to 30 min. Correspondingly, the extensor EMG signal magnitude increased by 13% after fatigue (Leger & Milner, 2000). Avela and Komi (1998a, 1998b) found that after exhaustive marathon runs lasting 2⅓ to 3½ hr, the soleus muscles' EMG activity decreased by 26.6%.

In the current experiment, measures taken to prevent muscle fatigue included rest breaks (30 s–5 min), randomization of trial order, and distribution of testing over two different days. Compared with studies using maximal efforts to measure stiffness (Avela & Komi, 1998a, 1998b; Leger & Milner, 2000), the current experiment did not demand the maximal capability of the participants, and the duration of each trial was short. Throughout the trials, although participants exerted an average of 56% of MVC, they did not report any fatigue in their hands or arms.

Kihlberg et al. (1995) used psychophysical methods to determine that 90% of their participants would operate a right-angle pneumatic power hand tool all day if its handle displacement was less than 3 cm and that 75% would accept a tool if its displacement was less than 4 cm. Handle displacement is the result of a whole system that includes not only the tool and the target but the operator as well. The current model can predict handle displacement for various combinations of tool, task, and work location. Therefore it may be possible to select or design a tool that is most desirable for a certain working condition. For example, right-angle Tool B and pistol-grip Tool D in the current experiment have similar torque output characteristics. The model estimates that for the same task, driving a nut on a soft joint at a far work location, using Tool D on a vertical surface results in an average hand displacement of 76.4 mm. If the task can be redesigned such that it can be executed on a near-horizontal surface and Tool B is used instead, the resultant hand displacement would be reduced to 42.8 mm because of the mechanical properties of the tool and the operator.

The current results validated that the passive single-degree-of-freedom mechanical model (Lin, 2001) is useful for representing hand-arm eccentric exertions in power hand tool operation. This model enables the prediction of handle kinematic responses for various tool and workstation parameters. This should allow designers of tools and workplaces to identify conditions that minimize corresponding displacements and forces.

REFERENCES

Armstrong, R. B., Warren, G. L., & Lowe, D. A. (1995). Mechanisms in the initiation of contraction-induced skeletal muscle injury. In S. L. Gordon & S. J. Blair & L. J. Fine (Eds.), *Repetitive motion disorders of the upper extremity* (pp. 339–349). Rosemont, IL: American Academy of Orthopaedic Surgeons.

Armstrong, T. J., Bir, C., Foulke, J., Martin, B., Finsen, L., & Sjøgaard, G. (1999). Muscle responses to simulated torque reactions of hand-held power tools. *Ergonomics, 42,* 146–159.

Avela J., & Komi, P. V. (1998a). Interaction between muscle stiffness and stretch reflex sensitivity after long-term stretch-shortening cycle exercise. *Muscle and Nerve, 21,* 1224–1227.

Avela J., & Komi, P. V. (1998b). Reduced stretch reflex sensitivity and muscle stiffness after long-lasting stretch-shortening cycle exercise in humans. *European Journal of Applied Physiology, 78,* 403–410.

Basmajian, J. V., & Blumenstein, R. (1989). Electrode placement in electromyographic biofeedback. In Basmajian (Ed.) *Biofeedback: Principles and practice for clinicians* (pp. 369–382). Baltimore: Williams & Wilkins.

Boppart, M. D., Aronson, D., Gibson, L., Roubenoff, R., Abad, L. W., Bean, J., et al. (1999). Eccentric exercise markedly increases c-Jun NH_2-terminal kinase activity in human skeletal muscle. *Journal of Applied Physiology, 87,* 1668–1673.

Brown, S. J., Child, R. B., Day, S. H., & Donnelly, A. E. (1997). Exercise-induced skeletal muscle damage and adaptation following repeated bouts of eccentric muscle contractions. *Journal of Sports Sciences, 15,* 215–222.

Bureau of Labor Statistics, Department of Labor. (2002). *Number of nonfatal occupational injuries and illnesses involving days away from work by source of injury or illness and selected events or exposures leading to injury or illness, 2001* [Table]. Retrieved September 26, 2003, from http://www.bls.gov/iif/oshwc/osh/case/ostb1182.pdf

Cannon, S. C., & Zahalak, G. I. (1982). The mechanical behavior of active human skeletal muscle in small oscillations. *Journal of Biomechanics, 15,* 111–121.
Clarkson, P. M., & Sayers S. P. (1999). Etiology of exercise-induced muscle damage. *Canadian Journal of Applied Physiology, 24,* 234–248.
Dagalakis, N. G., Muehlhouse, C., Wakamiya, S., & Yang, J. C. S. (1987). Loss of control biomechanics of the human arm-elbow system. *Journal of Biomechanics, 20,* 385–396.
Dolezal, B. A., Potteiger, J. A., Jacobsen, D. J., & Benedict, S. H. (2000). Muscle damage and resting metabolic rate after acute resistance exercise with an eccentric overload. *Medicine and Science in Sports and Exercise, 32,* 1202–1207.
Freivalds, A., & Eklund, J. (1993). Reaction torques and operator stress while using powered nutrunners. *Applied Ergonomics, 24,* 158–164.
Fritz, M. (1991). An improved biomechanical model for simulating the strain of the hand-arm system under vibration stress. *Journal of Biomechanics, 24,* 1165–1171.
Griffin, J. W. (1987). Differences in elbow flexion torque measured concentrically, eccentrically, and isometrically. *Physical Therapy, 67,* 1205–1208.
Henriksson, J., Knuttgen, H. G., & Bonde-Peterson, F. (1972). Perceived exertion during exercise with concentric and eccentric muscle contractions. *Ergonomics, 15,* 538–544.
Kearney, R. E., Stein, R. B., & Parameswaran, L. (1997). Identification of intrinsic and reflex contributions to human ankle stiffness dynamics. *IEEE Transactions on Biomedical Engineering, 44,* 493–504.
Kihlberg, S., Kjellberg, A., & Lindbeck, L. (1993). Pneumatic tool torque reaction: Reaction forces, displacement, muscle activity and discomfort in the hand-arm system. *Applied Ergonomics, 24,* 165–173.
Kihlberg, S., Kjellberg, A., & Lindbeck, L. (1995). Discomfort from pneumatic tool torque reaction: Acceptability limits. *International Journal of Industrial Ergonomics, 15,* 417–426.
Kihlberg, S., Lindbeck, L., & Kjellberg, A. (1994). Pneumatic tool torque reactions: Reaction forces, tool handle displacements, and discomfort ratings during work with shut-off nutrunners. *Applied Ergonomics, 25,* 242–247.
Komi, P. V., & Buskirk, E. R. (1972). Effect of eccentric and concentric muscle conditioning on tension and electrical activity of human muscle. *Ergonomics, 15,* 417–434.
Leger, A. B., & Milner, T. E. (2000). Passive and active wrist joint stiffness following eccentric exercise. *European Journal of Applied Physiology, 82,* 472–479.
Lin, J.-H. (2001). *A dynamic biomechanical model of the human operator response to impulsive reaction forces.* Unpublished doctoral dissertation, University of Wisconsin-Madison.
Lin, J.-H., Radwin, R. G., & Richard, T. G. (2001). Dynamic biomechanical model of the hand and arm in pistol grip power handtool usage. *Ergonomics, 44,* 295–312.
Lindqvist, B. (1993). Torque reaction in angled nutrunners. *Applied Ergonomics, 24,* 174–180.
Louda, L., & Lukas, E. (1977). Hygienic aspects of occupational hand-arm vibration. In D. E. Wasserman & W. Taylor (Eds.), *Proceedings of the International Occupational Hand-arm Vibration Conference* (pp. 60–66). Cincinnati, OH: National Institute for Occupational Safety and Health.
McHugh, M. P., Connolly, D. A. J., Eston, R. G., Kremenic, I. J., Nicholas, S. J., & Gleim, G. W. (1999). The role of passive muscle stiffness in symptoms of exercise-induced muscle damage. *American Journal of Sports Medicine, 27,* 594–599.
Myers, J. R., & Trent, R. B. (1988). Hand tool injuries at work: A surveillance perspective. *Journal of Safety Research, 19,* 165–176.
Oh, S. A., & Radwin, R. G. (1997). The effects of power hand tool dynamics and workstation design on handle kinematics and muscle activity. *International Journal of Industrial Ergonomics, 20,* 59–74.
Oh, S. A., & Radwin, R. G. (1998). The influence of target torque and build-up time on physical stress in right angle nutrunner operation. *Ergonomics, 41,* 188–206.
Osu, R., & Gomi, H. (1999). Multijoint muscle regulation mechanisms examined by measured human arm stiffness and EMG signals. *Journal of Neurophysiology, 81,* 1458–1468.
Pandolf, K. B. (1977). Psychological and physiological factors influencing perceived exertion, In G. Borg (Ed.), *Physical work and effort* (pp. 371–378). New York: Pergamon.
Radwin, R. G., & Haney, J. T. (1996). *An ergonomics guide to hand tools.* Fairfax, VA: American Industrial Hygiene Association.
Radwin, R. G., VanBergeijk, E., & Armstrong, T. J. (1989). Muscle response to pneumatic hand tool torque reaction forces. *Ergonomics, 32,* 655–673.
Rasch, P. J. (1974). The present status of negative (eccentric) exercise: A review. *American Corrective Therapy Journal, 28,* 77–94.
Reynolds, D. D. (1977). Hand-arm vibration: A review of 3 years' research. In D. E. Wasserman & W. Taylor (Eds.), *Proceedings of the International Occupational Hand-Arm Vibration Conference* (pp. 99–128). Cincinnati, OH: National Institute for Occupational Safety and Health.
Reynolds, D. D., & Soedel, W. (1972). Dynamic response of the hand-arm system to a sinusoidal input. *Journal of Sound and Vibration, 21,* 339–353.
Sinkjær, T., & Hayashi, R. (1989). Regulation of wrist stiffness by the stretch reflex. *Journal of Biomechanics, 22,* 1133–1140.
Stauber, W. T. (1989). Eccentric action of muscles: Physiology, injury and adaptation. *Exercise and Sports Reviews, 17,* 157–185.
Talag, T. S. (1973). Residual muscular soreness as influenced by concentric, eccentric, and static contractions. *Research Quarterly, 44,* 458–469.
Tsuji, T., & Kaneko, M. (1996). Estimation and modeling of human hand impedance during isometric muscle contraction. In *Proceedings of the ASME Dynamics Systems and Control Division* (Vol. 58, pp. 575–582). Fairfield, NJ: American Society of Mechanical Engineers.
Walmsley, R. P., Pearson, N., & Stymiest, P. (1986). Eccentric wrist extensor contractions, and the force velocity relationship in muscle. *Journal of Orthopedic and Sports Physical Therapy, 8,* 288–293.
Wood, L. A., Suggs, C. W., & Abrams, C. F., Jr. (1978). Hand-arm vibration: Part III. A distributed parameter dynamic model of the human hand-arm system. *Journal of Sound and Vibration, 57,* 157–169.
Zahalak, G. I., & Heyman, S. J. (1979). A quantitative evaluation of the frequency-response characteristics of active human skeletal muscle in vivo. *Journal of Biomedical Engineering, 101,* 28–36.

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