ERGONOMICS, 2001, VOL. 44, NO. 3, 295–312

Dynamic biomechanical model of the hand and arm in pistol grip power handtool usage

JIA-HUA LIN, R. G. RADWIN* and T. G. RICHARD

University of Wisconsin-Madison, Madison, WI 53706, USA

Keywords: Force; eccentric exertion; musculoskeletal disorders; cumulative trauma.

The study considers the dynamic nature of the human power handtool operator as a single degree-of-freedom mechanical torsional system. The hand and arm are, therefore, represented as a single mass, spring and damper. The values of these mechanical elements are dependent on the posture used and operator. The apparatus used to quantify these elements measured the free vibration frequency and amplitude decay of a known system due to the external loading of the hand and arm. Twenty-five subjects participated in the investigation. A full factorial experiment tested the effects on the three passive elements in the model when operators exerted maximum effort for gender, horizontal distance (30, 60, 90 cm), and vertical distance (55, 93, 142 190 cm) from the ankles to the handle. The results show that the spring element stiffness and mass moment of inertia changed by 20.6 and 44.5% respectively with vertical location ($p < 0.01$), and 23.6 and 41.2% respectively with horizontal location ($p < 0.01$). Mass moment of inertia and viscous damping for males were 31.1 and 38.5% respectively greater than for females ($p < 0.01$). Tool handle displacement and hand force during torque build-up can, therefore, be predicted based on this model for different tool and workplace parameters. The biomechanical model was validated by recalling five subjects and having them operate a power handtool for varying horizontal distances (30, 60, 90 cm), vertical distances (55, 93, 142 cm), and two torque build-up times (70, 200 ms). Tool reaction displacement was measured using a 3D-motion analysis system. The predictions were closely correlated with these measurements ($R = 0.88$), although the model underpredicted the response by 27%. This was anticipated since it was unlikely that operators used maximal exertions for operating the tools.

1. Introduction

Industrial power handtools such as nutrunners, screwdrivers and drills require the operator to react against non-harmonic forces generated by the tool and transmitted through the handle. Torque build-up during power handtool operation constitutes a relatively short period of time, but its influence on muscle exertion is most significant due to repeated exposure to relatively high reaction forces. As the operator attempts to maintain static equilibrium by posturing the body and contracting upper limb muscles, it has been found that muscle contraction is rarely

*Author for correspondence. 1410 Engineering Drive, Madison, WI 53706, USA; e-mail: radwin@engr.wisc.edu

Ergonomics ISSN 0014-0139 print/ISSN 1366-5847 online © 2001 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/00140130010010649

isometric (Oh and Radwin 1997 1998, Oh *et al.* 1997). Typically, the operator initially overcomes the tool reaction force with a concentric exertion, but as the force rapidly rises the operator is overcome by the tool, resulting in upper limb motion in opposition to muscle contraction, producing in eccentric muscle exertions.

Eccentric exertions are sometimes considered more efficient since strength for eccentric contractions is generally greater than for isometric or concentric contractions (Walmsley *et al.* 1986, Griffin 1987). Furthermore, the physiological cost as well as perceived exertion are less for eccentric contractions compared with other types at similar intensities (Henriksson *et al.* 1972, Rasch 1974, Pandolf 1977, Stauber 1989). Eccentric contractions, however, have reported negative consequences including onset of muscle soreness (Komi and Buskirk 1972, Talag 1973), greater strength decrements compared with isometric and concentric exertions, and possibly greater risk for injuries (Komi and Rusko 1974, Fridén *et al.* 1983, McCully and Faulkner 1985, Lieber *et al.* 1991). A theoretical model for the early stages of contraction-induced micro-injury in skeletal muscle was proposed by Armstrong *et al.* (1993), suggesting that high-level eccentric contractions with high-level velocities may be related to power handtool operation.

In a survey of hand-tool related accidents by Aghazadeh and Mital (1987), 'struck by or struck against power handtools' were responsible for 62.6% of all 14 002 accident cases from eight states in the USA. The second cause was 'over-exertion', which included 27.9% of all cases. It is generally agreed that using tools that minimize force, shock, recoil and vibration can reduce physical stress, fatigue and musculoskeletal disorders. Control of these factors depends on tool selection and on installation appropriate for the specific application. Two important parameters are reaction force magnitude and build-up time (Radwin *et al.* 1989).

Studies of the biomechanical effects of continuous random vibration on the hand and arm have considered 1–2 degrees-of-freedom passive models (Reynolds and Soedel 1972, Suggs 1972, Louda and Lukas 1977, Wood *et al.* 1978) or higher 3–4 degrees-of-freedom models (Reynolds and Keith 1977, Suggs and Mishoe 1977, Reynolds and Falkenberg 1982, Fritz 1991). In those models, however, mass, stiffness and damping constants, or mechanical impedance, were calculated based on the stimulus–response relationship in the range of 20–2000 Hz. Typical torque build-up time for power nutrunners ranges from 35 ms to 2 s corresponding to 0.5–28 Hz in the frequency spectrum (Radwin *et al.* 1989, Kihlberg *et al.* 1995, Oh and Radwin 1998, Armstrong *et al.* 1999). These frequencies of impulsive reaction forces for power nutrunners are far less than those studied in previous biomechanical models; therefore, those models may not be adequate for the reaction forces encountered in nutrunner usage.

Hand force needed for power handtool operation was estimated under the limiting assumption of static equilibrium (Radwin *et al.* 1989, 1995). Oh *et al.* (1997) developed a dynamic model to estimate hand-arm responses for right angle nutrunner operation that added an inertial element to the model. Different torque build-up profiles were produced and controlled by a computer. The results showed that the difference between the static and dynamic model was greatest when the build-up time was shortest (35 ms). The dynamic model predicted the hand force better than a static model did because the inertial force was included. However, the model did not consider the capacity of the operator in relation to different postures or differences between individual operators.

Lindqvist (1993) hypothesized that a power nutrunner operator can be represented mechanically as a single degree-of-freedom mechanical system. The data for impulsive loads in the hands demonstrated that handle displacement due to torque inputs for hard and medium-soft joints were consistent with that hypothesis, but no specific model parameters were proposed.

The aim of the present study was to develop a biomechanical model to help understand the response of the hand and arm to mechanical shock in power nutrunner operation. The responses include hand kinetics and kinematics during reaction force build-up. The current model considers the forearm rotational reaction to impulsive pistol grip handtool loading as a single degree-of-freedom passive mechanical system. The parameters of the model elements include an equivalent mass moment of inertia, a linear rotational spring and a viscous damper. It is hypothesized that these mechanical system parameters are affected by the horizontal and vertical locations in which the tool is operated. Such a dynamic model should be useful for designing specific handtools and workstations suitable for a population of operators that minimize reaction in the hands and reduce eccentric forearm muscle contractions by considering the capacity of human operators to react against impulsive loads.

2. Experiment I: model parameters

2.1. *Methods*

An apparatus was constructed to deliver a controlled harmonic input to the hand and arm through a 4.4 cm diameter handle in a manner similar to a pistol grip power handtool (figure 1). The apparatus consisted of a mechanical system containing a known stiffness (k_0), damping (negligible), and an inertial mass (J_0). The passive element parameters for the human operator ($k_{subject}$, $J_{subject}$, $c_{subject}$) were identified by measuring the effect that the operator had on the dynamic response, $\theta(t)$, of the known system. The input, T(t), to the hand and arm was a damped sinusoid with a rise time consistent with impulsive forces found in power handtools. Free vibration of the system produced a hand–arm damped rotational vibration at a frequency of ~4 Hz for 2.5 s (figure 2). Handle rotation had a maximum peak-to-peak arc length of 2.8 cm at the centre of grip. Subjects held the handle at 20 cm below the axis of rotation, similar to a pistol grip tool handle. A beam was affixed to the centre of rotation, containing an inertial mass on one end and a linear spring on the other end to produce the equivalent mechanical system illustrated in figure 1. The mass and spring could be varied to achieve different free-vibration responses. When one end of the beam was initially displaced and released, the beam oscillated harmonically around the spindle axis of rotation (figure 2). Handle displacement, quantified as the arc length that the hand circumscribed as the hand grasped the handle attached to the rotating spindle, was measured using an linear voltage differential transformer (LVDT) attached to a fixed point on the beam. Through geometric transformation, this measurement was converted and calibrated to handle displacement. The data acquisition sampling rate was 1000 samples s^{-1}.

Subjects were instructed to grasp the handle and to hold it as hard as they could to inhibit oscillations, similar to operating a power handtool like a drill or screwdriver. The resulting stiffness, moment of inertia, and damping constant for the

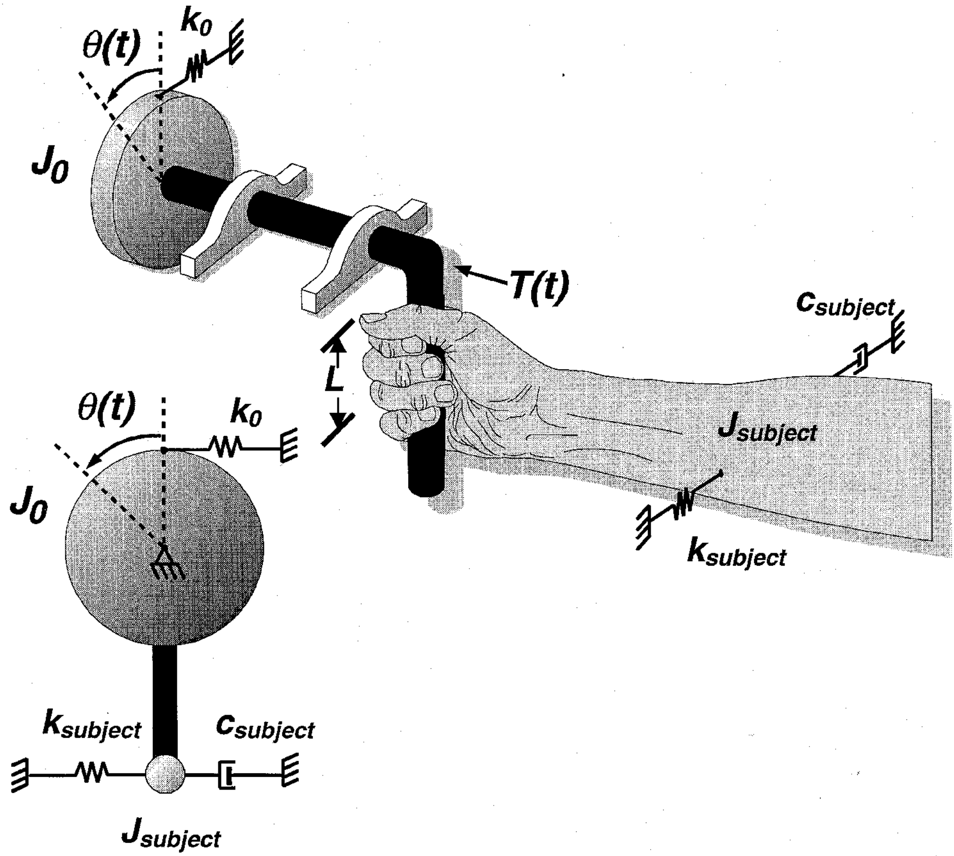

Figure 1. Test apparatus used in parameter extraction from free vibration (experiment I).

hand and arm in maximal voluntary effort were estimated for a variety of vertical and horizontal operator positions.

The angular displacement, $\theta(t)$, was measured from the static equilibrium position of the mass moment of inertia J. The governing equation of motion that describes the characteristic response of this system is:

$$J\ddot{\theta} + c\dot{\theta} + k\theta = 0 \tag{1}$$

When the hand and arm loads the apparatus, the physical parameters of the combined system are the sum of the contributions of the apparatus, applied mass, and the hand–arm system such that:

$$J = J_0 + J_{\text{mass}} + J_{\text{subject}} \tag{2}$$

$$k = k_0 + k_{\text{subject}} \tag{3}$$

$$c = c_0 + c_{\text{subject}}. \tag{4}$$

The natural frequency of this system is:

$$\omega_n = \sqrt{\frac{k}{J}} \tag{5}$$

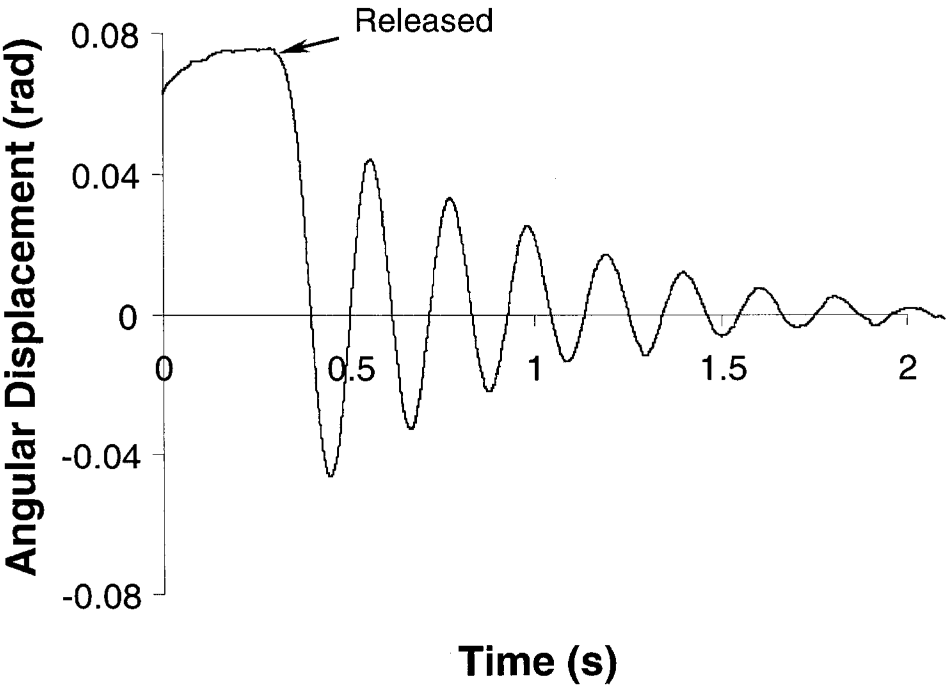

Figure 2. Plot of forearm angular displacement versus time following apparatus displacement and release.

and the damping ratio of the system can be written as:

$$\zeta = \frac{c}{2J\omega_n} \tag{6}$$

Substituting equations (2) and (3) into equation (5), the relationship between the mass moment of inertia of the applied mass and the resultant frequency is:

$$J_{\text{mass}} = k\frac{1}{{\omega_n}^2} - (J_0 + J_{\text{subject}}) \tag{7}$$

When substituting equations (2), (4) and (5) into equation (6), the mass moment of inertia of the applied mass can be written as:

$$J_{\text{mass}} = c\left(\frac{1}{2\omega_n\zeta}\right) + \text{constant} \tag{8}$$

A plot of the frequency obtained for several applied masses in the form of equation (7), has a resulting slope equivalent to the torsional stiffness k, and the intercept is the combined moment of inertia for the apparatus and the subject. Plotting the frequency and the damping ratio for several applied masses in the form of equation (8) provides the torsional damping constant c from the resulting slope. Based on these parameters, the equivalent stiffness, mass and damping constant for the forearm can be extracted.

The full-factorial experiment consisted of three applied masses (4.59, 9.11, 11.38 kg) which generated vibration frequencies between 3.2 and 4.8 Hz, four vertical distances between the handle and the floor (55, 93, 142, 190 cm), and three horizontal distances from the ankles to the handle (30, 60, 90 cm). The experimental conditions were presented to the subjects in a random order. Subjects first practised several trials to become familiar with the task. Subjects were given a 3-min rest after every nine trials to prevent fatigue. A typical experimental session lasted <1 h.

Twenty-five subjects (12 males, 13 females) participated in the experiment. All subjects were volunteers with informed consent, recruited from the University of Wisconsin-Madison campus, and were free of hand, arm or shoulder conditions that might affect performance. The average age was 23 years (SD 4 years). Average stature was 173.7 (9.8) cm, and average body mass was 66.3 (13.8) kg. Five subjects were recalled 2 months later to test the repeatability of the experiment. Twelve postures were the same as previously described. A 9.11 kg applied mass was used and the resultant vibration frequencies were measured.

2.2. *Results*

The main effects of vertical distance, horizontal distance and gender are plotted for stiffness, mass moment of inertia, and damping in figure 3. ANOVA results are summarized in table 1. Torsional stiffness was affected by horizontal distance ($p<0.01$), vertical distance ($p<0.05$), and gender ($p<0.05$). No significant interactions were observed. Mass moment of inertia was affected by vertical distance ($p<0.001$), horizontal distance ($p<0.001$), gender ($p<0.01$), and the interaction between vertical and horizontal distance ($p<0.01$). The interaction between vertical and horizontal distance changed the hand–arm moment of inertia 0.066 m^2kg ($p<0.01$) when horizontal and vertical distances were at their greatest. The handarm torsional damping constant was affected by horizontal distance ($p<0.01$), vertical distance ($p<0.01$), gender ($p<0.01$), and the interaction between gender and vertical distance ($p<0.01$). The vertical and horizontal distance interaction affected the damping constant by 1.438 m N s rad^{-1} ($p<0.001$) when horizontal and vertical distances were at their greatest. Histograms for the three model parameters plotted by gender (figure 4) demonstrate population differences.

The *post-hoc* Tukey pairwise test indicated that as the vertical distance increased, the stiffnesses for 55 and 190 cm were significantly different ($p<0.05$). Although the stiffnesses for middle distances were not significantly different from those at 55 and 190 cm, it showed a trend of increasing magnitude as the vertical distance increased.

Table 1. Analysis of variance summary of system parameters (experiment I).

		Torsional stiffness		Mass moment of inertia		Damping constant	
Effect	d.f.	MS	*F*	MS	*F*	MS	*F*
Horizontal distance (H)	2	1764.7	5.384‡	1.39e-2	7.703‡	6.953	10.334‡
Vertical distance (V)	3	1154.3	3.522†	9.33e-3	5.182‡	3.042	4.522‡
Gender (G)	1	1644.1	5.016†	2.27e-2	12.595‡	14.792	21.987‡
H*V	6	182.7	0.557	6.66e-3	3.699‡	3.168	4.708‡
H*G	2	74.4	0.227	6.09e-4	0.338	0.189	0.281
V*G	3	125.2	0.382	4.24e-4	0.235	1.147	1.705
H*V*G	6	265.4	0.810	4.01e-3	2.228‡	0.383	0.569
Error	271	327.8		1.80e-3		0.673	

†$p<0.05$; ‡$p<0.01$.

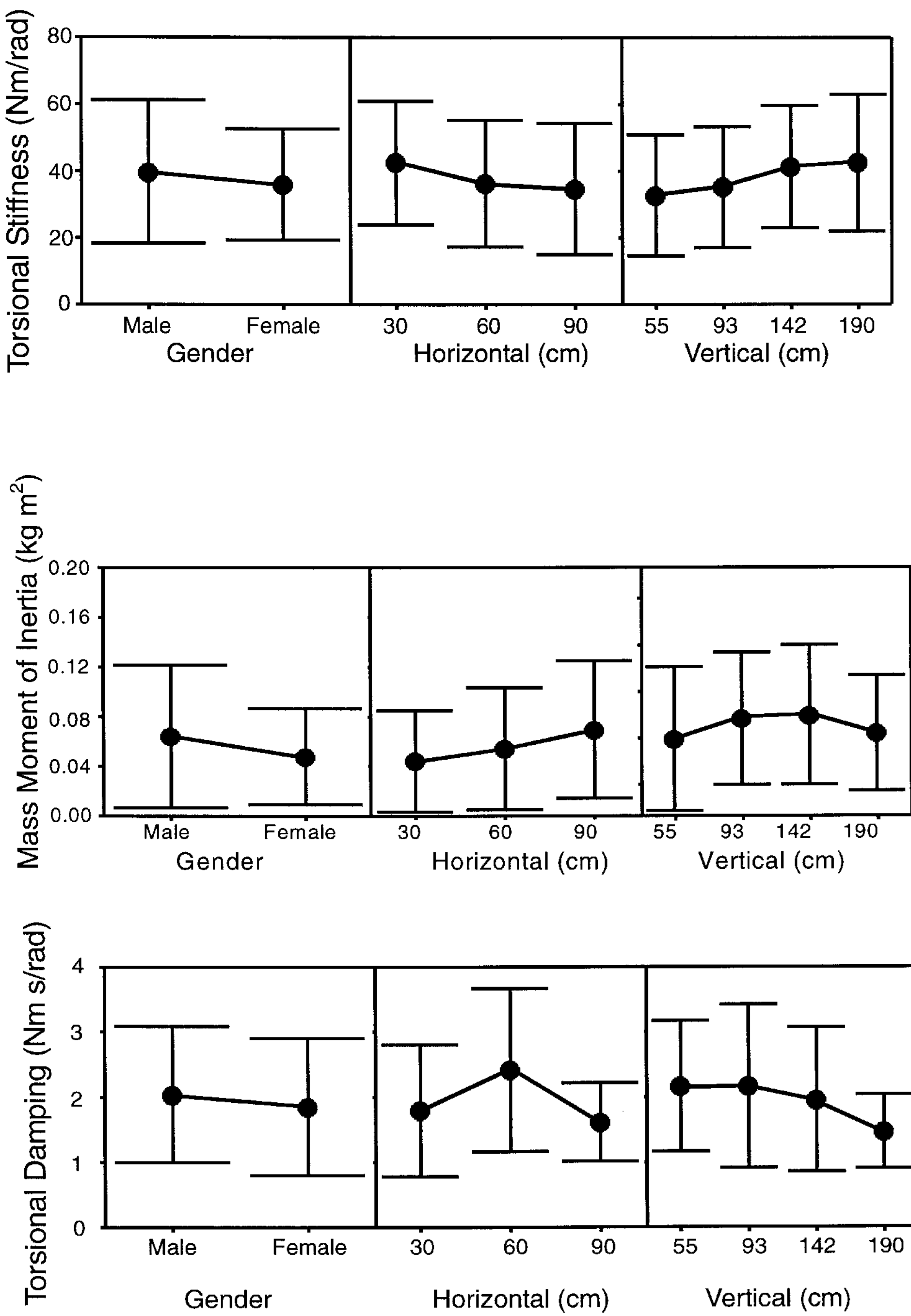

Figure 3. Average (1 SD error bars) system parameters for the hand–arm in pistol grip tool operation (25 subjects).

The mass moment of inertia for a vertical distance of 55 cm was significantly less than for 93 and 142 cm ($p < 0.01$), but not for 190 cm. Subjects at the 55 and 93 cm vertical locations had significantly greater damping constant than at 190 cm ($p < 0.05$).

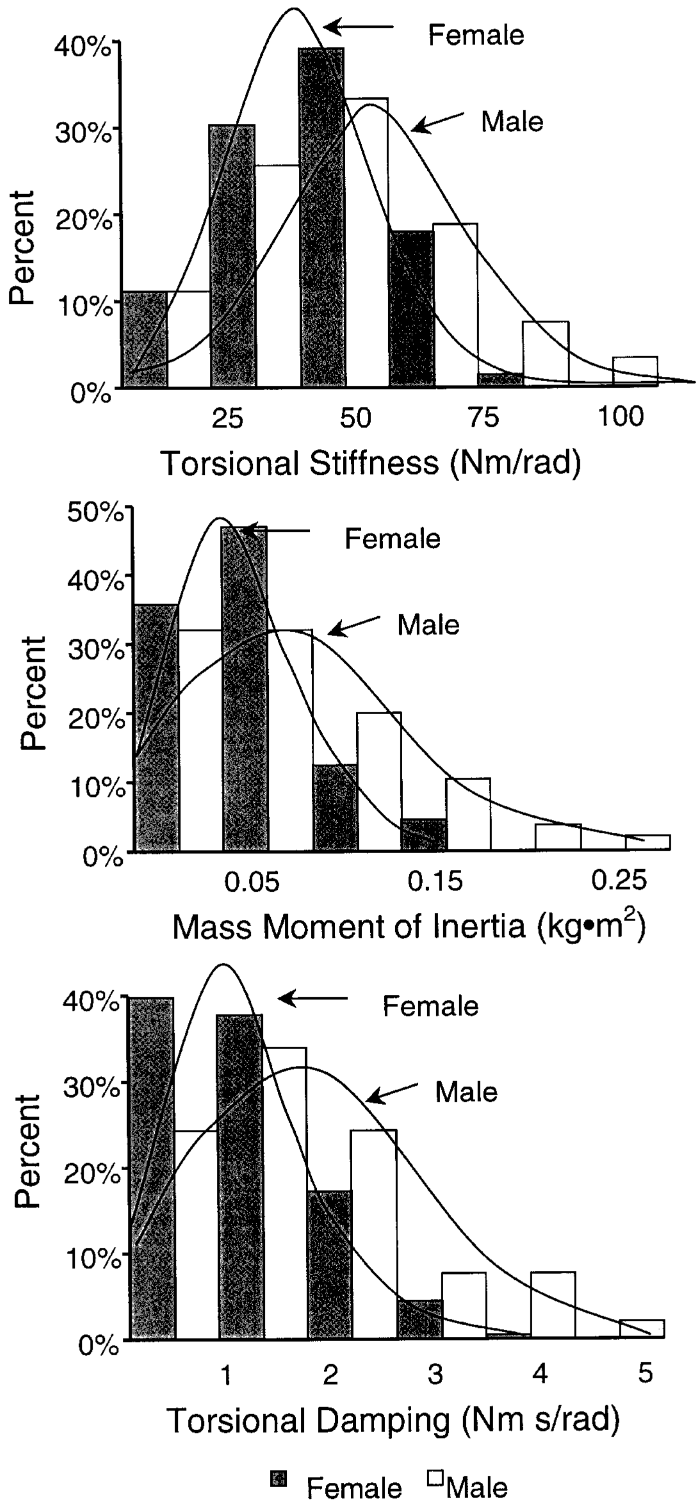

Figure 4. Histograms and normal distribution curves of model stiffness, mass moment of inertia and damping constant by gender, showing the differences in means among males and females.

Horizontal distance had a significant effect on all three model parameters. The Tukey test showed that stiffness was greater for 30 than for 90 cm ($p < 0.01$), while the 60 cm location was not significantly different with either of the other two distances. However, the stiffness consistently decreased from 30 to 90 cm. The mass moment of inertia for 30 cm was significantly less than for 90 cm ($p < 0.001$), but for 60 cm it was not significantly different from that at the other two distances. The mass moment of inertia consistently increased as the horizontal distance increased. The damping constant for 90 cm was significantly different from that at the other two distances ($p < 0.05$).

As a repeatability test, k, J, and c of each recalled subject and handle location from the previous results were used to predict the system frequency. The measured frequency from the repeatability test was plotted against predicted frequency (figure 5). The slope of the regression line between predicted and measured frequencies was 1.09 and the correlation coefficient was 0.9.

3. Experiment II: validation using actual tool operation

3.1. *Methods*

Handle motion during torque build-up was measured and compared with the model predictions when subjects operated an actual pistol grip nutrunner. An Ingersoll–Rand air shut-off pneumatic nutrunner (4RTPS1) was used for the experiment. Its free running speed was 452 rpm and its stall torque was 4.5 Nm. The mass of the tool was 1.42 kg. The location of the centre of mass of the tool was determined using the free suspension system method (Radwin and Haney 1996). The tool was suspended by a line in two different orientations and the intersection of two vertical plumb lines was used as the location of the centre of mass. The mass moment of

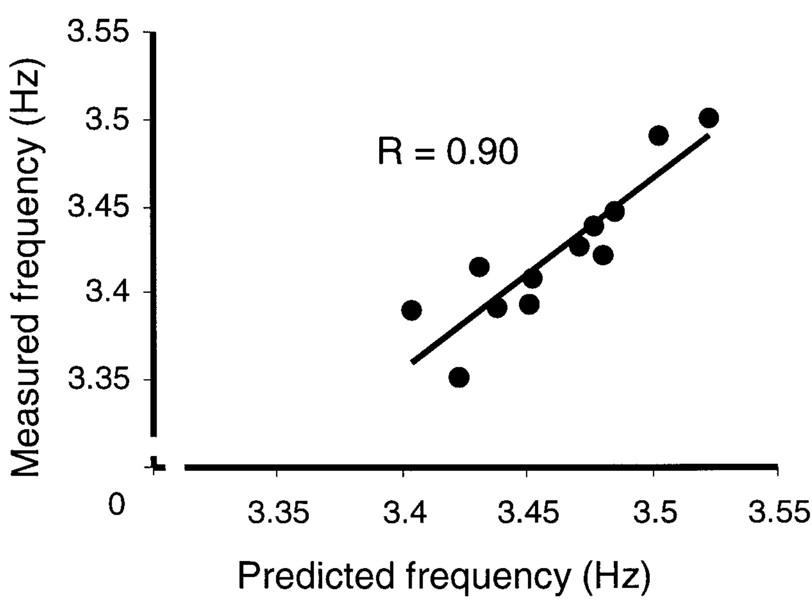

Figure 5. Repeatability of system response. Each point represents the mean of five subjects. Predicted frequencies were calculated from the model parameters of the recalled subjects and these frequencies were compared with the measured frequencies in a second test.

inertia of the tool was measured using the oscillation frequency method (Drillis *et al.* 1964). The tool was clamped between two metal pins so that friction was negligible and set into free oscillation. By knowing the location of the centre of mass, the moment produced during oscillation was calculated based on the frequency of oscillation. The inertia about the supporting point (I) can be expressed as

$$\omega_n = \sqrt{\frac{WR}{\mathrm{I}}} \tag{9}$$

where ω_n is the natural frequency, W is the tool weight and R is the moment arm from centre of mass to the suspension point. The mass moment of inertia about the centre of mass, obtained using parallel axis theorem, was 0.001457 m^2kg.

The motion of the handle during tool operation was measured directly using an OptoTrak 3020 3D motion analysis system. This system tracks and records the 3D coordinates of light-emitting diode (LED) markers in real-time. One LED marker was attached to the end of the handle; another was attached to the handle in-line with the spindle of the tool. The distance between the OptoTrak system and the subject was 5 m. The sampling rate was 400 samples s^{-1}. The tracking error associated with this configuration was <0.45 mm. Five subjects from the previous experiment were recalled to participate in this validation experiment. Three were females and two males.

When the tool was operated at different heights, the length of air hose between the floor and the tool changed. The inertia of the air hose connected to the tool and held at different vertical distances was determined using the free oscillation method as described and calculated using equation (9). The values were then added to the mass moment of inertia of the tool for correction. A custom made joint simulator was used for simulating different threaded fastener joint rates. Similar to products commercially available for testing tools, the simulator contained a hex screw that compressed Belleville spring washers when the screw was tightened. Changing the number of Belleville spring washers varied the joint rates. OptoTrak LED markers were attached to the joint base to monitor the fastener travel during torque build-up. The simulator screw head was located on a height adjustable table in order to vary its vertical distance from the floor.

The experiment was a three-factor, full factorial design. The three factors were vertical distance between hand and ground (55, 93, 142 cm); horizontal distance between hand and ankle (30, 60, 90 cm); and torque build-up time (70, 200 ms). There was a total of nine trials for each subject. The order of vertical and horizontal distance conditions was presented in a random order. Rest breaks of 1 min were given after every three consecutive trials. Each session lasted $\sim$20 min. The displacement of the handle was the sum of the linear displacements of the two LED markers attached to the handle. The linear displacement approximated to the handle curvilinear displacement (arc) due to the small angular rotations ($<20^\circ$).

The hypothesis was that tool operation could be represented mechanically as a single degree-of-freedom system (figure 1), with J_{tool} and k_{tool} replacing J_0 and k_0. This system consisted of a tool with mass moment of inertia (J_{tool}), torsional stiffness for the hand and arm (k_{subject}), rotational damping element for of the hand and arm (c_{subject}), and an effective mass moment of inertia of the hand and arm (J_{subject}). The angular response of the system $\theta(t)$ was determined by tool torque build-up $T(t)$ as the input. The equation of angular motion describing this system of tool operation is:

$$(J_{\text{subject}} + J_{\text{tool}})\frac{d^2\theta}{dt^2} + c_{\text{subject}}\frac{d\theta}{dt} + k_{\text{subject}}\theta = T(t) \quad (10)$$

Using the central difference method, the response of the system is approximated as a function of stiffness, damping constant, mass moment of inertia, and the input torque, where Δt is a time resolution unit, and 1 ms was used for the calculation:

$$\theta_{i+1} = \left\{ \frac{1}{\frac{J_{\text{subject}} + J_{\text{tool}}}{(\Delta t)^2} + \frac{c_{\text{subject}}}{2\Delta t}} \right\} \left[\left\{ \frac{2(J_{\text{subject}} + J_{\text{tool}})}{(\Delta t)^2} \right\} \theta_i + \left\{ \frac{c_{\text{subject}}}{2\Delta t} \frac{2(J_{\text{subject}} + J_{\text{tool}}}{(\Delta t)^2} \right\} \theta_{i-1} + T_i \right] \quad (11)$$

The hand force, F_{hand}, can be obtained using equation (12), where L is the moment arm of the hand force defined by the vertical distance between the hand grip and the tool spindle (figure 1):

$$F_{\text{hand}} = \left(c_{\text{subject}}\frac{d\theta(t)}{dt} + k_{\text{subject}}\theta(t)\right)/L \quad (12)$$

3.2. *Results*

The torque build-up for this tool (figure 6) shows predicted hand force and handle displacement for a single set of conditions. The starting and ending points of the build-up process were indicated by the displacement of the threaded fastener of the joint simulator, measured using an LED marker. Measuring the difference between the two end points plotted the data for each trial. The mean displacement was 54.4 (SD 2.17) mm for the soft joint and 36.6 (1.26) mm for the medium joint.

The predicted displacement was computed based on the k, j and c of each individual subject from the previous experiment. The predictions of hand force and displacement for two torque build-up times based on the means of the mechanical parameters of the 25 subjects from experiment I is demonstrated in figure 7. The relationship between predicted and the measured displacements in this validation experiment is shown in figure 8. Each datum point represents the mean of five subjects. The regression slope was 0.73 mm mm^{-1} and the intercept was 25.5 mm. The correlation coefficient between the model prediction and the measurement was 0.88. The regression analysis showed that the model tended consistently to underestimate handle displacement by 27%.

4. Discussion

Experiment I was based on the assumption that the operator hand–arm can be modelled as a rotational mass-spring–damper mechanical system. Muscle has been modelled as a viscoelastic mechanical system for decades since both the Hill and the Levin–Wyman models were developed (Gasser and Hill 1924, Levin and Wyman 1927). The models suggested that an undamped spring and a damped elastic element could represent the muscle. The representation has been widely accepted because of

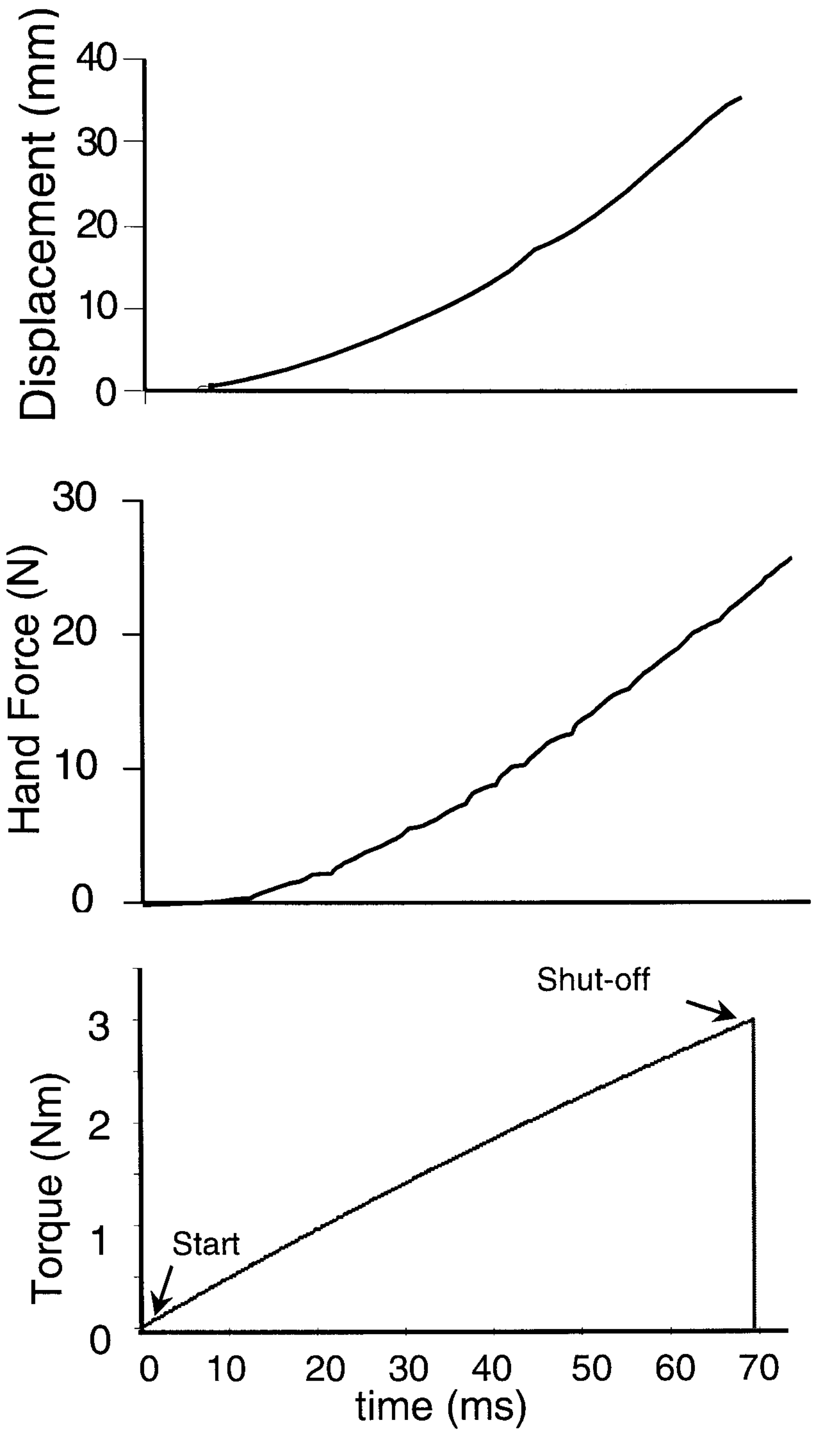

Figure 6. Plots of (bottom) test tool torque build-up, (middle) hand force prediction and (top) measured displacement over time on a medium (70 ms) joint. Parameters used for the calculation were means for the subjects in experiment I converted into torsional values, $J_{subject}$ = 0.0055 kg·m^2, $k_{subject}$ = 436.5 Nm/rad^{-1}, $c_{subject}$ = 0.11 Nm·s/rad^{-1}.

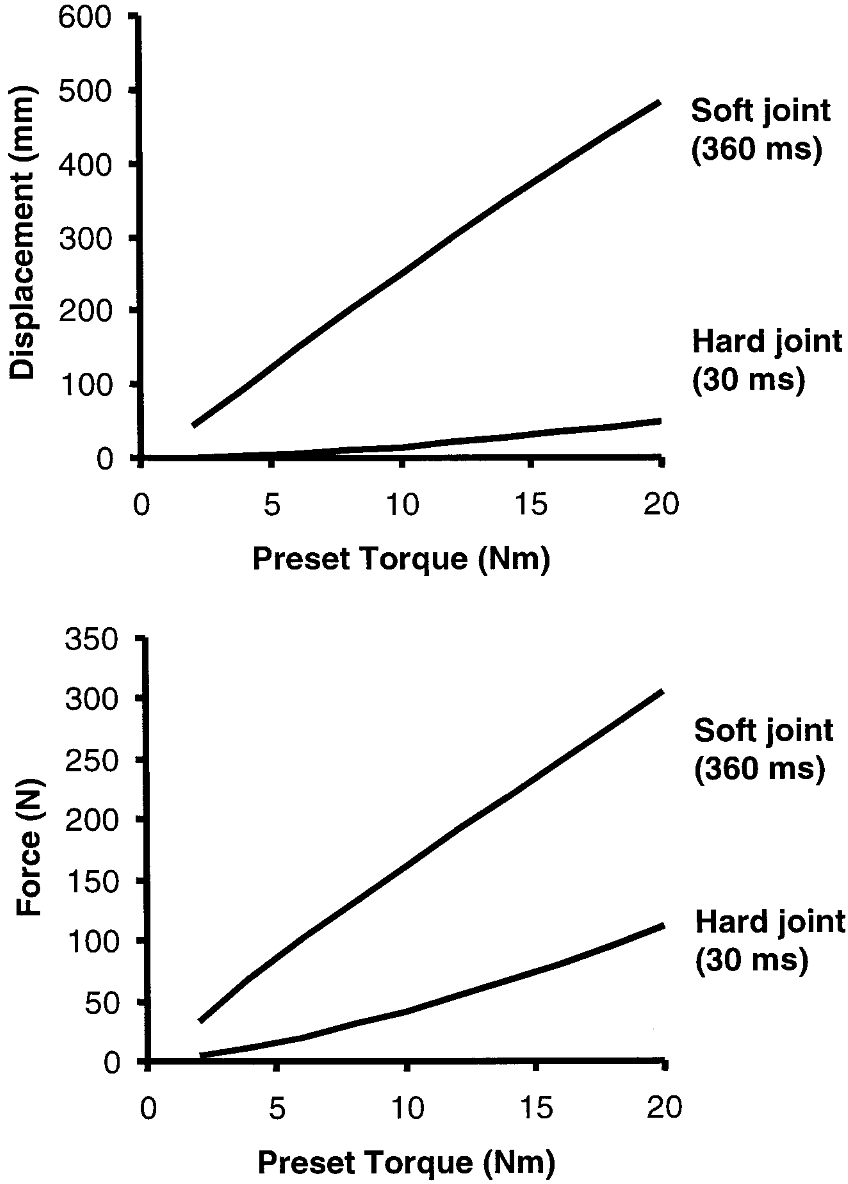

Figure 7. Plots of preset target torque versus predicted hand displacement (top) and hand force (bottom) for two torque build-up times.

its simplicity and experimental and mathematical advantages (Cole *et al.* 1996), despite the lack of connection to the actual physiological mechanisms of muscle contraction (Winters 1990, Zahalak 1990).

Based on the Hill model, the dynamic responses of single and multi-articular systems were modelled using an additional inertial element (Hogan 1990, Seif-Naraghi and Winters 1990). Hogan (1990) suggested that the inertial behaviour is important during fast dynamic events because it is not subject to voluntary control.

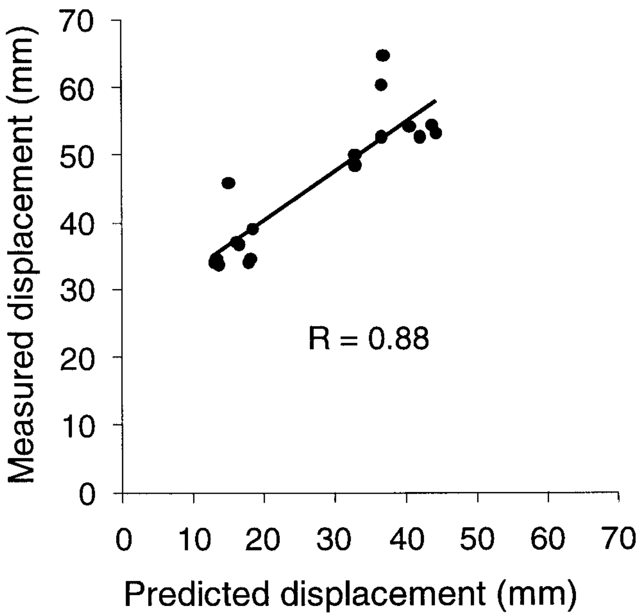

Figure 8. Plot of predicted versus measured displacement.

The position of the limb determines the distribution of inertia and, therefore, is a strategy to optimize the dynamic response of the body.

Investigators have considered the hand – arm as a passive mechanical system for harmonic vibration inputs and for translational vibration inputs with frequencies >20 Hz. Reynolds and Soedel (1972) modelled the hand – arm system in three directions using 1 and 2 degrees-of-freedom mechanical models. Mass, stiffness and viscous damping were calculated in the 20 – 500 Hz frequency range. Suggs (1972) observed that stiffness and damping for a 2 degrees-of-freedom mechanical model were not constant for changing grip force. Although these models were applicable to periodic and random vibration produced by abrasive tools like grinders and sanders, they did not apply to the reaction force and shock in nutrunner or drill operation. The data obtained in experiment I of the present study provide the mechanical properties for the low frequency range, which is more relevant to shock and reaction forces produced by power nutrunners, drills and other power handtools.

Oh *et al.* (1997) developed a dynamic mechanical model for a right-angle nutrunner. They concluded that a dynamic model predicted the hand force better than a static model did because the inertial force was included. However, the dynamic model overestimated peak hand force by 9% for the hard (35 ms) joint. Their model used a point mass applied on the tool handle. Also, the Oh *et al.* model considered a constant hand mass, which the current data show is affected by work location and varies between individual operators. The current model, with the combination of masses, springs and dampers, should be sufficient to describe dynamic responses.

Work location is an important factor influencing torque exertion capabilities (Armstrong *et al.* 1989, Ulin *et al.* 1992, 1993). Current results are consistent with previous research. Lundströd and Burström (1989) measured hand – arm impedance within the range of 20 – 1500 Hz and concluded that impedance was affected by posture. Hogan (1990) pointed out that posture influenced hand stiffness, viscosity and inertia. Örtengren *et al.* (1991) studied the effects of working heights on muscle activity and found that for pistol grip tool operation muscle activity and perceived exertions were different for three handle orientations. This suggests that the muscle responses, which affect their mechanical properties, change as work locations are changed. The present study is consistent with these findings and shows that horizontal and vertical distance affects stiffness, inertia and damping elements in the hand and arm.

Ulin *et al.* (1992) learned that for pistol grip tools the least perception of exertion occurred when the work location was closest to the body horizontally. The farther the work location, the greater was the perceived exertion. Figure 3 reveals that stiffness of the hand and arm decreases as the horizontal distance increases. As the elbow extends, the muscles work less effectively to act against the reaction force. In the vertical direction, the least perceived exertion occurred at 114 cm above the ground. The present data also show that the hand and arm stiffness increases and the moment of inertia is maximum between 93 and 142 cm above the ground. Stiffness and moment of inertia are mechanical properties that resist motion. The greater these elements, the less displacement is expected when the hand reacts against tool build-up force. Armstrong *et al.* (1989) found the interval of 0 – 38 cm horizontally and 102 – 152 cm vertically yielded the least discomfort for pistol grip power nutrunner operation. The present data are consistent with that study.

The biodynamic model developed in the present study is intended for estimating hand – arm response to tool reaction forces for a range of operators. Rather than accounting for anthropometric and posture differences, the variance between subjects was measured to calculate the population distribution for each model parameter. These results may be used for understanding the range of capabilities, analogous to strength data. Absolute work locations were used instead of controlling specific joint angles in order for the model to be applied more practically in the workplace. A similar practical approach for approximating posture has been used by NIOSH (1981).

The variance among subjects is given in figure 4. Individual differences, including physical capability and posture assumed during tool operation for a given set of horizontal and vertical conditions, which was limited by individual stature, may be attributed to this variance.

The current model can predict the hand motion and associated forces using tool parameters and workplace design factors affecting the location of the tool with respect to the operator. An application is presented in figure 7. Discomfort experienced by operators during power handtool operation may be considered a surrogate for hand displacement and force. Kihlberg *et al.* (1995) found a strong correlation among reaction force, perceived discomfort and hand displacement. Johnson and Childress (1988) report similar outcomes. Hand displacement is affected by torque build-up time (Oh *et al.* 1997). This is indicated in the results of experiment II (figure 7). Greater handle displacement is the result of a tool producing force or torque that exceeds operator balance or strength capacity. To minimize the hand displacement, a torque reaction bar can be added to the tool for tasks that would result in hand displacement so great it will overcome the operator (Kihlberg *et al.* 1993, Radwin and Haney 1996). When a reaction bar is not used, the hand – arm system will absorb the reaction.

Eccentric contractions often occur during power tool torque build-up (Oh and Radwin 1997). When the tool torque overpowers the static strength of the operator, it moves in the direction opposite to muscle contraction. Passive stretching for a muscle – tendon unit was successfully modelled as a passive 1 degree-of-freedom biomechanical system by Taylor *et al.* (1990). The present model combines these and shows that a passive spring – mass-damper system can be used to describe the hand and arm response to torque reaction.

Results in experiment II show that the model tends to underestimate the displacement measured in actual tool operation. In Experiment I, subjects were asked to hold the handle and work as hard as they could to react against the shock input. It is not likely that tool operators hold tools using maximum effort during normal use. The mechanical properties obtained may, therefore, represent the physical capacity of subjects, similar to strength measurements. The results in experiment II confirm this. The pistol grip tool delivered 3 Nm torque and the resulting displacement was greater than the model predicted. If subjects worked at their maximum effort the displacement would undoubtedly be less. When the stiffness parameter (k) was reduced by 75%, the resulting regression slope for 75% effort became 0.9 and the intercept reduced to 9.9 mm, with a correlation coefficient of 0.78. This indicates that the effort level likely influenced the predictability of this model. Further investigation incorporating EMG as an index of muscle exertion will be considered in future studies.

Results in experiment II also show that the displacement predictions for soft joints were better than for medium joints. When the tool worked on a soft joint, it took longer for the tool to reach the target torque and shut off. It took less time on a medium joint. Oh *et al.* (1997) observed that as torque build-up rate increases, so does the angular acceleration. Since the inertial force is proportional to acceleration, the tool produced more of the reaction force. Over the course of torque build-up, the force impulse created for a soft joint was greater than that for a medium joint. The resulting reaction force for a medium joint was, therefore, less demanding than for a soft joint. The current study only tested two joint types: medium and soft. Adapting a tool – joint system that produces greater reaction force could potentially extend the scope of experiment II to determine the level of effort used during actual operation. Tests will be done in subsequent experiments.

The results indicate that a passive single degree-of-freedom mechanical model can be useful for representing the hand – arm eccentric exertion in power handtool operation under the condition that the tool operators use their maximum effort. These parameters may be used for modelling the hand – arm response to power handtool loading for different handtool and work place designs. This model can predict the handle motion and hand force when power handtool operators use their maximum capability.

References

Aghazadeh, F. and Mital, A. 1987, Injuries due to handtools, *Applied Ergonomics*, **18**, 273 – 278.

Armstrong, T. J., Bir, C., Foulke, J., Martin, B., Finsen, L. and Sjögaard, G. 1999, Muscle responses to stimulator torque reactions of hand-held power tools, *Ergonomics*, **42**, 146 – 159.

Armstrong, T. J., Buckle, P., Fine, L. J., Hagberg, M., Jonsson, B., Kilbom, Å. Kuorinka, I. A. A., Silverstein, B. A., Sjögaard, G. and Viikari-Juntura, E. R. A. 1993, A conceptual model for work-related neck and upper-limb musculoskeletal disorders, *Scandinavian Journal of Work Environmental Health*, **19**, 73 – 84.

Armstrong, T. J., Punnett, L. and Ketner, P. 1989, Subjective worker assessments of hand tools used in automobile assembly, *American Industrial Hygiene Association Journal*, **50**, 639–645.

Cole, G. K., van den Bogert, A., Herzog, W. and Gerritsen, K. G. M. 1996, Modelling of force production in skeletal muscle undergoing stretch, *Journal of Biomechanics*, **29**, 1091–1104.

Drillis, R., Contini, R. and Bluestein, M. 1964, Body segments parameters: A survey of measurement technique, *Artificial Limbs*, **8**, 44–66.

Fridén, J., Sjöström, M. and Ekblom, B. 1983, Myofibrillar damage following intense eccentric exercise in men, *International Journal of Sports Medicine*, **4**, 170–176.

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.

Gasser, H. S. and Hill, A. V. 1924, The dynamics of muscular contraction, *Proceedings of the Royal Society of London, Series B*, **96**, 398–437.

Griffin, J. W. 1987, Differences in elbow flexion torque measured concentrically, eccentrically, and isometrically, *Physical Therapy*, **67**, 1205–1208.

Henriksson, J., Knuttgen, H. G. and Bonde-Peterson, F. 1972, Perceived exertion during exercise with concentric and eccentric muscle contractions, *Ergonomics*, **15**, 538–544.

Hogan, N. 1990, Mechanical impedance of single- and multi-articular systems, in J. M. Winters and S. L.-Y. Woo (eds), *Multiple Muscle Systems* (New York: Springer), 149–164.

Johnson, S. L. and Childress, L. J. 1988, Powered screwdriver design and use: tool, task, and operator effects, *International Journal of Industrial Ergonomics*, **2**, 183–191.

Kihlberg, S., Kjellberg, A. and 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. and Lindbeck, L. 1995, Discomfort from pneumatic tool torque reaction: acceptability limits, *International Journal of Industrial Ergonomics*, **15**, 417–426.

Komi, P. V. and Buskirk, E. R. 1972, Effect of eccentric and concentric muscle conditioning on tension and electrical activity of human muscle, *Ergonomics*, **15**, 417–434.

Komi, P. V. and Rusko, H. 1974, Quantitative evaluation of mechanical and electrical changes during fatigue loading of eccentric and concentric work, *Scandinavian Journal of Rehabilitation Medicine*, **suppl. 3**, 121–126.

Levin, A. and Wyman, J. 1927, The viscous elastic properties of muscle, *Proceedings of the Royal Society of London, Series B*, **101**, 218–243.

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

Lindqvist, B. 1993, Torque reaction in angled nutrunners, *Applied Ergonomics*, **24**, 174–180.

Louda, L. and Lukas, E. 1977, Hygienic aspects of occupational hand–arm vibration, in *Proceedings of the International Occupational Hand–Arm Vibration Conference* (Cincinnati: National Institute for Occupational Safety and Health), 60–66.

Lundströd, R. and Burström, L. 1989, Mechanical impedance of the human hand–arm system, *International Journal of Industrial Ergonomics*, **3**, 235–242.

McCully, K. K. and Faulkner, J. A. 1985, Injury to skeletal muscle fibers of mice following lengthening contractions, *Journal of Applied Physiology*, **59**, 119–126.

National Institute for Occupational Safety and Health 1981, *A Work Practices Guide for Manual Lifting*. Technical report no. 81–122 (Cincinnati: US Department of Health and Human Services, CDC, NIOSH).

Oh, S. A. and 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. and 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.

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

Örtengren, R., Cederqvist, T., Lindberg, M. and Magnusson, B. 1991, Workload in lower arm and shoulder when using manual and powered screwdrivers at different working heights, *International Journal of Industrial Ergonomics*, **8**, 225–235.

Pandolf, K. B. 1977, Psychological and physiological factors influencing perceived exertion, in G. Borg (ed.), *Physical Work and Effort: Proceedings of the First International Symposium held in the Wenner–Gren Center, Stockholm* (New York: Pergamon), 371–378.

Radwin, R. G. and Haney, J. T. 1996, *An Ergonomics Guide to Hand Tools* (Fairfax: American Industrial Hygiene Association).

Radwin, R. G., Oh, S. and Fronczak, F. J. 1995, A mechanical model of hand force in power hand tool operation, in *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting, San Diego, October* (Santa Monica: HFES).

Radwin, R. G., van Bergeijk, E. and 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. and Falkenberg, R. J. 1982, Three- and four-degrees-of-freedom models of the vibration response of the human hand, in A. J. Brammer and W. Taylor (eds), *Vibration Effects on the Hand and Arm in Industry* (New York: Wiley), 117–132.

Reynolds, D. D. and Keith, R. H. 1977 Hand–arm vibration, Part I: Analytical model of the vibration response characteristics of the hand, *Journal of Sound and Vibration*, **51**, 237–253.

Reynolds, D. D. and Soedel, W. 1972, Dynamic response of the hand–arm system to a sinusoidal input, *Journal of Sound and Vibration*, **21**, 339–353.

Seif-Naraghi, A. H. and Winters, J. M. 1990, Optimized strategies for scaling goaldirected dynamic limb movements, in J. M. Winters and S. L.-Y. Woo (eds), *Multiple Muscle Systems* (New York: Springer), 312–336.

Stauber, W. T. 1989, Eccentric action of muscles: physiology, injury and adaptation, *Exercise and Sports Reviews*, **17**, 157–185.

Suggs, C. W. 1972, Modelling of the dynamic characteristics of the handarm system, in W. Taylor (ed.), *The Vibration Syndrome* (New York: Academic Press), 169–186.

Suggs, C. W. and Mishoe, J. W. 1977, Hand–arm vibration: implications drawn from lumped parameter models, in *Proceedings of the International Occupational Hand–Arm Vibration Conference, Cincinnati, October 1975* (Cincinnati: National Institute for Occupational Safety and Health), 136–141.

Talag, T. S. 1973, Residual muscular soreness as influenced by concentric, eccentric, and static contractions, Research Quarterly, **44**, 458–469.

Taylor, D. C., Dalton, Jr, J. D., Seaber, A. V. and Garrett, Jr, W. E. 1990, Viscoelastic properties of muscle–tendon units—the biomechanical effects of stretching, *American Journal of Sports Medicine*, **18**, 300–309.

Ulin, S. S., Armstrong, T. J., Snook, S. H. and Monroe-Keyserling, W. 1993, Examination of the effect of tool mass and work postures on perceived exertion for a screw driving task, *International Journal of Industrial Ergonomics*, **12**, 105–115.

Ulin S. S., Snook, S. H., Armstrong, T. J. and Herrin, G. D. 1992, Preferred tool shapes for various horizontal and vertical work locations, *Applied Occupational and Environmental Hygiene*, **7**, 327–337.

Walmsley, R. P., Pearson, N. and Stymiest, P. 1986, Eccentric wrist extensor contractions, and the force velocity relationship in muscle, *Journal of Orthopaedic and Sports Physical Therapy*, **8**, 288–293.

Winters, J. M. 1990, Hill-based models: a systems engineering perspective, in J. M. Winters and S. L.-Y. Woo (eds), *Multiple Muscle Systems* (New York: Springer), 69–92.

Wood, L. A., Suggs, C. W. and Abrams, Jr, C. F. 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. 1990, Modeling muscle mechanics (and energetics), in J. M. Winters and S. L.-Y. Woo (eds), *Multiple Muscle Systems* (New York: Springer), 1–23.