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A single-degree-of-freedom dynamic model predicts the range of human responses to impulsive forces produced by power hand tools

Jia-Hua Lin[a], Robert G. Radwin[b,*], Terry G. Richard[b]

[a] *Liberty Mutual Research Institute for Safety and Health, 71 Frankland Road, Hopkinton, MA 01748, USA*
[b] *University of Wisconsin-Madison, 1410 Engineering Drive, Madison, WI 53706, USA*

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Abstract

The human operator is modelled as a single-degree-of-freedom dynamic mechanical system for predicting the response to impulsive torque reaction forces produced by rotating spindle power hand tools such as nutrunners or screwdrivers. The model uses mass, spring and damping elements to represent the standing operator supporting the tool in the hand. It was hypothesized that these mechanical elements are affected by work location and vary among individuals. These elements were ascertained by measuring the resulting frequency and amplitude of a freely oscillating defined mechanical system when externally loaded using maximal effort to oppose its motion. Twenty-five subjects (13 female, 12 male) participated in the full factorial experiment that measured the effects of gender, vertical and horizontal work location for various tool shapes (in-line, pistol, right angle), and orientations (horizontal and vertical). The mean operator stiffness decreased from 1721 to 1195 N/m when the horizontal work location increased from 30 to 90 cm in front of the ankles for a pistol-grip handle used on a vertical surface. Males had greater mass moment of inertia of (0.0099 kg m^2) than females (0.0072 kg m^2) for an in-line handle used on a horizontal surface. Internal validation by independently measuring apparatus torque found that the model satisfactorily explained the measured operator dynamics with an average error of 2.86%. Group variance reflects the range of operator capacities to react against power hand tool generated forces for the sample group and therefore it may also be useful for understanding the range of capacities among a group of operators performing similar tasks.

Keywords: Motion and force modelling; Work-related musculoskeletal disorders; Eccentric muscle contractions; Force; Torque

1. Introduction

Force in power hand tool use is dynamic. As tool reaction force rapidly rises, the tool overcomes the operator by moving the upper limb in opposition to muscle contraction, resulting in eccentric dynamic muscle contractions (Radwin et al., 1989; Oh and Radwin, 1998; Armstrong et al., 1999). This is of particular interest because large eccentric exertions may be associated with increased risk of muscle damage and injury (Best and Hunter, 2000; Fridén and Lieber, 1998). Power hand tool use is considered a risk factor for work-related musculoskeletal disorders because of the repetitive and forceful exertions associated with their use (Armstrong et al., 1986; Bureau of Labor Statistics, 2000; Muggleton et al., 1999; National Institute for Occupational Safety and Health, 1997; National Research Council, 2001). Previous studies have shown that numerous factors including tool size, shape, output capacity, and operator posture, affect the forces acting against the operator for rotating spindle power hand tools, such as drills and screwdrivers, and hence the effort to use them (Armstrong et al., 1989; Hallbeck, 1994; Radwin et al., 1989; Ulin et al., 1993).

Simple mechanical systems have been successfully used for modelling human response to transient disturbances. Hunter and Kearney (1982) concluded that a single-degree-of-freedom linear model, which contains individual inertial, viscous and elastic terms, satisfactorily described passive ankle response for disturbance frequencies between 0.5 and 20 Hz. Lindqvist (1993) hypothesized that a power nutrunner operator can be represented mechanically as a single-degree-of-freedom mechanical system. The data for

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*Corresponding author. Tel.: +1-608-263-6596; fax: +1-608-265-9239.

E-mail address: radwin@engr.wisc.edu (R.G. Radwin).

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impulsive loads in the hands demonstrated that handle displacement due to reaction force inputs for various torque build-up times were consistent with that hypothesis; however, no specific model parameters were proposed. Lin et al. (2001) considered the human operator a single-degree-of-freedom torsional mechanical model for griping a pistol-grip tool with torque acting in the vertical (frontal) plane but the results were limited to that specific application.

The objective of the current study was to quantify single-degree-of-freedom mechanical model parameters for various handle and work surface locations using an approach similar to Lin, et al. (2001). Model parameters were identified for three conventional tool handle shapes (pistol, right angle, and in-line), tool orientations (horizontal and vertical), and work locations (horizontal and vertical distance from the ankles). The study also investigated variations among individual tool operators, and group characteristics such as gender. The single-degree-of-freedom mechanical model can aid in tool and workplace design by considering the range of dynamic responses of a group of operators for specific tool and workplace factors.

2. Methods

The human operator is considered as a single-degree-of-freedom mechanical system (Fig. 1). This lumped parameter model contains equivalent stiffness, mass moment of inertia and damping elements corresponding to the mechanical characteristics of the operator for the various experimental conditions. The specific mechanical elements are identified by measuring changes in the free vibration responses of a defined mechanical apparatus when loaded by the human operator coupled through a handle (Fig. 1). The equation of motion for the combined system can be written as

$$(J_{\text{subject}} + J_{\text{apparatus}})\ddot{\theta} + (c_{\text{subject}} + c_{\text{apparatus}})\dot{\theta} + (k_{\text{subject}} + k_{\text{apparatus}})\theta = 0, \tag{1}$$

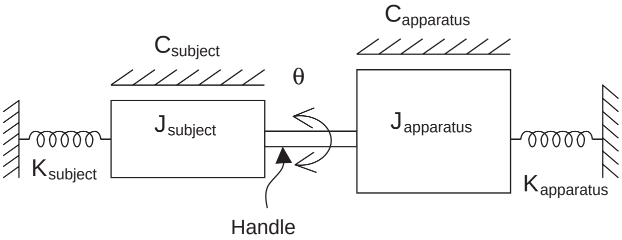

Fig. 1. Dynamic mechanical model of the human operator and experimental apparatus. Both the loading apparatus (right) and the subject (left) are represented using a single-degree-of-freedom systems coupled by a rigid handle. Mass moment of inertia of the handle and the torsional spring are included in $J_{\text{apparatus}}$.

where $\ddot{\theta}$ is the angular acceleration, $\dot{\theta}$ is the angular velocity, and θ is the angular displacement. The passive element parameters for the human operator (k_{subject}, J_{subject}, and c_{subject}) can be identified by measuring the effect that the operator imposes on the dynamic angular response, $\theta(t)$, of the apparatus. These parameters are also affected by the location of the grip when the handle is perpendicular to the rotating axis. Details describing these calculations are provided in Lin et al. (2001).

The apparatus delivered a controlled harmonic input to the hand and arm through a 4.6 cm diameter handle. It was mounted on a height adjustable lift table. The apparatus contained a torsional spring with stiffness ($k_{\text{apparatus}}$) of 50 m N/rad, and an inertial mass ($J_{\text{apparatus}}$) that could be varied from 0.06, 0.08, and 0.10 $\text{kg}\,\text{m}^2$ to achieve natural frequencies of 4.6, 4 and 3.6 Hz, respectively (Fig. 1).

Four handle configurations were tested (Fig. 2). A trigger was mounted on the handle at a location similar to actual tools and was activated using the index finger for pistol grip and in-line handles, and the thumb for right-angle handles. When the trigger was pressed, the torsional mass was released by a Warner (South Beloit, IL) model CBC-802 electromagnetic brake and oscillated harmonically around the axis of rotation for at least 1.5 s. Subjects were instructed to use maximum effort to counteract the impulsive torque, similar to operating a power hand tool. The center of grip was located 11.75 cm from the spindle.

Handle displacement was measured using a Trans-Tek (Ellington, CT) model 600-0000 angular displacement transducer (ADT). A custom full bridge strain gauge torque transducer was installed in the apparatus spindle. The handle torque and displacement signals were digitized and sampled using a National Instruments Lab-PC+ data acquisition board with a sampling rate of 1000 samples/s.

Dynamic stiffness of the system, defined as the peak-to-peak handle torque and displacement ratio during oscillation, was measured and used for model validation. The dynamic stiffness can be expressed using the following equation over a complete oscillation period:

$$\frac{\Delta T}{\Delta \theta} = k_{\text{subject}} - \omega^2 (J_{\text{subject}} + J_{\text{apparatus}}). \tag{2}$$

The correlation between the dynamic stiffness predicted using the model and the independently measured outcome was used to validate the model. The predicted dynamic stiffness for each subject was calculated based on measured model parameters and was the independent variable (right side of Eq. (2)). Two consecutive cycles of free rotation were used to measure peak-to-peak displacement and torque. The average was the dependent variable (left side of Eq. (2)). The regression slope between the two variables should be unity for a perfect fit. The model error was defined as the difference

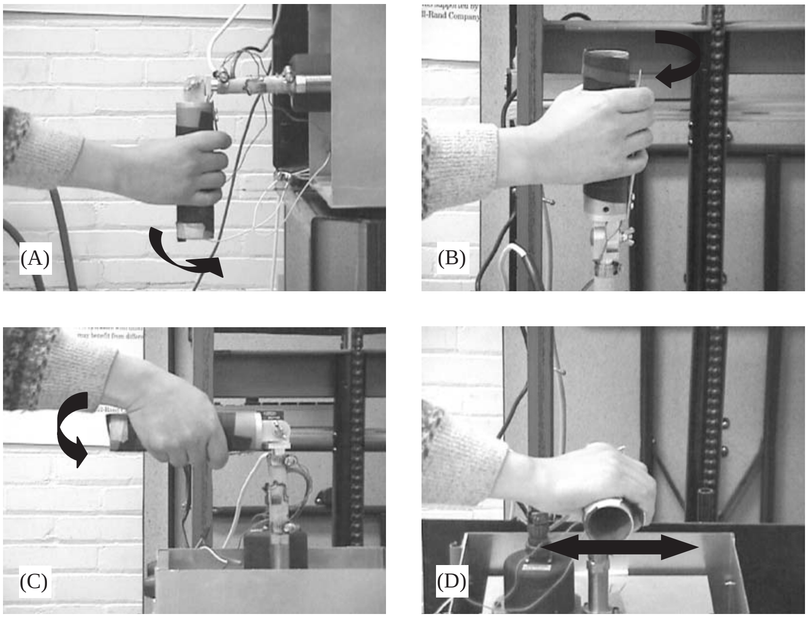

Fig. 2. Handle shapes and orientations: (A) a pistol-grip handle on a vertical surface; (B) an in-line handle on a horizontal surface; (C) a pistol-grip handle on a horizontal surface; and (D) a right-angle handle on a horizontal surface.

between unity and the actual slope, and the correlation coefficient demonstrated the aptness of the model.

The experiment employed a full-factorial design, requiring every subject to experience all conditions (Table 1). These specific work locations were selected because they represented common tool applications and because they were within the static standing reach envelops of most (greater than 95%) US adult civilians (Gordon et al., 1989). The three mechanical parameters were measured for each subject. For configurations (Fig. 2A, 2C, and 2D) where the handle was perpendicular to the rotating axis, the mechanical parameters were calculated by taking out the distance between the hand location and the rotating spindle. Therefore linear values for stiffness, inertial mass, and damping were considered for these configurations. Analysis of variance was used to examine the main effects and interactions of vertical and horizontal locations, and gender on the model parameters. Post hoc Tukey contrast tests were performed for significant effects.

Subjects performed several trials to become familiar with the task prior to data collection. They were allowed a 3-min rest period after every nine tests to avoid fatigue build-up. The experiment consisted of two sessions on different days lasting less than 1 h each.

The experiment protocol was approved by University of Wisconsin Human Subjects Institutional Review Board. All subjects were student volunteers randomly recruited from the University of Wisconsin campus. They were free of hand, arm or shoulder conditions that might otherwise affect their performance, and participated with informed consent. A total of 25 participants (13 female, 12 male) were tested. The average age was 23.6 years (S.D. = 4.9 years). The mean stature of this subject group (166.3 cm for female and 177.7 cm for male) was not significantly different ($p > 0.05$) than US military personnel (Gordon et al., 1989). The mean female (60.6 kg) and male (80.8 kg) body mass were also not significantly different ($p > 0.05$) than US military personnel (Gordon et al., 1988).

Table 1
Model parameters were measured for the following experimental conditions. Subjects stood without bending knees, and both feet were parallel to each other

Handle shape	Work surface	Horizontal location (cm)[a]		
		30	60	90
		Vertical location (cm)[b]		
A: Pistol grip	Vertical	55	55	
		93	93	93
		142	142	142
		188	188	
B: In-line	Horizontal	90	90	90
		120	120	120
C: Pistol grip	Horizontal	80	80	80
		110	110	110
		140	140	
D: Right angle	Horizontal	80	80	80
		110	110	110
		140	140	

[a] Distance from the ankles.
[b] Distance above the ground.

3. Results

The resulting model parameters for vertical and horizontal locations and different handle configurations are plotted in Figs. 3–6. Post hoc Tukey contrast analysis for significant effects are listed in Table 2.

3.1. Pistol-grip handle on a vertical surface (Fig. 2A)

Stiffness was affected by vertical location ($F(3,230)=9.116$, $p<0.0001$) and horizontal location ($F(2,230)=7.625$, $p<0.001$). The average female and male stiffness was 1640 N/m (S.D. = 1028) and 1324 N/m (S.D. = 836), respectively ($F(1,138)=8.627$, $p<0.05$). Stiffness decreased from 1721 (S.D. = 1095) to 1195 (S.D. = 743) N/m as the horizontal location increased from 30 to 90 cm. Vertical location ($F(3,230)=13.405$, $p<0.0001$) and horizontal location ($F(2,230)=5.905$, $p<0.005$) were significant factors for the inertial mass parameter. Vertical location ($F(3,230)=3.058$, $p<0.05$) and gender ($F(1,230)=9.283$, $p<0.005$) were significant for the damping constant.

3.2. In-line handle (Fig. 2B)

Stiffness decreased ($p<0.005$) from 14.3 Nm/rad (S.D. = 7.1) to 10.5 Nm/rad (S.D. = 5.6) when the horizontal location increased from 30 to 90 cm. The mean female stiffness (9.8 Nm/rad) was significantly less ($p<0.0001$) than the male stiffness (14.4 Nm/rad). Gender ($F(1,138)=8.627$, $p<0.005$), and horizontal location ($F(2,138)=30.08$, $p<0.0001$) were significant

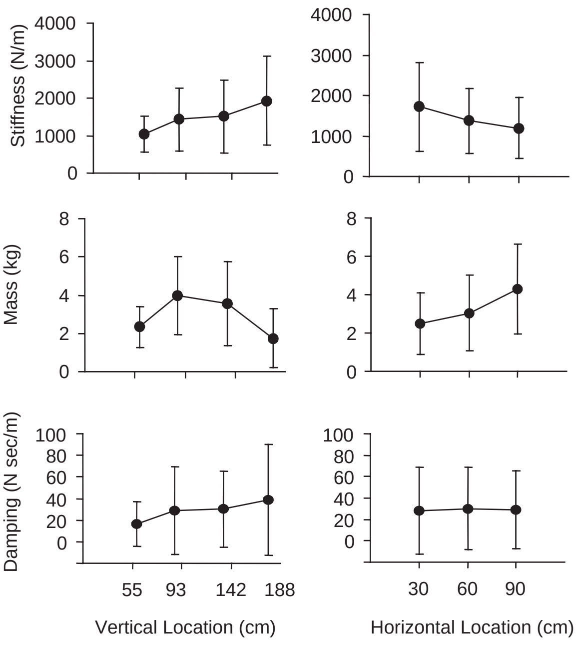

Fig. 3. Sample means and standard deviations of subject stiffness, mass, and damping constant for a pistol-grip handle used on a vertical surface. These plots illustrate the model parameters as a function of vertical and horizontal work locations. Note that linear components are reported after taking the distance between the hand-held location and the rotating axis out of their torsional counterparts.

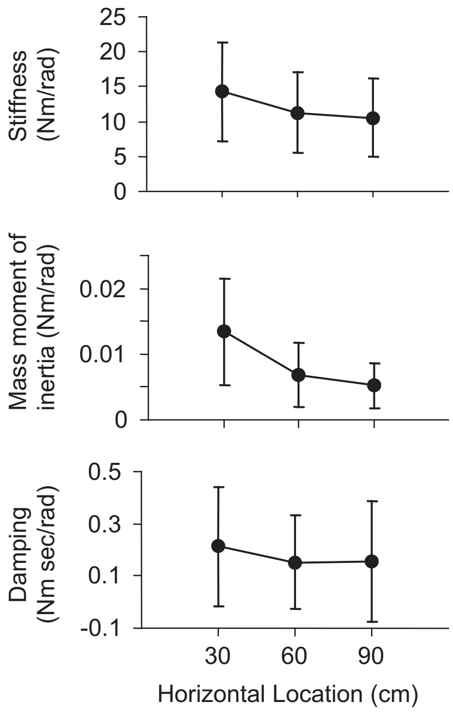

Fig. 4. Sample means and standard deviations of subject torsional stiffness, mass moment of inertia, and torsional damping constant for an in-line handle used on a horizontal surface. These plots illustrate the changes as a function of horizontal work locations.

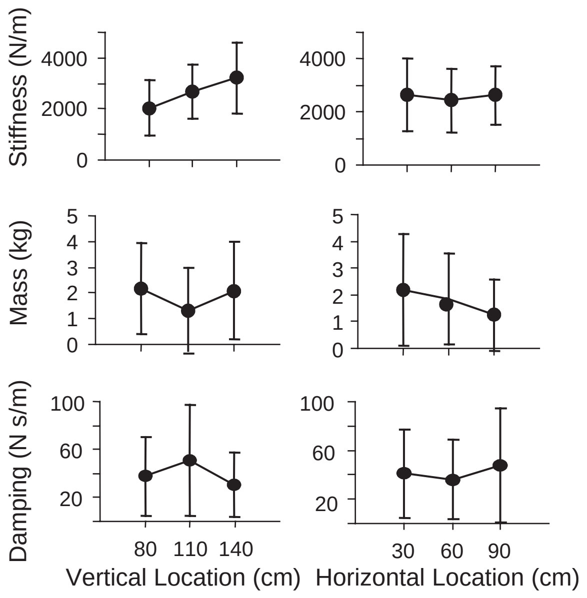

Fig. 5. Sample means and standard deviations of subject stiffness, mass, and damping constant for a pistol-grip handle used on a horizontal surface. These plots illustrate the changes as a function of vertical and horizontal work locations. Note that linear components are reported after taking the distance between the hand-held location and the rotating axis out of their torsional counterparts.

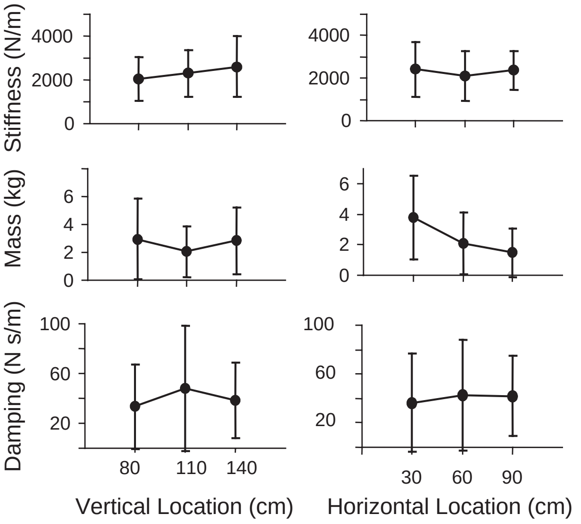

Fig. 6. Sample means and standard deviations of subject stiffness, mass, and damping constant for a right-angle handle used on a horizontal surface. These plots illustrate the changes as a function of vertical and horizontal work locations. Note that linear components are reported after taking the distance between the hand-held location and the rotating axis out of their torsional counterparts.

Table 2
Post hoc Tukey contrasts for statistically significant effects. Insignificant effects are neglected. Levels of the same superscript indicate no significant differences among them ($p > 0.05$)

Condition	Parameter	Effect
Pistol-grip handle on vertical surface	Stiffness	V 55^{a} 93^{a,b} 142^{b} 188^{c} H 30^{a} 60^{b} 90^{b}
	Mass	V 55^{a} 93^{b} 142^{b} 188^{a} H 30^{a} 60^{a} 90^{b}
	Damping	V 55^{a} 93^{a} 142^{a} 188^{b}
In-line handle on horizontal surface	Stiffness	H 30^{a} 60^{b} 90^{b}
	Mass	H 30^{a} 60^{b} 90^{b}
Pistol-grip handle on horizontal surface	Stiffness	V 80^{a} 110^{b} 140^{c}
	Mass	V 80^{a} 110^{b} 140^{a} H 30^{a} 60^{a,b} 90^{b}
	Damping	V 80^{a} 110^{a,b} 140^{b}
Right-angle handle on horizontal surface	Stiffness	V 80^{a} 110^{a,b} 140^{b}
	Mass	V 80^{a} 110^{b} 140^{a,b} H 30^{a} 60^{b} 90^{b}

factors for the mass moment of inertia. The average mass moment of inertia was 0.0099 kg m^2 (S.D. = 0.008) for the males and was 0.0072 kg m^2 (S.D. = 0.0051) for the females.

3.3. *Pistol-grip handle on a horizontal surface (Fig. 2C)*

Vertical location was a significant factor for stiffness ($F(2,184) = 17.924$, $p < 0.0001$), inertial mass ($F(2,184) = 4.6$, $p < 0.05$), and viscous damping ($F(2,184) = 3.874$, $p < 0.05$). Horizontal location was a significant factor for stiffness ($F(2,184) = 2.943$, $p < 0.1$) and mass ($F(2,184) = 4.108$, $p < 0.05$). The inertial mass decreased from 2.18 kg (S.D. = 2.05) to 1.24 kg (S.D. = 1.9) when the horizontal distance increased from 30 to 90 cm. No significant gender differences for this condition were observed for any of these three parameters. However, males had a greater mean stiffness and mass components (2629 N/m, 2.01 kg) and less damping (38.2 Ns/m) than females (2504 N/m, 1.65 kg, and 43.3 Ns/m, respectively).

Table 3
Model validation analysis using the regression equation: Measured $\Delta T/\Delta\theta = A \times$ Modelled $\Delta T/\Delta\theta$

Condition	A	Correlation
Combined handle configurations	1.0286	0.92
Pistol-grip handle on a vertical surface (Fig. 2A)	1.12	0.78
In-line handle on a horizontal surface (Fig. 2B)	1.01	0.97
Pistol-grip handle on a horizontal surface (Fig. 2C)	1.01	0.96
Right-angle handle on a horizontal surface (Fig. 2D)	1.04	0.86

3.4. *Right-angle handle on a horizontal surface (Fig. 2D)*

Vertical location ($F(2,184) = 4.865$, $p < 0.01$), horizontal location ($F(2,184) = 2.712$, $p < 0.07$), and gender ($F(1,184) = 10.710$, $p < 0.001$) were significant factors. The average male stiffness was 2552 N/m (S.D. = 1312) and the average female stiffness was 2035 N/m (S.D. = 927). Vertical location ($F(2,184) = 3.25$, $p < 0.005$) and horizontal location ($F(2,184) = 18.423$, $p < 0.0001$) were also significant for the inertial mass parameter; however, no factors significantly affected damping.

3.5. *Dynamic stiffness validation*

When regression was performed for data from all four handle configurations, the correlation coefficient was 0.92 and the overall error was 2.86% (Table 3). Among the four handles, the in-line handle had the best correlation (0.97) and least error (1%).

4. Discussion

The current model uses lumped elements to collectively characterize the mechanical response of the human operator to power hand tool torque reaction. The model has a stiffness element that may be related to actively contracting muscles and passive connective tissues (Latash and Zatsiorsky, 1993). The mass element of the model may correspond to the effective mass in the reaction response that changes with posture as different body segments are involved in supporting the tool. Viscous damping properties may be dependent on the velocity of limb displacement (Lin and Rymer, 1998; Milner and Cloutier, 1998). The measurements in the current experiment were on the same order as those reported in Lacquaniti et al. (1982) and Reynolds and Soedel (1972). Differences might arise from the different postures and motions, and that the input frequency range in the latter study was much greater (20–100 Hz) than in the current experiment. Previous studies of upper limb dynamic response considered only a single fixed posture (Cannon and Zahalak, 1982; Dagalakis et al., 1987; Sinkjær and Hayashi, 1989). These models were therefore unable to account for work location effects.

Power hand tool operation has been considered an important factor affecting operator subjective perceived exertion and discomfort (Armstrong et al., 1989; Ulin et al., 1992, 1993). Chang and Wang (2001) reported increasing muscular activity as distance increased for screw driving work. Ulin et al. (1992) learned that for pistol grip and in-line tools, the perception of exertion was least when the work location was horizontally closest to the body, and increased as the location moved farther. These findings correspond to the outcome of the current study. Stiffness increased as the horizontal distance decreased (Figs. 3 and 4), which has the effect of reducing the kinematic response to torque reaction from the power hand tool.

It might be argued that when force is exerted closer to the body, better mechanical advantages may be the cause for less resultant handle displacement, and hence less effort would be required to stabilize a handle. This effect might be confounded by dynamic parameter differences in the model. Although such factors are not specifically modelled, their effects are included in the different parameters associated with the various postures used for working in different locations and orientations. Consequently if there is such an effect, it is already included in the measured parameters. We do not try to model individual components of the hand/arm system, but instead we lump their influences. Therefore, the net outcome of the model predictions should be accurate. This is supported by the validation results, which showed that the model satisfactorily explained the observed dynamic hand torque and displacement responses for all handle configurations with high correlation (0.92).

Work locations, rather than joint angles were controlled in order to account for the variability among tool operators over a range of anthropometric characteristics for a given set of physical workplace conditions. This makes it possible to use the model for predicting the range of operator responses to a given workplace geometry where such coordinates are practically measurable and are usually established independent of the specific operator doing the task. This allows for determining the work location and orientation that minimizes the operator response. Such a lumped parameter model is therefore more practical for ergonomics design of hand tool work by predicting a distribution of responses among operators of varying capacities.

Similar to upper limb strength (Mathiowetz et al., 1985; Swanson et al., 1970), gender was a significant factor for most of the parameters modelled in the current study. Schulze et al. (1995) found that when using in-line tools for screw driving tasks, experienced female operators produced more defects than male operators by not setting a screw to the required depth. They considered the hand size as the main factor. Based on the current study results for the in-line handle, the resultant average female stiffness (9.8 Nm/rad) and mass moment of inertia (0.0072 kg m^2) was less than the average male (14.4 Nm/rad, 0.0099 kg m^2). These differences in these mechanical parameters may contribute to the performance differences observed because these mechanical parameters are important factors for stabilizing a tool during rapid torque build-up. As the case with static strength, considerable overlap was observed among individual male and female operators.

Unlike model fitting studies that control and correct for individual differences, the observed variances among subject parameters was anticipated in the results (Figs. 3–6), similar to other types anthropometric or strength measurements. Individual differences, including physical capacity and posture assumed during tool operation for a given set of horizontal and vertical conditions may contribute to these variances. This extends the findings of Hunter and Kearney (1982) where each of five subjects had different mechanical properties. The mechanical model parameters also varied for different handle shapes and orientations. Different groups of muscles and body linkages clearly react against impulsive forces for different tool shapes and orientations. It is therefore anticipated that these differences contributed to the model parameter differences observed.

Kearney and Hunter (1990) reviewed dynamic biomechanical models and concluded that nonparametric models do not consider system structure or order, and are assumed infinite in nature and require numerous parameters to describe the system behavior. Parametric models, on the other hand, require relatively few parameters and based on prior experience, the system behavior can be satisfactorily understood. The current model intentionally reduced the complexity of the model for practical applications. The results showed good predictive capabilities while the underlying physiological phenomenon was intentionally ignored. This tradeoff is justified by its application in ergonomic design.

The model better accounted for the in-line and pistol-grip handles used on a horizontal surface than for a pistol-grip handle used on a vertical surface. Different handle configurations, work locations and orientations result in different degrees of upper limb complexity. For instance, an in-line handle on a horizontal surface involves wrist flexion/extension, while a pistol-grip handle uses forearm rotation for supporting the tool and reacting against tool-generated forces. Furthermore a pistol-grip handle on a vertical surface involves additional shoulder abduction, rotation and flexion than the previous two conditions. Hence, the single-degree-of-freedom model was slightly better when less complex postures were involved.

One limitation of the current study is that the results are limited to operators reacting against a force or torque that has a very low frequency response, such as the torque build-up occurs in a screw-driving task. It is anticipated that the operator would have different mechanical characteristics when encountering higher frequency forces from vibrating tools. The model prediction is also limited to the postures assumed for the location and orientations conditions used. In an actual workplace, an individual tool user might develop a different foot position or a different tool gripping technique, and hence the capabilities to react to the disturbance may be different from the current results.

The significance of this study is that the model parameters were measured for a sample population and they may be used to predict operator responses to workplace and tool conditions for ergonomic design. Group variance reflects the range of operator capacities to react against power hand tool generated forces for the sample group and therefore the model may also be useful for understanding the range of capacities among a group of operators performing similar tasks. The results extended the previous model (Lin et al., 2001) by including various tool handle shapes and orientations. These parameters can be used for modelling the hand-arm response to power hand tool loading for different hand tool and work place designs. Ultimately such a model should be useful for designing industrial hand tools that consider operator capacity to react against tool-generated forces and for designing power hand tool operations that optimize work location and orientation in order to minimize physical stresses acting on the operator.

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