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Ergonomics Applications of a Mechanical Model of the Human Operator in Power Hand Tool Operation

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Applications of a new model for predicting power threaded-fastener-driving tool operator response and capacity to react against impulsive torque reaction forces are explored for use in tool selection and ergonomic workplace design. The model is based on a mechanical analog of the human operator, with parameters dependent on work location (horizontal and vertical distances); work orientation (horizontal and vertical); and tool shape (in-line, pistol grip, and right angle); and is stratified by gender. This model enables prediction of group means and variances of handle displacement and force for a given tool configuration. Response percentiles can be ascertained for specific tool operations. For example, a sample pistol grip nutrunner used on a horizontal surface at 30 cm in front of the ankles and 140 cm above the floor results in a predicted mean handle reaction displacement of 39.0 (SD = 28.1) mm for males. Consequently 63% of the male users exceed a 30 mm handle displacement limit. When a right angle tool of similar torque output is used instead, the model predicted that only 4.6% of the male tool users exceed a 30 mm handle displacement. A method is described for interpolating individual subject model parameters at any given work location using linear combinations in relation to the range of modeled factors. Additional examples pertinent to ergonomic workstation design and tool selection are provided to demonstrate how the model can be used to aid tool selection and workstation design.

Keywords eccentric muscle contrations, human motion and force, torque reaction force, upper extremity biomechanical model, work-related musculoskeletal disorders

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Power hand tools such as nutrunners and screwdrivers are widely used in modern manufacturing for numerous industrial applications. Tools are available in a variety of shapes, sizes, and capacities and are operated in a multitude of working positions and orientations. Any combination of these factors greatly affects the capacity of the human operator to react against forces resulted from power hand tool operations.

Power hand tools were associated with 24.8% of all hand tool related injuries in the United States in 2002[1] and have been considered a risk factor for upper extremity musculoskeletal disorders.[2–4] Threaded-fastener-driving tools, such as nutrunners and screwdrivers, generate impulsive reaction forces during torque buildup that often displace the operator hand and arm.[5–9] It was found that operator forearm muscle activities were more than four times greater during torque buildup than other tool operation phases due to the need to sustain the reaction force.[10] Psychophysical methods have shown that subjective ratings of perceived exertion and discomfort are highly correlated with the resulting handle displacement due to torque reaction.[5–7] Kihlberg et al.[11] tested four right angle nutrunners with target torque levels ranging from 50 to 75 Nm. They concluded that for a tool to be acceptable to 90% of the operators, the tools should induce a handle displacement of less than 30 mm. However, no practical method had been established for predicting handle displacement in nutrunner operation.

Empirical studies have identified tool, workstation, and operator factors that can affect handle kinetics and kinematics in tool operation.[11–15] Given the wide variety of conditions in which power hand tools are used in the workplace, the empirical approach is far too limited for industrial tool selection, workplace ergonomics, and tool design. An earlier study suggested that the operator hand-arm can be represented using a spring-mass system during the dynamic torque reaction phase.[8] Lin et al.[16–18] therefore considered a deterministic approach and developed a dynamic mechanical model of the human operator based on a single degree-of-freedom analog in order to quantify tool handle displacements and forces resulting from the impulsive reaction forces for a combination of tool handle shapes, work locations, and orientations. The passive mechanical model consisted of elastic, damping, and mass moment of inertia elements that represented the operator exerting maximum effort during fastener-driving tool use. The study yielded model parameters for each member of a group of 25 participants (13 females and 12 males) for four tool operation configurations (consisting of variations of tool shape and orientation) at assigned vertical and horizontal locations. The model was validated using actual tool operations, and the overall prediction error for handle displacement was 3%.[19]

Factors such as the tool shape, work location, and work surface orientation influence how operators react against impulsive reaction torque. Use of this model makes it possible to consider the influence these factors have on the kinematic response for a group of operators on an industrial job. Tools having similar torque output levels but having different tool, work, and task factors can be used for the same job for tightening a threaded fastener joint and, consequently, may expose tool operators to a range of reaction responses. The mechanical model can be used for selecting tools and designing workstations in order to reduce physical demands on the tool operators.

This study explored the use and applications of this model for the design, selection, and installation of power threaded-fastener-driving tools in industrial jobs. This article provides examples of how such a model can be used to improve tool selection and work design so that operator physical stress (handle displacement and force) can be reduced. Since the model parameters were measured for discrete horizontal and vertical work locations, an interpolation method was developed to estimate model parameters for arbitrary work locations within the test range, so the model can be used for general practical applications. The aforementioned 30 mm, psychophysically based displacement limit for right angle nutrunners does not represent a universally accepted standard, nor does the limit apply to tools of different shapes. It will be used here as an example of how an arbitrary exposure limit might be applied to evaluate the physical stress associated with tool use.

METHODS

Model

A threaded-fastener-driving power hand tool operation consists of three components: (1) the tool, (2) the fastening task, and (3) the operator. The dynamic characteristics of tools and the fastening task have been fully analyzed in a previous study,[20] in which an exponential function was developed to describe the reaction torque buildup.

The human operator model,[16–18] which can predict kinetic and kinematic responses to impulsive forces generated from power fastener-driving tools, was constructed for various workstation geometries and three common tool shapes: pistol grip, right angle, and in-line tools. The passive mechanical model contains three parameters including: (1) a spring element with stiffness of $k_{subject}$, (2) a viscous damping element $c_{subject}$, and (3) a mass moment of inertia element. When a tool allows the operator to grasp a handle perpendicular to the spindle, such as a pistol grip or a right angle tool, mass moment of inertia $J_{subject} = M_{subject} * h^2$, where h is the distance between the spindle and the hand position. Therefore $J_{subject}$ would be different if the length of tool handle or hand position changes, while the equivalent mass $M_{subject}$ as a model parameter remains the same and is used in this article. For an in-line tool that rotates in the handgrip, $J_{subject}$ is used instead. These parameters are affected by work location (vertical and horizontal distance from the ankles), work surface orientation (horizontal or vertical), handle shape (pistol grip, right angle, and in-line), and individual differences. These parameters can be used for directly solving handle displacement and hand force resulting from a transient force input.

The parameters $k_{subject}$, $J_{subject}$ (or $M_{subject}$), and $c_{subject}$ were estimated using an apparatus that measured the change in the dynamic response of a known mechanical system (frequency and amplitude of free oscillations) when subjects used maximal effort to grasp a handle in a similar manner as operating a power hand tool, to oppose the free vibration motion of the apparatus. The method is fully described in Lin et al.[16–18] The histograms for the distribution of the model parameters resemble normal distributions.[17]

The governing dynamic equation for the single degree-of-freedom operator-tool-task system, which is subject to a tool reaction force input $T(t)$, can be expressed as:

$$(J_{subject} + J_{tool})\frac{d^2\theta(t)}{dt^2} + c_{subject}\frac{d\theta(t)}{dt} + k_{subject}\theta(t) = T(t) \quad \textbf{(1)}$$

where $\theta(t)$ is the variable for angular displacement and J_{tool} is the mass moment of inertia of the tool about its spindle. The system response $\theta(t)$ can be solved using the discrete central difference method:

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

where θ_{i+1} is the ith sample ($i = 0 \ldots n$), and Δt is the time step increment.

The handle force $F(t)$ acting against the tool operator is due to the kinetic energy stored in the spring and damping elements of the system. It can be predicted using the finite difference Equation 3.

$$F_i = \frac{\frac{\theta_{i+1}-\theta_{i-1}}{\Delta t}c_{subject} + k_{subject}\theta_i}{h} \quad \textbf{(3)}$$

where F_i is the handle force at sample i and h is the hand location on the tool.

The mechanical parameter magnitudes ($k_{subject}$, $J_{subject}$ or $M_{subject}$, and $c_{subject}$) are used for quantifying the capacity of an operator to react against a transient tool-generated force. The correlations between the three parameters were less than 0.4.[16] These parameters together completely characterize the operator response to a transient torque input typically encountered in power threaded-fastener-driving tool operations. For tool selection and workstation design purposes, it is desired to obtain the population response. Since Equations 2 and 3 together require all three model parameters, it is not possible to simply average parameters among subjects to determine the mean response for the group. It is possible, however, to

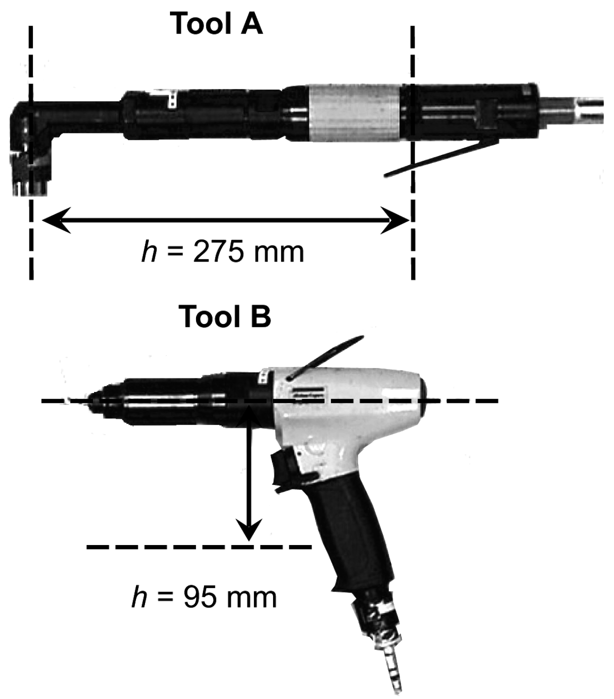

FIGURE 1. Two example tools used in this study with arrows indicating the distance h from the handheld location to the spindle.

calculate the individual responses in the group using measured parameters for each subject tested, and then averaging their responses in order to estimate the group response.

Model Applications

The tool handle force and displacement was calculated using the model for the following threaded-fastener-driving tools, operators, and work location conditions. A computer program was written to process the iteration equations.

Tools

Two different tools are considered. Tool A (Figure 1) is a right angle torque-adjustable pneumatic nutrunner that has a tool mass moment of inertia about its spindle, $J_{tool} = 0.12\ \text{kg} \cdot \text{m}^2$, a spindle free running speed of 76.4 rad/s (713 rpm), and a maximum torque output of 9 Nm. The tool is used for tightening a threaded fastener that requires 5.2 radians (300 degrees) of spindle rotation in order to achieve the target torque of 8.2 Nm. Tool B (Figure 1) is a pistol grip nutrunner that has $J_{tool} = 0.0052\ \text{kg} \cdot \text{m}^2$. The maximum torque output is 10 Nm, spindle free running speed is 75 rad/s (716 rpm), and the target torque is set at 8.2 Nm.

Operators

The response for a male operator M at a given working location is used to illustrate use of the above equations. The model parameters measured for this operator using a right angle tool on the horizontal surface are listed in Table I.(16) Tool operators were previously observed exerting an average of 56% of their maximum capacity based on surface electromyography monitoring of forearm extensors during tool operation(19) and hence the parameter $k_{subject}$ is adjusted proportionally in the calculations.

The responses for a group of operators using tools at selected work locations are calculated in a similar manner. The 25 operators in this example consist of 13 females and 12 males, whose model parameters were measured previously.(16)

Work Location and Orientation

Operator mechanical parameters vary with horizontal and vertical locations.(16–18) The work locations analyzed in the current example are detailed in previous studies.(16–18) In order to highlight the effect of work location on tool operator response for each type of tool, two locations, "near" and "far," (Figure 2) are considered in this article. Pistol grip tools used on both vertical and horizontal work surfaces is considered to demonstrate the effect of work orientation.

Parameter Interpolation

The human operator mechanical model spring, mass, and damping elements were previously measured at discrete work locations;(16–18) however, a power hand tool may be operated at arbitrary locations so the exact mechanical parameters may not be empirically available. Each mechanical parameter is considered an individual attribute distributed among a population

TABLE I. Parameters Estimated for Operator *M* Using a Right Angle Tool on Horizontal Surface

	$H^A = 30$			$H^A = 60$			$H^A = 90$		
V^B	$k_{subject}$ (N/m)	$M_{subject}$ (kg)	$c_{subject}$ (Ns/m)	$k_{subject}$ (N/m)	$M_{subject}$ (kg)	$c_{subject}$ (Ns/m)	$k_{subject}$ (N/m)	$M_{subject}$ (kg)	$c_{subject}$ (Ns/m)
80	2655	7.63	8.14	1931	4.78	13.19	1289	0.51	54.31
110	2075	4.46	7.67	1742	0.51	20.68	3117	2.95	120.86
140	3051	6.75	55.60	1339	1.04	8.39	—C	—C	—C

Note: Operator M is Subject #17; Reference 16.
[A] H is the horizontal location measured from the ankles to the hand in centimeters.
[B] V is the vertical location measured from the floor to the hand in centimeters.
[C] Parameters were not measured at this location; Reference 16.

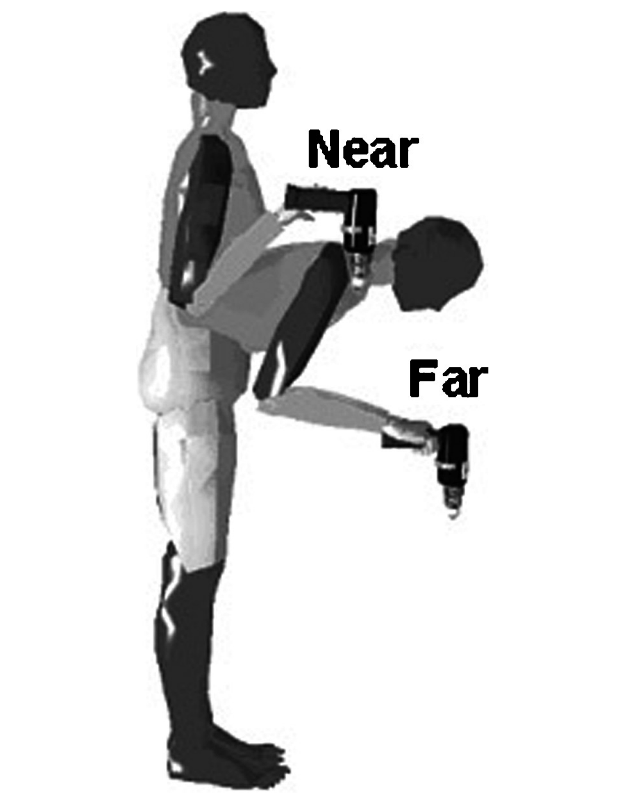

FIGURE 2. Two example work locations used in this study. The "near" location is 30 cm in front of the ankles and 140 cm above floor. The "far" location is 60 cm in front of the ankles and 80 cm above the floor.

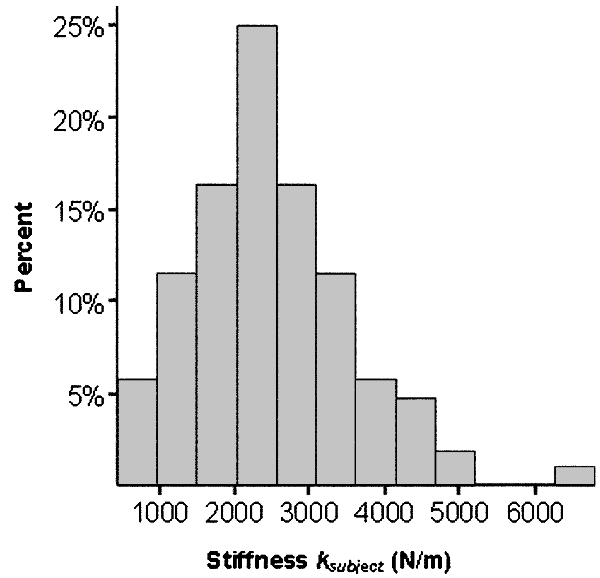

FIGURE 3. Histogram of the stiffness parameter $k_{subject}$ for female operators using pistol grip handles on a horizontal surface. Data were obtained in Lin.[16]

(Figure 3). Therefore an interpolation method to estimate parameters was developed in order to apply the model for broader industrial conditions.

Because the coefficients of variance for the three parameters for all tool configurations were not affected by vertical and horizontal distances,[16] the variability of these parameters within the population was assumed to not fluctuate greatly. Furthermore, it is uncertain whether the variability due to work location is greater than due to individual differences in the population. Therefore, for the purpose of estimating parameters within the tested work locations, linear interpolation method was used. The parameter value at a given location is considered the linear combination of the parameters of its four known neighboring locations (Figure 4). For example, to obtain the stiffness k for location X, it is first necessary to linearly interpolate the known stiffness at locations A, B, C, and D in Figure 4:

$$k = \alpha H + \beta V + \chi HV + \delta \quad (4)$$

where α, β, χ, and δ are interpolation coefficients, H is the horizontal handle location measured from the ankles in cm, and V is the vertical location measured from the floor in cm. By solving the set of four equations formed by substituting the corresponding values estimated at the four locations A, B, C, and D into Equation 4, the four coefficients can be obtained.

There are three equations available to calculate three parameters (k, J or M, and c) in the three zones (I, II, and III) for each operator operating a right angle tool on a horizontal surface (Figure 4). This method may be used to estimate the

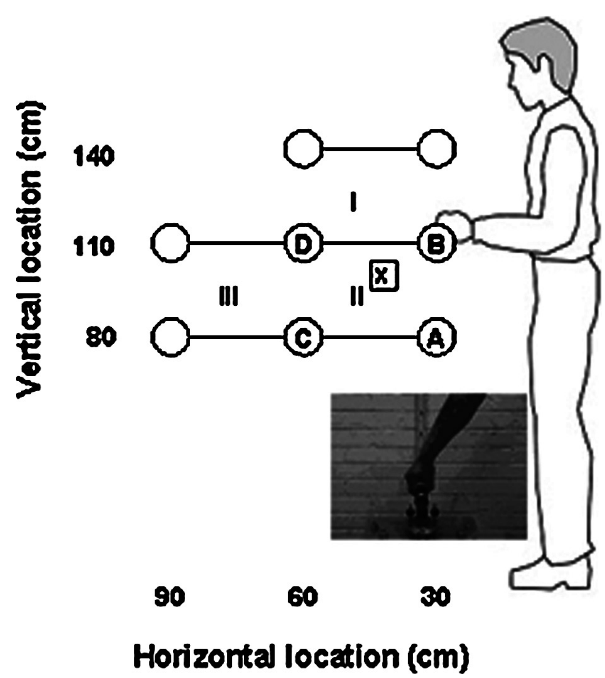

FIGURE 4. Work locations (circles) relative to operator ankles when a right angle tool used on a horizontal surface[18] and the designated linear combination zones (I, II, and III) for parameter interpolation. Mechanical parameters in zone II can be estimated from parameters measured in locations A, B, C, and D.

TABLE II. Predicted Means and Standard Deviations of Handle Displacement (disp) and Hand Force (force) Experienced by 25 Operators

			Male		Female	
Tool	Location	Response	Mean	SD	Mean	SD
Right angle tool A on horizontal surface	Far	Disp (mm)	25.4	17.4	27.7	11.6
		Force (N)	36.3	5.8	38.1	6.0
	Near	Disp (mm)	13.8	9.6	17.8	8.8
		Force (N)	36.0	5.5	38.8	4.3
Pistol grip tool B on horizontal surface	Far	Disp (mm)	64.5	27.2	64.8	35.3
		Force (N)	99.2	7.3	102.9	9.0
	Near	Disp (mm)	39.0	28.1	31.5	17.3
		Force (N)	95.0	12.4	91.6	13.6
Pistol grip tool B on vertical surface	Far[A]	Disp (mm)	82.9	28.9	116.7	24.3
		Force (N)	98.2	8.6	90.2	13.6
	Near	Disp (mm)	50.5	21.0	69.6	43.1
		Force (N)	103.2	9.5	100.9	8.0

[A]Responses were calculated based on the mechanical parameters estimated using the interpolation method.

model parameters at any given horizontal and vertical location within the range.

RESULTS

Model Applications

Resulting arc length displacement for an impulsive torque reaction was calculated by solving Equation 1, and multiplying $\theta(t)$ by the radius formed between the hand and the spindle. Equation 2 was solved by arbitrarily setting Δt to 1 ms with initial conditions $\theta_{-1} = 0$ and $\theta_0 = 0$. When operator M uses tool A at a location 110 cm vertically above the floor and 30 cm horizontally from the operator ankles, it results in a 30.8 mm peak linear handle displacement. The operator also experiences a peak resultant handle force of 37.4 N according to Equation 3.

The predicted tool responses for a group of operators are summarized in Table II. These results suggest that the operator response is affected by tool configuration and work location. For example, when pistol grip tool B is used at the near work location on the horizontal surface, the average displacement was 11.5 mm less for male operators and 38.1 mm less for female operators than on the vertical surface. The least handle displacement for tool B occurs when it is held at the near location on the horizontal surface. Over all of the work conditions, right angle tool A results in less displacement and requires less hand force than pistol grip tool B, considering they have similar torque output.

The effects of horizontal and vertical locations on handle displacement for different tools are demonstrated in Figures 5 and 6. When right angle tool A is used on the horizontal surface at various working distances, the peak handle displacement occurs when the tool is used at 60 cm away from the ankles with the exception for males at 110 cm above the floor (Figure 5). When tool B is used on the vertical surface, the greatest average handle displacement occurs when the tool is held at the lowest level (55 cm above floor) for both male and female operators (Figure 6).

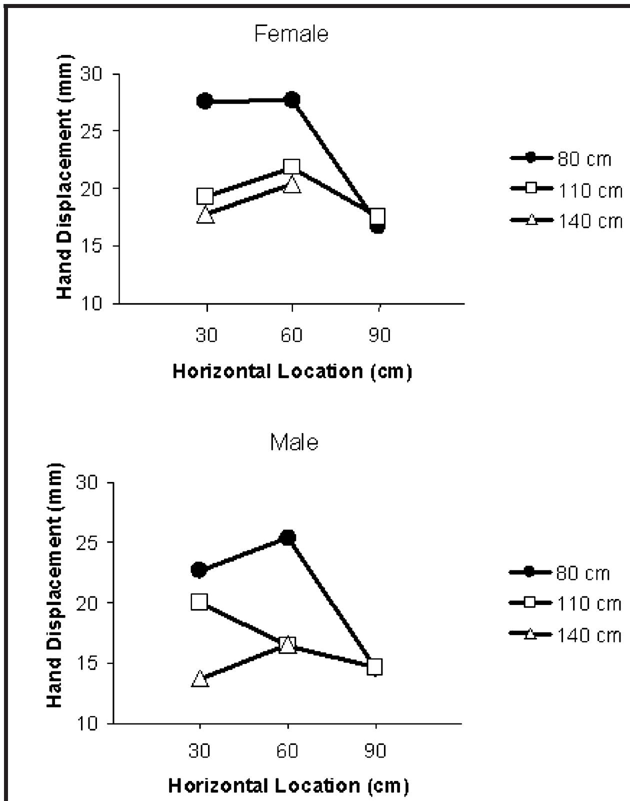

FIGURE 5. Effect of horizontal and vertical work locations on mean peak hand displacement for male (N = 12) and female (N = 13) operators using tool A on a horizontal surface.

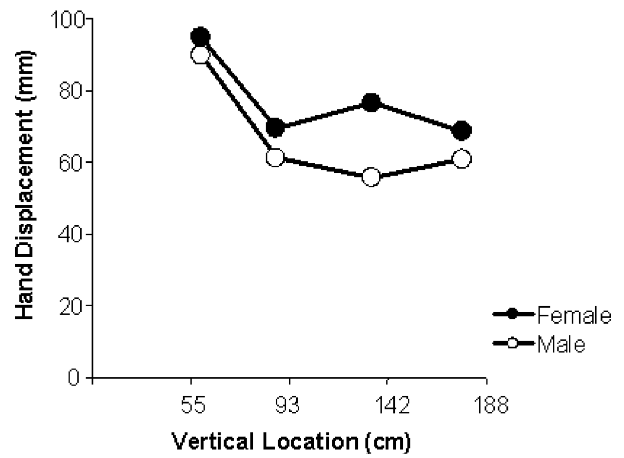

FIGURE 6. Effect of vertical location on mean peak hand displacement when male (N = 12) and female (N = 13) operators use tool B on a vertical surface.

Parameter Interpolation

The mechanical parameters for a given horizontal and vertical location are calculated using Equation 4. The interpolation coefficients for operator M corresponding to the three zones of right angle tool use can be ascertained (Table III).[16] If a right angle tool is operated 100 cm vertically above the floor and 40 cm horizontally from the ankles (X in Figure 4), the mechanical parameters can be estimated using Equation 4:

$$k_{subject} = -58.89(40) - 32.37(100) + 0.43(40)(100) + 5968.33 = 2095.73 \text{ (N/m)}$$

$$M_{subject} = 0.0028(40) - 0.069(100) - 0.0012(40)(100) + 16 = 4.412 \text{ (kg)}$$

$$c_{subject} = -0.539(40) - 0.281(100) + 0.0088(40)(100) + 25.57 = 11.11 \text{ (Ns/m)}$$

To estimate the response distributions (handle displacement and hand force) for a group of operators, the same method should be applied for all of the group members in order to obtain their individual parameters. These parameters can then be substituted into Equations 2 and 3 for the individual impulse responses so that the response distributions (i.e., means and standard deviations) for a given condition can be obtained. In Table II, the far location where tool B is used on a vertical surface 80 cm above the floor and 60 cm in front of the ankles was not measured elsewhere.[18] Therefore, the mechanical parameters were estimated for this location using the interpolation method, and handle displacement and force were calculated based on the individual parameter estimates.

DISCUSSION

The proposed single degree-of-freedom mechanical model was tested in a previous study and was considered capable of satisfactorily predicting kinematic responses of actual power hand tool operations.[19] The correlation between predicted and measured handle displacement was found strong (r = 0.98) and the model over-predicted the handle displacement by 3%.[19] The mechanical parameters were previously measured relative to work locations, rather than subjective anthropometric measures, to account for the variability among operators for defined workplaces.[18] Therefore, variances in the mechanical parameters and hence the tool use responses due to individual differences such as weight, stature, or strength are anticipated. The applications described in this article used this mechanical model to predict the range of operator responses.

The model can predict responses among a group of operators based on various tool and workstation factors, and therefore predict group response distributions. Kihlberg et al.[11] suggested a tool handle displacement limit of 30 mm for right angle tools based on psychophysical data. Such a limit can be compared against the distribution in order to predict the group capacity to react against tool-generated forces, analogous to how strength distributions are used in ergonomics design.

The results show that while operating the tested pistol grip nutrunner on a horizontal surface for a soft threaded fastener

TABLE III. Interpolation Coefficients Used in Equation 4 for Operator M Operating a Right Angle Tool on Horizontal Surface

Parameter	Zone	α	β	χ	δ
$k_{subject}$ (N/m)	I	157.44	78.5	−1.53	−6227.00
	II	−58.89	−32.37	0.43	5968.33
	III	−200.69	−140.77	2.24	14476.33
$M_{subject}$ (kg)	I	0.0834	0.135	−0.002	−6.44
	II	0.0028	−0.069	−0.0012	16.00
	III	−0.7388	−0.590	0.0075	60.49
$c_{subject}$ (Ns/m)	I	1.823	0.348	−0.0126	−43.66
	II	−0.539	−0.281	0.0088	25.57
	III	−3.879	−3.688	0.0656	225.96

Note: Data obtained from Reference 16.

joint at 80 cm vertically above the floor and 60 cm horizontally from the ankles, the average handle displacement was 64.5 mm (SD = 27.2) for males and 64.8 mm (SD = 35.3) for females. This means that 90% of the male and 84% of the female operators would exceed the 30 mm limit at this work location. If the work location was redesigned so that the tool was operated at 140 cm above the floor and 30 cm from the ankles, the displacement would decrease to 39.0 mm (SD = 28.1) for the males and 31.5 mm (SD = 17.3) for the females because of mechanical advantages. The percentage of operators experiencing handle displacement greater than 30 mm would decrease to 63% for males and 54% for females. This means that if the tool can be used at a location nearer to the body, the physical stress is reduced because of less resultant handle displacement.

Work surface orientation was found to affect handle velocity and displacement as well as handle force,[(21)] and it was reflected in the current model. At the near work location where the tool is held 140 cm vertically above the floor and 30 cm horizontally from the ankles, using a pistol grip tool on a vertical surface results in a mean displacement of 50.5 mm (SD = 21.0) for males and 69.6 mm (SD = 43.1) for females. Eight-four percent of the male and 82% of the female operators would exceed the 30 mm limit. The responses for a vertical surface were greater than for a horizontal surface where fewer operators (63% and 54%, respectively) exceeded the 30 mm limit. Therefore, if the work orientation was changed from a vertical to horizontal surface, the handle displacement, and hence physical stress, may be reduced.

Different tool shapes provided different mechanical advantages so the preference towards a given tool shape is determined by the specific work location and orientation.[(22)] The current application provides a potential explanation. If a right angle tool having the same torque output level were used instead of a pistol grip tool on the horizontal surface at the same near location, 95% of the male and 92% of the female operators would have handle displacement less than 30 mm. The handle force decreased by 58% for female operators working at this location.

Horizontal and vertical work locations were demonstrated as significant factors ($p < 0.05$) influencing mechanical parameters in previous studies,[(16−18)] and hence the resultant kinematic response such as handle displacement and velocity during tool torque buildup.[(21)] Stiffness has been found to be proportional to the muscle contraction, which is influenced by posture.[(23−25)] For pistol grip tools used on the vertical surface, when the tool was held at the lowest height the operator stiffness was smallest,[(18)] and therefore the handle displacement is greatest (Figure 6). The current result further demonstrates that the optimum working distance may be different at each working height (Figure 5). The magnitude of handle displacement is dependent on the operator mechanical parameters, especially the stiffness component, across the working distance.[(18)]

Previous studies have identified gender as a significant factor affecting the mechanical parameters.[(16−18)] On average, female operators are predicted to have greater handle displacements than males (Figure 6). There are some exceptions (Table II) in which females could result in less handle displacement. This is anticipated because the average stiffness and mass moment of inertia for females was less than males.[(16,18)] Yet, the least handle displacement occurred at different vertical locations for males and females. Stature and hence the relative body posture variance may also be attributed to these gender differences. Operators of different stature and anthropometric characteristics assume different postures and joint angles for different work locations. Stiffness was affected by posture[(23,24)] and therefore the stiffness change along with vertical location was different for each subject. It is important to note that the relationships pertaining to gender are for group averages, and distribution of male and female mechanical parameters are such that there are cases where an individual female operator could have less handle displacement responses than an individual male operator.

This study used linear interpolation to estimate the model parameter values in between horizontal and vertical locations measured. Because the original studies tested only three levels of work height and distance, higher order polynomial functions could not be considered. Data from two previous studies[(17,18)] were used for testing the validity of the linear interpolation method. Both studies measured the model mechanical parameters for pistol grip hand tools used on a vertical surface at various working locations. One study[(17)] tested subjects at vertical locations 55, 93, 142, and 190 cm off the floor. The other study[(18)] was performed at the same locations except that the last height was 188 cm. The mechanical parameters at two different locations (188 cm vertically, and 30 cm and 60 cm horizontally in front of the ankles) were interpolated from their adjacent test locations for each subject (N = 25) in the first study. The results were then compared with those actually measured in the other study at corresponding locations (N = 25). It was demonstrated that the interpolated and measured mechanical parameters were not significantly ($p > .05$) different (Table IV). This validation, however, is limited by the close proximity between 188 cm in one study and 190 cm in the other.

The interpolation method allows model users to estimate mechanical parameters at any given work location where the parameters are not available yet within the tested range. Therefore it is possible to estimate the response of a group of tool operators at that location.

This article describes a method to obtain the response distributions for a group of power tool operators at given horizontal and vertical work locations. The method enhances the understanding of power tool selection and workstation design and can be applied with several limitations. The model was constructed with regard to power threaded-fastener-driving tools such as nutrunners and screwdrivers. Further investigation is needed for valid application of this model toward tools of different categories. The interpolation functions assumed that the model parameters were linear between four adjacent test locations. This assumption was made because it was subject to least error when the true relationships were unknown. Future

TABLE IV. Average (SD) Values of the Interpolated and Measured Mechanical Parameters for Pistol Grip Tools

Distance (cm)		Interpolated[A]	Measured[B]	p-value
30	$k_{subject}$ (N/m)	1270.4 (364.0)	1627.3 (1002.1)	0.1
	$M_{subject}$ (kg)	1.21 (0.60)	1.24 (1.41)	0.91
	$c_{subject}$ (Ns/m)	30.55 (45.32)	30.66 (20.79)	0.99
60	$k_{subject}$ (N/m)	1126.8 (457.1)	1162.4 (630.20)	0.82
	$M_{subject}$ (kg)	1.71 (0.69)	1.29 (0.90)	0.07
	$c_{subject}$ (Ns/m)	26.01 (27.18)	24.68 (15.52)	0.83

Note: Tools were used on a vertical surface at a vertical height of 188 cm above the floor and at two horizontal distances.
[A] Interpolated from parameter values measured at adjacent locations, Reference 17.
[B] The values were obtained from the study reported in Reference 18.

study is warranted to test the linearity of these parameters. The interpolation method used data measured for young (average age was 23.6 years), healthy, and inexperienced tool operators.[16,18] Therefore, the current applications are limited to a group of operators of similar attributes. Future studies should explore additional factors that might affect the mechanical parameters, such as tool operation experience, age, and fatigue. There exists only one physical exposure limit for right angle tool use.[11] The exposure thresholds or limits for tools of other shapes are in need to improve tool and workplace design and selection.

CONCLUSIONS

Applications are provided to demonstrate how to reduce physical stress (handle displacement and hand force) by considering work locations and orientations and by selecting the appropriate tool for a task using a dynamic mechanical model of the human operator. This model may be used for modeling the operator responses to power hand tool loading for different hand tools and workplace designs. This article concludes that:

1. The proportion of operators that exceed arbitrary exposure limits for a given task can be estimated.
2. Linear combinations may be used to interpolate mechanical parameters so the model can be applied to threaded-fastener-driving tool applications at any given work location within the test range.
3. Workplaces and tool operations can be designed to reduce the physical stress experienced by the tool operators by minimizing handle displacement and force based on model predictions and thereby improve the ergonomic properties of these jobs.

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