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Forces associated with pneumatic power screwdriver operation: statics and dynamics

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The statics and dynamics of pneumatic power screwdriver operation were investigated in the context of predicting forces acting against the human operator. A static force model is described in the paper, based on tool geometry, mass, orientation in space, feed force, torque build up, and stall torque. Three common power hand tool shapes are considered, including pistol grip, right angle, and in-line. The static model estimates handle force needed to support a power nutrunner when it acts against the tightened fastener with a constant torque. A system of equations for static force and moment equilibrium conditions are established, and the resultant handle force (resolved in orthogonal directions) is calculated in matrix form. A dynamic model is formulated to describe pneumatic motor torque build-up characteristics dependent on threaded fastener joint hardness. Six pneumatic tools were tested to validate the deterministic model. The average torque prediction error was 6.6% (SD = 5.4%) and the average handle force prediction error was 6.7% (SD = 6.4%) for a medium-soft threaded fastener joint. The average torque prediction error was 5.2% (SD = 5.3%) and the average handle force prediction error was 3.6% (SD = 3.2%) for a hard threaded fastener joint. Use of these equations for estimating handle forces based on passive mechanical elements representing the human operator is also described. These models together should be useful for considering tool handle force in the selection and design of power screwdrivers, particularly for minimizing handle forces in the prevention of injuries and work related musculoskeletal disorders.

1. Introduction

Inappropriate selection or use of power hand tools such as power screwdrivers or nutrunners, that demand excessive force beyond an operator's capacities can cause loss of control, muscle fatigue, or localized discomfort (Radwin and Haney 1996, Kattel and Fernandez 1998, Armstrong *et al.* 1999). Repetitive forceful exertions are associated with increased risk for musculoskeletal disorders (NIOSH 1997, Muggleton *et al.* 1999, Bureau of Labor Statistics 2001, NRC 2001). When forces exceed the force capacity of human muscle, the potential for an injury is enhanced (Lieber and Friden 1999). It is important that forces acting against the tool operator's hands be controlled in order to reduce the risk of injuries, disorders and

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muscle fatigue. Numerous factors can influence handle force in power hand tool operation.

Tool geometry, mass, moment of inertia, and centre of gravity (COG) are important factors in the design and selection of power hand tools because they directly affect handle force in a complex manner. The handle length of pistol grip and right angle tools, and the diameter of in-line tool handles also affect hand exertions by providing mechanical advantages (Huston *et al.* 1984, Deivanayagam and Weaver 1988, Radwin *et al.* 1995). Tool load affects grip force (Westling and Johansson 1984, Grant *et al.* 1992, Cook *et al.* 1996, Kattel and Fernandez 1998), fatigue onset (Hallbeck *et al.* 1992), task performance (Drury and Hibschweiller 1994) and subjective preference of tool operators (Armstrong *et al.* 1989, Örtengren *et al.* 1991, Ulin *et al.* 1993). In addition to the static forces exerted by an operator when carrying and positioning tools or when a tool is running at a constant state, the impulsive forces and torques produced by rotating spindle power hand tools are dynamic. The torque build-up generated by threaded fastener driving tools such as power nutrunners and screwdrivers is of particular interest. Radwin *et al.* (1989) found that during a nutrunning task, muscle activity was more than three times greater during the torque build-up phase than during the other phases, even though it was sustained for a relatively short duration. Given the wide variety of hand tools available, it is important for tool and work designers to have a deterministic model for predicting how these numerous factors affect forces and torques involved in power hand tool operation.

Following the concept developed by Radwin *et al.* (1995), this paper builds on the static equilibrium mechanical model of power hand tool operation. The model predicts static handle force based on external tool and task factors. Tool factors include tool geometry and inertial properties. Task factors are parameters specific to the operation, such as spindle torque, feed force, and tool orientation in space. This paper also models pneumatic motor torque build-up based on specific characteristics of the air motor and the threaded fastener mechanical joint hardness. Applications of these equations in conjunction with a dynamic tool operator model are also introduced.

2. Development of models

2.1. *Handle force model: statics*

Wells and Greig (2001) proposed a framework to characterize hand prehensile forces and moments as internal and external forces. A similar approach was used to characterize tool handle force for the current model. Simplified diagrams of the tools showing the main force and torque components and the biodynamic Cartesian coordinate system used for the model in compliance with ISO Standard 5349 (ISO 1986) are shown in figure 1. Right-handed operation is used for the purposes of illustration. This coordinate system has the x-axis perpendicular to the palm, the y-axis parallel to the axis of grip, and the z-axis in line with the forearm. The origin of the coordinate system is defined as the end of the tool bit or socket. In this model, all parameters are represented by vectors consisting of three orthogonal components. All forces are assumed to act on the tool without producing coupling moments. The variables used in the model are summarized in table 1.

When a tool is in static equilibrium (figure 1), the sums of all forces ($\mathbf{F}$), and moments ($\mathbf{M}$) about the origin, and grip moments generated by the spindle ($\mathbf{M_G}$) acting on the system are zero. Therefore three vector equations can be developed:

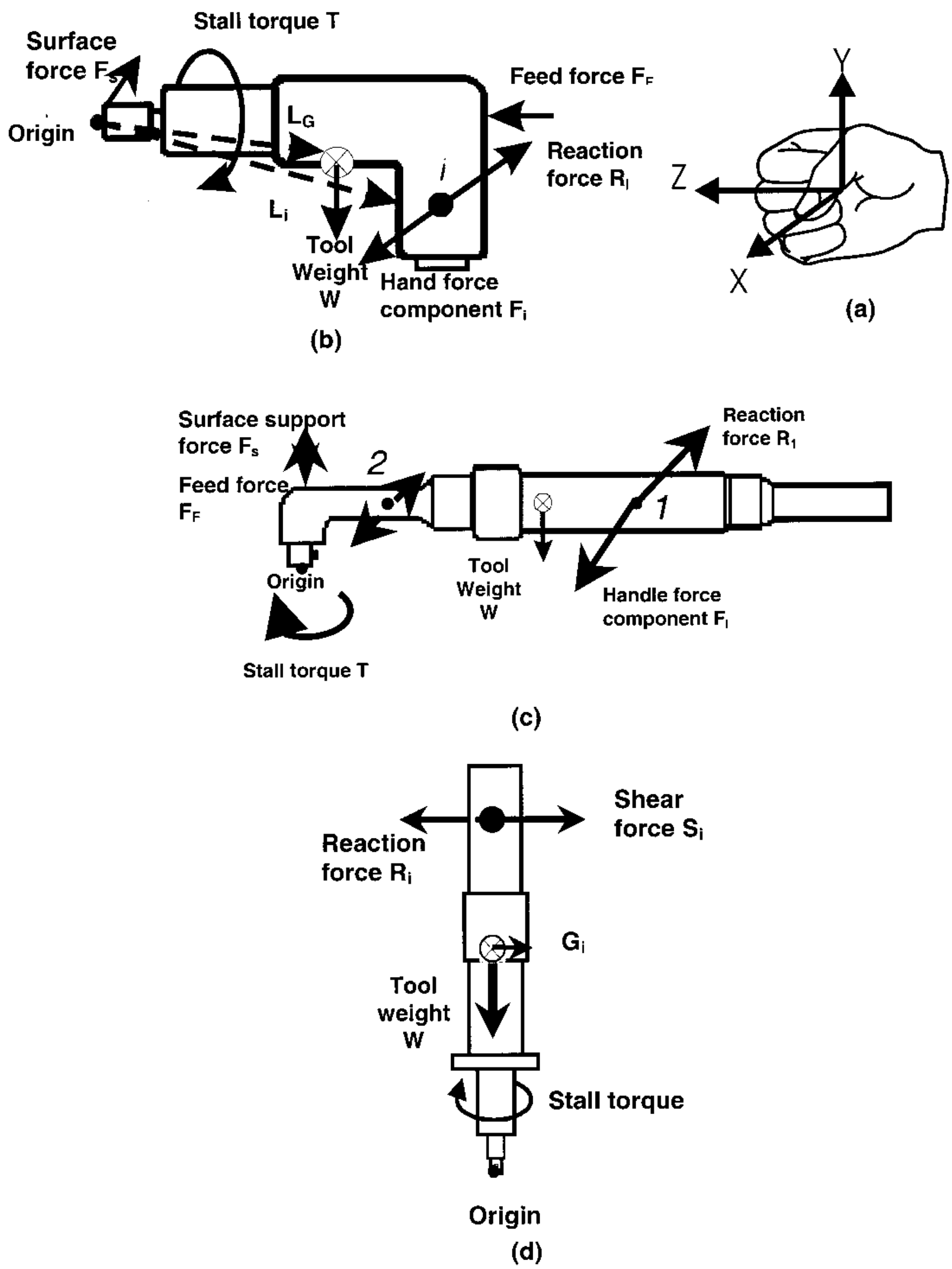

Figure 1. (a) The coordinate system used, and simplified (b) pistol grip, (c) right angle, and (d) in-line power tool diagrams.

Table 1. Notation for variables used in model.

Variable*	Description
$\mathbf{F_i}$	Handle force acting on hand *i*.
$\mathbf{S_i}$	Shear force acting in hand *i*, applied when the handle rotates in the *y*-axis.
$\mathbf{R_i}$	Reaction force produced by the spindle torque at point *i*.
$\mathbf{W}$	Tool weight.
$\mathbf{F_F}$	Feed force. Not applicable when carrying a tool.
$\mathbf{F_s}$	Surface support force. Not applicable when carrying a tool.
$\mathbf{T}$	Tool torque.
$\mathbf{L_i}$	Location vector of point *i*.
$\mathbf{L_G}$	Location vector of the centre of gravity.
$\mathbf{G_i}$	Grip radius at point *i*, applied when the handle rotates in the y-axis.

* All the variables shown in bold are vectors. Subscript ***i*** represents a specific hand used in operating the tool. The right hand is annotated using subscript$_1$ and the left hand is annotated using subscript$_2$.

$$\Sigma\ \mathbf{F_i} + \Sigma\ \mathbf{R_i} + \mathbf{W} + \mathbf{F_F} + \mathbf{F_s} = \mathbf{0} \quad (\Sigma\mathbf{F} = \mathbf{0}) \tag{1}$$
$$\Sigma\ (\mathbf{F_i} + \mathbf{R_i}) \times \mathbf{L_i} + \mathbf{W} \times \mathbf{L_G} = \mathbf{0} \quad (\Sigma\mathbf{M} = \mathbf{0}) \tag{2}$$
$$\Sigma\ \mathbf{S_i} \times \mathbf{G_i} + \mathbf{T} = \mathbf{0} \quad (\Sigma\mathbf{M_G} = \mathbf{0}) \tag{3}$$

These vector equations can be written in matrix form:

$$\begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & L_{1z} & -L_{1y} & 0 & L_{2z} & -L_{2y} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -L_{1z} & 0 & L_{1x} & -L_{2z} & 0 & L_{2x} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ L_{1y} & -L_{1x} & 0 & L_{2y} & -L_{2x} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & G_{1x} & 0 & 0 & G_{2x} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & G_{1y} & 0 & 0 & G_{2y} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & G_{1z} & 0 & 0 & G_{2z} & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} F_{1x} \\ F_{1y} \\ F_{1z} \\ F_{2x} \\ F_{2y} \\ F_{2z} \\ S_{1x} \\ S_{1y} \\ S_{1z} \\ S_{2x} \\ S_{2y} \\ S_{2z} \\ F_{sx} \\ F_{sy} \\ F_{s2} \end{bmatrix} =$$

$$\begin{bmatrix} -W_x - R_{1x}R_{2x} - F_{Fx} \\ -W_y - R_{1y} - R_{2y} - F_{Fy} \\ -W_z - R_{1z} - R_{2z} - F_{Fz} \\ L_{1z}R_{1y} - L_{1y}R_{1z} + L_{2z}R_{2y} - L_{2y}R_{2z} - L_{Gz}W_y - L_{Gy}W_z \\ L_{1x}R_{1z} - L_{1z}R_{1x} + L_{2x}R_{2z} - L_{2z}R_{2x} - L_{Gx}W_z - L_{Gz}W_x \\ L_{1y}R_{1x} - L_{1x}R_{1y} + L_{2y}R_{2x} - L_{2x}R_{2y} - L_{Gy}W_x - L_{Gx}W_y \\ -T_x \\ -T_y \\ -T_z \end{bmatrix} \tag{4}$$

The full model considers forces and moments exerted by both hands, but not all of these equations are required for all situations, and the system of equations may be reduced in certain cases depending on tool shape and operating conditions. For example, shear force is needed for in-line tools (figure 1d) but is insignificant for pistol grip tools except when a hand grasps the tool around the spindle. The tool torque and feed force are assumed to always act in a single axis. When the matrix becomes degenerate or singular, additional assumptions are needed in order to solve for handle force. Examples are provided later to demonstrate the resulting matrix reduction for three common tool shapes.

2.1.1. *Pistol grip tools*: One of the most common conditions for pistol grip tools is shown in figure 2a. In the case of one-handed operation, the right hand (subscript$_1$) reacts against all tool forces and torques. Equation 4 can therefore be reduced to:

$$\begin{bmatrix} 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & L_{1z} & -L_{1y} & 0 & 0 \\ L_{1y} & 0 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} F_{1x} \\ F_{1y} \\ F_{1z} \\ F_{sy} \\ F_{sz} \end{bmatrix} = \begin{bmatrix} 0 \\ -W_y \\ -F_{Fz} \\ -W_y L_{Gz} \\ -T_z \end{bmatrix}. \tag{5}$$

2.1.2. *Right angle tools*: Right angle tools have short spindles that are perpendicular to the longitudinal axis of the handle. When these tools are used one-handed, equation 5 applies. Because the handle is usually longer than the length of the spindle, these tools are often held in two hands (figure 2b). In this case, the right hand (subscript$_1$) grasps the tool at the distal end of the tool handle while the left hand (subscript$_2$) grasps the tool proximal to the spindle. It is further assumed that equal amounts of force are exerted by both hands in order to react against tool torque along the long axis of the handle, and hence $F_{1z} = F_{2z}$. The resulting matrix is:

$$\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & L_{1y} & 0 & L_{2y} \\ L_{1y} & 0 & L_{2y} & 0 \end{bmatrix} \times \begin{bmatrix} F_{1x} \\ F_{1z} \\ F_{2x} \\ F_{2z} \end{bmatrix} = \begin{bmatrix} -W_x \\ 0 \\ -T_x \\ -W_x L_{Gy} \end{bmatrix}. \tag{6}$$

2.1.3. *In-line tools*: In the case of in-line tools, assuming the right hand (subscript$_1$) supports the tool (figure 2c), the static handle force matrix is:

$$\begin{bmatrix} 1 & 0 \\ 0 & G_{1x} \end{bmatrix} \times \begin{bmatrix} F_{1y} \\ S_{1y} \end{bmatrix} = \begin{bmatrix} -W_y \\ -T_y \end{bmatrix} \tag{7}$$

2.1.4. *Model applications*: The resultant handle force or moment is the vector sum of three corresponding scalar components. The static model matrix therefore provides a way for examining the effects of specific tool design factors (e.g. weight, handle length, spindle length, use of an accessory handle, etc.) or work factors (feed force, stall torque, orientation, etc.), and interactions among factors on hand exertions. Theoretical analysis was performed using a custom computer program. An example will be used later in this article to illustrate the effect of handle length on handle force when feed force or tool stall torque is varied.

2.2. *Tool torque build-up model*

There are three elements involved in a power screwdriver/nutrunner operation: the operator, the tool, and the mechanical joint that joins or clamps two objects together. Fastener joint hardness is analogous to the stiffness of a spring. The more the fastener rotates, the more torque is needed to rotate the fastener due to friction.

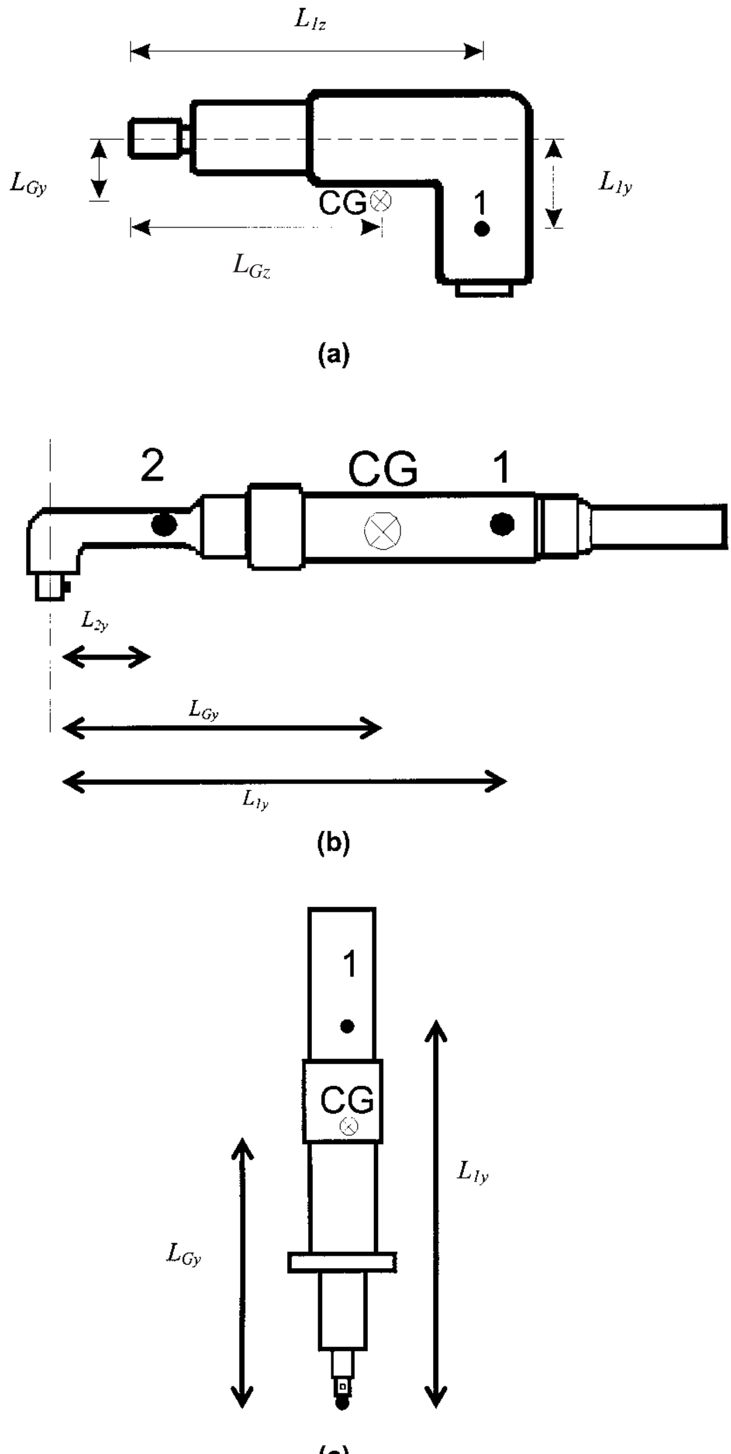

Figure 2. (a) One-handed pistol grip tool operation, (b) two-handed right angle tool operation, (c) one-handed in-line tool operation.

The clamping force of a threaded fastener is therefore proportional to torque. A desired clamping force is achieved by rotating the fastener to a specific target torque. The spindle torque and angular displacement during torque build-up have a linear relationship such that:

$$\theta(T) = \frac{\theta_t}{T_t - T_0}(T - T_0), \tag{8}$$

where T is the tool spindle torque, θ is the spindle angular displacement, T_t is the target torque, T_0 is the rundown torque, and θ_t is the target angle.

Pneumatic motors have a distinctive speed-torque relationship. The motor does not produce torque at the free running speed, while it exerts maximum torque when the motor stalls. The spindle speed can be described using the equation:

$$S(T) = S_0(1 - \frac{T}{T_{max}}), \tag{9}$$

where S is the spindle speed expressed as a function of torque T, T_{max} is the motor maximum torque output, and S_0 is the free running speed.

Since speed in equation 9 is the derivative of angular displacement in equation 8, the unique solution for the differential equation is the torque delivered to the spindle:

$$T(t) = T_{max} + (-T_{max} + T_0)e^{-\frac{(T_t - T_0)S_0}{\theta_t T_{max}}t}. \tag{10}$$

The force experienced by the hand can be obtained by dividing equation 10 by the distance of the hand from the rotating spindle.

2.2.1. *Experimental validation*: Six pneumatic right angle nutrunners (shown in figure 3) were tested in compliance with ISO 6544 (ISO 1981) in order to validate equation 10. Detailed tool specifications and operating conditions are listed in table 2. The spindle free running speed was measured using an AMETEX digital tachometer model 1726 prior to the experiment.

The experimental arrangement is illustrated in figure 4. An Intool joint simulator used Belleville spring washers to simulate different joint stiffness levels by adjusting the number of washers. Two levels of joint stiffness were tested (Figure 5): a hard joint (30 degrees of spindle rotation) and a medium-soft joint

Table 2. Tool specifications and operating conditions.

Tool	Mass (kg)	L_{1y}* (cm)	L_{Gy}* (cm)	Free speed S_0 (rpm)	Target Torque T_t (Nm)
A	1.70	31.8	17.8	713	8.8
B	1.40	28.5	16.7	442	18.4
C	1.90	31.4	17.0	457	10.0
D	1.66	27.6	11.9	390	22.0
E	2.38	36.8	17.6	615	26.0
F	2.27	41.0	18.9	366	18.4

*Defined in figure 2b.

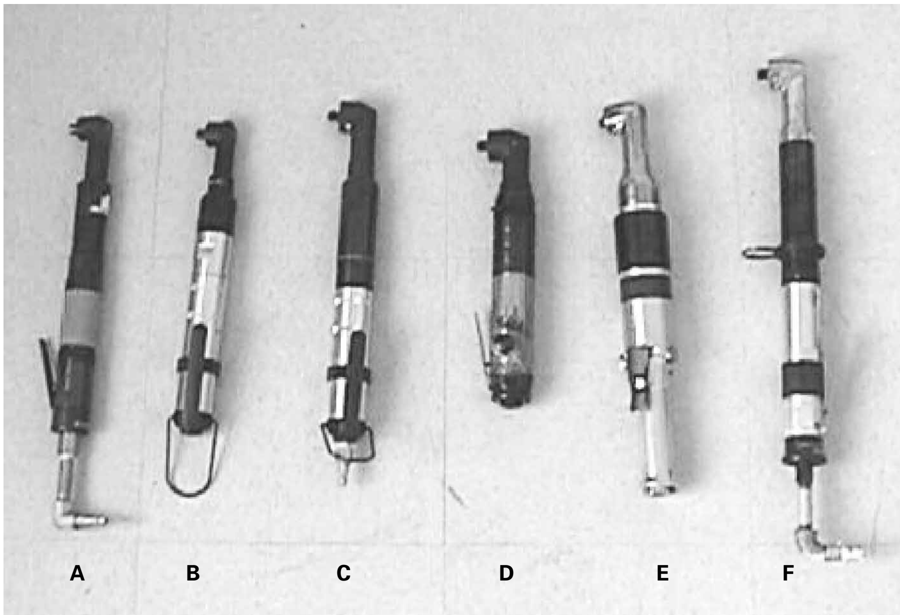

Figure 3. Six pneumatic right angle nutrunners used in the experiment.

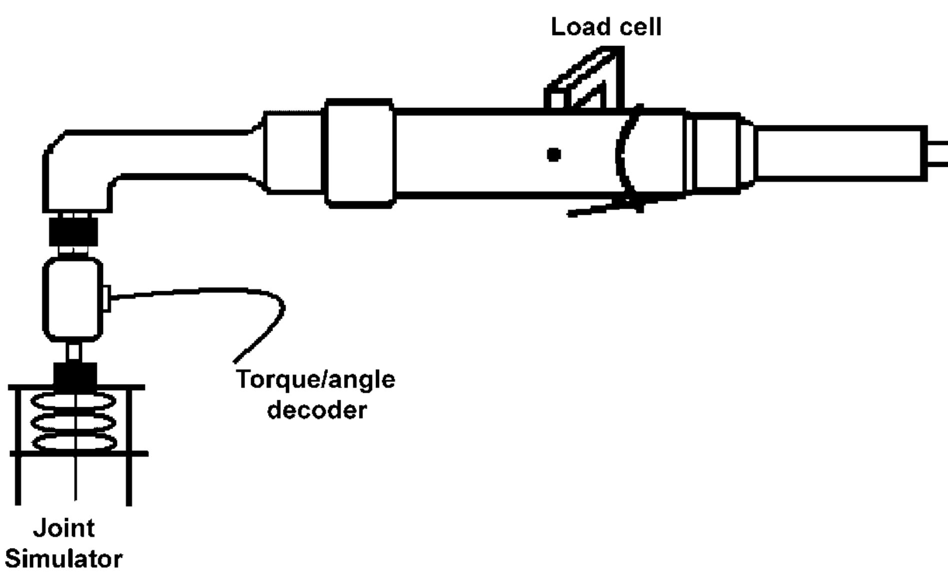

Figure 4. Diagram of the experimental arrangement. The tool was rigidly fixed to a platform to minimize inertial effect.

(210 degrees of spindle rotation). A GSE torque transducer with an angle encoder (67.8 Nm range) was connected between the tool spindle and the joint simulator. An Interface load cell SM-100 (445 N range) was positioned at the hand location (L_{1y}) to measure handle reaction force. The tools were rigidly fixed on the

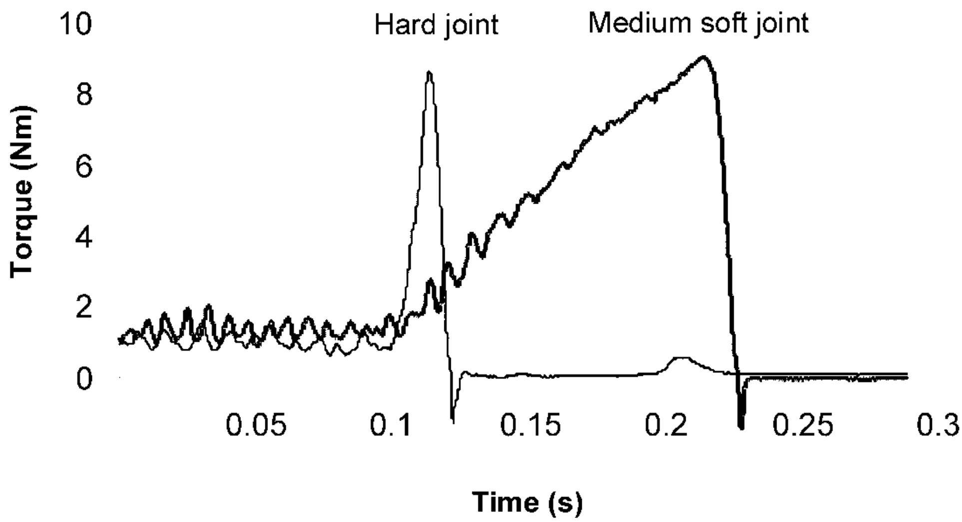

Figure 5. Recording of torque build-up profiles for hard (light line) and medium-soft (heavy line) joints when Tool A was used on the joint simulator in compliance with ISO-6544 (ISO 1981).

platform to minimize inertial effects. Torque and force signals were conditioned using a Daytronic 9178A strain gauge amplifier. The angle pulses and the resulting torque and force signals were sampled using a Pentium computer with a National Instrument Lab-PC + data acquisition board. The sample rate was 10 000 samples s^{-1}.

Spindle angle, torque, and handle reaction force profiles were calculated using equation 10. Every tool was tested five times for each joint. Regression between the predictions and the actual measurements were employed to test the model.

3. Results

3.1. *Handle force model: statics*

Theoretical analysis for a pistol grip nutrunner used on a vertical surface is used to demonstrate the effects of various tool and task factors. Because the model is generic (equation 4), the analysis applies to all three shapes of tools (figures 1 and 2). The relationships between some tool factors and handle force are generally direct. For example, the greater the tool weight, the more force is needed (figure 6). The closer to the spindle the hand grasps the tool, the more force the hand needs to exert to react against the spindle torque because of the shorter handle moment arm.

The vertical distance from the origin to the hand along the y-axis, L_{Hy}, corresponds to the handle length. The handle force decreases as L_{Hy} increases, as shown in figure 7a.

The handle length influence on handle force changes for different spindle stall torques as shown in Figure 7a. Handle length does not have a great effect on handle force for low torque levels (e.g. 1.5 Nm), but when the spindle torque is 15 Nm and the hand is relocated from 7 cm to 17 cm, the required handle force decreases 126 N.

The effect of handle length on handle force also varies for different levels of feed force, as shown in Figure 7b. The handle force magnitude varies more than 10 N for

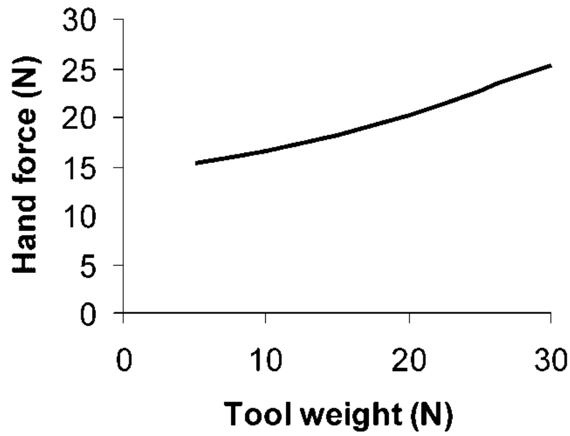

Figure 6. Handle force vs. tool weight in tool operation.

Table 3. Regression analysis results of actual measurements vs. model predictions on tool torque output and handle force during torque build-up for six right angle pneumatic nutrunners. Regression coefficient (Reg. Coef.) and R-squared (R^2) values are the average of five trials. All statistical significance tests (p-values) for regression were less than 0.0001.

Tool	Medium Soft Joint				Hard Joint			
	Torque		Force		Torque		Force	
	Reg. Coef.	R^2	Reg. Coef.	R^2	Reg. Coef.	R^2	Reg. Coef.	R^2
A	1.046	0.963	0.962	0.832	1.115	0.699	1.012	0.723
B	1.009	0.970	1.033	0.932	1.015	0.974	1.036	0.950
C	1.039	0.968	0.970	0.888	1.124	0.925	0.988	0.904
D	1.153	0.871	1.073	0.919	1.026	0.952	1.013	0.930
E	1.112	0.940	1.193	0.874	1.001	0.922	1.091	0.813
F	1.036	0.948	1.032	0.892	0.970	0.930	0.948	0.685

low feed forces. Changes in handle length, however, did not greatly affect handle force magnitude for higher feed forces. A local minimum handle force was observed for a given handle length when feed force was high (e.g. a minimum handle force of 25 N for 15 N feed force occurs when the hand vertical location was 13 cm from the origin).

3.2. *Tool torque build-up model*

The regression between measurements and model predictions for both tool torque and force build-up are summarized in table 3 for all six tools. A representative plot of spindle angular displacement, spindle torque, and force build-up for Tool A on a medium-soft joint is shown in figure 8. The mean regression error of the torque build-up model (equation 10) for all these six tools on a medium-soft joint was 6.6% (SD = 5.4%), and mean R^2 was 0.94 (SD = 0.04). The mean error for the handle force build-up prediction was 6.7% (SD = 6.4%), and R^2 greater than 0.87 (mean = 0.89, SD = 0.04).

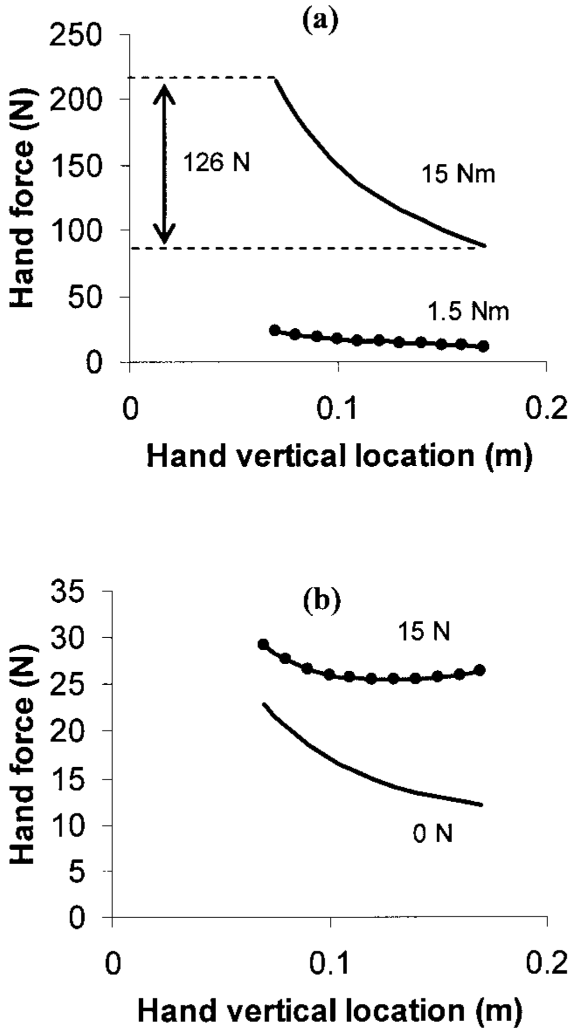

Figure 7. Hand vertical location vs. handle force for tool operations using different: (a) spindle stall torques, and (b) feed forces.

The prediction errors for a hard joint ranged from 0.1% to 12.4% (5.2 ± 5.3%) for the torque build-up model, and 1.2–9.1% (3.6 ± 3.2%) for the force model. The mean R^2 was 0.90 (SD = 0.10) for the torque model, and 0.82 (SD = 0.12) for the force model.

4. Discussion

4.1. *Handle force model: statics*

The static handle force model expands the equations originally developed by Radwin *et al.* (1996). The equations presented here are more general and consider additional parameters. The general system of equations for the current static handle force model can be reduced to the same as described in Radwin *et al.* (1995) when similar assumptions and limitations are imposed.

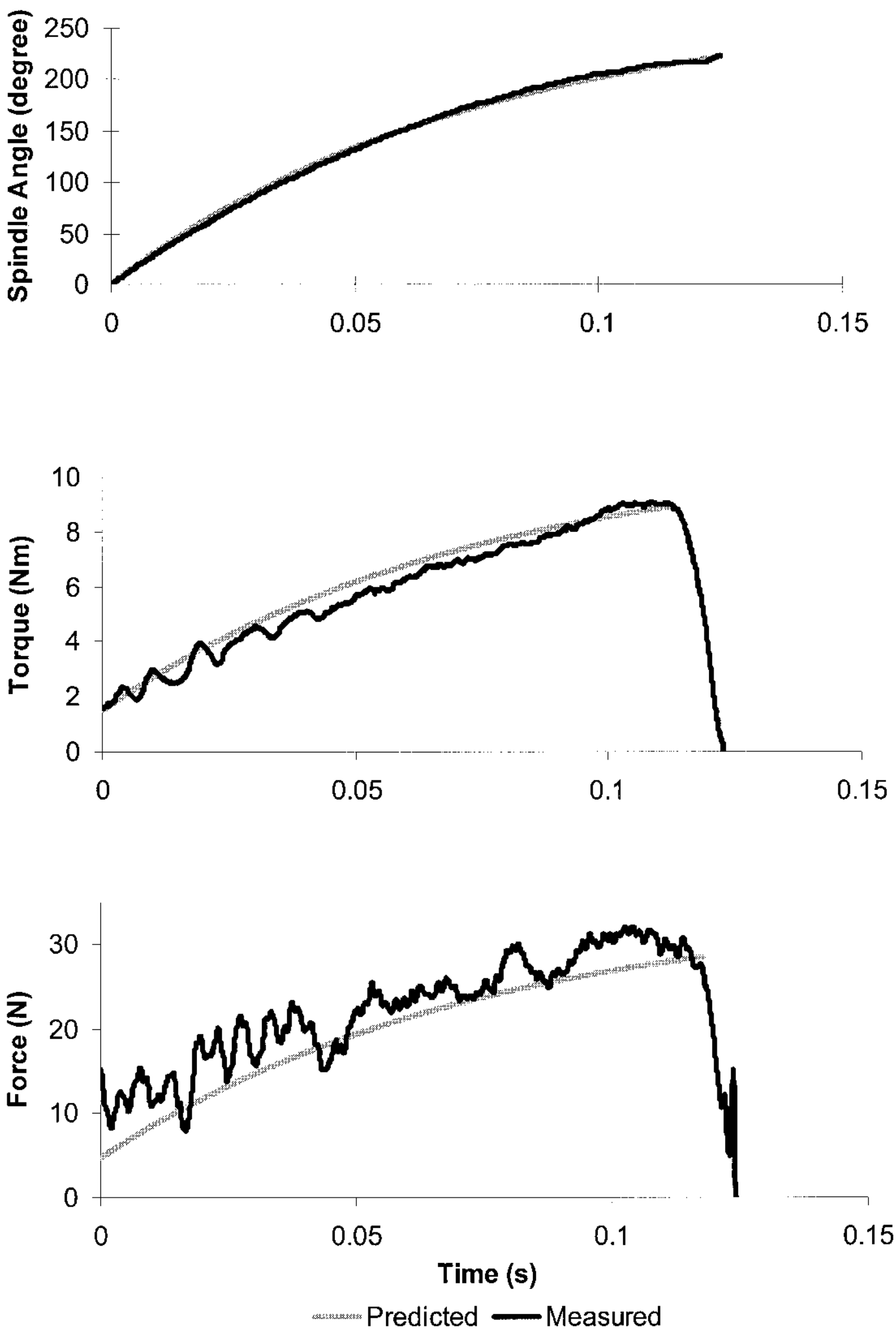

Figure 8. Predicted and measured plots for Tool A: (top) spindle rotation angle vs. time, (middle) spindle torque vs. time, and (bottom) handle reaction force vs. time, during torque build-up when the tool was operated on a medium-soft joint.

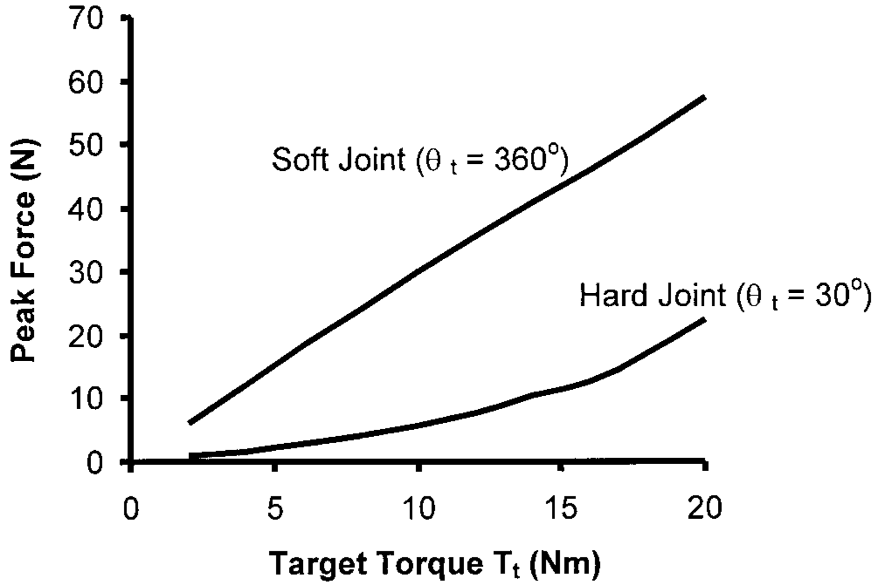

Figure 9. Plots of target torque vs. predicted handle force for two threaded fastener joint rates using a right angle tool ($W = 2.27$ kgw, $I_{tool} = 0.001457$ kg·m^2, $T_{max} = 25$ N, $S_0 = 366$ rpm, $L_{1y} = 34.5$ cm). Parameters used for the calculation are from Lin (2001): $J_{subject} = 0.299$ kg·m^2, $k_{subject} = 283.6$ Nm/rad, $c_{subject} = 5.95$ N·m·sec/rad.

The handle length of pistol grip and right angle tools and the handle radius of in-line tools create the moment arms that operators use for acting against tool-generated torque at the spindle, and are usually considered the limiting factor in torque reaction strength (Replogle 1983, Huston *et al.* 1984, Deivanayagam and Weaver 1988, Adams and Ma 1989). In-line tool operation involves shear reaction forces in the hand. In this case hand torque strength is directly proportional to the moment arm, which is the radius of the tool handle (Cochran and Riley 1986, Adams and Peterson 1988, Adams and Ma 1989). The static model described here provides comparable results.

A study conducted by Ulin *et al.* (1993) on subjective perception of handle force in power hand tool operation (using different tool weights) showed that, no matter what the orientation of the tool, the ratings of perceived exertion increased 18–100% with each 1 kg increase in tool mass. Another study found that tools with mass 0.9–1.75 kg were rated 'just right' by workers (Armstrong *et al.* 1989). The current model shows that when the tool mass increases from 0.5 kg to 3 kg, the handle force increases from 15 N to 25 N when the tool is supported by the surface.

In addition to supporting the tool weight, the hands often exert feed force. Feed force is the force that advances a drill, keeps a bit or socket engaged, or even triggers the tool (Radwin and Haney 1996). The static model shows that a local minimum handle force occurs at an optimal handle length for a given feed force level (top trace in figure 7b). This relationship should be considered when designing tools for different situations. For example, along with the relationship between hand location and feed force, handle length should be considered for locating the handle on a power drill where feed force may be large and torque is relatively small. This is in contrast to a nutrunner where there is a small feed force but a large stall torque.

One limitation of the current model is that certain assumptions are needed in order to solve the system of equations, and these assumptions might not always hold. For example, when operating a right angle tool using both hands to react against the tool-generated torque, the forces exerted by the two hands are assumed equal, similar to a pulling task. It is not definitive that this assumption accurately portrays the forces in the two-handed tool operation. When specific information that overrides these assumptions is available, the equations can be adapted accordingly.

The static model developed in the current paper should be useful for ergonomic analysis when the tool is not running or running at a constant torque level. However, it is limited in that it cannot account for the dynamic nature of torque build-up encountered in fastener-driving tool operations and hence the total torque reaction experienced by the operator. The components of torque reaction include torque build-up time, amplitude, and shut-off mechanism. It can affect the resultant handle force and displacement (Kihlberg *et al*. 1993, Lindqvist 1993, Oh and Radwin 1997), muscle activity (Oh and Radwin 1997), and operator discomfort (Kihlberg *et al.* 1993, 1994, 1995). Therefore the dynamic phase must also be considered as discussed in 4.2.

4.2. *Tool torque build-up model*

The length of time an operator is exposed to the reaction torque of a nutrunner depends on the fastener joint and the tool shut-off mechanism. Automatic shut-off tools cease operation when the desired torque level is achieved, and therefore have a shorter exposure time compared to stall tools (Radwin and Haney 1996). Furthermore, the longer the torque rise time, the more observed muscle exertion, and the greater perceived exertion (Freivalds and Eklund 1993, Oh and Radwin 1998). Torque build-up contributes to the dynamic forces acting against the tool operator.

The experimental results (table 3) showed that the error for predicting pneumatic tool torque build-up ranged between 0.1% (Tool E for a hard joint) and 15% (Tool D for a medium soft joint). The force build-up prediction error ranged from 1.2% (Tool C for a hard joint) to 19% (Tool E for a medium-soft joint). There were several potential factors contributing to these errors. Some torsional energy was lost through the coupling and adapters between the tool spindle and the torque transducer, and between the transducer and the threaded fastener. Factors that may introduce additional error in the force model may be due to the non-rigid platform structure. The air hose at the end of the tool was not included in the model, which may influence the force model because some of the energy may be absorbed by its elasticity.

The plots show that the model could reasonably predict the relationship between spindle rotation angle, spindle torque, and handle reaction force during torque build-up. The regression analysis supported this conclusion despite the possible limitations described above. The static mechanical model is limited to understanding the handle force encountered when the tool spindle is stalled or is running under a constant torque. The static model can be used together with a dynamic mechanical model (Lin *et al*. 2001) for predicting operator kinetics and kinematics during torque build-up, as described next.

4.3. *Handle force model: dynamics*

A dynamic mechanical model of the power hand tool operator was developed to describe operator response during torque build-up (Lin *et al.* 2001). The human operator was represented using a single degree-of-freedom mechanical system consisting of a mass, spring, and damper. These operator parameters were found dependent on the work location and individual operator, and they were measured for a group of operators for different work locations (Lin *et al.* 2001). The model satisfactorily predicted the tool handle kinetic response with a correlation coefficient of 0.88 between model-predicted and measured handle displacements during torque build-up in actual tool operation. A complete list of stiffness, inertial mass and viscous damping parameters for in-line, pistol grip and right angle tools is available in Lin (2001). The operator-hand tool system has an equation of motion described by equation (11) (Lin *et al.* 2001). This torque build-up model developed in the current paper can be used as the input $T(t)$ in order to describe the reaction torque acting against the human operator such that:

$$T(t) = (J_{subject} + J_{tool})\frac{d^2\theta}{dt^2} + c_{subject}\frac{d\theta}{dt} + k_{subject}\theta, \tag{11}$$

where $J_{subject}$, $c_{subject}$, and $k_{subject}$ are subject mechanical parameters, J_{tool} is the mass moment of inertia of the tool about its spindle, θ is the resultant hand displacement. The resultant handle force F can therefore be predicted by solving equation (12).

$$F_i = \frac{\frac{d\theta}{dt}c_{subject} + k_{subject}\theta_i}{L1y} \tag{12}$$

The model predictions of handle response using Tool F for two different joints using the subject parameters measured in Lin (2001) are demonstrated in figure 9.

5. Conclusions

This paper combines the static and dynamic aspects of power hand tool operation. The static force model calculates the handle force during tool carrying and when spindle torque is constant. The tool torque build-up model provides a deterministic description for the reaction force encountered during tool operation and was validated in laboratory experiments. The torque build-up model can be further used to understand how operators react to specific inputs by using a dynamic mechanical model of the power hand tool operator (Lin *et al.* 2001). Upon understanding the contributing factors, these models together provide quantitative means for ergonomically designing and selecting tools that can minimize physical demands on the users.

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