Factors Influencing Power Hand Tool Fastening Accuracy and Reaction Forces

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Objective: A laboratory study investigated the relationship between power hand tool and task-related factors affecting threaded fastener torque accuracy and associated handle reaction force.

Background: We previously developed a biodynamic model to predict handle reaction forces. We hypothesized that torque accuracy was related to the same factors that affect operator capacity to react against impulsive tool forces, as predicted by the model.

Method: The independent variables included tool (pistol grip on a vertical surface, right angle on a horizontal surface), fastener torque rate (hard, soft), horizontal distance (30 cm and 60 cm), and vertical distance (80 cm, 110 cm, and 140 cm). Ten participants (five male and five female) fastened 12 similar bolts for each experimental condition.

Results: Average torque error (audited − target torque) was affected by fastener torque rate and operator position. Torque error decreased 33% for soft torque rates, whereas handle forces greatly increased (170%). Torque error also decreased for the far horizontal distance 7% to 14%, when vertical distance was in the middle or high, but handle force decreased slightly 3% to 5%.

Conclusion: The evidence suggests that although both tool and task factors affect fastening accuracy, they each influence handle reaction forces differently. We conclude that these differences are attributed to different parameters each factor influences affecting the dynamics of threaded faster tool operation. Fastener torque rate affects the tool dynamics, whereas posture affects the spring-mass-damping biodynamic properties of the human operator.

Application: The prediction of handle reaction force using an operator biodynamic model may be useful for codifying complex and unobvious relationships between tool and task factors for minimizing torque error while controlling handle force.

Keywords: biomechanics, ergonomic design, occupational safety and health, power hand tool, screwdriver

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INTRODUCTION

The selection and installation of power hand tools for specific assembly applications is a complex process. Both qualitative and quantitative methods exist but uniformity from one industry to another, or even among various manufacturers within the same industry, is lacking. This process is often guided by previous experience for similar tools in similar situations; by manufacturers' data; by in-house, quasi-static tool testing; or trial and error methods.

An ideal process for tool selection is one that together considers the (a) task to be performed, (b) workstation, (c) tool characteristics, and (d) capacity of the human operator. This tool selection process would empirically combine factors associated with each of the above-mentioned variables while considering quality in the assembly process and the capacity of the tool operator to sustain the process without fatigue or injury. The value of this tool selection process is that it considers the whole system involved in manufacturing or assembly for a specific work location.

Torque buildup during nutrunner operation constitutes a relatively short period of time, but its influence on muscle exertion is most significant due to repeated exposure to relatively high impulsive reaction forces (Oh & Radwin, 1997, 1998; Oh, Radwin, & Fronczak, 1997; Radwin, Vanbergeijk, & Armstrong, 1989). Our previous work (Oh & Radwin, 1997) has shown that subjects operating right-angle nutrunners experience eccentric muscle activity during the torque buildup phase. We have also demonstrated (Lin, Radwin, & Richard, 2001) that tool handle displacement and velocity is greater for subjects operating nutrunners with high peak torques as compared to low peak torques, and greater for slow buildup rate (soft joints) as compared to fast buildup rate (hard joints).

Several studies have found that the greater the reaction torque generated by power hand tools, the greater the subjective ratings of perceived exertion (Freivalds & Eklund, 1993; Oh & Radwin, 1998). Handle displacement has also been found to increase with increasing power tool peak torques and increasing hand displacement is correlated with increasing subjective perceived exertions (Armstrong et al., 1999; Kihlberg, Kjellberg, & Lindbeck, 1993). Handle force is also affected by power tool peak torques (Oh et al., 1997). Torque buildup rate has been found to affect handle displacement and operator discomfort (Armstrong et al., 1999; Lindqvist, 1993; Oh & Radwin, 1998; Radwin et al., 1989). Oh et al. (1997) compared right-angle nutrunner operations for five torque buildup rates and three target torques and found that handle force was significantly affected by these two factors.

Tool mass, mass moment of inertia, and center of gravity are important factors in the design and selection of power hand tools because they directly affect loads acting against the handle. Furthermore, the ability for operators to respond to power hand tool–generated torques depends on the shape and orientation of the tool (Oh, 1995). The dimensions of the tool handle directly influence hand exertions by providing mechanical advantages (Deivanayagam & Weaver, 1988; Huston, Sanghavi, & Mital, 1984).

Our laboratory has developed a biodynamic model for predicting forces acting against the human tool operator (Lin et al., 2001). The operator is modeled as a dynamic single degree-of-freedom mechanical system for predicting the response to impulsive torque reaction forces produced by rotating spindle tools such as nutrunners or drills. The model uses mass, spring, and damping elements to represent the standing operator supporting the tool in the hand. A dynamic model is necessary because static models cannot account for the impulsive nature of today's tools, particularly shutoff torque-controlled tools often used in automobile production. The model therefore enables us to evaluate power hand tool reaction forces quantitatively. This model may be used for comparing a particular operation against operator capacities measured in laboratory studies that we previously conducted.

We have biomechanically modeled the human operator for determining reaction forces and predicting operator capacity to react against these forces. In this model, Lin et al. (2001) represented tool operation as a single degree-of-freedom system. This system consists of a tool with mass moment of inertia (J_{tool}), torsional stiffness of the hand and arm (k_{subject}), rotational damping element for the hand and arm (c_{subject}), and an effective mass moment of inertia of the hand and arm (J_{subject}). The angular deflection response of the system $\theta(t)$ was determined by tool torque buildup $T(t)$ as the input. The equation of angular motion describing this system of tool operation is,

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

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

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

The estimated handle force, F_{handle}, can be obtained using the following equation,

$$F_{handle} = \left(c_{subject}\frac{d\theta(t)}{dt} + k_{subject}\theta(t) \right) / L \quad (3)$$

where, L is the moment arm of the handle force defined by the vertical distance between the hand grip and the tool spindle. These model predictions have been previously shown to be related to the risk of OSHA log injuries in an automobile assembly plant (Ku, Radwin, & Karsh, 2007).

The current study examines whether or not tool, task, and workstation factors that reduce handle force may similarly affect threaded fastener torque accuracy. In operation, as the target torque is approached, the torque that the fastener applies against the tool reacts against the torque (for a pistol grip tool) or moment (for a right-angle tool) generated by the handle force, as well as the torque resulting in acceleration/deceleration of the tool body and its internal rotating components. That is, as the target torque is approached, only a portion of the torque that the fastener exerts on the tool (and thus the torque that the tool exerts on the fastener) reacts against the tool handle force. The remainder of the torque causes acceleration of the tool body and also deceleration of the rotating elements of the tool. It is therefore anticipated that if a greater handle force is applied, a greater torque would be exerted on the fastener by the tool.

A laboratory study was conducted to assess how tool type (a selected pistol grip and right-angle nutrunner), work orientation, fastener joint stiffness, and distance from the operator affect accuracy while considering the physical stress acting against the tool operator. It was hypothesized that factors that decrease handle force also decrease threaded fastener torque accuracy.

METHOD

Human Subjects

Ten healthy participants (five male and five female) were recruited from the university community for this study. Average age of participants was 24 years (*SD* = 4.8). Average weight and height of participants was 71.8 kg (*SD* = 11.9) and 175 cm (*SD* = 9), respectively. They were asked to refrain from any upper-extremity exercise for at least 24 hr before testing. All subjects read and signed an institutional review board–approved informed consent document prior to participating in the study. Subjects also completed a general health and demographics questionnaire containing questions about gender, age, height, weight, hand dominance, and previous upper-extremity injuries. Volunteers were excluded if they reported any physical conditions or injuries that would limit their ability to operate an industrial power hand tool.

The participants were all inexperienced power hand tool operators. They were trained on the operation of the power hand tools and were provided practice until they reported that they were confident in their use.

Experimental Design

Four independent variables representing factors that affect handle reaction force in threaded fastening operations were examined. These included tool type (a selected pistol and right-angle nutrunner), fastening joint stiffness (hard and soft), horizontal distance from the operator ankles to the fastener (near and far), and vertical distance between the floor and the fastener (low, middle, and high). Twelve replications for each factor were performed in sequence for a total of 288 fastening operations per subject.

Two different air powered nutrunners were used. They included an Atlas Copco LTV27-SR009-6 pistol grip nutrunner and an Ingersoll Rand DAA15N2S6 right-angle nutrunner. Both were automatic torque shutoff tools. The ultimate target torque for the pistol grip tool was set to 5 Nm and the right-angle tool was set to 15 Nm. These tools were selected because they represented the range of tools typically used for a 12 mm size bolt. The higher torque tools are more commonly right-angle tools.

Horizontal distances were measured from the head of the fastener to the midpoint between the ankles of the subject. The two horizontal distances were 30 cm and 60 cm. Vertical distances were measured from the head of the fastener to the floor. The three vertical distances were 80 cm, 110 cm, and 140 cm.

The pistol grip tool was used to tighten fasteners located on a vertical surface, with the axis of the fastener in a horizontal orientation. The tool was operated using the right hand only. The right-angle tool was used to tighten fasteners located on a horizontal surface with the axis of the fastener in a vertical orientation. The right-angle tool was used with two hands, with the subject's left hand on the neck of the tool near the spindle and the subject's right hand located near the opposite end of the tool.

Fastening joint torque rate included two levels, hard and soft. A hard joint was defined as less than 90° of rotation between the end of the prevailing and the target torque. A soft joint was defined as more than 300° of rotation between the end of the prevailing and the target torque. The joint was simulated by using a 12 mm bolt, a steel flat washer, on a Unistrut (Wayne, MI) frame, and steel channel nut. Belleville spring washers were stacked under each bolt to produce the desired joint stiffness.

A stack of Belleville spring washers in series, formed by putting them together by joining the

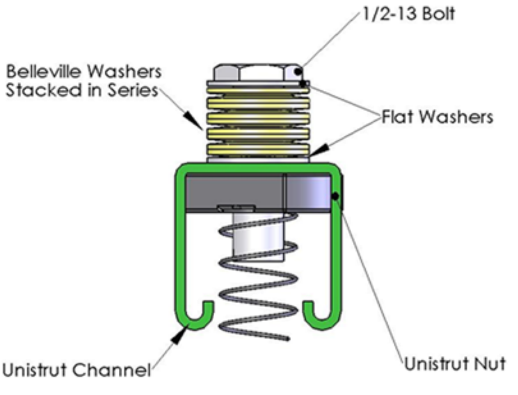

Figure 1. Joint simulator created using a Belleville spring washer in a Unistrut channel. Note that the spring comes attached to the Unistrut nuts for convenience of installation. Since it is facing the open portion of the channel, it has no effect on the joint stiffness.

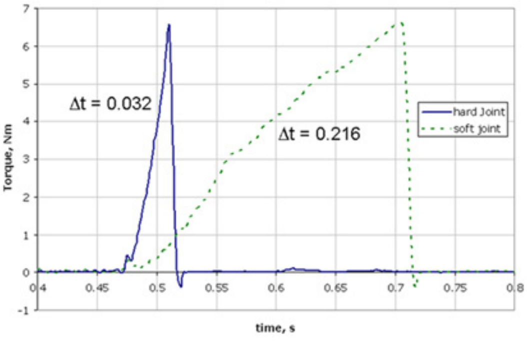

Figure 2. Torque buildup rates for hard and soft joint fastener torque rates.

alternate faces, produced deflection n times the individual deflection, where n is the number of washers in a series stack (Figure 1). They also lowered the stiffness of the individual joint by a factor of n. Ten washers in series produced the desired joint stiffness. The joint simulator torque buildup profile for hard joints and soft joints is shown in Figure 2. Torque buildup rate is slower for soft joints and faster for hard joints.

The same bolt and washer sets were reused for the entire study. The threads of the bolts were lubricated to reduce the effect of friction during tightening. The variation within a set or between sets was not measured. Although the bolts and washers were reused for each subject, given their large diameter and relatively low torques, they were considered unaffected by repetitive tightening. The hard joint didn't use spring washers, just a steel flat washer and the angle of rotation was much less than 90°. The soft joints were designed for 360° of rotation.

An in-line accessory torque transducer (Transducer Techniques Model RSS-600, 600 ft-lb., Temecula, CA) and a grounded nutrunner were used for calibrating the torque rate but were not used for the human participant trials. The variability of torque error imparted by the tool alone is much less than the variability imparted by the human operator. Since the pneumatic air tools in this study were not equipped with internal electronic torque transducers an independent torque measurement was utilized to audit the ultimate torque. The experimenter used a calibrated electronic torque wrench to audit the torque achieved for each fastener following completion of each session. The wrench used was an Ingersoll-Rand Expert Audit Wrench Model ETW-A25. This model is typically used to audit torque values in production settings. The dynamic tightening torque was measured by tightening the fastener further using the torque audit wrench. Since the static torque was greater than the dynamic torque, the user must overcome the static torque until the fastener turns, at which point the dynamic torque is being measured. The wrench continuously records the torque value and then interprets which value is the static torque and which values represent dynamic torque. The dynamic torque value measured was considered the audited ultimate torque.

Experimental Procedures

The experiment was divided into two 1-hr sessions with at least 24 hr in between. The fastening conditions were counterbalanced using a Latin squares design. The two sessions included the near condition and all three vertical distances on one day, and the far condition and all three vertical distances on the alternate day. Subjects started either with the pistol tool or the right-angle tool and tightened all fasteners for that tool.

Since the apparatus could contain only half the number of fasteners needed to perform the entire experiment, the experiment was designed so that the fasteners could be measured and reset without the subject present. Changing tools also reduced possible effects of fatigue due to the different forces and exertions involved.

Participants were provided an explanation and demonstrated how to operate each tool. A short practice session was provided and volunteers had the opportunity to operate each tool as many times as they needed until they reported that they were comfortable using them.

Subjects performed 144 fastening operations during each session, divided into 12 replications for each experimental factor. To prevent fatigue, a 1-min break was given between each set of 12 fastening operations, and a 5-min break was given halfway through each session. Subjects were instructed to stand in the appropriate position for each fastener, using a mark on the floor, and to squeeze the tool trigger until the tool automatically shut off.

Data Analysis

Torque error was defined as the difference between the audited torque and the target torque. Since the tools were both automatic shutoff tools there is no judgment on the part of the operator. The torque error is strictly a function of the mechanical interaction between the torque shutoff tool and the dynamic mechanical coupling between the tool operator and the tool handle, which is an individual factor analogous to dynamic strength. A "poorer" coupling results in more torque error. The variability comes from trial-to-trial variations in mechanical coupling, which is dependent on operator posture, dynamic strength, and biomechanics.

The biodynamic tool operator model was used to predict mean handle force for each experimental condition. Handle forces were calculated using the stiffness, inertial mass, and damping coefficients for each of the 24 cases as described in Lin, Radwin, and Richard (2003), and averaged. Corresponding average predicted handle forces were compared against torque error for each experimental condition that had a significant effect on torque error.

Repeated measures analysis of variance was used to determine the significance of main and interaction effects of vertical distance, horizontal distance, joint torque rate, and tool type on torque error. Significance was set at $p < .05$.

RESULTS

Descriptive statistics for torque error stratified against the independent variables vertical distance, horizontal distance, joint torque rate, and tool type are provided in Table 1. An analysis of variance table is given in Table 2. Significant main effects were observed for vertical distance, $F(2, 18) = 28.87$, $p < .001$, joint torque rate, $F(1, 9) = 10$, $p = .012$, and tool, $F(1, 9) = 187.17$, $p < .001$. As vertical distance increased from the low to middle level, torque error averaged over all other conditions, remained unchanged. In contrast, the average torque error for the high vertical distance significantly decreased relatively by 20% from 2.10 Nm to 1.69 Nm. Average torque error, averaged over all other conditions, was 0.78 Nm greater for hard joints than for soft joints. The pistol grip tool had 2.16 Nm less torque error than the right-angle tool.

Significant interaction effects were also observed for vertical distance × horizontal distance, $F(2, 18) = 4.33$, $p = .03$, vertical distance × tool, $F(2, 18) = 9.45$, $p = .002$, joint × tool, $F(1, 9) = 14.97$, $p = .004$, and vertical distance × joint × tool, $F(2, 18) = 4.87$, $p = .02$. Average torque error was greater for the near horizontal distance than for the far horizontal distance when the vertical distances were the middle or high levels (Figure 3). Average torque error decreased relatively by 15% from 1.83 Nm to 1.56 Nm, for the far horizontal distance, when vertical distance was high. Average torque error also decreased when vertical distance increased for the pistol grip tool but torque error was greatest at middle vertical distance for the right-angle tool (Figure 4). The difference between torque error for the hard and soft joints was greater for the pistol grip tool in comparison to the difference in the torque error for the hard and soft joints for the right-angle tool (Figure 5).

Average handle force predicted by the biodynamic operator model is plotted for significant effects in Figures 3 through 5. Handle force was most affected by soft fastener joints and increased when operating both tools in the near horizontal distance and the high vertical distance. The handle

TABLE 1: Mean and Standard Deviation of Torque Error (Nm) for Vertical Distance, Horizontal Distance, Torque Rate, and Tool Type

	Torque Error (Nm)			
	Pistol Grip (Target Torque = 5 Nm)		Right Angle (Target Torque = 15 Nm)	
	M	*SD*	*M*	*SD*
Vertical distance				
High	0.70	1.01	2.70	1.46
Middle	0.87	1.17	3.34	1.53
Low	1.07	1.51	3.09	1.68
Horizontal distance				
Near	0.86	1.19	3.22	1.62
Far	0.90	1.31	2.87	1.52
Torque rate				
Hard	1.43	1.41	3.28	1.61
Soft	0.32	0.74	2.81	1.51

force was greatest for the pistol grip tool when the torque rate was soft.

DISCUSSION

Torque accuracy was affected by factors directly related to tool, task, and workstation design. Overall the right-angle tool had greater torque error than the pistol grip tool (Figures 4 and 5). The spindle target torque for the right-angle tool was 3 times greater than the pistol grip tool (5 Nm for the pistol grip and 15 Nm for the right-angle tool), but the percentage-wise error was slightly less for the pistol grip tool (18% vs. 20%). For both tools, when the threaded fastener joint rate was hard, torque error was less than the hard joint (33%). Although torque error was less for soft joints, handle forces were greater (170%).

This inverse relationship between torque error and handle force can be explained by understanding the dynamics of the tool and the human operator. First consider the torque associated with the acceleration of the tool housing and the torque associated with the deceleration of the rotating elements of the tool. When the tool target torque is established at constant velocity (including static) conditions, the dynamic effects are not accounted for. Consequently, the greater the difference between steady-state conditions and actual operating conditions, the greater the error between target torque and actual fastener torque would be expected. When different operating conditions result in different handle reaction forces, it corresponds to a difference in the amount of torque that is associated with the tool dynamic effects. Consequently, the greater the handle reaction force, the smaller the torque error would be expected.

This mechanically explains the relationship observed between torque error and handle reaction force. It is also consistent with the smaller torque error associated with soft joints (i.e., soft joints experience lower accelerations/decelerations and a greater part of the handle force goes toward the torque exerted on the fastener by the tool). Consequently the forces/torques associated with dynamic effects are smaller; hence there is less difference between target torque setting and operating conditions.

When the threaded fastener joint stiffness decreases from hard to soft, torque buildup rate decreases. However torque buildup rate is also dependent on spindle speed. When the spindle rotates at a slower speed, the torque buildup rate is slower. Some DC electric tools decrease torque buildup rate by slowing the spindle speed to improve torque accuracy, effectively "softening" the threaded fastener joint (Johnson et al., 2008; Sommerich, Gumpina, Roll, Le, & Chandler, 2009). Based on the findings in the current

TABLE 2: ANOVA Table for Torque Error

Source	Sum of Squares	*df*	Mean Sum of Squares	*F*	*p* Value
Vertical distance	8.37	2	4.18	28.87	.000*
Error	2.61	18	0.15		
Horizontal distance	1.44	1	1.44	0.45	.518
Error	28.68	9	3.19		
Torque rate	37.41	1	37.41	10.00	.012*
Error	33.67	9	3.74		
Tool	281.43	1	281.43	187.17	.000*
Error	13.53	9	1.50		
Vertical distance × horizontal distance	0.53	2	0.26	4.33	.029*
Error	1.10	18	0.06		
Vertical distance × torque rate	0.09	2	0.05	0.55	.585
Error	1.50	18	0.08		
Horizontal distance × torque rate	3.26	1	3.26	2.72	.133
Error	10.77	9	1.20		
Vertical distance × horizontal distance × torque rate	0.27	2	0.13	1.04	.374
Error	2.33	18	0.13		
Vertical distance × tool	2.82	2	1.41	9.45	.002*
Error	2.68	18	0.15		
Horizontal distance × tool	2.23	1	2.23	1.42	.264
Error	14.16	9	1.57		
Vertical distance × horizontal distance × tool	0.11	2	0.06	0.82	.457
Error	1.22	18	0.07		
Joint × tool	6.08	1	6.08	14.97	.004*
Error	3.65	9	0.41		
Vertical distance × torque rate × tool	1.56	2	0.78	4.87	.02*
Error	2.88	18	0.16		
Horizontal distance × joint × tool	0.04	1	0.04	0.12	.738
Error	3.10	9	0.34		
Vertical distance × horizontal distance × torque rate × tool	0.13	2	0.07	0.28	.757
Error	4.18	18	0.23		

*$p < .05$.

research, slowing the spindle speed under certain conditions may unwittingly increase handle force. Consequently slowing torque buildup rate to improve torque accuracy under certain conditions might have an adverse effect on physical stress. This study was limited to just two torque buildup rates and therefore future work should investigate the effect of torque buildup rate in more detail to more fully explore this relationship.

Another factor independently affecting torque accuracy was work and task design. Vertical distance and horizontal distance both had effects on average torque error. Torque error was greatest

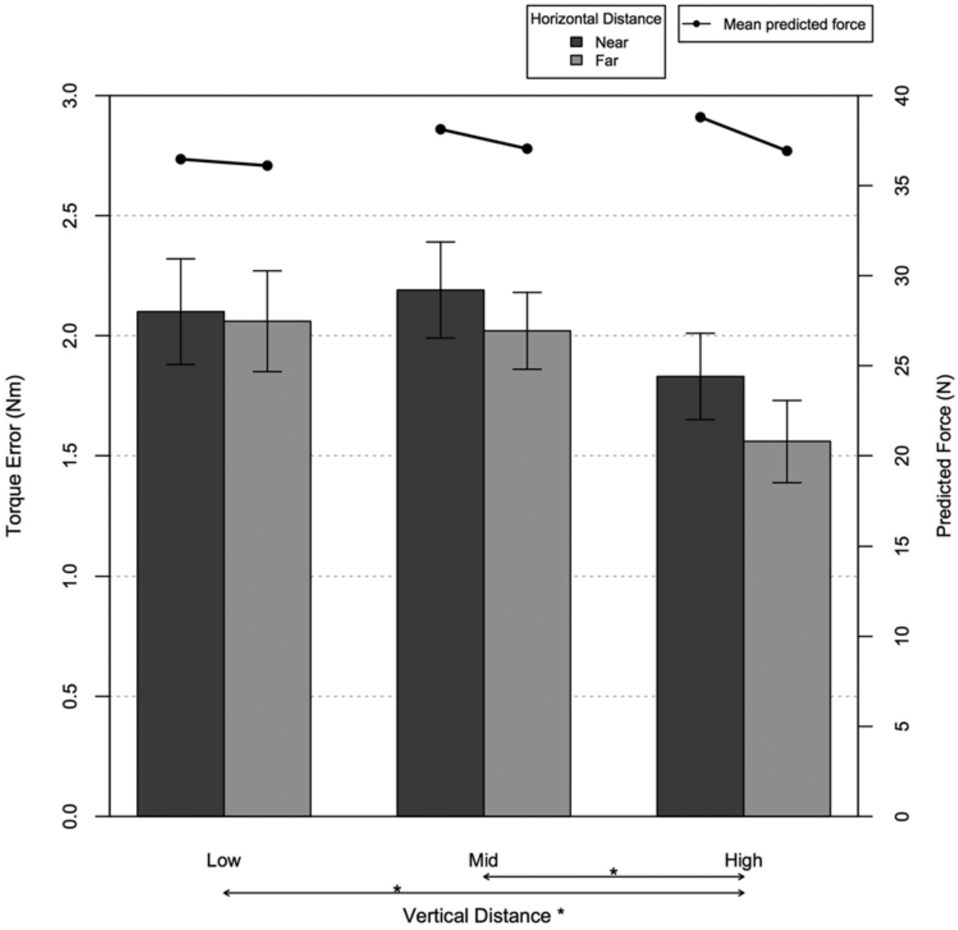

Figure 3. Torque error interaction between vertical and horizontal distance (bars). Mean (*SD*) indicated. Corresponding predicted handle force is also plotted for each vertical and horizontal distance (solid lines). Significant torque error differences were observed between the middle and high vertical distances for both near and far horizontal distances, but no differences were observed for the low horizontal distance. $^*p < .05$.

on average when working at the low and middle vertical distances and was least when working at the high vertical height for the far horizontal distance. The greater torque error (22% to 24%) when the vertical height was low or middle compared to when vertical height was high, or when horizontal distance was near (8%) than far, shows that the operator's position relative to the fastener is an important consideration for achieving torque accuracy.

Torque error for the far horizontal distance was less than for the near horizontal distance when the vertical distance was high (Figure 3), however in this scenario, predicted handle force actually decreased by 5% with decreased torque error. This relationship was opposite to the association between handle force and torque error for the torque buildup rate effect.

It should be noted that torque error is highly dependent on the product and tolerances acceptable for the design. We have observed that in the automobile industry acceptable torque error can range from 4% to greater than 30%, which encompasses the range of error observed in the current study.

Estimated handle force changed for different work locations because operator mechanical mass-spring-damping parameters are related to

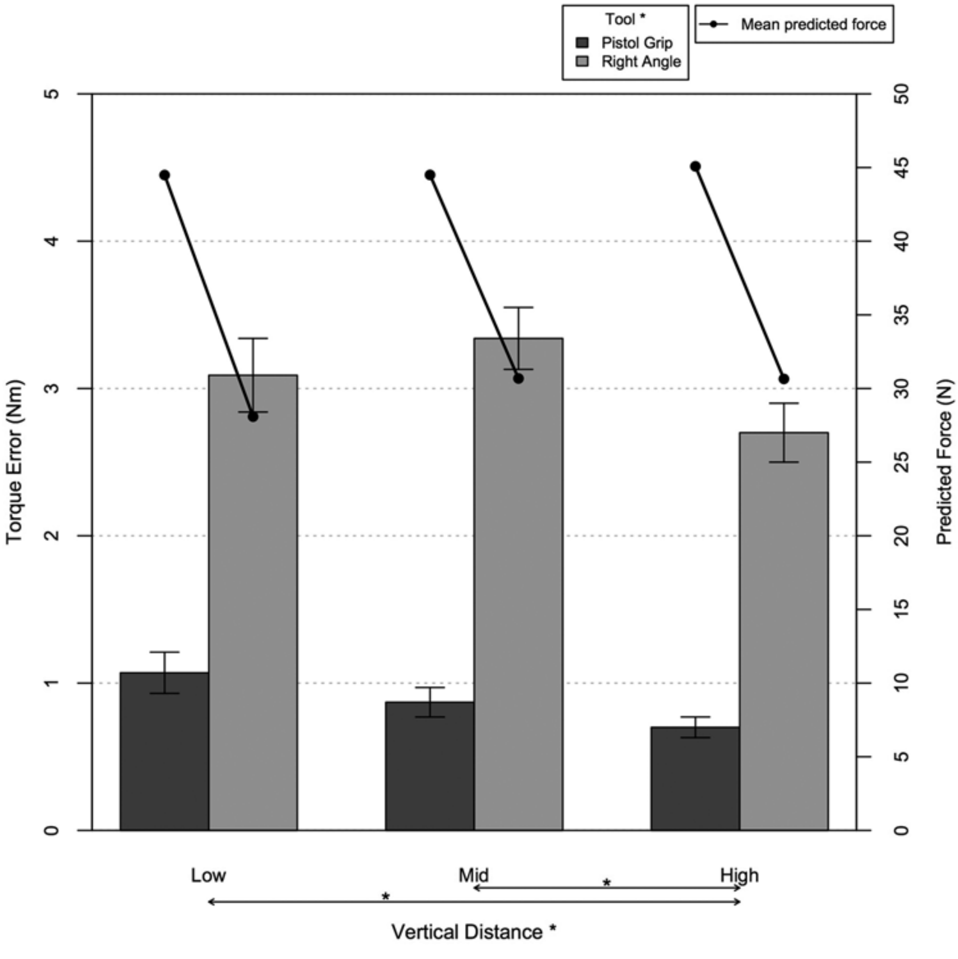

Figure 4. Torque error interaction between vertical distance and tool (bars). Mean (*SD*) indicated. Corresponding predicted handle force is also plotted for each vertical distance and tool (solid lines). Significant torque error differences were observed between high and middle and high and low vertical distances for the right-angle tool, whereas no significant differences were observed between the low and middle vertical distances for the right-angle tool or in vertical distance for the pistol grip tool. *$p < .05$.

posture (Lin et al., 2001; Lin et al., 2003; Lin, Radwin, & Nembhart, 2005). Lin et al. (2001) found that the mechanical properties of the human operator were influenced by these factors so changes in capacity to act against tool reaction forces should be anticipated. These observations suggest that different dynamics components affecting handle force might affect tool accuracy differently. That is, tool dynamics and operator dynamic parameters were both affected differently.

By far the greatest factor affecting handle force was buildup torque rate, which is related to the velocity and acceleration of force buildup in the hand. The work and task factors associated with operator position may affect the human operator spring-mass-damping mechanical characteristics, which appear to affect torque error differently than torque buildup rate effects. Future research should consider a larger variety of task conditions that can affect handle force to distinguish between operator factors affecting

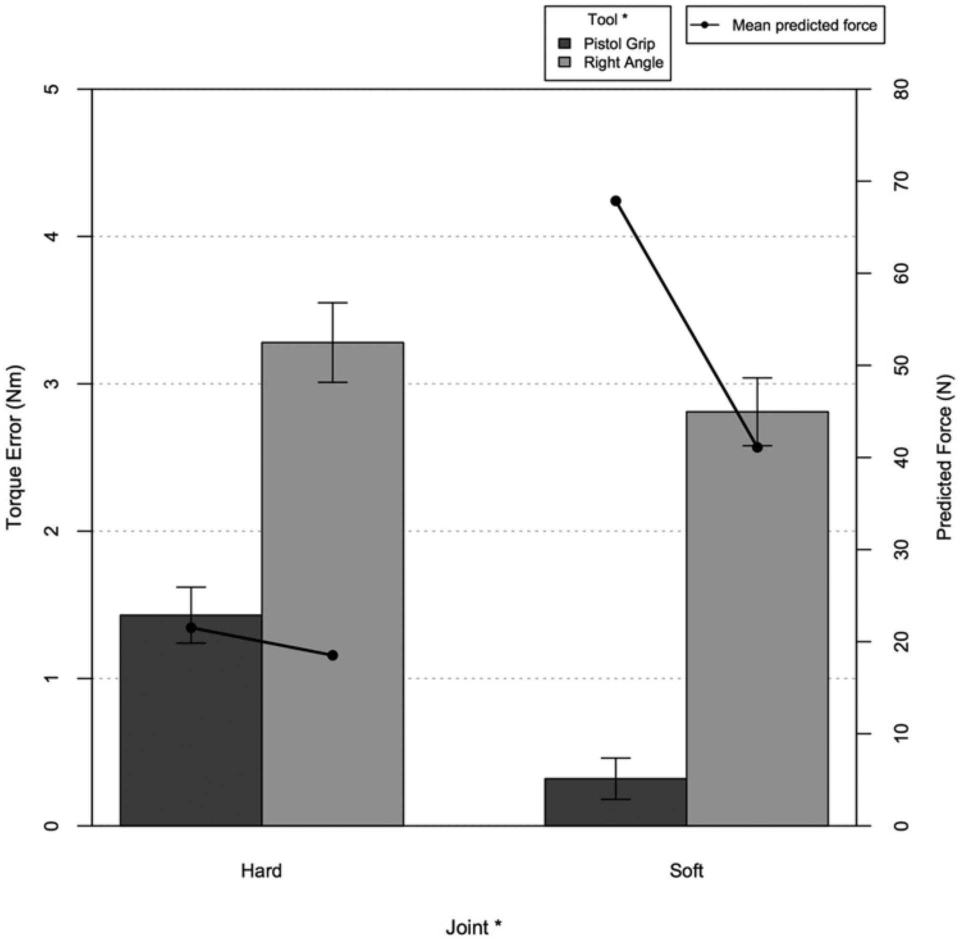

Figure 5. Torque error interaction between tool and joint (above). Mean (*SD*) indicated. Corresponding predicted handle force is also plotted for each joint and tool (below). Significant torque error differences were observed between joint for the pistol grip tool, whereas no significant differences were observed for the right-angle tool. $*p < .05$.

dynamic forces independent from torque buildup rate and operator mechanical parameters. This may also suggest tool installation approaches to mitigating the undesirable effects on handle force acting against the tool operator when slowing the tool spindle to achieve less torque error.

A biodynamic tool operator model may help evaluate the relative effects of individual operators (i.e., percentiles), workstation and job design, tool, and task factors. In practice this application might comprise of optimizing workstation and tool factors in a manner consistent with maximizing torque accuracy while minimizing handle force acting against the tool operator. Handle force predictions might also be useful for tool manufacturers to evaluate the associated handle forces acting against the tool operator when designing power hand tool tasks for improving accuracy.

CONCLUSIONS AND RECOMMENDATIONS

1. Soft joint torque buildup rate had 33% less torque error on average and 170% greater handle force on average than hard joint torque buildup rate.
2. Torque accuracy for the far horizontal distance, when vertical distance was high, was 14% less than for a near horizontal distance.

3. The study reveals that it is important to consider effects on forces acting against the operator when slowing torque buildup rate to improve torque accuracy.
4. Biodynamic models for predicting handle force in power hand tool operation may be useful for indicating how changes in task factors and work design for improving tool accuracy might affect handle force acting against the operator.

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KEY POINTS

- Slower torque buildup rate can improve torque accuracy, but under certain conditions it may increase estimated forces acting against the operator.
- Some operator positions can improve torque accuracy and also reduce estimated force acting against the operator.
- These contradictory outcomes are plausible because a fastener torque buildup rate influences the tool dynamics, whereas posture influences the spring-mass-damping biodynamic properties of the human operator.

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