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Power Hand Tool Kinetics Associated with Upper Limb Injuries in an Automobile Assembly Plant

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This study investigated the relationship between pneumatic nutrunner handle reactions, workstation characteristics, and prevalence of upper limb injuries in an automobile assembly plant. Tool properties (geometry, inertial properties, and motor characteristics), fastener properties, orientation relative to the fastener, and the position of the tool operator (horizontal and vertical distances) were measured for 69 workstations using 15 different pneumatic nutrunners. Handle reaction response was predicted using a deterministic mechanical model of the human operator and tool that was previously developed in our laboratory, specific to the measured tool, workstation, and job factors. Handle force was a function of target torque, tool geometry and inertial properties, motor speed, work orientation, and joint hardness. The study found that tool target torque was not well correlated with predicted handle reaction force ($r = 0.495$) or displacement ($r = 0.285$). The individual tool, tool shape, and threaded fastener joint hardness all affected predicted forces and displacements ($p < 0.05$). The average peak handle force and displacement for right-angle tools were twice as great as pistol grip tools. Soft-threaded fastener joints had the greatest average handle forces and displacements. Upper limb injury cases were identified using plant OSHA 200 log and personnel records. Predicted handle forces for jobs where injuries were reported were significantly greater than those jobs free of injuries ($p < 0.05$), whereas target torque and predicted handle displacement did not show statistically significant differences. The study concluded that quantification of handle reaction force, rather than target torque alone, is necessary for identifying stressful power hand tool operations and for controlling exposure to forces in manufacturing jobs involving power nutrunners. Therefore, a combination of tool, work station, and task requirements should be considered.

Keywords musculoskeletal disorders, nutrunners, power hand tools, repetitive motion injuries, screwdrivers, tool force, tool torque

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INTRODUCTION

This study investigates the handle forces acting against power screwdriver and nutrunner operators in an automobile assembly plant. Pneumatic and electric nutrunners are widely used in automobile assembly line processes. These power hand tools often tighten threaded fasteners to a preset peak torque (i.e., target torque) using an automatic shut-off or clutch mechanism. The tool is usually adjusted to the target torque for a specific fastener when the tool is installed in a workstation and frequently monitored. Many power hand tools are adjustable over a range of torques and are available in numerous geometries and forms. Therefore a similar tool used in one workstation might be installed in a different workstation using a different target torque.

Work-related musculoskeletal disorders (MSD) have been associated with risk factors present in occupational power hand tool use,[1,2] including forceful exertions.[3–6] Previous studies have not measured forces associated with industrial nutrunner operation but rather estimated exertions using surrogate measures, such as psychophysical correlates or EMG.

Freivalds and Eklund[7] investigated power hand tool reaction force parameters (i.e., peak torque, rise time, duration, and impulse), muscle activity, and operator discomfort relationships with regard to work surface orientation (vertical and horizontal), threaded fastener joint hardness, tool RPM, air pressure, and handle orientation. They concluded that peak reaction torque and impulse were correlated with subjective ratings of perceived exertion.

Based on EMG studies, Radwin et al.[8] observed that the tool torque magnitude and buildup time affected grip force for right-angle nutrunners. Oh and Radwin[9,10] showed that greater torque reaction force resulted in less stable handle control and more movement. Longer buildup time caused greater muscle activity for both horizontal and vertical workstations. Both torque reaction force and buildup time had significant effects on subjective ratings of perceived exertion and task acceptance rate. Armstrong et al.[11] studied muscle activity and response to torque buildup and decay of in-line power screwdrivers. The conclusions were similar to the Radwin et al.[8] right-angle tool experiments. Torque decay times did not affect peak wrist muscle activity and handle excursion.

Fennigkoh[6] found a positive relationship between torque magnitude and grip force using a pistol grip tool simulator.

Across all conditions, pre-torque grip force, torque duration, thrust force, and gender, the high torque magnitude (6.1 Nm) resulted in higher net changes in grip force than low torque magnitude (2.6 Nm) did, but grip force was not significantly affected by the buildup duration over the 0.5–2 sec range used in this study.

Schulze et al.(12) were interested in body posture assumed by gender, experience, work piece orientation (angled, current, and low), and tool type (pistol grip and straight grip). They concluded that tool shape and workstation orientation affected operator posture. Kihlberg et al.(13) used a modified Borg's CR-10 rating scale and found that rated discomfort was associated with the tool displacement.

Generally, most of the above referenced ergonomic research involved laboratory studies and were limited in workstation orientation, tool size, shape, and characteristics, torque, and the individual operators. Because these results were limited in range, they may not be representative of the wide variety of conditions observed in the manufacturing environment. A practical method is needed for estimating reaction forces encountered during actual tool operation.

To understand the complex mechanical properties of power hand tool operators, Lin et al.(14,15) developed a deterministic human operator model based on Lindqvist's hypothesis(16) that a power nutrunner operator can be represented mechanically as a single degree-of-freedom mechanical system. The dynamic passive model considers the tool operator as an equivalent moment of inertia, a linear rotational spring, and a viscous damper. An apparatus with known stiffness, damping, and inertial mass was used in the laboratory to estimate the stiffness, damping, and moment of inertia ($k_{subject}$, $c_{subject}$, $J_{subject}$) of the human operator by measuring the variations in the frequency and angular displacement that human subjects impose when grasping the apparatus. The observed tool operator parameters and the mechanical model are then used to deterministically estimate the resulting handle displacement and force from a transient torque input in a power hand tool operation.

The biomechanical model was validated by recalling five subjects and having them operate a power hand tool for varying horizontal distances, vertical distances, and torque buildup times.(14) The correlation between the model prediction and the measurement was $r = 0.88$. When stiffness was normalized using EMG as an index of exertion, the model predicted actual peak handle displacement within 3%.

The goal of this study was to apply Lin's dynamic tool operator model using tool and workstation data collected from actual assembly operations. This should allow evaluation of a variety of tool geometries, shapes, tool motor characteristics (i.e., free running speed, stall torque), work locations (i.e., horizontal and vertical distance from the operator), tool orientation (i.e., horizontal or vertical), and threaded fastener tightening operations (joint hardness and target torque) on peak handle force and displacement, and to compare these handle forces and displacements against the injury experience in the plant.

METHODS

Jobs Studied

At least one power hand tool was used in 193 of 393 workstations in the trim and chassis departments of an automobile assembly plant in the midwestern United States. A total of 69 workstations in the trim and chassis areas of the plant were selected for study. The criterion for selection was that the job used only a single pneumatic power nutrunner and that the tools were installed without a counterbalance or reaction bar. The plant had two daily shifts so at least two operators worked at each job, involving a total of 138 operators. The tool parameters described below were collected for the 15 distinct pneumatic nutrunners that were used in the 69 workstations and can be described as right-angle or pistol grip types.

Procedures

Specific tool and job parameters were measured to apply the Lin et al.(14,15,17) tool operator mechanical model for estimating tool handle reaction force and displacement. The tool parameters measured included tool geometry (i.e., handle and tool lengths), shape (i.e., pistol or right angle), mass (kg), motor free running speed (RPM), motor stall torque (Nm), location of the center of mass (cm), mass moment of inertia (Kgm^2), target torque (Nm), and threaded fastener joint hardness (soft, medium, and hard). The job parameters were fastener horizontal and vertical distances from the operator, and tool orientation (i.e., horizontal or vertical). Measurement procedures for each of these parameters are described below.

Tool Parameters

Tool type, free running speed, target torque, and stall torque data were obtained from tool manufacturer catalogs and from plant standard production sheets. An electronic scale (UES64; Universal Enterprises, Beaverton, Ore.) was used to weigh the tools. Threaded fastener joints were classified as hard, medium, or soft according to the materials that were joined. If both fastened materials were metals, the joint was classified as a hard joint. If a sheet of metal was fastened to a piece of plastic, the joint was classified as a medium joint. A joint was classified as soft if tightened materials were both plastic, or there was foam or an O-ring between the joined materials.

The free suspension method(18) was used to measure the location of the center of mass of pistol grip tools by assuming the tool cross sections were symmetric. Tools were suspended by a flexible cable in two different orientations, and the intersection of two vertical plumb lines was used as the location of the center of mass, as shown in Figure 1. By finding the balance point for the right-angle tools, the centroid was located at the fulcrum, as shown in Figure 2.

The moment of inertia of pistol grip tools was measured by using the oscillation method.(19) Each pistol grip tool was held horizontally by a specially designed apparatus at both ends, as shown in Figure 3. The natural period of oscillation was

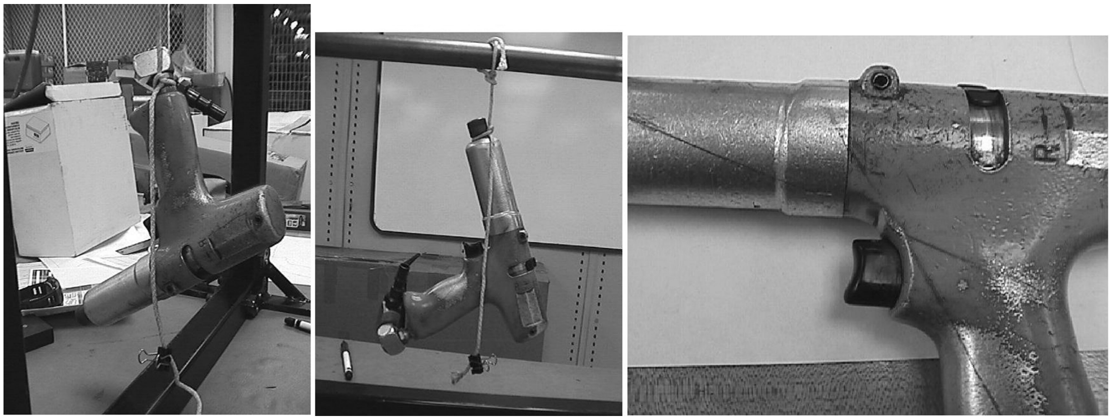

FIGURE 1. The suspension method used for determining the centroid of pistol grip tool.

obtained by swinging the tool. The moment of inertia about the spindle axis can be expressed as

$$J_{spindle} = mgh/(2\pi f)^2 \tag{1}$$

where mg is the weight of the tool (N), h is the distance between the spindle axis and the centroid (m), and f is the oscillation frequency (Hz), which is the inverse of the oscillation period of the tool.

The bifilar pendulum method was used to measure the moment of inertia of right-angle tools, which were suspended horizontally by two strings as shown in Figure 4. The two strings were parallel to each other and hung the same distance from the centroid, denoted as d(m). The distance between the holding bar and right-angle tools was denoted as L (m). Oscillation period was measured by swinging the tool in the longitudinal direction. The following formula was applied to calculate the moment of inertia:

$$J_{cm} = mg/d(2f2\pi/L)^2 \tag{2}$$

$$J_{tool} = I_{cm} + mh^2 \tag{3}$$

where J_{cm} is the moment of inertia about the center mass axis, J_{tool} is the moment of inertia about the spindle axis, mg is the weight of the tool (N), f is the oscillation frequency (Hz), d is

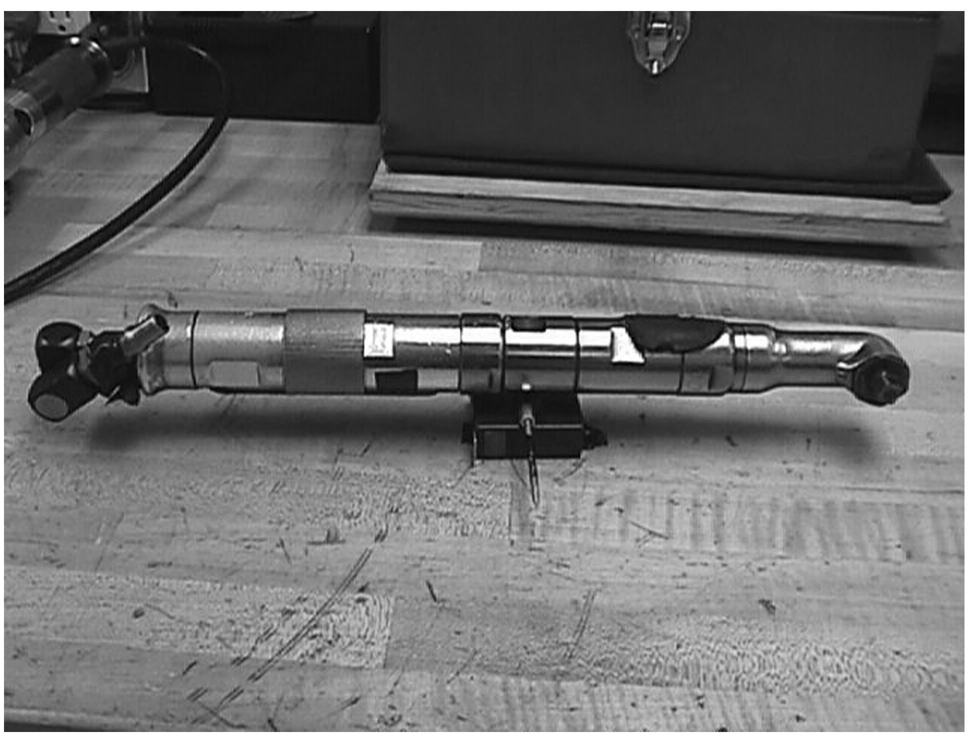

FIGURE 2. The centroid of a right-angle tool is located at the balance point.

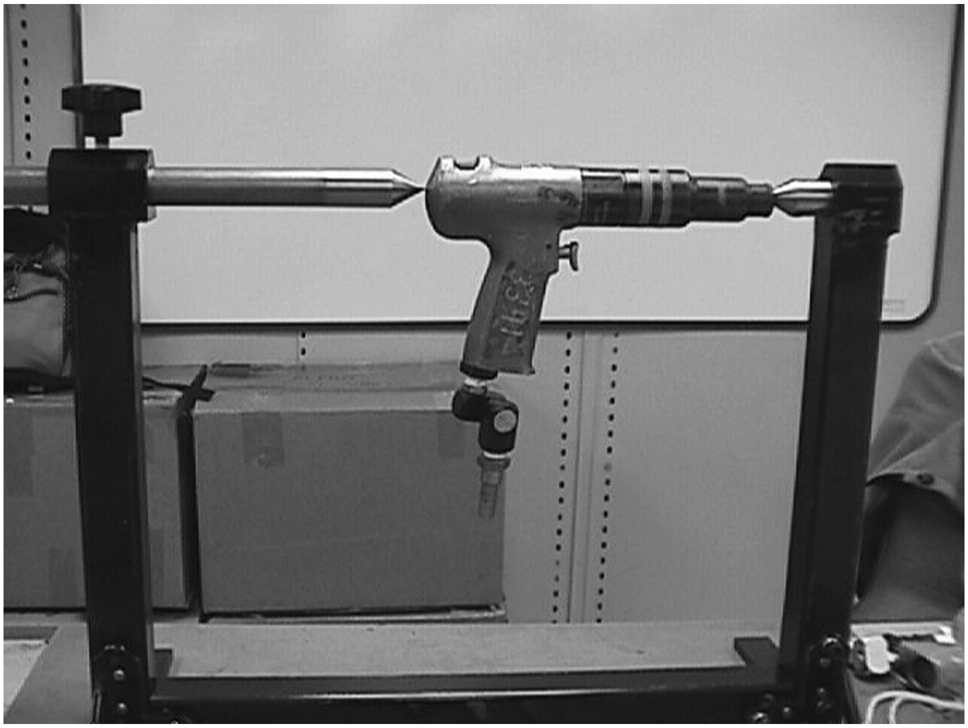

FIGURE 3. Pistol grip tools were clamped to a frame as illustrated.

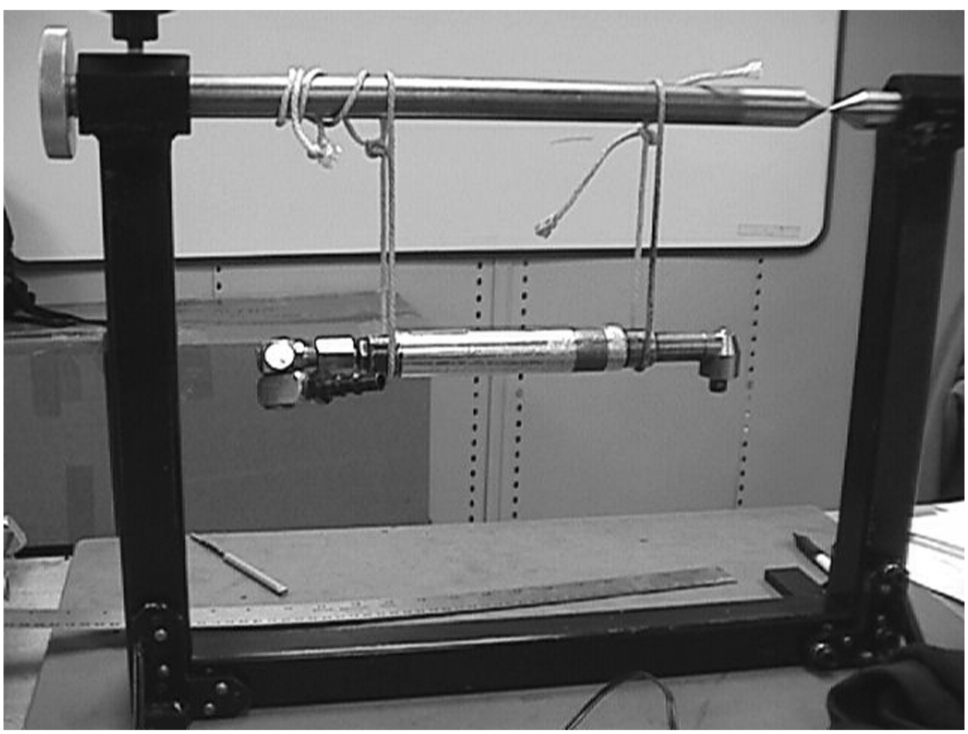

FIGURE 4. Two strings were used to hang a right-angle tool.

the distance between the string hanging point and the centroid (m), L is the length of the string (m), and h is the distance between the spindle axis and the centroid (m).

Operator Mechanical Parameters

Lin et al.[15] measured the rotational stiffness ($k_{subject}$), mass moment of inertia ($J_{subject}$), and the viscous damping ($c_{subject}$) constants for 25 subjects operating power hand tools in various vertical and horizontal locations. A linear combination of mechanical parameters was used to interpolate dimensions such that

$$k_{subject} = \alpha H + \beta V + \chi HV + \delta \tag{4}$$

where $k_{subject}$ is the stiffness, H is the horizontal distance measured from the operator's ankle to the joint, V is the vertical distance measured from the floor to the joint. The variables α, β, χ, and δ are coefficients derived from the regression method. The coefficients (α, β, χ, and δ) for moment of inertia ($J_{subject}$) and viscous damping ($c_{subject}$) were also determined using linear regression in a manner similar to Eq. 4.

In this study, the linear horizontal and vertical distances of each workstation were measured while operators were performing assembly operations. The horizontal distance was measured from the tool handle to the ankles, and the vertical distance was measured from tool handle to the ground. If several tasks were performed at different locations, the average of those horizontal distances and the average of the vertical distances were calculated to represent the average horizontal and vertical distances of this workstation.

The handle displacement and force were estimated by using Eqs. 5 and 6,[14] where the operator mechanical parameters were inserted and time setup increment Δt was set at 1 ms.

$$\theta i + 1 = \left\{ \frac{1}{\frac{Jsubject + Jtool}{(\Delta t)^2} + \frac{csubject}{2\Delta t}} \right\} \times \left[\left\{ \frac{2\left(J_{subject} + J_{tool}\right)}{(\Delta t)^2} \right\} \theta i + \left\{ \frac{c_{subject}}{2\Delta t} \frac{2\left(J_{subject} + J_{tool}\right)}{(\Delta t)^2} \right\} \theta i - 1 + Ti \right] \tag{5}$$

where $\theta(t)$ is the variation of angular displacement with time, J_{tool} is the moment of inertia of the tool about its spindle, and $T(t)$ is the variation of tool torque buildup.

$$F = \left(c_{subject} \frac{d\theta(t)}{dt} + k_{subject}\theta(t) \right) \Big/ L \tag{6}$$

where F is the hand force and L is the hand location on the tool handle. A plot of displacement and force against time using this model is available in Lin et al.[20]

Plant Injury Data

Injury data was collected from the plant OSHA 101 and 200 logs at the manufacturing facility. The time period considered in this study was 12 months within the automobile model year for which the tool data was obtained. Complete OSHA logs contained employee names, department, bay location, job station number, date of injury, and type of injury. An upper extremity MSD was considered if the data indicated a nonacute injury to the fingers, hands, wrists, forearms, upper arms, or shoulders. Examples of such disorders included, but were not limited to, tenosynovitis, epicondylitis, tendonitis, strain, and carpal tunnel syndrome. Because data were not stored electronically, each OSHA 101 and 200 form was studied and the data was transcribed into an Access database. Records up through 15 months were reviewed to help ensure that most of the MSDs occurring within the 12-month period were included.

RESULTS

Handle Force and Displacement

The type of tool and threaded fastener joint hardness both had a significant effect on peak handle force and displacement ($p < 0.05$). Handle force and displacement is summarized in Table I, and Figures 5 and 6. The average peak handle force ranged from 1.37 N to 57.81 N for right-angle tools, and 0.35 N to 18.14 N for pistol grip tools. The average displacement ranged from 0.32 mm to 38.4 mm for right-angle tools and 0.19 mm to 9.21 mm for pistol tools. A wide variation of forces and displacements was also observed within similar types of tools, which were greatly influenced by workstation and job parameters. The average peak handle force of Tool 1, for instance, was 31.8N, whereas the standard deviation (SD)

TABLE I. Predicted Peak Handle Force and Displacement

		Right-Angle Tools							Pistol Grip Tools							
Tool		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Jobs (n)		5	3	2	7	2	3	4	1	2	2	27	4	3	2	2
Force	Mean	31.8	1.37	4.94	19.22	1.83	57.81	25.76	11.54	0.35	6.76	10.74	18.14	13.47	3.65	12.26
(N)	SD	31.5	.010	5.84	12.91	0.34	19.47	2.39	—	0.00	1.28	10.39	0.22	11.31	0.00	13.61
Displacement	Mean	25.1	0.32	6.21	17.65	0.38	38.40	11.32	9.21	0.19	5.16	9.34	6.73	1.97	0.42	7.78
(mm)	SD	29.1	0.00	8.20	14.87	0.07	19.40	0.55	—	0.00	1.24	11.14	0.15	1.41	0.00	9.43

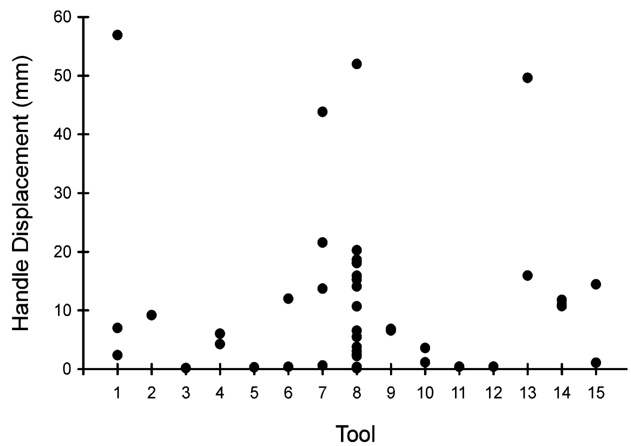

FIGURE 5. Scatter plot of predicted peak handle displacement for the 15 tools studied.

was 31.5 N. The average peak handle displacement for tool 8 was 9.34 mm and the SD was 11.14 mm.

Handle forces and displacements were also affected by tool shape and fastener joint hardness, as indicated in Tables II and III, and Figures 7 and 8. Handle forces and displacements for right-angle tools were significantly greater than for pistol grip tools ($p < 0.05$). The average handle force of right-angle tools was 22.6 N, which was twice as much as that of pistol grip tools (10.71 N). The average peak handle displacement of right-angle tools (16.3 mm) was also twice as much as that of pistol grip tools (7.47 mm).

Soft joints had greater handle force and displacement than the hard joints. Furthermore, joint hardness had a greater effect on handle displacement than on handle force. The average peak handle force for soft joints (20.69 N) was two times greater than for hard joints (8.89 N), but the average peak handle displacement for soft joints (18.65 mm) was five times greater than for hard joints (3.75 mm).

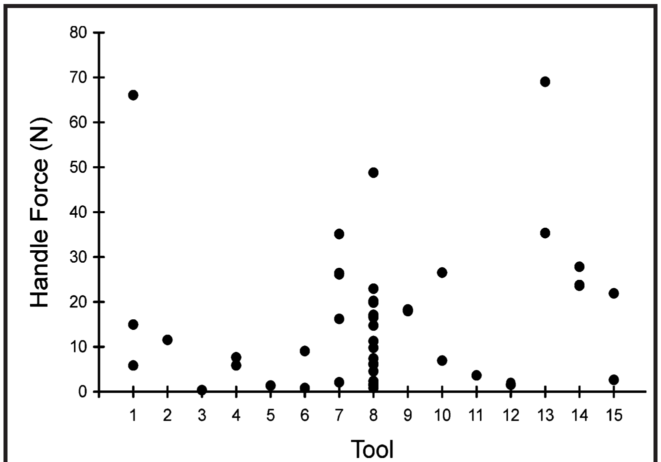

FIGURE 6. Scatter plots of predicted handle force for the 15 tools studied.

TABLE II. Peak Handle Force and Displacement

	Right Angle 26		Pistol Grip 43	
Jobs (n)	Mean	SD	Mean	SD
Force (N)^A	22.60	22.70	10.71	9.57
Displacement (mm)^A	16.30	19.00	7.47	9.42

$^A p < 0.05$.

Right-angle tools used for soft joints had the greatest peak handle force (mean = 45.57 N) and displacement (mean = 38.78 mm), as illustrated in Figures 7 and 8. Joint hardness had a greater effect for right-angle tools than for pistol grip tools on both handle force and handle displacement. The average peak handle force for soft joints (45.57 N) was four times greater than that of hard joints (10.16 N) using right-angle tools, whereas the average peak handle force for soft joints (14.8 4 N) was twice than for hard joints (7.86 N) using pistol grip tools. The average peak handle displacement for right-angle tools used for soft joints (38.76 mm) was eight times greater than for hard joints (4.80 mm), whereas the average peak handle displacement for soft joints (13.91 mm) was five times greater than for hard joints (2.90 mm) using pistol grip tools.

Predicted peak handle force and handle displacement were highly correlated (0.939), but target torque had a much weaker correlation with predicted handle force and handle displacement (0.495 and 0.285, respectively), as calculated from collected manufacturing target torque data.

Injury Experience

Handle forces for workstations where injuries were reported were significantly greater than stations without injuries ($p = 0.045$). The 95% confidence of interval for peak handle force differences between injury and noninjury jobs was from 0.43 N to 33.61 N. The mean peak handle force between injury stations

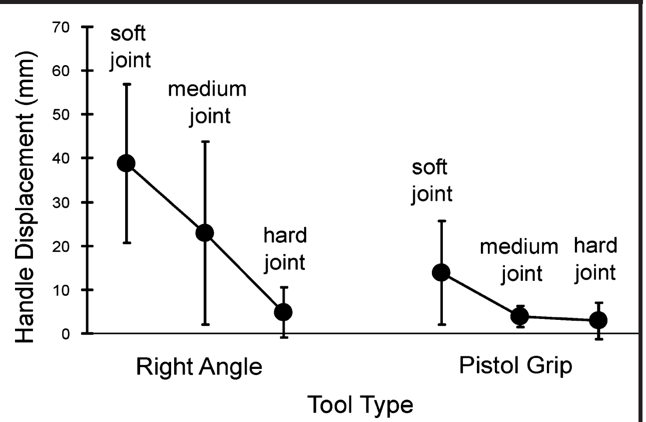

FIGURE 7. Average predicted peak handle displacement plotted against tools and joint hardness.

TABLE III. Peak Handle Force and Displacement for Joint Jobs

	Hard Joint 27		Medium Joint 17		Soft Joint 21	
Jobs (n)	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Force (N)^{A}	8.89	9.63	18.72	9.44	20.69	19.48
Displacement (mm)^{B}	3.75	4.96	12.88	17.06	18.65	16.17

$^{A}p < 0.05$. $^{B}p < 0.01$.

(29.99 N) and noninjury stations (12.97 N) is provided in Table IV.

The difference in peak handle displacement between injury and noninjury work stations did not reach statistical significance ($p = 0.077$) even though the mean displacement of injury stations was 2.5 times greater than for noninjury work stations. Target torque showed no relationship with injury ($p = 0.688$).

Individual work stations were classified into four groups of increasing increments of 10 N handle force. Injury risk was calculated by dividing the number of injuries by the total number of workers within each force grouping. Figure 9 shows that injury risk increased with peak handle force. When peak handle force increased from the 0–10 N level to the 10–19.9 N level, injury risk increased form 1.3% to 10.0%. Injury risk was 14.3% when hand force was greater than 30 N. A directly proportional increase in injury risk was not observed for increasing target torque, as illustrated in Figure 10.

Because there was a significant difference in the mean peak handle force between injury stations and noninjury stations, a logistic regression model was tested to predict injury status from hand force. The model was significant (chi-square = 6.398, $p = 0.01$), and the Hosmer and Lemeshow goodness-of-fit test indicated the model fit the data (chi-square = 3.8180, $p > 0.80$). The odds of an injury case increased nearly 5% for every additional Newton of hand force (OR = 1.0465, 95% CI: 1.0101–1.0842). The predicted probability monotonically increased to 0.60 for a 70 N peak hand force, but it did not resemble a sigmoidal function in the studied force range.

DISCUSSION

The deterministic tool operator mechanical model developed by Lin et. al.[14,15,17] was used for estimating peak handle force and displacement of tools in an automobile manufacturing plant using workplace and tool parameters measured in the field. Target torque, joint hardness, and work orientation all affected handle force, even for the same pneumatic tools. For example, two workstations that had the same pneumatic tool and target torque but different joint hardness and workstation orientations had peak handle forces of 0.87 N and 7.42 N, respectively. Workstations 192 and 237 were similar; both had the same pneumatic tool and joint hardness but different target torque and orientations, and peak handle forces were 40.16 N and 30.64 N, respectively. Tool type by itself therefore was not the only important parameter. Target torque, joint hardness, and orientation must be considered all together. The tool operator model was useful for taking all of these factors into account.

The model did not, however, account for individual operator differences, such as strength, experience, fatigue, and handedness. Similarly, the model did not consider tool installation differences, such as the effects of air hoses; however, these effects were minimized by involving only workstations that did not include balancers and other accessories.

The peak handle displacement for injury stations and noninjury stations were not significantly different in the current study. Wide variation of displacements may explain this result. Kihlberg et al.[13] concluded that mean correlation between rated discomfort and the peak handle displacement

TABLE IV. Peak Gandle Force and Displacement for Injury and Noninjury Jobs

	Handle Force (N)		Handle Displacement (mm)		Target Torque (Nm)	
	Injury	**Noninjury**	**Injury**	**Noninjury**	**Injury**	**Noninjury**
Jobs (n)	9	60	9	60	9	60
Mean	29.99	12.97	22.52	9.04	6.84	6.10
SD	21.23	14.92	19.69	12.65	4.86	6.02
Median	21.89	6.94	14.45	3.80	6.21	3.19
Maximum	66.06	69.05	56.93	51.99	14.69	25.72
Minimum	9.77	0.35	6.55	0.15	2.03	0.00

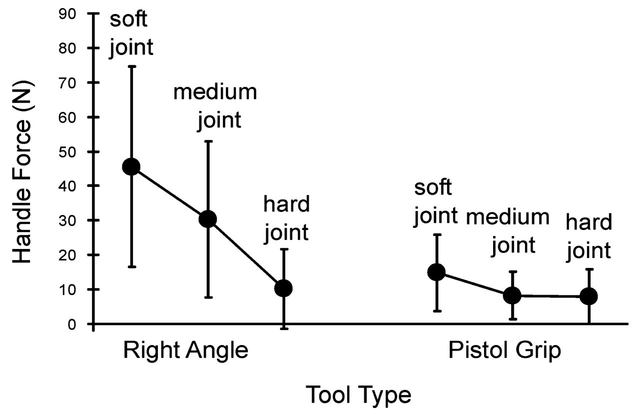

FIGURE 8. Average predicted handle force plotted against tools and joint hardness.

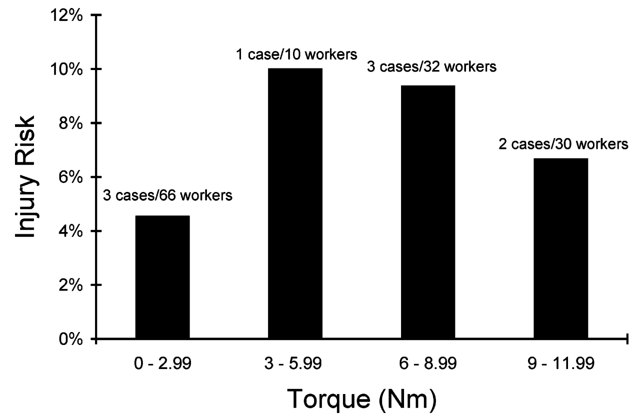

FIGURE 10. Injury risk plotted against target torque levels.

was 0.87. Kihlberg's study was conducted in a laboratory under controlled experimental conditions, whereas the current study was carried out in an actual working environment with greater variances. The results of the two studies suggest that additional data may corroborate these findings.

Fennigkoh[(6)] found a positive relationship between torque magnitude and grip force using a pistol grip tool simulator, but the correlation between target torque and hand (grip) force was not strong in that study. Target torque was not the only variable affecting handle force, as suggested by the current study.

The current study outcome suggested dose-response relationship between injury risk and handle force; however, with limited data that statement cannot be made with confidence. The risk of injury increased when peak handle force increased, as shown in Figure 9. The greatest difference occurred between the first and the second force levels, whereas the smallest difference occurred between the third and the highest force increments. Jobs could not be classified into smaller force ranges of force due to limitation of the sample size. Future studies should include a larger sample and focus on the injury risk and peak handle force range between 10 N to 20 N.

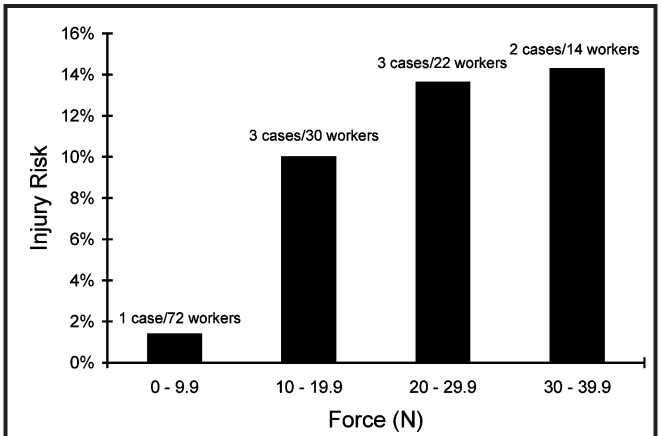

FIGURE 9. Injury risk plotted against handle force levels.

The results of the logistic regression indicated that as peak hand force increased, there was a significant increase in the odds of an injury case. This is an important finding with clear implications for design. However, these results must be interpreted cautiously for a number of reasons. First, the logistic regression function did not resemble the sigmoidal function associated with logistic regression curves in the studied force range, and the highest predicted probability approached only 0.60. This may be due to the limited number of injury cases in the sample and the limited sample size overall. With additional data, the true nature of the relationship between hand force and injury status should become more apparent.

Second, and also related to the limited sample size, is the fact that the logistic regression model contained only the one predictor variable: hand force. There are certainly other variables that have predicted the development of upper extremity musculoskeletal injuries, such as repetition and duration, but sample size precluded their inclusion. Such model misspecification may affect the magnitude of the hand force-injury status relationship. Nonetheless, the results suggest an important predictor of upper extremity musculoskeletal injuries that is need of more in-depth investigation.

Risk of injury was not related to target torque, and an increasing trend in risk was not observed for torque (Figure 10). One explanation is that as torque levels increase, additional factors such as mechanical advantages and tool shape are used for controlling hand force. This means that measuring target torque by itself, as often done in practice, may be insufficient for identifying hazardous jobs. Handle force was the better indicator and was a function of target torque, work orientation, and joint hardness. Therefore, tool, work station, and task requirements all need to be considered for controlling upper extremity MSD.

Handle force was better associated with injury than handle displacement and target torque. The repetition rate in this study was not considered, since the production rate was the same for all workstations and no observable differences existed among tool operations studied. Also, individual operator parameters such as age, working history, body mass index, and physical condition (such as fatigue) were not considered in this study. Due to the number of subjects in the 69 workstations, it was not practical to record individual operator characteristics in the current study. The use of pneumatic tool characteristics alone could explain some of the additional variance in the results.[21] High-handle force tools were observed in some workstations where there were no injuries recorded. Furthermore, it was possible that some of the tools observed may not have been in use when an injury was recorded, and work methods may have also been changed. Future research should involve a greater study population with similar high exposures and account for additional job factors, including repetitive motions and exertions.

CONCLUSION

The deterministic tool operator mechanical model successfully estimated peak handle reaction force and displacement of tools used in an automobile manufacturing plant based on workplace and tool parameters measured in the field. This study found a good association between predicted handle force and upper extremity MSD in assembly jobs involving intensive repetitive tool use. Target torque by itself, which is sometimes used in practice, was insufficient for identifying hazardous jobs.

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