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The effects of power hand tool dynamics and workstation design on handle kinematics and muscle activity

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Abstract

Reaction force and workstation design aspects of right angle nutrunner operation were studied in order to better understand their effects on handle kinematics and muscle activity. Tool reaction force factors included spindle target torque (25 Nm and 50 Nm) and joint hardness (35 ms and 900 ms build-up time). Workstation factors included orientation (horizontal and vertical) and operator distance (10 cm and 35 cm) from the tool. Dependent variables included handle displacement and velocity, work done on the tool–hand system, power involved in doing work, and EMG activity in the forearm and upper arm muscles. Isometric and eccentric strength corresponding to exertions against the tool for velocities of 0 m/s, 0.084 m/s, 0.251 m/s, 0.503 m/s and 0.754 m/s were measured and the relationship between strength and handle kinematics during tool operation was studied. Six inexperienced volunteers (four males and two females) participated. Subjects operated a 58.5 cm long, 3.6 kg right angle nutrunner on a fastener 120 cm off the floor using the right hand while standing. The handle was most stable (defined as minimum average peak velocity and displacement) when torque was 25 Nm, when vertical workstations were closest (10 cm) to the operator, or when horizontal workstations were farthest (35 cm) from the operator. Greater handle stability was observed for the horizontal workstation than for the vertical workstation. The hard joint (35 ms build-up) resulted in 307% greater peak handle velocity and 195% greater average power acting against the operator compared to the soft joint, however total work against the operator was 134% less for the hard joint. Little correlation was observed between static or dynamic strength and handle kinematics. EMG latency was measured from the onset of torque build-up. The average latency was 38 ms for the hard joint and 171 ms for the soft joint.

Relevance to industry

Ergonomic aspects of right angle nutrunner parameters are important for designing workstations and selecting power hand tools in assembly operations that maximize performance and quality, while minimizing physical stress. These parameters include process factors (torque and joint hardness) and workstation design factors (orientation and distance from the operator).

Keywords: Power hand tools; Electromyography; Workstation design; Dynamic strength

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1. Introduction

Threaded fastener power hand tools are widely used in assembly and manufacturing. Ford motor company estimates that the use of powered nutrunners accounts for 75% of all the tools used in an automobile assembly plant (VanBergeijk, 1987). Power hand tool design, selection, installation and use should consider the operator's ability to handle tools so that work performance is maximized, quality is enhanced, and physical stress is avoided. Inappropriate selection of power hand tools can result in excessive exertions, greater perceived effort and discomfort, and less handle stability (Armstrong, 1989; Kihlberg et al., 1995; Oh and Radwin, 1994; Radwin et al., 1989; Ulin et al., 1990, 1992, 1993a,b). An understanding of factors that influence power hand tool operation can be used for establishing safe power hand tool operation conditions and for developing better power hand tool ergonomic guidelines.

Ergonomics research has provided some guidance for power hand tool grip size and shape, tool weight, trigger design, shut-off, and workstation design (Armstrong, 1989; Armstrong et al., 1994; Johnson and Childress, 1988; Kihlberg et al., 1995; Meager, 1987; Oh and Radwin, 1993, 1994; Radwin et al., 1989; Stevenson and Baidya, 1984; Ulin et al., 1992), but generalizations from available studies are limited since power hand tools are used for such a wide variety of applications requiring different torque outputs and are used in different workstation configurations.

This study investigates how power hand tool torque build-up and workstation factors affect an operator's ability to handle a power hand tool. Handle kinematics, including peak handle velocity (PHV) and peak handle displacement (PHD) are considered since these variables are believed to measure how a tool operator reacts against torque build-up. When the operator has sufficient strength to react against the torque reaction force, then the tool should be stable throughout the tightening process. In this case, both PHV and PHD should be near zero. However, when torque generated by the tool overpowers the operator, then the operator's hand will move along with the tool handle (negative work). Therefore, by measuring PHV and PHD, the degree to which the tool reaction torque overpowers the operator can be assessed. If a tool overpowers the operator, safety is a concern since hands might collide with objects or disturb the operator's balance. In addition, forceful exertions can cause fatigue (Misner et al., 1990; Petrofsky et al., 1980), and force is considered a risk factor for musculoskeletal disorders (Armstrong et al., 1986; Silverstein et al., 1987). Quality is also a concern because if the hand cannot provide adequate force to react against the tool, then achieving accurate target torque may not be possible.

The objectives of this study were: (1) To evaluate the effects of tool dynamics (including torque and joint hardness) and workstation layout (including orientation and distance) on the ability to stabilize a tool, (2) to determine the conditions that minimize tool instability, and (3) to compare operator strength and the ability to stabilize the tool. The hypothesis was that a tool operator can maintain better control of a tool as long as force generated by the power hand tool does not exceed the operator's dynamic strength. Since movement often occurs during tool operation, isometric as well as dynamic eccentric strength were measured.

2. Methods

2.1. Apparatus

Isometric and eccentric strength were measured using a Biodex strength measurement system. The system consists of a powerhead, a torque sensor and controller circuitry. A simulated tool handle was fashioned and attached to the shaft of the Biodex powerhead. The handle had the same length and diameter as the power hand tool used in the study. The powerhead shaft was oriented either along the horizontal or vertical plane. The workstation orientation was horizontal or vertical depending on the orientation of the simulated power hand tool spindle. If the longitudinal axis of the Biodex shaft was perpendicular to the ground, then handle movement occurred in the plane parallel to the ground and this workstation was termed horizontal. If the longitudinal axis of the shaft was parallel to the ground, then the workstation was referred to as vertical. The shaft was stationary (zero velocity) for isometric strength tests and rotated counterclockwise at a constant velocity for eccentric strength tests. Analog outputs from the Biodex system included angular position, angular velocity and applied torque. The torque applied to the shaft was divided by the handle length (0.48 m) in order to convert torque into force. A 120 cm handle height was used both for tool operation and for the isometric and eccentric strength tests. All strength measurements were made while the operator was standing.

Three sets of bipolar Ag–AgCl surface electromyogram (EMG) electrodes (in vivo metric) measured muscular activity during the strength tests and tool operation. The electrodes were affixed over the forearm finger flexors, biceps and triceps of the right upper extremity. These muscles were selected based on function and accessibility. The electrodes were placed according to Basmajian (1983). EMGs were measured differentially with respect to a reference ground electrode which was attached near the superficial medial epicondyle. Amplified signals were converted into root-mean-squared (rms) outputs. Biodex outputs and rms EMGs were sampled using a GW Instruments MacADIOS II 12-bit analog-to-digital converter and an Apple Macintosh IIfx microcomputer. The sampling frequency was 250 Hz.

Power tool operation was studied using a computer-controlled electric-powered nutrunner (see Fig. 1). The apparatus consisted of an Atlas Copco Tensor right angle tool motor (ETV-G100-L13N-CTAD), a modified Atlas Copco tool controller (FOCUS 1000), and an Atlas Copco power supply (Tensor Drive Type-G). The power supply controlled the tool spindle speed. A torque transducer and an angle encoder were integrated into the tool spindle head which outputted analog torque and digital angular rotation signals. Specific tool parameters are listed in Table 1.

Table 1
Tool parameters

Parameter	
Tool length	58.5 cm
Spindle to center of grip length	48.0 cm
Handle circumference	11.5 cm
Weight	37 N
Free speed	220 rpm
Torque range	30 to 100 N m

A flexible strain gage electrogoniometer (Penny and Giles) was used to monitor angular handle displacement during tool operation (see Fig. 2). A similar method was used by Kihlberg et al. (1995). The goniometer was calibrated by measuring voltage levels at several known angles and fitting the data to a first order linear regression model. Angular handle velocity was calculated by taking a derivative of angular handle displacement. Angular handle velocity and displacement were multiplied by the tool handle length (0.48 m) in order to calculate linear tangential velocity and displacement respectively. The velocity signal was conditioned using a digital low pass filter that had a cut-off frequency of 55 Hz. The digital filter was a 251 coefficient finite impulse response (FIR) filter designed using the Parks-McClellan optimal FIR filter algorithm in MATLAB™. This design was selected for its linear phase shift and stability. Handle movement direction was defined as positive when the handle moved in the direction of tool reaction torque (see Fig. 2).

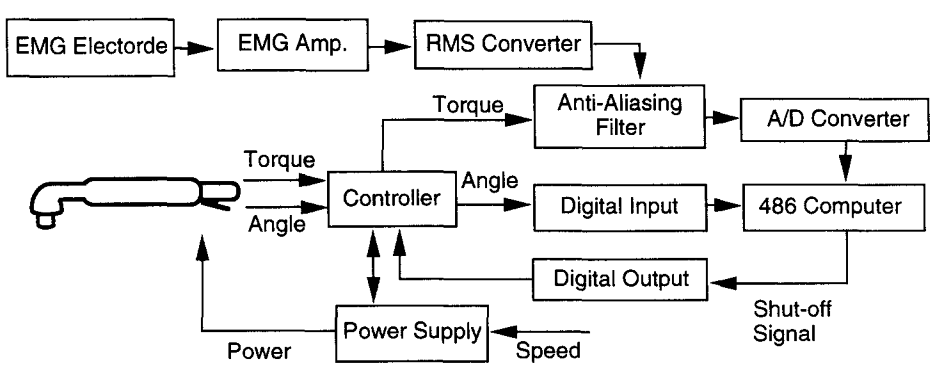

Fig. 1. Experimental set-up.

An Indresco joint simulator with a 1.9 cm (0.75 inch) hex screw head was mounted on a height adjustable platform. The torque build-up time could be varied by changing combinations of the tool spindle speed and the number of Bellevile spring washers in the joint simulator. A spring tool balancer was used for counterbalancing the weight of the electric power cords but did not interfere with tool movement along the plane of spindle rotation.

An i486 microcomputer and a MetraByte 12-bit data acquisition board (Das-1602) sampled the analog and digital data from the power hand tool and EMG amplifier. Torque, spindle angle, handle movement, and rms EMG signals were sampled at 500 Hz. The computer controlled the target torque by sending a shut-off signal when the spindle torque reached a preset shut-off torque level. Fourth-order Butterworth (Exar XR-1002CP) analog anti-aliasing filters with a cut-off frequency of 220 Hz were used for all analog signals. Representative outputs during tool operation are plotted against time in Fig. 3.

The nutrunner shut-off torque was calibrated by simultaneously measuring voltage output from the torque transducer and corresponding torque ranging from 20 Nm to 90 Nm, while the tool was supported against a rigid bar. A first order linear regression model was used to determine the relationship between the output voltage and spindle torque. To compensate for shut-off torque overshoot, a Pascal program was developed to empirically search for the best shut-off torque level that produced the desired target torque. The program increased or decreased the shut-off torque level, depending on the difference between peak torque and target torque. When torque fell between 90% and 110% of the target torque, then it was considered acceptable. The calibration program terminated when the shut-off torque level produced an acceptable target torque five times in succession. The shut-off torque produced the desired target torque only when there was a rigid support, and therefore needed to be re-adjusted when the tool was operated by a subject without any rigid support. The same computer program was used to empirically search for the best shut-off torque level for each subject.

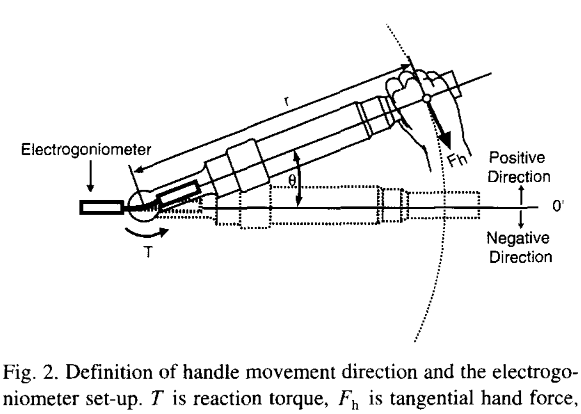

Fig. 2. Definition of handle movement direction and the electrogoniometer set-up. T is reaction torque, F_h is tangential hand force, and θ is angular handle displacement.

2.2. Experimental procedures

The experiment consisted of three sessions. Subjects learned how to operate the power hand tool and performed the strength tests in the first session. Different workstation orientations (horizontal and vertical) were presented in the next two sessions. The presentation of workstation orientation was counterbalanced between subjects. Isometric and eccentric strength were measured while subjects stood and held the handle in the right hand using the same posture as in power tool operation. The strength measurements were made for linear tangential velocities of 0 m/s (isometric), 0.084 m/s, 0.251 m/s, 0.503 m/s and 0.754 m/s which correspond to angular velocities of 0 deg/s, 10 deg/s, 30 deg/s, 60 deg/s and 90 deg/s, respectively. The velocity conditions were presented randomly. Three replications were made for each condition, and data from the last two trials were used for statistical analysis. Auditory signals from the computer indicated the start and the end of each trial. Isometric strength was sampled for three second exertions followed by a two minutes rest period after each trial. Isometric strength was calculated as the average force during one second of a steady exertion after isometric strength reached a plateau.

The Biodex system required approximately 0.5 s to achieve target velocity. This time delay was compensated for eccentric strength measurements by pre-positioning the shaft. The starting handle position for the eccentric strength test was preset $-5°$ for 0.084 m/s, $-10°$ for 0.251 m/s, $-15°$ for 0.503 m/s, and $-20°$ for 0.754 m/s. Because of this limitation, the actual average velocity was between 95% and 97% of the target velocity. Three replications were made for each eccentric strength test condition. There was a brief rest period between trials and a two minutes rest period after three replications. The average force was measured when the handle was 0° to 20° and the handle velocity exceeded 90% of the target velocity.

Subjects operated the right angle nutrunner using the right hand while standing. A tone readied subjects to hold the tool in position. A second tone indicated when to press the trigger. Subjects were instructed not to release the tool until a third tone sounded indicating the end of the trial. Seven replicates were made for each experimental condition. The last three were used for data analysis in order to minimize learning effects. A one minute rest period was given after each experimental condition.

Four male and two female volunteers aged between 18 to 36 years participated (mean = 23 years, sd = 7 years). Average stature was 173.3 cm (sd = 9.5 cm) and average body weight was 69.3 kg (sd = 6.9 kg). All subjects reported that they were

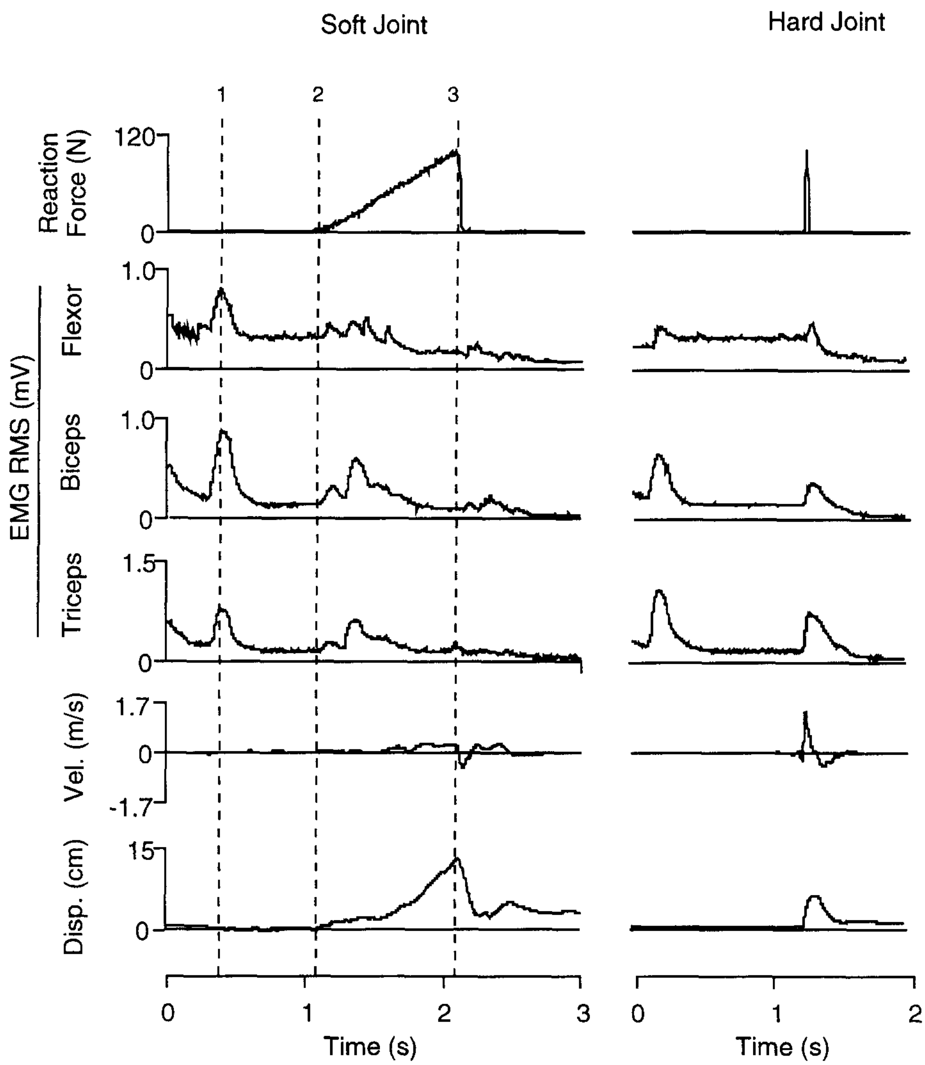

Fig. 3. Representative torque reaction force, EMG, and handle kinematics data. Event 1 indicates squeezing the tool trigger. Event 2 is the onset of torque build-up and event 3 represents tool shut-off.

Table 2
Independent variables for tool operation

Factors		Effects	Levels
Orientation	(O)	fixed	horizontal, vertical
Distance	(D)	fixed	10 and 35 cm [a]
Torque reaction force	(T)	fixed	52.1 and 104.2 N
Build-up	(B)	fixed	35 ms and 900 ms
Subject	(S)	random	6 subjects

[a] Average distance between toes and the handle center.

free from any history of hand conditions that might influence power tool operation. Subjects were paid on an hourly basis for their participation.

2.3. Experimental design and analysis

The experiment was a five-factor, full-factorial design with subject as a random variable (see Table 2). Static torque reaction force of 52.1 N and 104.2 N corresponded to 25 Nm and 50 Nm target torque for the tool used in this study. The order of workstation orientation presentation was counterbalanced between subjects. The combinations of all other conditions were presented randomly. Dependent variables and their abbreviations are listed in Table 3. Relative handle kinematics during tool operation was quantified using peak handle velocity (PHV) and peak handle displacement (PHD) in the positive direction.

Work done on the tool–hand system and power involved in doing work are measured during torque build-up. Work is the product of force and corresponding displacement such that:

$$W = F_h \cdot r \cdot \theta = T \cdot \theta$$

where W is work, F_h is tangential hand force, r is the radius between the spindle and the center of the handle, T is tool reaction torque, and θ is angular handle displacement (see Fig. 2). Work is positive when concentric contraction occurs (work done against the tool) and negative when eccentric contraction occurs (work done against the operator). Power is the time rate of work described by the equation:

$$P = \frac{dW}{dt} = F_h \cdot r \cdot \frac{d\theta}{dt} = T \cdot \frac{d\theta}{dt}$$

where P is power and $d\theta/dt$ is angular handle velocity. Power is positive when muscle contraction and handle velocity occur in the same direction towards the operator. The more stable the tool–hand system is, the less are displacement and velocity resulting in less work and power.

Since superficial EMG is affected by posture, direct comparison of EMG across all orientation and distance conditions is not possible. Therefore, EMG data analysis is limited to four distinct groups (2 orientations × 2 distances) corresponding to four different postures. Torque reaction force and build-up time effects are analyzed within these groups separately. Integrated RMS EMG, peak RMS EMG, average RMS EMG and RMS EMG latency are measured for monitoring muscle activity (see Table 3).

A burst of muscle activity was often observed after the onset of torque build-up (see Fig. 4) as described in Radwin et al. (1989). The start of this event was determined when RMS EMG exceeded a threshold level which was arbitrarily taken as the mean plus five standard deviations of RMS EMG activity occurring between 150 ms and 350 ms before the onset of torque build-up. EMG latency was the time difference from the onset of torque build-up to the onset of the muscle activity burst.

Velocity was used as a measure of relative stability. Positive velocity indicated that the tool had

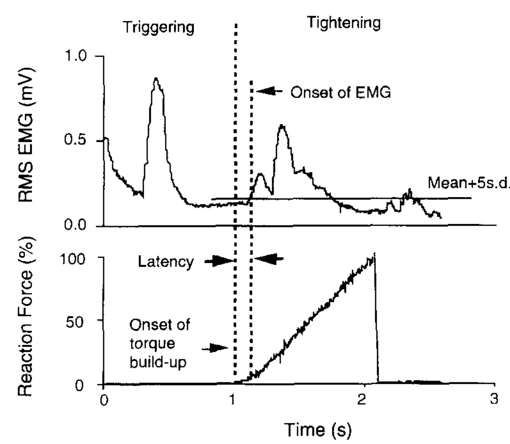

Fig. 4. Relationship between the EMG onset and torque build-up. This event is indicated when the EMG signal crosses the mean plus five standard deviations of the EMG during the run-down period. EMG latency is the time difference between the onset of EMG and torque build-up. The burst of EMG occurring before the onset of torque build-up indicates when the operator squeezes the trigger.

Table 3
Descriptions of dependent variables and their abbreviations

Dependent var.	Abbr.	Unit	Description
Peak handle velocity	PHV	m/s	Maximum positive handle velocity during torque build-up
Peak handle displacement	PHD	cm	Maximum positive handle displacement during torque build-up
Work	work	N m	Work done on the tool–hand system during torque build-up
Power	power	N m/s	Power involved in doing work during torque build-up
Integrated EMG	IEMG	mV s	Area under the rms EMG time series during torque build-up
Peak EMG	$PEMG_p$	mV	Peak EMG occurred between 100 ms and 0 ms before the onset of torque build-up
	$PEMG_b$	mV	Peak EMG occurred during torque build-up
	$PEMG_a$	mV	Peak EMG occurred between 0 ms to 350 ms after tool shut-off
Average EMG	$AEMG_p$	mV	Average EMG occurred between 100 ms and 0 ms before the onset of torque build-up
	$AEMG_b$	mV	Average EMG occurred during torque build-up
	$AEMG_a$	mV	Average EMG occurred between 0 ms to 350 ms after tool shut-off
EMG latency	EMG latency	s	Time difference from the onset of torque build-up to the onset of the muscle activity burst
Time at velocity zero-crossing	t_{cross1}	s	Time difference from the onset of torque build-up to the first velocity zero crossing during torque build-up
	t_{cross2}	s	Time difference from the onset of torque build-up to the last velocity zero-crossing occurred before tool shut-off
Torque reaction	F_{cross1}	N	Torque reaction force at t_{cross1}
Force at velocity zero-crossing	F_{cross2}	N	Torque reaction force at t_{cross2}

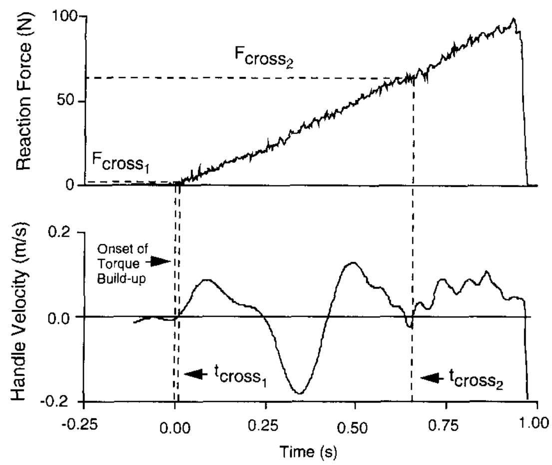

Fig. 5. Velocity zero crossing points and corresponding torque reaction force levels (F_{cross1} and F_{cross2}). Times t_{cross1} and t_{cross2} are the times elapsed from the onset of torque build-up and the first and last velocity zero-crossing during torque build-up.

overpowered the operator (negative work), and zero or negative velocity indicated that the operator exertion was equal to or exceeded the power hand tool reaction force (positive work). The velocity zero-crossing was the transition point when handle velocity changed direction from negative to positive (see Fig. 5). This point indicated that the torque reaction force produced by the tool overpowered the operator from reacting against the tool. The corresponding torque reaction force was defined as F_{cross}. If velocity zero crossing occurred more than once as operators regained control (see Fig. 5), the first crossing was designated as F_{cross1} and the last crossing which occurred before the tool shut-off was called F_{cross2}. The time corresponding to F_{cross} was referred to as t_{cross}.

Gaining the control of the tool after shut-off was monitored by comparing handle velocity just before and after tool shut-off. If handle velocity increased after shut-off, the tool and hand system was considered unstable. The handle velocity was averaged 20 ms to 0 ms before shut-off and 40 ms to 60 ms after shut-off. The frequency that handle instability increased after shut-off was calculated to determine the probability that the operator regains control of the tool after tool shut-off.

Repeated measures analysis of variance (ANOVA) was used to determine statistically significant effects on strength, handle stability, muscular activity, t_{cross} and F_{cross}. Correlation between strength, handle stability, and F_{cross} were calculated. Post-hoc Tukey contrast tests were performed for selected significant effects. All statistical analysis was performed using BMDP statistical software.

3. Results

3.1. Strength

Strength was significantly ($F(4, 20) = 40.7$, $p < 0.01$) affected by handle velocity (see Fig. 6). A post-hoc Tukey pairwise contrast test found no significant difference ($p > 0.05$) between isometric strength and eccentric strength when velocity was 0.084 m/s. Strength for 0 m/s and 0.084 m/s velocity were significantly less than strength for 0.251 m/s or greater handle velocity ($p < 0.05$).

Workstation orientation had an significant effect on strength ($F(1, 5) = 12.8$, $p < 0.05$). Average strength was 35% greater for the vertical (mean = 142.1 N, sd = 43.2 N) than for the horizontal workstation (mean = 105.2 N, sd = 37.0 N). Isometric and eccentric strength were strongly correlated ($0.71 < r < 0.88$). The greatest correlation was between isometric strength and eccentric strength for a 0.084 m/s velocity ($r = 0.88$). The least correlation was between isometric strength and eccentric strength for a 0.754 m/s velocity ($r = 0.71$).

3.2. Handle kinematics

Tool dynamics and workstation orientation had numerous significant effects on handle kinematics

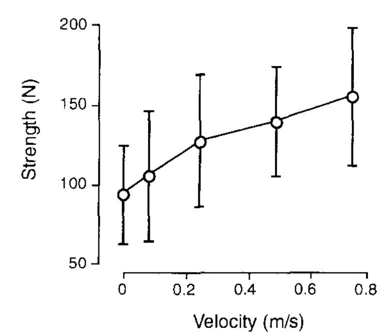

Fig. 6. Average isometric and eccentric strength plotted against handle velocity (error bars represent one standard deviation).

Table 4
Significant effects for handle stability variables and F_{cross}

Effect	Dependent Var.	$F(1, 5)$	p
T	PHV	192.2	< 0.01
	PHD	48.3	< 0.01
	work	99.1	< 0.01
	power	268.6	< 0.01
	F_{cross2}	101.2	< 0.01
B	PHV	83.9	< 0.01
	work	15.3	< 0.05
	power	97.2	< 0.01
	F_{cross2}	13.6	< 0.05
$T \times B$	PHV	22.4	< 0.01
	PHD	9.0	< 0.05
	work	21.9	< 0.01
	power	114.1	< 0.01
	F_{cross1}	17.4	< 0.01
	F_{cross2}	9.8	< 0.05
O	PHV	7.2	< 0.05
	PHD	6.5	< 0.05
	Work	8.6	< 0.05
	F_{cross2}	9.3	< 0.05
$O \times D$	PHV	10.6	< 0.05
	PHD	11.2	< 0.05
$B \times O$	F_{cross2}	9.3	< 0.05
$B \times D$	F_{cross1}	10.8	< 0.05

(see Tables 4 and 5). Greater torque reaction force resulted in greater PHV and PHD. As torque reaction force increased from 52.1 N to 104.2 N for corresponding target torque conditions, PHV increased 61% and PHD increased 103% (see Table 5). Increased build-up time resulted in a significant PHV decrement. Overall, PHV decreased 307% as build-up time increased from 35 ms to 900 ms (see Table 5).

The interaction between $T \times B$ was significant for handle stability effects (see Fig. 7). As handle reaction force increased from 52.1 N to 104.2 N, average PHV increased by 53% for the long build-up time (soft joint) and 50% for the short build-up time (hard joint), and average PHD increased by 80% for the short build-up time and 113% for the long build-up time. A post hoc Tukey pairwise contrast test showed that PHV for each combination of $T \times B$ was significantly different ($p < 0.01$). PHV was the greatest for 104.2 N torque reaction force and 35 ms build-up, and the least for 52.1 N torque reaction force and 900 ms build-up. The greatest PHD occurred for 104.2 N torque reaction force and 900 ms build-up time. PHD for 52.1 N target torque reaction force was not significantly different ($p > 0.1$) regardless of build-up time.

Orientation had a significant main effect for both PHV and PHD. PHV was 27% greater and PHD was 30% greater for the vertical workstation than for the horizontal workstation (see Table 5). The $O \times D$ interaction (see Fig. 8) had a significant effect on PHV and PHD. As distance increased from 10 cm to 35 cm, PHV and PHD increased by 9% and 26%, respectively, for the vertical workstation, while PHV and PHD decreased by 15% and 30%, respectively, for the horizontal workstation.

As torque reaction force increased from 52.1 N to 104.2 N, the magnitude of total work against the operator increased by 362%, and the magnitude of average power acting against the operator increased by 262% (see Table 5). Torque build-up time also

Table 5
Descriptive statistics for T, B and O main effects (one standard deviation in the parenthesis)

Dependent Var.	Torque reaction force		Build-up time		Orientation	
	52.1 N	104.2 N	35 ms	900 ms	horizontal	vertical
PHV (m/s)	0.47	0.75	0.98	0.24	0.54	0.68
	(0.35)	(0.50)	(0.34)	(0.12)	(0.41)	(0.48)
PHD (cm)	2.69	5.46	ns	ns	3.62	4.68
	(1.31)	(2.84)			(2.08)	(2.93)
Work (N m)	−0.26	−1.21	−0.45	−1.03	−0.58	−0.90
	(0.19)	(0.90)	(0.30)	(1.02)	(0.51)	(0.84)
Power (N m/s)	−1.67	−6.04	−6.63	−1.08	ns	ns
	(1.60)	(4.87)	(4.40)	(1.04)		
F_{cross2} (N)	40.5	67.3	46.3	61.4	49.5	58.3
	(9.9)	(23.2)	(18.8)	(22.9)	(23.5)	(20.2)

ns: not significant at $p = 0.05$.

had a significant effect on both work and power. As build-up time increased from 35 ms to 900 ms, the magnitude of work against the operator increased significantly by 132% and the magnitude of average power acting against the operator decreased significantly by 515% (see Table 5).

The $T \times B$ interaction (see Fig. 7) was significant for work and power. A post-hoc Tukey contrast test showed that the magnitude of work against the operator (negative work) was greatest when torque reaction force was 104.2 N for a 900 ms build-up time, followed by 104.2 N for a 35 ms build-up time ($p < 0.01$). The negative work for a 52.1 N torque reaction force was not significantly different regardless of build-up time ($p > 0.05$). The least average power acting against the operator occurred for 52.1 N torque reaction force and a 900 ms build-up time, and was greatest for a 104.2 N torque reaction force and a 35 ms build-up time (see Fig. 7). The effect of workstation orientation was significant for work against the operator. Negative work was 55% more for the vertical workstation than for the horizontal workstation (see Table 5).

The probability of gaining control of the tool after shut-off was significantly influenced by torque build-up time. The probability of increased average hand velocity after shut-off decreased from 72% (sd = 45%) to 25% (sd = 43%) when build-up time increased from 35 ms to 900 ms ($F(1, 5) = 17.4$, $p < 0.01$).

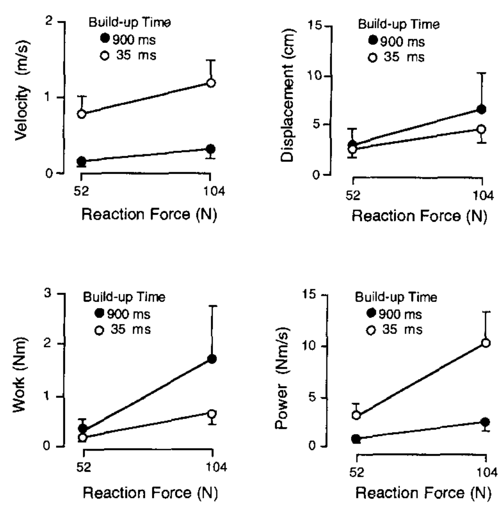

Fig. 7. Interaction between torque reaction force × build-up time. Peak handle velocity and average power were significantly greatest for the 104.2 N torque reaction force and 35 ms build-up time. Peak handle displacement and total work were greatest for 104.2 N torque reaction force and 900 ms build-up time.

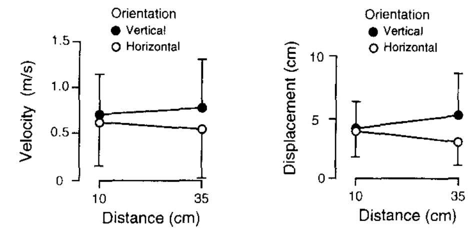

Fig. 8. Interaction between orientation × distance for peak handle velocity and peak handle displacement (error bars represent one standard deviation). As distance increased from 10 cm to 35 cm, PHV and PHD decreased for a horizontal workstation while PHV and PHD increased for a vertical workstation.

3.3. Velocity zero crossing

The interaction between $T \times B$ and $B \times D$ had significant effects on the torque reaction force corresponding to the first velocity zero crossing point (F_{cross1}), however, the magnitude of these effects were small (0.15 Nm maximum difference). Average F_{cross1} was 2.2 N (sd = 1.2 N).

Torque reaction force, build-up time and the $T \times B$ interaction had significant effects on F_{cross2} (see Table 4). F_{cross2} increased by 66% when torque reaction force increased from 52.1 N to 104.2 N and it was 33% greater for long build-up times than for short build-up times (see Table 5). The $T \times B$ interaction effect for F_{cross2} showed that as torque reaction force increased from 52.1 N to 104.2 N, F_{cross2} increased 47% and 82% for short and for long build-up times respectively (see Fig. 9). Orientation had a significant effect for F_{cross2}. F_{cross2} was 18% greater for the vertical workstation than for the horizontal workstation. The significant $B \times O$ interaction showed that increasing build-up time from 35 ms to 900 ms resulted in a 10% F_{cross2} increase for the vertical workstation, whereas it resulted in a 66% F_{cross2} increase for the horizontal workstation (see Fig. 9).

3.4. Muscle activity

For all conditions of orientation and distance, average IEMG for all three muscle groups were

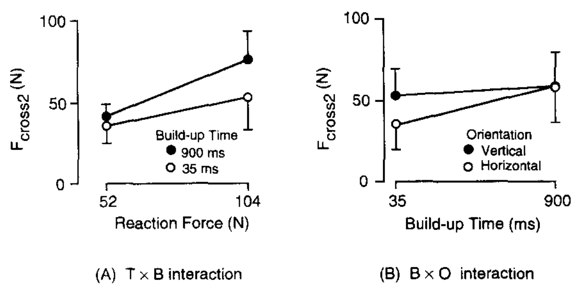

Fig. 9. Torque reaction force corresponding to the last velocity zero-crossing point was significantly influenced by the interaction between $T \times B$ and between $B \times O$ (error bars represent one standard deviation).

significantly greater for the long (soft joint) build-up time than for the short (hard joint) build-up time. The IEMG difference between short and long build-up time ranged from 2.682% to 6.831% (see Table 6).

Overall, the onset of distinct EMG bursts occurred (see Fig. 4) 74% of the time for the finger flexors, 80% for the biceps, and 75% for the triceps for all 663 trials. Some main effects (O, D, T, B) and two-way interactions ($O \times T$, $O \times B$, $T \times B$) had significant effects on EMG latency. However, these effects were small (accounting for less than 5% of the total variance) except for the build-up time effect. Overall, average EMG latencies increased significantly ($F(1, 5) = 8.8$ to 16.3, $p < 0.05$) as build-up time increased (see Fig. 10).

There was no consistent trend for PEMG and AEMG across any conditions of orientation and distance for all three muscles. Although the effects of torque and build-up time were significant for $PEMG_p$ and $AEMG_p$, these effects were small (accounting for less than 0.5% of the total variance). Build-up time had a significant effect on $PEMG_b$ for some combinations of orientation and distance (see Table 6). $PEMG_b$ from the biceps increased by 70% and $PEMG_b$ from the triceps increased by 54% as build-up time increased from 35 ms to 900 ms for a horizontal workstation with 35 cm distance. $PEMG_b$ for all muscles were significantly influenced by the build-up time for a vertical workstation and 15 cm distance. As build-up time increased from 35 ms to 900 ms, $PEMG_b$ increased by 72% for the finger flexors, 88% for the biceps, and 103% for the triceps.

Table 6
Build-up time effect on EMG variables

O	D (cm)	Dependent variable [a]	$F(1, 5)$	p	Increase [b] (%)
H	10	$IEMG_1$ (mV s)	13.7	< 0.05	3703
		$IEMG_2$ (mV s)	16.5	< 0.01	3452
		$IEMG_3$ (mV s)	25.1	< 0.01	2682
H	35	$PEMG_{b2}$ (mV)	7.1	< 0.05	70
		$PEMG_{b3}$ (mV)	8.3	< 0.05	53
		$IEMG_1$ (mV s)	19.4	< 0.01	4202
		$IEMG_2$ (mV s)	40.3	< 0.01	3146
		$IEMG_3$ (mV s)	35.7	< 0.01	3266
V	10	$PEMG_{b1}$ (mV)	13.6	< 0.05	72
		$PEMG_{b2}$ (mV)	9.1	< 0.05	89
		$PEMG_{b3}$ (mV)	10.7	< 0.05	103
		$IEMG_1$ (mV s)	46.7	< 0.01	3373
		$IEMG_2$ (mV s)	48.4	< 0.01	3950
		$IEMG_3$ (mV s)	28.7	< 0.01	4641
V	35	$AEMG_{b2}$ (mV)	11.8	< 0.05	39
		$AEMG_{b3}$ (mV)	13.8	< 0.05	90
		$IEMG_1$ (mV s)	43.0	< 0.01	4039
		$IEMG_2$ (mV s)	58.4	< 0.01	4842
		$IEMG_3$ (mV s)	31.6	< 0.01	6831

[a] Subscription 1,2 and 3 represent finger flexors, biceps and triceps, respectively.
[b] As build-up time increased from 35 ms to 900 ms.

$AEMG_b$ for the triceps and biceps were significantly affected by build-up time only when the workstation was vertically oriented and distance was 35 cm (see Table 6). Under this condition, $AEMG_b$ from the biceps and $AEMG_b$ from the triceps increased by 90% as build-up time increased from 35 ms to 900 ms. Torque reaction force and the $T \times B$ interaction were significant ($p < 0.05$) in some cases, however these effects were small. The effects of T, B and $T \times B$ were also significant for $AEMG_a$ for the biceps, however, the effects were small (account-

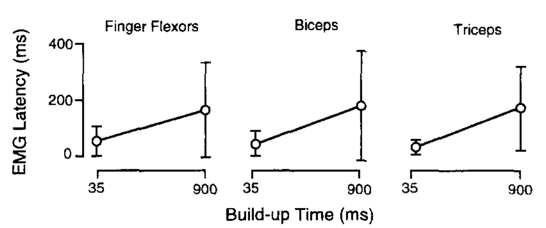

Fig. 10. Effect of build-up time on EMG latency (error bars represent one standard deviation).

ing for less than 1% of the total variance). Tool dynamics had no significant effect ($p > 0.05$) on $PEMG_a$.

3.5. Correlation

Little correlation was observed between strength and handle kinematics ($0.01 < r < 0.33$). None of the isometric and eccentric strength measurements were good predictors of the velocity zero crossing point where the handle started to become unstable. The correlation between strength and F_{cross} was between 0.1 and 0.23. Peak handle velocity and displacement were not strongly correlated ($0.03 < r < 0.36$).

4. Discussion

The objective of this study was to determine the conditions that minimize tool instability by evaluating the effects of tool dynamics and workstation layout on the ability to stabilize the tool. The results of this study suggested that right angle power nutrunner operation was most stable when torque reaction force was least, vertical workstations were located closer (10 cm) to the operator, or horizontal workstations were located farther (35 cm) from the operator. The most stable condition was 52.1 N torque reaction force, corresponding to 25 Nm torque, and 900 ms torque build-up time.

Previous studies have shown that reaction torque was related to handle stability, perceived discomfort and exertion, and muscle activity (Armstrong et al., 1994; Freivalds and Eklund, 1991; Johnson and Childress, 1988; Oh and Radwin, 1994; Radwin et al., 1989). Radwin et al. (1989) studied muscle responses using hand and wrist flexor and extensor EMGs while subjects operated four pneumatic right angle nutrunners with different target torque levels (from 30 Nm to 100 Nm). They found that as torque increased from 30 Nm to 100 Nm, flexor EMG activity, scaled for grip force, increased by 21%. Similar findings were reported using a pneumatic in-line screwdriver (Johnson and Childress, 1988) and an in-line power hand tool simulator (Armstrong et al., 1994). The current study suggests that handle stability was significantly influenced by torque. As peak torque reaction force increased from 52.1 N to 104.2 N, PHV increased 61% and PHD increased 103%.

Radwin et al. (1989) observed that although average grip force was less for long build-up times (2 s) than for short build-up times (0.5 s), the integrated grip force was greater for long build-up times than for short build-up times. Based on muscle response, Armstrong et al. (1994) suggested using slow torque build-up (> 250 ms) in order to minimize peak EMGs. Freivalds and Eklund (1991) studied power nutrunners with peak torque ranging from 1.05 Nm to 5.0 Nm and found that subjective ratings of perceived exertion correlated directly with the torque impulse and peak torque level. The perceived exertion was greater for greater torque impulse, and for greater peak torque. A widely accepted theory about build-up time is that the faster spindle speeds and greater torque rates are less stressful (Lindqvist et al., 1986; Lindqvist, 1993). One rationale behind this is that a faster tool results in less torque impulse which should require less exertions by the operator. Another rationale is when torque buildup is fast then the inertial effects of the tool become large and absorbs more torque reaction than for a slower buildup. The current study showed that integrated muscular exertion and the magnitude of work against the operator were less for the short build-up time (35 ms), which is consistent with that theory. However, the short build-up time also resulted in greater peak handle velocity and average power acting against the operator which does not lend its support. The significant build-up time effect on handle stability reduced PHV by 307% as build-up time increased from 35 ms to 900 ms. As build-up time increased from 35 ms to 900 ms PHD increased for 104.2 N torque reaction force (see Fig. 7). Because of this conflicting build-up time effect definitive conclusions are not possible about which condition is the most favorable.

It was hypothesized that when build-up time was short, the restoring forces were mainly due to the inertial effects of tool mass and hand-and-arm system mass. Whereas, when build-up time was long, the restoring forces were mainly from the muscles. The EMG results showed that average latencies for the finger flexors, biceps and triceps were 44 ms, 39 ms and 30 ms, respectively, for the 35 ms build-up time (see Fig. 10). This suggested that for a hard joint, there was not enough time to react against torque disturbances in the handle until after maximum torque output was achieved. Since this response is likely a reflex, it is involuntary and limited by the neuromuscular system's ability to respond to rapid stimuli. The muscle reflexes which occurred close to shut-off might contribute to less handle displacement for the hard joint. The first velocity crossing occurred at around 2 N torque reaction force regardless of tool parameters and workstation layout. This indicates that there was not enough restoring force to react against the tool at the start of tool operation.

The interaction between $O \times D$ for handle stability indicates that the tool is more stable when the body is located closer to the threaded fastener (10 cm) for the vertical orientation, and when the body is farther from the fastener (35 cm) for the horizontal orientation. One rationale for this interaction effect is that when the operator stands close to the vertical workstation, it is possible to lean over the tool so that the operator could use more body weight for reacting against the torque. In order to use body weight for the horizontal orientation, the operator needs to lean backward while holding the tool. In this case, if the elbow joint is flexed, the torque created by the body weight might act on the elbow joint which would extend the elbow joint while reacting against torque build-up. Therefore, the operator might not be able to fully utilize body weight while maintaining a flexed elbow joint. In the case of an extended elbow joint, all the torque created by the body weight could be used to react against the tool.

Although some interesting $O \times D$ effects were observed for handle kinematics, generalization of these results are limited because only two distances were tested. Ulin et al. (Ulin et al., 1990, 1992, 1993a,b) did extensive studies using psychophysical methods for evaluating the effect of workstation layout on the operator in terms of perceived exertion. They found that when working on a horizontal work surface, perceived exertion level increased as horizontal distance increased farther than 38 cm among four horizontal locations tested (ranging from 13 cm to 88 cm). A survey conducted by Armstrong (1989) showed similar results. Based on interviews of 23 automobile assembly plant operators on their currently used power hand tools and workstations, they found that workers rated the horizontal distance within 38 cm as the most comfortable location. The current study involved much shorter distances (10 cm and 35 cm) than the above mentioned psychophysical studies which reported no difference in perceived exertion for this range. The difference between the current study and the previous study might come from the fact that the torque range in the current study was far greater than the torque level in the studies of Ulin et al. (Ulin et al., 1990, 1992, 1993a,b). It is also possible that these kinematic differences are imperceivable by the operator.

One of the objectives of this study was to compare operator strength and the ability to stabilize the tool. The results of the current study showed that both the isometric and eccentric strength had low correlation with handle kinematics. This low correlation might result from the discrepancy between tool operation and isokinetic strength tests using the Biodex system. A major difference was that strength was measured for a constant velocity while handle velocity during tool operation was more variable (see Fig. 5). The inertial effect would be zero during isokinetic strength tests due to zero acceleration, while this was not the case for tool operation. Also, subjects might have used different muscle recruitment strategies for strength tests and tool operation. During tool operation, the subjects were instructed to keep the tool as stable as possible. If torque reaction force was less than a subject's dynamic strength, the subject might choose to exert less than maximum capacity (100% MVC) in order to match the reaction torque. Subjects exerted 100% MVC for the strength tests. In addition, posture differences might have had some influence on the strength measurements. When strength was measured using the Biodex system, the measurement was made between 5° to 20° greater than the range of interest in order to compensate for a time delay to reach a target velocity. Therefore, the starting posture was different than for tool operation.

Regardless of any tool, joint or workstation parameters, the most favorable condition would be the one in which torque reaction force is as small as possible so that the tool can be under the best control. Controllability of the tool is important because it is related to task performance and safety. When a tool operator has less control, the tool rotates around its spindle and the hand and body will move with the tool possibly resulting in contact with an object. Radwin et al. (1989) suggested several methods to limit torque reaction force. These include using torque reaction bars, installing torque absorbing suspension balancers, and installing tool supports. Also hand reaction forces during tool operation may be reduced when a power hand tool is used that has a greater mechanical advantage.

Negative work occurs when the tool torque reaction force overpowers the operator's static strength, and eccentric muscle contractions occur. Eccentric motion is sometimes considered more efficient since strength for eccentric contractions are generally greater than strength for other types of contractions (Griffin, 1987; Walmsley et al., 1986). In addition, the physiological cost as well as perceived exertion are less for eccentric contractions compared to other types of muscle contractions at similar intensities (Henriksson et al., 1972; Pandolf, 1977; Rasch, 1974; Stauber, 1989). Eccentric contractions, however, might have negative consequences.

The onset of muscle soreness is one of the reported noticeable effects of eccentric contraction (Komi and Buskirk, 1972; Talag, 1973). In addition, eccentric contraction is related to greater strength decrements after exertion compared to isometric and concentric exertion. Lieber et al. (1991) stretched the rabbit tibialis anterior muscles by 125% of resting muscle length for 30 min and found the strength dropped by 69% for eccentric contraction, 31% for passive stretch, and 13% for isometric contraction. The authors argued that the time course of tension decline suggested that eccentric-induced injury occurred during the first minutes of treatment. A similar result was found with mouse extensor digitorum longus (McCully and Faulkner, 1985), human knee extensors (Friden et al., 1983) and human forearm flexors (Komi and Rusko, 1974). Other often cited symptoms include fiber degeneration, including Z-band streaming, broadening and total disruption (Friden et al., 1983; Friden and Lieber, 1992; Lieber et al., 1991; Stauber, 1989). Uncontrolled eccentric contractions may be associated with injury to the muscle tissue (Minor, 1995). A theoretical model for the early stages of contraction-induced microinjury in skeletal muscles is proposed by Armstrong et al. (1995). This model suggests that some of the initial causes of contraction induced injury were high eccentric contraction level and high eccentric velocity which may be related to power hand tool operation. Although results from these eccentric contraction studies might not be directly applicable to the current study, extensive use of power hand tools under eccentric contractions may induce these negative effects on the operator. Therefore, it is necessary to better understand the effects of eccentric contraction on the operator during tool operation.

5. Conclusions

(1) Right angle power hand tool operation on a horizontal workstation was more stable than on a vertical workstation. The total work against the operator was 55% greater, peak handle velocity was 27% greater, and peak handle displacement was 35% greater for the vertical workstation than for the horizontal workstation.

(2) Less torque reaction force resulted in more stable power hand tool operation. Peak handle velocity was 362%, peak handle displacement was 262%, work was 132%, and power was 515% greater for 104.2 N than for 52.1 N torque reaction force.

(3) Torque build-up time effects on handle stability variables showed conflicting results. This study found that peak handle velocity was greater for hard joints, and peak handle displacement was greater for soft joints.

(4) Power hand tool operation induced involuntary muscle reflexes for the finger and wrist flexors, the biceps and the triceps. Average EMG latency occurred 38 ms after the onset of torque build-up for a hard joint. This suggested that reaction time was inadequate for providing restoring force from muscle contraction for the hard joint during torque build-up and that restoration forces were mostly due to inertial effects. Average EMG latency for the soft joint was 171 ms.

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References

Armstrong, R.B., Warren, G.L. and Lowe, D.A., 1995. Mechanisms in the initiation of contraction-induced skeletal muscle injury. In: S.L. Gordon, S.J. Blair and L.J. Fine (Eds.), Repetitive Motion Disorders of the Upper Extremity, pp. 339–349.

Armstrong, T.J., Radwin, R.G., Hansen, D.J., Kennedy, K.W., 1986. Repetitive trauma disorders: Job evaluation and design. Human Factors, 28(3): 325–336.

Armstrong, T.J., 1989. Subjective worker assessments of hand tools used in automobile assembly. American Industrial Hygiene Association Journal, 50(12): 639–645.

Armstrong, T.J., Bir, C., Finsen, L., Foulke, J., Martin, B., Siogaard, G. and Tseng, K., 1994. Muscle responses to torques of hand held power tools. Journal of Biomechanics, 26(6): 711–718.

Basmajian, J.V., 1983. Biofeedback: Principles and Practice for Clinicians. William and Wilkins, Baltimore.

Freivalds, A. and Eklund, J., 1991. Subjective ratings of stress levels while using powered nutrunners. In: W. Karwowski and J.W. Yates (Eds.), Advances in Industrial Ergonomics and Safety III. Taylor and Francis, New York, pp. 379–386.

Friden, J., Sjostrom, M. and Ekblom, B., 1983. Myofibrillar damage following intense eccentric exercise in man. International Journal of Sports and Medicine, 4: 170–176.

Friden, J. and Lieber, R.L., 1992. Structural and mechanical basis of exercise-induced muscle injury. Medicine and Science in Sports and Exercise, 24(5): 521–530.

Griffin, J.W., 1987. Differences in elbow flexion torque measured concentrically, eccentrically and isometrically. Physical Therapy, 67(8): 1205–1208.

Henriksson, J., Knuttgen, H.G. and Bonde-Petersen, F., 1972. Perceived exertion during exercise with concentric and eccentric muscle contractions. Ergonomics, 15(5): 538–544.

Johnson, S.L. and Childress, L.J., 1988. Powered screwdriver design and use: Tool, task, and operator effects. International Journal of Industrial Ergonomics, 2: 183–191.

Kihlberg, S., Kjellberg, A. and Lindbeck, L., 1995. Discomfort from pneumatic tool torque reaction: Acceptability limits. International Journal of Industrial Ergonomics, 15: 417–426.

Komi, P.V. and Buskirk, E.R., 1972. Effect of eccentric and concentric muscle conditioning on tension and electrical activity of human muscles. Ergonomics, 15(4): 417–434.

Komi, P.V. and Rusko, H., 1974. Quantitative evaluation of mechanical and electrical changes during fatigue loading of eccentric and concentric work. Scandinavian Journal of Rehabilitation Medicine, Suppl. 3: 121–126.

Lieber, R.L., Woodburn, T.M. and Friden, J., 1991. Muscle damage induced by eccentric contraction of 25% strain. Journal of Applied Physiology, 70(6): 2498–2507.

Lindqvist, B., 1993. Torque reaction force reaction in angled nutrunners. Applied Ergonomics, 24(3): 174–180.

Lindqvist, B., Ahlberg, E. and Skogsberg, L., 1986. Ergonomic Tools in our Time. TR Tryck, Stockholm, Sweden.

McCully, K.K. and Faulkner, J.A., 1985. Injury to skeletal muscle fibers of mice following lengthening contractions. Journal of Applied Physiology, 59(1): 119–126.

Meager, S.W., 1987. Tool design for prevention of hand and wrist injuries. Journal of Hand Surgery A, 12: 855–857.

Minor, S., 1995. Personal conversation on eccentric movement and power hand tool operation.

Misner, J.E., Massey, B.H., Going, S.B., Bemben, M.G. and Ball, T.E., 1990. Sex differences in static strength and fatigability in three different muscle groups. Research Quarterly, 61(3): 238–242.

Oh, S. and Radwin, R.G., 1993. Pistol grip power tool handle and trigger size effects on grip exertions and operator preference. Human Factors, 35(3): 551–569.

Oh, S. and Radwin, R.G., 1994. Dynamics of power hand tools on operator hand and arm stability. In: Proc. of the Human Factors and Ergonomics Society 38th Annual Meeting. Human factors and ergonomics society, Santa Monica, pp. 602–606.

Pandolf, K.B., 1977. Psychological and physiological factors influencing perceived exertion. In: G. Borg (Ed.), Physical Work and Effort; Proc. of the 1st International Symposium held at the Wenner-Gren Center, Stockholm, 1975. Pergamon Press, New York, pp. 371–383.

Petrofsky, J.S., Williams, C., Kamen, G. and Lind, A.R., 1980. The effect of handgrip span on isometric exercise performance. Ergonomics, 23(12): 1129–1135.

Radwin, R.G., VanBergeijk, E. and Armstrong, T.J., 1989. Muscle response to pneumatic hand tool torque reaction forces. Ergonomics, 32(6): 655–673.

Rasch, P.J., 1974. The present status of negative (eccentric) exercise: A review. American Corrective Therapy Journal, 28(3): 77–94.

Silverstein, B.A., Fine, L. and Armstrong, T.J., 1987. Occupational factors and carpal tunnel syndrome. American Journal of Industrial Medicine, 11: 343–358.

Stauber, W.T., 1989. Eccentric action of muscles: physiology, injury and adaptation. Exercise and Sport Reviews, 17: 157–185.

Stevenson, M.G. and Baidya, K.N., 1984. Design and selection of hand-held pneumatic power tools for assembly. In: Proc. of the 21st Annual Conference of the Ergonomics Society of Australia and New Zealand, Sydney, Australia, pp. 259–266.

Talag, T.S., 1973. Residual muscular soreness as influenced by concentric, eccentric and static contractions. The Research Quarterly, 44(4): 458–469.

Ulin, S.S., Ways, C.M., Armstrong, T.J. and Snook, S.H., 1990. Perceived exertion and discomfort versus work height with a pistol-shaped screwdriver. American Industrial Hygiene Association Journal, 51(11): 588–594.

Ulin, S.S., Snook, S.H., Armstrong, T.J. and Herrin, G.D., 1992. Preferred tool shapes for various horizontal and vertical work locations. Applied Occupational and Environmental Hygiene, 7(5): 327–337.

Ulin, S.S., Armstrong, T.J., Snook, S.H. and Keyserling, M.W., 1993a. Perceived exertion and discomfort associated with driving screws at various work locations and at different work frequencies. Ergonomics, 36(7): 833–346.

Ulin, S.S., Armstrong, T.J., Snook, S.H. and Franzblau, A.F., 1993b. Effect of tool shape and work location on perceived exertion for work on horizontal surfaces. American Industrial Hygiene Association Journal, 54(7): 383–391.

VanBergeijk, E., 1987. Selection of power tools and mechanical assists for control of occupational hand and wrist injuries. In: Ergonomic Interventions to prevent Musculoskeletal Injuries in Industry. Lewis Publishers, Chelsea, MI, pp. 151–159.

Walmsley, R.P., Pearson, N. and Stymiest, P., 1986. Eccentric wrist extensor contractions and the force velocity relationship in muscle. The Journal of Orthopedic and Sports Physical Therapy, 288–293.