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The influence of target torque and torque build-up time on physical stress in right angle nutrunner operation

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This study used a computer-controlled electric right angle nutrunner to investigate the relative effects of different power hand tool and process parameters on operator muscular exertions, handle stability and subjective ratings of perceived exertion. Target torque (25, 40 and 55 Nm), torque build-up time (35, 150, 300, 500 and 900 ms), and workstation orientation (horizontal and vertical) were studied. Dependent variables included EMG activity of the finger flexors, biceps, and triceps, handle velocity and displacement, work done on the tool-hand system and power involved in doing work, subjective ratings of perceived exertion, and task acceptance. Six inexperienced subjects (three females and three males) participated. Ten replications were performed for each combination of experimental conditions. The consequences of increasing the torque reaction force were greater handle instability and perceived exertion. The effect of torque build-up time on handle kinematics, muscular activity and perceived exertion was not monotonic. Among five build-up times tested, the hand was most unstable (greater peak handle velocity and power against the operator) for a 150 ms build-up time. Greater peak handle displacement, total work against the operator and average EMG were observed for 150 and 300 ms build-up times than for other build-up time conditions. Integrated EMG and EMG latency significantly increased as build-up time increased. Average EMG latency between the onset of EMG burst and the onset of torque build-up was 40 ms for a 35 ms build-up time and 330 ms for a 900 ms build-up time. Subjective ratings of perceived exertion were the least when torque build-up time was 35 ms, however greater peak torque variance was associated with this condition.

1. Introduction

Although manual hand tools rely on the human operator for generating force and torque, power hand tools depend on an external energy source (i.e. electric, pneumatic, and hydraulic). Consequently, the tool operator must react against force and torque produced by the power hand tool in addition to providing force for supporting the tool and for producing feed force. Nutrunners are power hand tools used for tightening threaded fasteners, such as screws and nuts, and are commonly found in manufacturing operations such as automobile assembly. Power nutrunner operation involves reacting against a much sharper torque reaction than the torque generated by the human hand for manual tools during tightening. Operators need to maintain control of the tool while torque rapidly builds up and is removed. The reaction force acting on nutrunner operators is a function of several factors including target torque, spindle speed, joint hardness, and torque build-up time. Some of these

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factors are interdependent. Faster spindle speed results in shorter torque build-up time, and softer joints are related to longer build-up times. Since the duration of exertion is directly related to torque build-up time rather than just the speed of the tool or joint hardness, this study focused on the independent effects of target torque and torque build-up time.

Previous studies have shown that the magnitude of torque reaction force as well as torque build-up time have a significant influence on human operators during power nutrunner use. Kihlberg *et al.* (1995) studied handle displacement using four different right angle nutrunners. Three nutrunners had different shut-off mechanisms (fast, slow and delayed) and were operated for a fixed 50 Nm target torque, and one had a delayed shutoff (stall) and a 75 Nm target torque. They found a strong correlation between perceived discomfort, handle displacement, and reaction forces. That study, however, did not investigate the effects of target torque and torque build-up time.

Radwin *et al.* (1989) investigated the effects of target torque and torque build-up time using four right angle pneumatic nutrunners with target torques ranging from 30 to 100 Nm. They found that average flexor rms electromyography (EMG) activity, scaled for grip force, increased from 372 N for the 30 Nm nutrunner to 449 N for the 100 Nm nutrunner, and the average grip force was 390 N for a long build-up time (2 s), and increased to 440 N for a short build-up time (0·5 s). They also reported that EMG latency was significantly affected by the build-up time. The results showed that the average latency between tool torque onset and peak flexor rms EMG for the long torque build-up time (2 s) was 294 ms, which decreased to 161 ms for the short build-up time (0·5 s). The findings suggested that right angle nutrunner torque reaction force can affect extrinsic hand muscles in the forearm, and hence exertions, by way of a reflex response. Johnson and Childress (1988) showed that low torque was associated with low muscular activity and subjective evaluations of exertion. Oh and Radwin (1994) studied the effects of target torque (29 to 67 Nm) and torque build-up time (35 versus 900 ms) and demonstrated that as torque increased, the handle was more unstable in terms of peak handle velocity and displacement.

Although these previous studies have shown that tool parameters influenced the operator, only few levels of torque and build-up times were considered. Therefore, it is difficult to establish a conclusive relationship between tool dynamics and operator response. Furthermore, previous findings on torque build-up time are conflicting. Radwin *et al.* (1989) and Armstrong *et al.* (1994) recommended the use of a longer build-up time (soft joint) based on muscular exertion measures, while Freivalds and Eklund (1991) and Lindqvist *et al.* (1986) recommended a shorter build-up time in order to reduce torque impulse. For this reason, the current research attempts to broaden and solidify the basis on which this relationship is established by considering a greater range of torque and build-up times than previously used. The purpose of this study was to investigate and quantify the effects of torque reaction force, torque build-up time and workstation orientation on power hand tool operators in terms of muscular activity, handle kinematics and subjective ratings of perceived exertion while using a right angle power nutrunner.

2. Methods

2.1. *Apparatus*

A computer-controlled power tool system was used to simulate right angle nutrunner operation in the laboratory. The system consisted of an Atlas Copco (Stockholm)

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), an i486 micro computer, and a MetraByte 12-bit data acquisition board (Oh 1995). The power supply controlled the tool spindle speed. A torque transducer and an angle encoder were integrated into the tool spindle head, which outputted analogue torque and digital angular rotation signals. Specific tool parameters are reported in Oh and Radwin (1997).

An Indresco joint simulator with a 1·9 cm (0·75 in) hex screw head was mounted on a height adjustable platform. The joint simulator could be oriented horizontally or vertically. The longitudinal axis of the joint head was perpendicular to the ground for the horizontal workstation setting, and parallel to the ground for the vertical workstation setting. A spring tool balancer was used to counterbalance the weight of the tool electric power cords, but did not interfere with tool movement along the plane of spindle rotation.

Three sets of bipolar Ag-AgCl surface EMG electrodes (Beckman Instruments) were affixed over the finger flexors, biceps and triceps of the right upper extremity in order to measure muscular activity during tool operation. Specific muscles were selected based on function and accessibility. The electrodes were placed according to Basmajian (1983). EMGs were amplified and converted into root-mean-squared (rms) outputs. Handle displacement during tool operation was measured using a flexible strain gauge electrogoniometer (Penny and Giles). The goniometer was attached to the tool (figure 1) similar to that in Kihlberg *et al.* (1995). It was calibrated by measuring voltage levels at several known angles and fitting the data using a first order linear regression model.

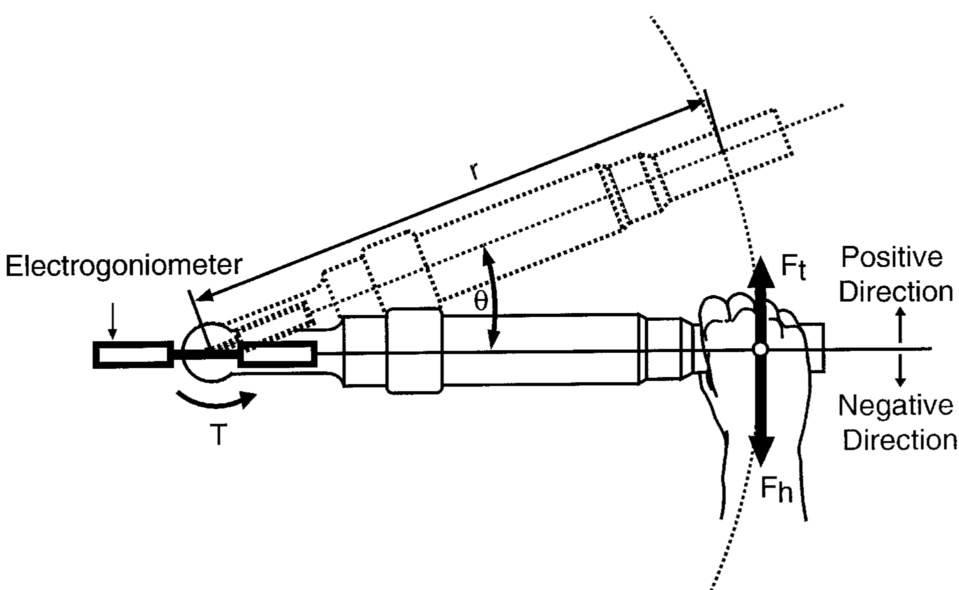

Figure 1. Electrogoniometer set-up to measure handle displacement during tool operation. T is reaction torque, r is handle length, θ is angular handle displacement, F_t is tangential tool force and F_h is tangential hand force.

Torque, spindle angle, angular handle displacement, and rms EMG signals were sampled at 500 Hz. Fourth-order Butterworth (Exar XR-1002CP) analogue anti-aliasing filters with a cut-off frequency of 220 Hz were used for all analogue signals. Angular handle velocity was calculated from the derivative of angular handle displacement. A 251 coefficient, finite impulse response (FIR) digital low-pass filter was used for handle velocity data with a cut-off frequency of 55 Hz. Linear tangential handle velocity and displacement were calculated by multiplying the tool handle length (0·48m), and angular velocity and displacement, respectively.

2.2. *Experimental procedures*

The experiment consisted of three sessions. Subjects learned how to operate the power hand tool in the first session. Different workstation orientations (horizontal and vertical) were presented in the next two sessions. The centre of the tool handle was located 120 cm from the ground, and 20 cm from the average distance between the toes. Subjects operated the right angle nutrunner on the joint simulator by using the right hand while standing. Auditory tones signalled the beginning and the end of a trial.

Subjects tightened a joint every 30 s. Ten replications were made for each experimental condition. A brief rest period was provided after each condition. Subjects were instructed to rate perceived effort in the task using the modified Borg 10-point ratio scale, where 0 represented 'none at all', and 10 was 'very very hard' (Borg 1980, 1982, Ulin *et al.* 1990, 1993a, b). Subjects were also asked to respond yes or no to the question 'is it possible to work a whole day using a tool that reacts like this?' in order to determine task acceptance (Kihlberg *et al.* 1995).

Three males and three females participated in this study. Subjects were recruited by posting advertisements on the university campus. Participants had to be free of any history of hand conditions that might influence tool operation. Subjects were paid on an hourly basis for their participation. The subjects' mean age was 21 years (SD = 1·5 years), mean stature was 167 cm (SD = 12 cm), and mean body weight was 72 kg (SD = 23 kg). All except one subject were right handed.

2.3. *Experimental design and analysis*

The experiment was a four-factor, full factorial design with subject as a random variable (table 1). Torque reaction force was defined as the torque at the tool spindle divided by the handle length (0·48 m). Torque reaction forces of 52·1, 83·3 and 114·6 N corresponded to 25, 40 and 55 Nm torque, respectively. The experimental conditions were selected based on typical torque build-up times and target torque (without torque reaction arm) used in industry. Typical torque build-up time for assembly operations range between 50 ms to 2 s for right angle nutrunners. The order of workstation orientation presentation was counterbalanced between subjects. Only one type of workstation orientation was presented per session. Combinations of all other conditions were presented randomly.

Joints are classified as soft or hard depending on the relationship between torque build-up and spindle angle. The International Organization for Standardization (ISO) specifies that a hard joint has an angular displacement $<30^\circ$ when torque increases from 50 to 100% of target torque, and a soft joint has an angular displacement $>360^\circ$ (ISO-6544 1981). One hard, two medium and two soft joints were included in the study (table 2).

Table 1. Independent variables.

Factors	Effects	Levels
Orientation (*O*)	Fixed	Horizontal, Vertical
Torque reaction force (*T*)	Fixed	52·1, 83·3 and 114·6 N
Build-up (*B*)	Fixed	35, 150, 300, 500, and 900 ms
Subject (*S*)	Random	6 Subjects

Table 2. Build-up time and corresponding spindle angular displacement and joint hardness. One standard deviation is shown in parentheses.

Build-up time (ms)	Average angular displacement (°)	Joint hardness†
35	18 (2)	Hard
150	112 (24)	Medium
300	249 (39)	Medium
500	435 (67)	Soft
900	622 (94)	Soft

†according to ISO-6455.

Representative torque reaction force, handle kinematics, and muscular activity are illustrated in figure 2. Since torque builds up in a clockwise direction, the reaction torque has a tendency to turn the tool counterclockwise (figure 1). When the operator has sufficient strength to react against the reaction torque, then the tool remains stationary or rotates clockwise and the operator exerts concentric muscle contractions against the tool (positive work). However, when the tool overpowers the operator, then it tends to move in a counterclockwise direction and the operator exerts eccentric muscle contractions against the tool (negative work). Therefore, measures of handle movement that occur (handle velocity and displacement) and the direction of rotation can indicate relative tool controllability. Handle movement direction was defined as positive when the handle moved in the direction of tool reaction torque (figure 1).

Relative handle stability during tool operation was quantified using peak handle velocity (PHV) and peak handle displacement (PHD) in the positive direction. PHV and PHD were measured during torque build-up. The average handle velocity (AHV) just before the shutoff (20 to 0 ms) and after the shutoff (40 to 60 ms) were compared. The probability that handle instability increases after shutoff (Pr_{loss}) was calculated to determine if the operator regained control of the tool after tool shutoff. If handle velocity increased after shutoff, it meant that the tool and hand were unstable. The work done on the tool-hand system and the power involved in doing work during torque build-up were also assessed. If the operator has the capacity to successfully react against the torque build-up (positive work), then the tool was considered stable. This occurred when handle displacement and velocity were less than zero. If the handle became unstable and the net handle displacement occurred in the direction of torque reaction away from the operator, then work and power were negative.

Integrated EMG (IEMG) was the area under the rms EMG time series starting from the onset of torque build-up until the tool shutoff. Average EMG (AEMG)

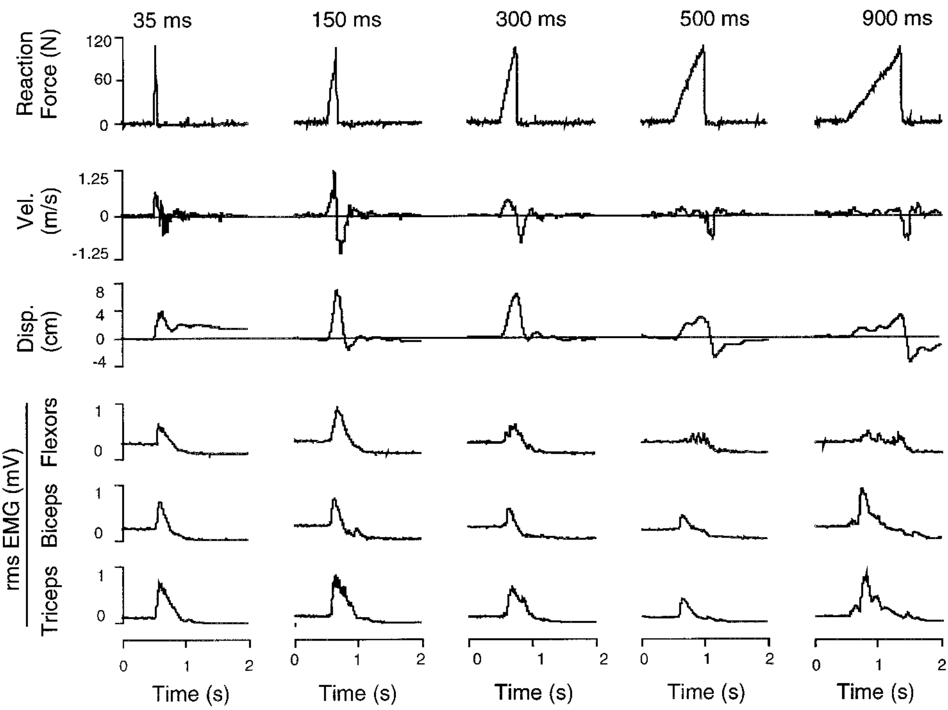

Figure 2. A representative of torque reaction force, handle kinematics and muscular activity measurements.

during torque build-up, and AEMG after shutoff (within 350 ms after shutoff) were calculated. Since rms EMG was influenced by posture, direct comparison of EMG across all orientations was not possible. Therefore, all EMG data were separated into two different orientations. Torque reaction force and build-up time effects were analysed separately within these groups.

A burst of muscle activity is often observed after the onset of torque build-up (Oh and Radwin 1997, Radwin *et al.* 1989). The start of this event was determined by the intersection of rms EMG and a threshold level that was arbitrarily taken as the mean plus five standard deviations of rms EMG activity occurring between 150 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.

The handle velocity zero crossing was the point where handle velocity changed direction from negative to positive and used as a measure of relative handle stability. This point indicated that the torque reaction force produced by the tool overpowered the capacity of the operator to maintain full control of the tool. The corresponding torque reaction force was defined as F_{cross}. If velocity zero crossing occurred more than once as operators regained control (Oh and Radwin 1997), the first crossing was designated as F_{cross1} and the last crossing which occurred before the tool shutoff was called F_{cross2}.

Repeated measures analysis of variance (ANOVA) was used to determine statistically significant effects for handle kinematics, work, power, muscular activity, and F_{cross}. Correlation between handle stability, F_{cross}, and perceived exertions was calculated. *Post-hoc* Tukey pairwise contrast tests were performed for selected significant effects. All statistical analysis was performed using BMDP (Los Angeles, CA) statistical software.

3. Results

3.1. *Handle stability*

A significant torque reaction force effect showed that as torque reaction force (T) increased from 52·1 to 114·6 N, PHV ($F(2,10) = 68·7$, $p < 0·01$) increased by 89%, and PHD ($F(2,10) = 36·2$, $p < 0·01$) increased by 113% (table 3). Torque build-up time (B) had a significant effect on PHV ($F(4,20) = 155·4$, $p < 0·01$) and PHD ($F(4,20) = 22·4$, $p < 0·01$). Tukey pairwise contrast tests showed that PHV at every build-up time were significantly different ($p < 0·05$). Overall, PHV was the greatest for a 150 ms build-up time, and the least for a 900 ms build-up time (table 4). Tukey pairwise contrast tests showed that PHD was greater for 150 and 300 ms build-up times, and the least for a 35 ms build-up time ($p < 0·05$). There was no significant PHD difference either between 150 and 300 ms build-up times, or between 500 and 900 ms ($p > 0·05$).

The significant $T \times B$ interaction for both PHV ($F(8,40) = 11·1$, $p < 0·01$) and PHD ($F(8,40) = 2·9$, $p < 0·05$) are illustrated in figure 3). A *post-hoc* Tukey pairwise contrast test showed that PHV was significantly greater for a 150 ms build-up, followed by a 35 ms build-up than for the other build-up times for all three torque reaction force levels ($p < 0·05$). The Tukey contrast test also showed that PHD was significantly greater for 150 and 300 ms build-up times than for the other build-up times when torque reaction force was 52·1 N ($p < 0·01$). PHD for 150 and 300 ms were significantly greater than PHD for 35 and 900 ms build-up times when torque reaction force was 83·3 N ($p < 0·05$). PHD for 150, 300 and 500 ms build-up times

Table 3. Summary statistics for significant torque reaction force effect.

	52·1 N		83·3 N		114·6 N	
Dependent variable	Mean	SD	Mean	SD	Mean	SD
PHV (m/s)	0·39	0·21	0·57	0·34	0·74	0·41
PHD (cm)	3·71	2·21	5·84	3·64	7·88	4·67
Work (Nm)	−0·56	0·40	−1·36	0·98	−2·54	1·81
Power (Nm/s)	−2·54	2·09	−5·80	4·74	−10·09	7·28

Table 4. Summary statistics for the significant torque build-up time effect.

	35 ms		150 ms		300 ms		500 ms		900 ms	
Dependent variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
PHV (m/s)	0·71	0·24	0·97	0·42	0·51	0·23	0·38	0·18	0·27	0·11
PHD (cm)	2·93	1·30	7·61	3·42	7·28	4·21	6·07	4·64	5·16	3·81
Work (Nm)	−0·39	0·24	−2·02	1·10	−1·99	1·72	−1·64	1·73	−1·39	1·30
Power (Nm/s)	−7·7	4·8	−12·1	6·8	−6·3	5·6	−3·0	3·1	−1·5	1·4
F_{cross2} (N)	37·6	28·0	14·6	9·3	25·1	24·5	50·2	27·8	51·4	21·4
Pr_{loss} (%)	58·9	49·3	5·6	23·0	18·3	38·8	12·8	33·5	13·3	34·1

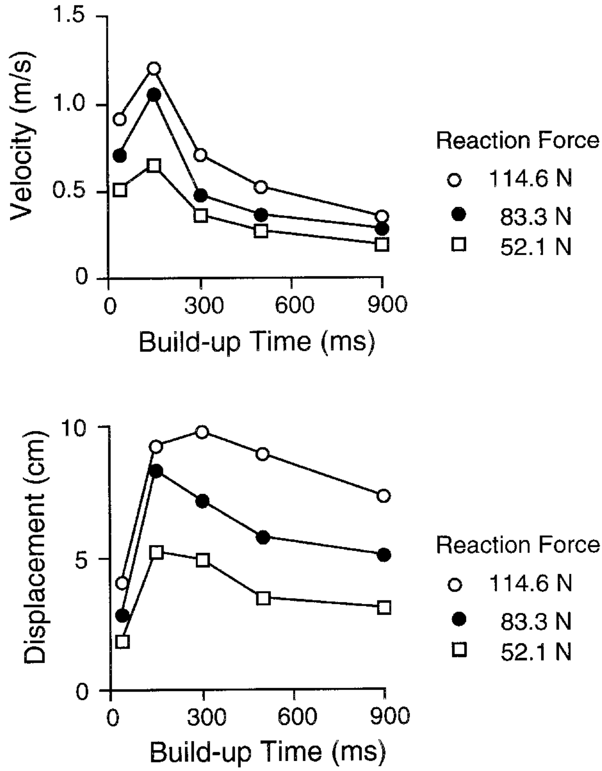

Figure 3. Significant torque reaction force and build-up time interaction effect on peak handle velocity and peak handle displacement.

were greater than for a 35 ms build-up time ($p<0{\cdot}01$) when torque reaction force was 114·6 N.

Workstation orientation also had a significant influence on handle stability. PHV was 46·7% less ($F(1,5) = 30{\cdot}1, p<0{\cdot}01$) for horizontal workstations (mean = 0·46 m/s, SD = 0·26 m/s) than for vertical workstations (mean = 0·67 m/s, SD = 0·34 m/s). A similar trend was observed for PHD ($F(1,5) = 30{\cdot}5$, $p<0{\cdot}01$). PHD for horizontal workstations (mean = 4·0 cm, SD = 2·2 cm) was 90·2% less than PHD for vertical workstations (mean = 7·6 cm, SD = 4·6 cm).

The work ($F(1,5) = 27{\cdot}6, p<0{\cdot}01$) and power ($F(1,5) = 17{\cdot}2, p<0{\cdot}01$) were clearly affected by workstation orientation. The magnitude of total work against the operator (negative work) was an average of 88% greater for vertical workstations (mean = −1·94 Nm, SD = 1·74 Nm) than for horizontal workstations (mean = −1·03 Nm, SD = 0·90 Nm). The magnitude of average power against the operator was 58% greater for vertical workstations (mean = −7·52 Nm/s, SD = 6·99 Nm/s) than for horizontal workstations (mean = −4·77 Nm/s, SD = 4·43 Nm/s).

As torque reaction force increased from 52·1 to 114·6 N, the magnitude of work against the operator ($F(2,10) = 52{\cdot}8$, $p<0{\cdot}01$) increased by 355%, and the magnitude of average power against the operator ($F(2,10) = 80{\cdot}7, p<0{\cdot}01$) increased by 303% (table 3). Table 4 summarizes the effect of build-up time on work ($F(4,20) = 26{\cdot}8$, $p<0{\cdot}01$) and power ($F(4,20) = 78{\cdot}8$, $p<0{\cdot}01$). A *post-hoc* Tukey pairwise contrast test showed that the magnitude of work against the operator was the least for a 35 ms build-up time and the greatest for 150 and 300 ms build-up times ($p < 0.05$). The magnitude of average power against the operator was least when build-up time was 900 ms and greatest when build-up time was 150 ms followed by 35 ms ($p < 0.05$). The significant $T \times B$ interaction for both work ($F(8,40) = 7.8$, $p < 0.01$) and power ($F(8,40) = 17.4$, $p < 0.01$) is plotted in figure 4. The Tukey pairwise contrast test showed that the magnitude of work against the operator was the least for a 35 ms build-up time for all three torque reaction forces. The magnitude of average power against the operator was the least for 500 and 900 ms build-up times ($p < 0.01$) when torque reaction force was 52·1 or 83·3 N. The magnitude of average power against the operator was the least for 900 ms build-up

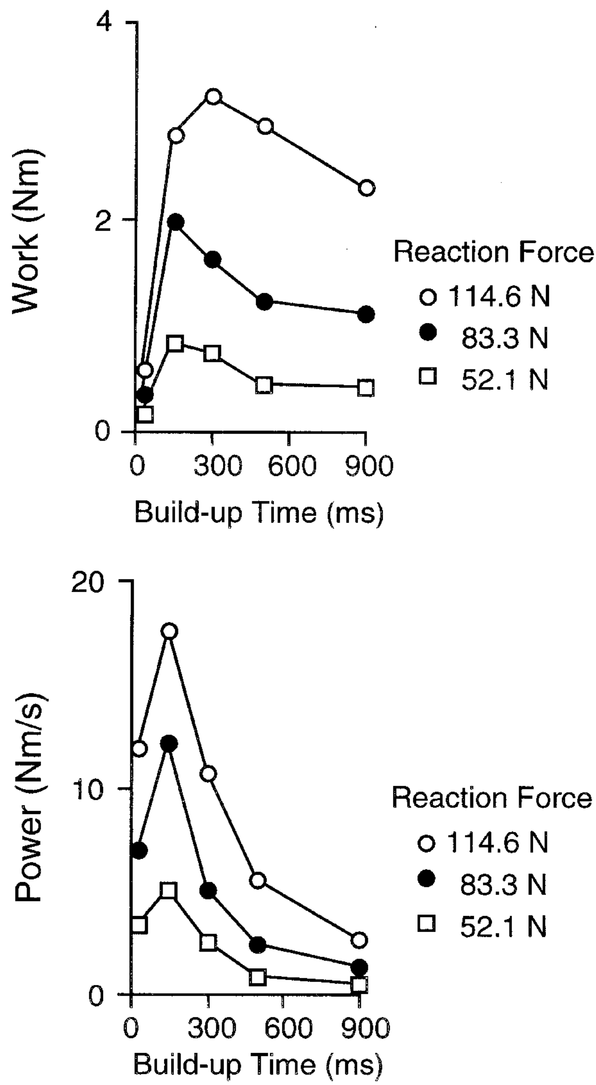

Figure 4. Interaction between torque reaction force and build-up time on total work and average power against the operator.

time when torque reaction force was 114·6 N and was the greatest for a 150 ms build-up time for all three torque reaction forces ($p < 0{\cdot}01$).

Both torque reaction force and torque build-up time had a significant effect on F_{cross1} ($p < 0{\cdot}05$). However, there was no practical difference for F_{cross1} at different torque reaction force and different build-up times. On the average, the first zero velocity crossing occurred 2 ms (SD = 17 ms) after the onset of torque build-up, and the corresponding torque reaction force level was 2·5 N (SD = 2·6 N). Torque reaction force had a significant effect on F_{cross2} ($F(2,10) = 17{\cdot}6$, $p < 0{\cdot}01$). As torque reaction force increased from 52·1 to 114·6 N, F_{cross2} increased by 105% (table 3). Significant build-up time effect (table 4) for F_{cross2} ($F(4,20) = 9{\cdot}8$, $p < 0{\cdot}01$) showed that F_{cross2} was the least for a 150 ms build-up time, and the greatest for 500 and 900 ms build-up times that were not significantly different from each other ($p > 0{\cdot}05$).

The probability of increased handle instability after tool shutoff (Pr_{loss}) was significantly influenced ($F(4,20) = 9{\cdot}0$, $p < 0{\cdot}01$) by torque build-up time when the probability was calculated based on AHV (table 4). A *post-hoc* Tukey pairwise contrast test showed that Pr_{loss} was the least for a 150 ms build-up time (5·6%) and the greatest for a 35 ms build-up time (58·9%). Neither torque reaction time (T) nor orientation (O) had a significant effect on Pr_{loss} ($p > 0{\cdot}05$).

3.2. *Muscle activity*

Integrated rms EMG (IEMG) from all three muscles was significantly affected by the build-up time ($F(4,20) = 29{\cdot}3$ to $55{\cdot}5$, $p < 0{\cdot}01$) for both horizontal and vertical workstations (figure 5). IEMG for a 900 ms build-up time was an average of 16 to 21 times greater than IEMG for a 35 ms build-up time.

Build-up time had a significant effect on AEMG during torque build-up (AEMGb), from the finger flexors ($F(4,20) = 6{\cdot}5$, $p < 0{\cdot}01$), the biceps ($F(4,20) = 3{\cdot}0$, $p < 0{\cdot}05$), and the triceps ($F(4,20) = 2{\cdot}8$, $p < 0{\cdot}05$) for horizontal workstations (figure 6). A *post-hoc* Tukey pairwise contrast test showed that AEMGb for 150 and 300 ms build-up times were significantly ($p < 0{\cdot}05$) greater than AEMGb at other build-up times for all three muscles. Finger flexor AEMGb ($F(4,20) = 3{\cdot}1$, $p < 0{\cdot}05$) and triceps AEMGb ($F(4,20) = 6{\cdot}4$, $p < 0{\cdot}01$) were significantly influenced by build-up time when the tool was operated at the vertical workstations (figure 6). The Tukey test showed that finger flexor AEMGb for a 900 ms build-up time was significantly less than finger flexor AEMGb for a 300 ms condition ($p < 0{\cdot}05$). AEMGb from the triceps for the 150 and 300 ms build-up times were significantly ($p < 0{\cdot}01$) greater than AEMGb at other build-up times for vertically oriented workstations.

AEMG after tool shutoff (AEMGa) for the finger flexors ($F(4,20) = 5{\cdot}0$, $p < 0{\cdot}05$), the biceps ($F(4,20) = 2{\cdot}8$, $p < 0{\cdot}05$), and the triceps ($F(4,20) = 7{\cdot}2$, $p < 0{\cdot}01$) were all significantly influenced by the build-up time when the tool was operated on a horizontal workstation (figure 6). AEMGa for the finger flexors and the triceps were significantly greater for 35 and 150 ms build-up times than AEMGa for other build-up times ($p < 0{\cdot}01$) for horizontal workstations. AEMGa for the biceps for a 35 ms build-up time was not significantly different from AEMGa for a 150 ms build-up time, and significantly greater than AEMGa for build-up times of 300 ms or more. Similar results were found for AEMGa for the finger flexors ($F(4,20) = 4{\cdot}0$, $p < 0{\cdot}05$) and the triceps ($F(4,20) = 6{\cdot}0$, $p < 0{\cdot}01$) for vertical workstations (figure 6). AEMGa for the finger flexors and the triceps were significantly greater for 35 and 150 ms build-up times than AEMGa for other build-up times ($p < 0{\cdot}05$).

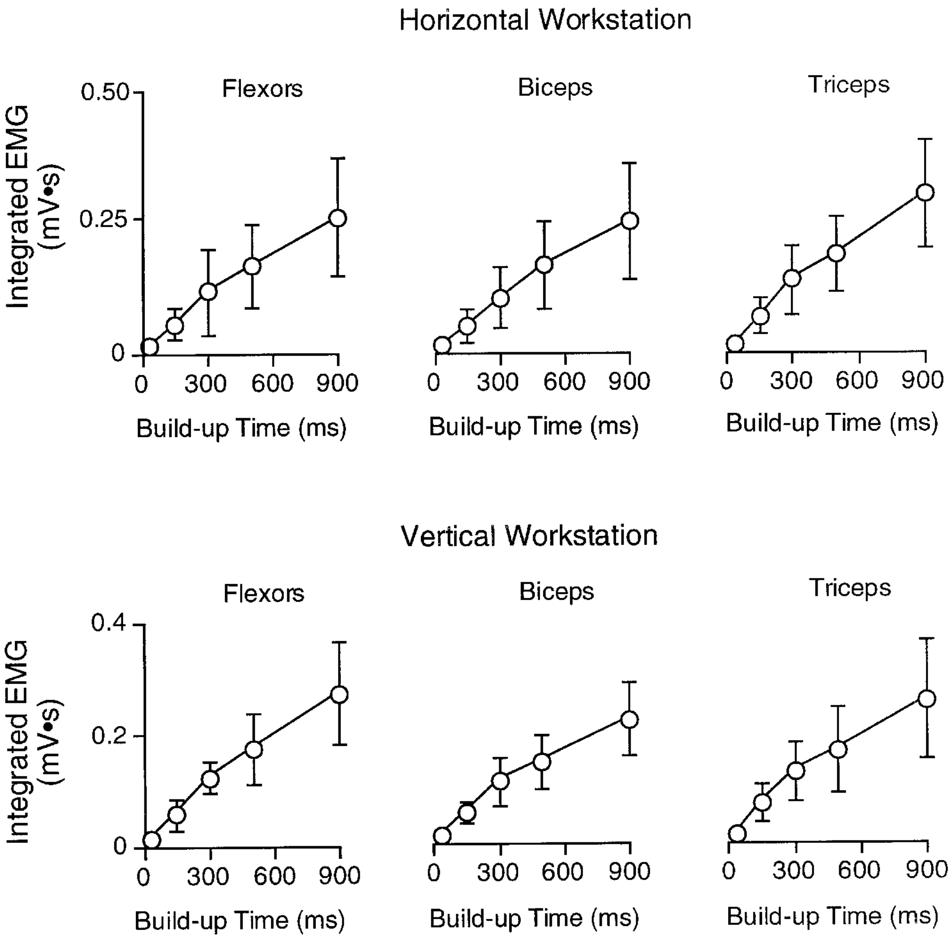

Figure 5. Integrated EMG from all three muscles (finger flexors, biceps and triceps) were significantly affected by the build-up time (bars represent 1 SD).

An EMG burst was observed 87% of the time for the finger flexors, 88% of the time for the biceps and 94% of the time for the triceps among 450 trials analysed. The time difference between the onset of torque build-up and the onset of EMG burst (LEMG) was significantly ($F(4,20) = 13{\cdot}4$ to $112{\cdot}4$, $p < 0{\cdot}01$) influenced by build-up time (figure 7). On the average, LEMG for a 900 ms build-up time was 8·6 to 14·9 times greater than LEMG for a 35 ms build-up time. Torque reaction force also had a significant effect on LEMG of all three muscles for both horizontal and vertical workstations ($F(2,10) = 7{\cdot}3$ to $170{\cdot}3$, $p < 0{\cdot}05$). As torque reaction force increased from 52·1 to 114·6 N, LEMG decreased by 50% to 147% (figure 7).

3.3. *Perceived exertion*

Both torque reaction force and build-up time had significant effects on subjective ratings of perceived exertion and task acceptance rate (figure 8). As torque reaction force increased from 52·1 to 114·6 N, the average perceived exertion level increased from 2·7 to 4·3 ($F(2,10) = 17{\cdot}7$, $p < 0{\cdot}01$), and the task acceptance rate dropped from

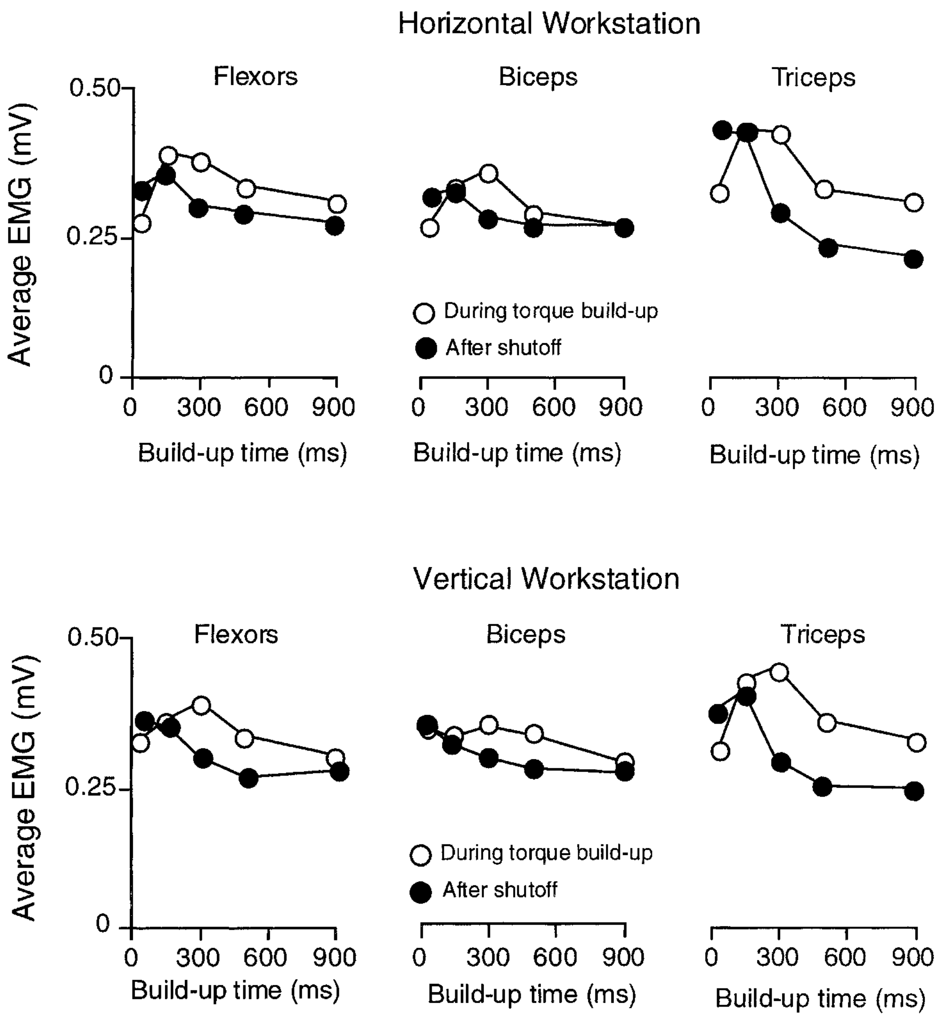

Figure 6. Significant build-up time effect for average EMGs during torque build-up and average EMG after shutoff.

73 to 28% ($F(2,10) = 12{\cdot}1$, $p < 0{\cdot}01$). Average perceived exertion ($F(4,20) = 15{\cdot}9$, $p < 0{\cdot}01$) and acceptance rate ($F(4,20) = 8{\cdot}4$, $p < 0{\cdot}01$) were influenced by build-up time. A Tukey pairwise contrast test showed that perceived ratings were significantly less, and acceptance rates were significantly greater for a 35 ms build-up time ($p < 0{\cdot}01$).

3.4. *Correlation*

Pairwise correlation coefficients were calculated among the handle kinematics, work, power, muscular activity, perceived exertion ratings and task acceptance rate. Total work was strongly correlated with PHV ($r = -0{\cdot}94$), and average power was strongly correlated with PHD ($r = -0{\cdot}92$). However, none of the handle stability measures were strongly correlated with either subjective ratings of perceived exertion

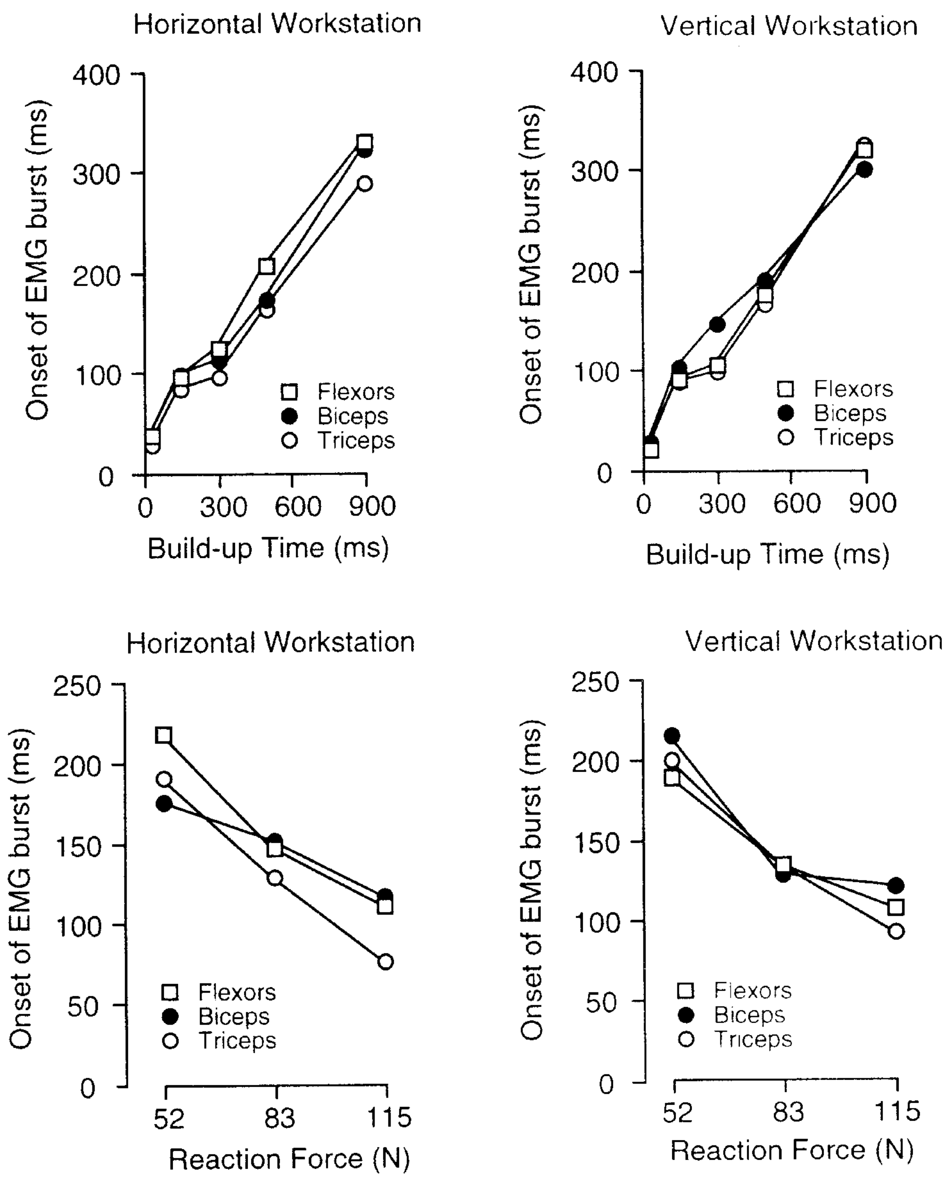

Figure 7. The time at the onset of EMG burst were significantly influenced by torque build-up times and torque reaction force.

($0.07 < r < 0.45$) or task acceptance rate ($-0.45 < r < -0.17$). The correlation between total work and average power was $r = 0.61$. PHV was negatively correlated with torque build-up time ($r = -0.6$).

Torque build-up time had a strong correlation with IEMG from all three muscles for both horizontal and vertical workstations ($0.76 < r < 0.86$). The time when the onset of the EMG burst occurred was correlated with build-up time for all three muscles ($0.69 < r < 0.75$). However, none of the EMG variables and none of the

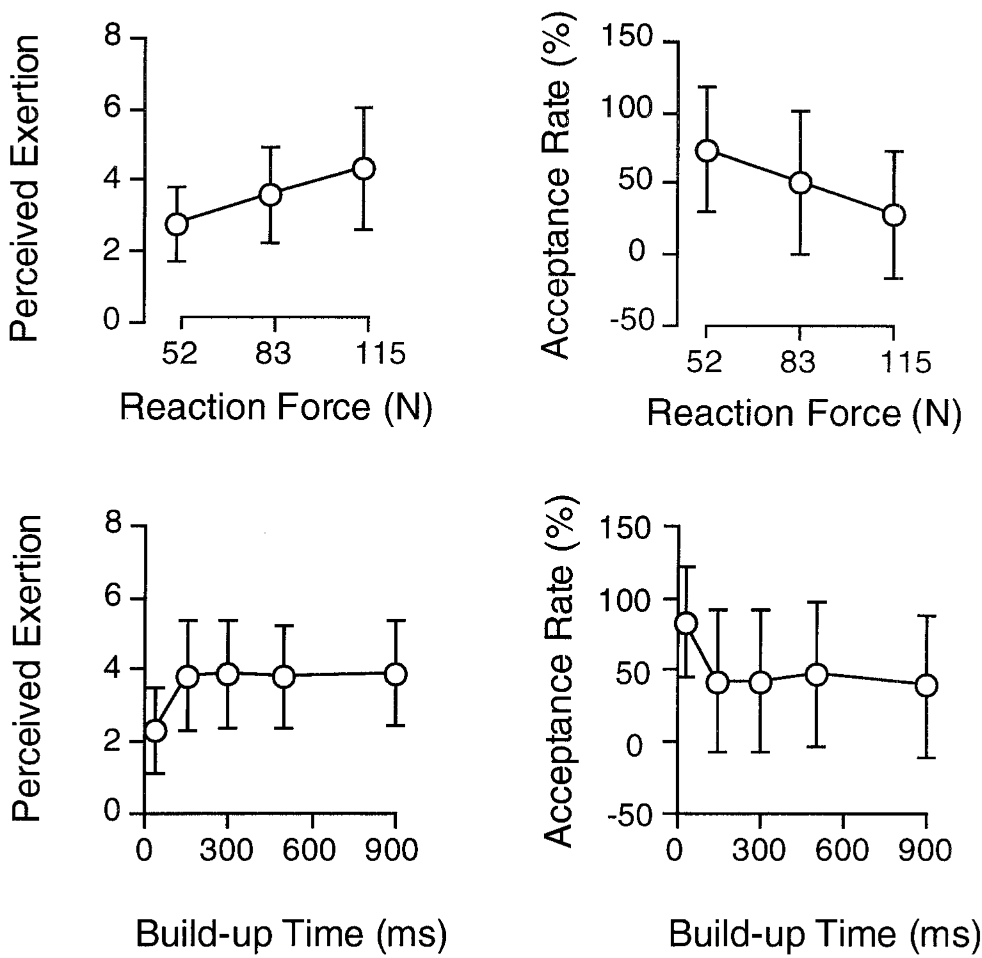

Figure 8. Significant build-up time and target torque reaction force effect on perceived exertion and task acceptance rate. Perceived exertions were significantly lower for the 35 ms build-up time, and acceptance rate was significantly higher for the 35 ms build-up time (bars represent 1 SD).

handle stability measures were strongly correlated to either subjective perceived exertion ratings or task acceptance rate ($-0{\cdot}46 < r < 0{\cdot}25$). Time at the final zero velocity crossing and build-up time had a correlation coefficient of 0·84.

3.5. *Peak torque variance*

The accuracy of final torque was measured by the following equation:

$$\text{Error}\ (\%) = \frac{3\sigma}{\mu} \times 100$$

where μ is the average peak torque and σ is one standard deviation of peak torque. The ANOVA results showed that error was significantly influenced by torque build-up time ($F(4,20) = 15{\cdot}2$, $p < 0{\cdot}01$). A *post-hoc* Tukey pairwise contrast test indicated

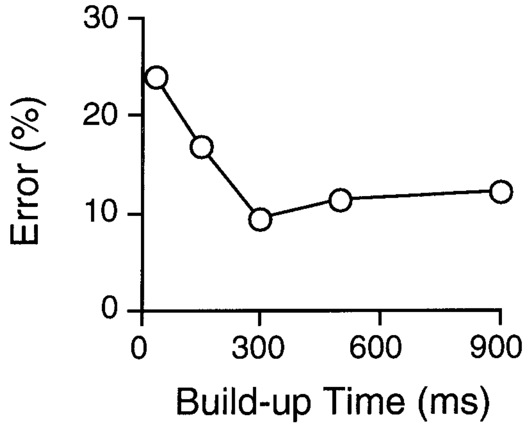

Figure 9. Effect of torque build-up time on the target torque error.

that the error for a 35 ms build-up time was greater ($p < 0{\cdot}01$) than any other build-up times (figure 9).

4. Discussion

The results of the current study suggest that workstation orientation and tool dynamics (target torque reaction force and torque build-up time) influenced operator muscular exertion and handle stability. In general, handle instability increased when the tool was operated on a vertical workstation (rather than a horizontal workstation), when torque reaction force was high (88·3 and 114·6 N), and for a 150 ms torque build-up time, regardless of torque reaction force.

Previous studies have demonstrated that a horizontal workstation is preferable for right angle tool use. Ulin *et al.* (1992) showed that average subjective ratings of perceived exertion were significantly less when the tool was operated on horizontal workstations rather than vertical workstations. The current study supports these findings. The PHV was 47% greater and the PHD was 90% greater for vertical workstations than for horizontal workstations. Also, 88% more negative work and 58% more power against the operator were recorded while the tool was operated on a vertical workstation. However, subjective ratings of perceived exertion and task acceptance rates did not differ significantly ($p < 0{\cdot}05$) between horizontal and vertical workstations. This might come from the fact that the torque levels in the current study were much greater than the torque level used in the study by Ulin *et al.* (1992).

The effect of target torque was consistent with previous studies that showed that target torque was related to muscular exertion, subjective perceived exertion and handle instability (Johnson and Childress 1988, Lindqvist 1993, Oh and Radwin 1994, Radwin *et al.* 1989). As torque reaction force increased from 52·1 to 114·6 N, PHV and PHD increased by 89 and 113%, respectively, the magnitude of negative work increased by 35%, and the magnitude of average power against the operator increased by 30%. Under these conditions, perceived exertion also increased from 2·7 to 4·3 (as rated on Borg's 10-point scale) and task acceptance rate decreased from 73 to 28%. When the tool was operated on a horitontal workstation, mean finger flexor EMG was significantly influenced by torque reaction force. As torque reaction force increased from 52·1 to 114·6 N, the average flexor EMG increased by 14% .

Torque build-up time is a concern because it is directly related to assembly time and exertion duration. Although longer build-up time results in longer exertions and greater torque impulse, it may have some benefits in terms of tool control since it gives the operator a longer time to react. The effect of torque build-up time on power hand tool operators has been studied in terms of perceived exertion, muscular activity and handle stability (Armstrong *et al.* 1994, Freivalds and Eklund 1991, Lindqvist *et al.* 1986, Oh and Radwin 1994, Radwin *et al.* 1989). However, some of these previous findings conflict.

With regard to the effect of build-up time on subjective ratings of perceived exertion, previous studies have indicated that these ratings were less under shorter build-up times. Other studies suggested that a longer build-up time was better for reducing muscular activities during torque build-up. Freivalds and Eklund (1991) studied the consequences of various tool types (in-line and pistol), joints (soft and hard), spindle speed (low and high), and workstation orientation. The authors reported that as torque impulse increased, subject-perceived exertion ratings increased. Based on this finding, they recommended that power tools should be run at high speed in order to minimize torque impulse. Lindqvist (1993) studied two different joints, one hard and one medium-hard joint, and found subjective ratings of perceived exertion were less for hard joints.

Contrary to the recommendations from the previous studies cited above, some studies recommended long build-up times. Radwin *et al.* (1989) showed that flexor rms EMG (scaled for hand grip force integrated over the torque build-up) was 839 Ns for a 2 s build-up time and 312 Ns for a 0·5 s build-up time. However, average EMG activity was greater for short build-up times than for long build-up times. These results led the authors to recommend that lower spindle speeds be used to minimize muscle response. Armstrong *et al.* (1994) studied three torque build-up times (50, 250 and 450 ms) using a simulated tool handle, and reported that peak EMG from the finger flexors increased as build-up time decreased. They also concluded that torque should build up slowly (longer than 250 ms) in order to minimize the peak EMG.

The results suggested that the effect of torque build-up on handle stability and EMG was more complex than a simple monotonic function. Although the effect might appear linear for limited build-up times, the build-up time effect was peaked (figure 3). The average EMG, PHD and the magnitude of total work against the operator were significantly greater for 150 and 300 ms build-up times ($p<0·05$). PHV and average power against the operator were greater for a 150 ms build-up time ($p<0·01$). Among the five build-up times tested, subjective perceived exertions were significantly less and task acceptance rate was greatest for a 35 ms build-up time. The average subjective perceived exertion was 2·3 (SD = 1·1) for the 35 ms build-up time where scale 2 was rated as 'easy' and scale 3 was rated as 'moderately hard'. This non-linear build-up time effect suggested that both torque reaction force and build-up time (torque rate) should be considered.

Although subject-perceived exertion was less and task acceptance rate was greater for a 35 ms build-up time than for longer build-up times, the results from the current study showed that the operator might not have enough time to voluntarily react against torque build-up with the 35 ms build-up time. On the average, the onset of the EMG burst occurred 40 ms after the onset of torque build-up for the 35 ms build-up time. This indicated that the muscles were not activated until a significant amount of torque had built up for the 35 ms build-up time. Average EMG data also supported that 35 ms build-up time might be too short for muscles to be activated for reacting torque build-up due to the EMG latency. AEMG measured before the shutoff was less than AEMG after the shutoff for the 35 ms build-up time (figure 6). Lack of muscular contraction during torque build-up might explain why the peak handle velocity was higher for short build-up times. Without muscular contractions, the inertia of the tool and hand had to absorb all of the reaction force. Short exertion duration and lack of muscular contractions due to EMG latencies might contribute to lower subjective ratings of perceived exertion for the 35 ms build-up.

The larger torque variance for the 35 ms build-up time indicated that even though subjective perceived exertion was less, this condition might result in more target torque error. Also, the probability of increased handle instability after shutoff was significantly greater for the 35 ms build-up time ($p < 0{\cdot}05$). This suggests that even after shutoff, operators did not have sufficient capacity to control the tool reaction torque. Therefore, the 35 ms build-up time increased handle stability in terms of peak handle displacement and negative work, and reduced subjective perceived exertion; however, the lack of muscular contraction during torque build-up reduced tightening quality.

The build-up time effect on EMG latency was consistent with the previous findings. Radwin *et al.* (1989) reported that the average latency between the onset of tool spindle torque and peak flexor rms EMG was 294 ms (SD = 133 ms) for 2 s build-up time and 161 ms (SD = 76 ms) for 0·5 s build-up time. The current study showed that average EMG latency at 0·5 s build-up time was 205 ms (SD = 102 ms) for a horizontal workstation, and 175 ms (SD = 112 ms) for a vertical workstation. The result also showed that EMG latency increased as build-up time increased (figure 7).

Studies in muscle reflexes showed that there exists short and long latency EMG activities when a human muscle is stretched. Although there were variations among muscles and methodologies used, reported short EMG latency was 25 to 50 ms, long EMG latency was 45 to 80 ms, and EMG latency longer than 100 ms was considered as voluntary activity (Agarwal and Gottlieb 1977, Balestra *et al.* 1992, Cody and Plant 1989, Gielen *et al.* 1988). Based on these previous studies, the EMG latency measured for a 35 ms build-up time seemed to be mainly from the involuntary reflex response. On the average, finger flexor EMG latency for the 35 ms build-up time was 43 ms (SD = 30 ms). Longer EMG latencies ($>$100 ms) measured for build-up times 300 ms or longer in this study seemed to come from the voluntary muscle contraction. This meant that the short and long latency EMG burst, due to muscle reflexes, might not have been detected and that voluntary contractions were measured for long build-up times ($\geqslant$300 ms). Cody and Plant (1989) showed that the amplitude of the short latency component decreased, when velocity of tendon extension decreased. If the amplitude of the short latency component became too small when build-up time increased, then this component might not have been detected since the current study used an arbitrary threshold level to determine the occurrence of EMG bursts. This may explain why voluntary muscle activities were detected for longer build-up times. Although a previous study reported that decreased movement velocity resulted in increased EMG latency for antagonistic muscle while flexing the elbow joint (Corcos *et al.* 1989), it is not understood why EMG latency increased as build-up time increased.

The handle velocity zero crossing point indicated when the tool started to overpower the operator. The last velocity zero crossing point is important because, after that point, the operator did not regain tool stability. The effect of torque build-up time on the torque reaction force corresponding to the last velocity zero crossing (F_{cross2}) was significant and showed that 150 ms build-up time resulted in the least F_{cross2}.

All subjects preferred a low target torque reaction force (52·1 N). Although four subjects preferred short build-up times (hard joint) and two subjects preferred long build-up times (soft joint), all subjects reasoned their preference based on perceived tool controllability. The subjects who preferred the short build-up time reported that they did so because they did not have to exert much force, and they perceived themselves to have better control because of minimal tool displacement. The other two subjects who preferred a long build-up time felt that they had more control over the tool since they had enough time to react against the torque reaction force by exerting force. Three subjects commented that for low torque reaction force a short build-up time was better, while for high torque reaction force, a long build-up time was preferable because they could exert the force necessary to control the tool.

This study was limited to short-term effects since inexperienced subjects tightened ten joints for each experimental condition. Consequently, fatigue effects and learning effects were not measured. Long build-up times were associated with less peak torque variance, peak handle velocity and power. However, these conditions were also related to larger integrated muscular exertions that might result in earlier onset of fatigue. With regard to the learning effect, experienced power hand tool operators might use different strategies to react against torque build-up that have not been identified. The long-term effects on the tool operator is needed for developing more comprehensive ergonomic guidelines for power hand tool use.

5. Conclusions

Using a right angle nutrunner on a horizontal workstation when the tool is at elbow height (120 cm), the least possible torque reaction force resulted in less handle instability and perceived exertion. Build-up times of 150 and 300 ms were associated with increased handle instability and greater muscular activity. When torque reaction force is greater than 83·3 N, 500 ms build-up times also resulted in greater handle displacement and work against the operator. Although the hard joint (35 ms build-up time) resulted in the least perceived exertion and the least work against the operator, this build-up time was related to more torque scatter and greater power.

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